DOC.20041020.0009

QA: QA

ANL-WIS-MD-000019 REV 02

October 2004

Features, Events, and Processes: System Level

Prepared for:
U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Office of Repository Development
1551 Hillshire Drive
Las Vegas, Nevada 89134-6321

Prepared by:
Bechtel SAIC Company, LLC
1180 Town Center Drive
Las Vegas, Nevada 89144

Under Contract Number
DE-AC28-01RW12101

QA: QA

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October 2004

OCRWM	Scientific Analysis Signature Page/ Change History	Page iii 1. Total Pages: 408

2. Scientific Analysis Title Features, Events, and Processes: System Level			
3. DI (including Revision Number) ANL-WIS-MD-000019 REV 02			
4. Total Appendices 4		5. Number of Pages in Each Appendix A-8, B-144, C-18, D-68	
	Printed Name	Signature	Date
6. Originator	Daniel McGregor	Daniel L. McGregor	10/14/~~05~~ 04 ENB 5/23/05
7. Checker	Bruce Hastings	Bruce Hastings	10/15/04
8. QER	Judith Gebhart	J Gebhart	10/15/04
9. Responsible Manager/Lead	Geoff Freeze Paul Dixon For	Paul	10-15-04
10. Responsible Manager	Geoff Freeze Paul Dixon For	Paul	10-15-04

11. Remarks

Appendix C of this revision addresses human intrusion and is an expansion of earlier work. Collaborating authors for Appendix C included Kevin Mon and Bryan Bullard, who originated early drafts of the material. Concepts and approaches from those early drafts have been incorporated herein.

Change History

12. Revision No.	13. Description of Change
00	Initial issue
01	Revision addresses updates in supporting information since TSPA-SR, includes two new FEPs for human intrusion, and is modified to address changes in implementing procedures.
02	Revision incorporates changes to generic text sections to increase readability, improve traceability, and provide consistency with other FEP AMRs. Attachments in previous revision changed to Appendix due to procedural change. Incorporated Repository Integration Team and key technical issue review comments. Extensive editorial changes in Sections 1 through 5. Issued without change bars due to extensive revisions.

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ACRONYMS

AMR	analysis model report
CSNF	commercial spent nuclear fuel
DHLW	DOE-owned high-level radioactive waste
DOE	U.S. Department of Energy
DSNF	DOE-owned spent nuclear fuel
EBS	engineered barrier system
EPA	U.S. Environmental Protection Agency
FEIS	final environmental impact statement
FEPs	features, events, and processes
HLW	high-level radioactive waste
IED	information exchange drawing
LA	License Application
NRC	U.S. Nuclear Regulatory Commission
PRD	Project Requirements Document
RMEI	reasonably maximally exposed individual
SNF	spent nuclear fuel
SZ	saturated zone
TNT	trinitrotoluene (dynamite)
TSPA	total system performance assessment
TSPA-LA	total system performance assessment for license application
TSPA-SR	total system performance assessment for site recommendation
UZ	unsaturated zone
YMP	Yucca Mountain Project

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1. PURPOSE

The purpose of this analysis report is to evaluate and document the inclusion or exclusion of the system-level features, events, and processes (FEPs) with respect to modeling used to support the total system performance assessment for the license application (TSPA-LA). A screening decision, either Included or Excluded, is given for each FEP along with the technical basis for screening decisions. This information is required by the U.S. Nuclear Regulatory Commission (NRC) at 10 CFR 63.113 (d, e, and f) (DIRS 156605).

The system-level FEPs addressed in this report typically are overarching in nature, rather than being focused on a particular process or subsystem. As a result, they are best dealt with at the system level rather than addressed within supporting process-level or subsystem-level analyses and models reports. The system-level FEPs also tend to be directly addressed by regulations, guidance documents, or assumptions listed in the regulations; or are addressed in background information used in development of the regulations. For included FEPs, this analysis summarizes the implementation of the FEP in the TSPA-LA (i.e., how the FEP is included). For excluded FEPs, this analysis provides the technical basis for exclusion from the TSPA-LA (i.e., why the FEP is excluded). The initial version of this report (Revision 00) was developed to support the total system performance assessment for site recommendation (TSPA-SR). This revision addresses the license application (LA) FEP List (DIRS 170760).

1.1 PLANNING AND DOCUMENTATION

Documentation requirements for this analysis report are described in the technical work plan entitled *Technical Work Plan for: Regulatory Integration Team Revision of Features, Events, and Processes (FEPs) Analysis Reports Integration* (BSC 2004 [DIRS 170408]). There are no changes in the assigned system-level FEP list for TSPA-LA from that described in the technical work plan, aside from use of the updated FEP list (DIRS 170760).

1.2 SCOPE

The scope of this report is to describe, evaluate, and document screening decisions and technical bases for the system-level FEPs for TSPA-LA. For FEPs that are included in the TSPA-LA, this analysis report provides a TSPA-LA disposition, which is a consolidated summary of how the FEP has been included and addressed in the TSPA-LA model. In other FEP analysis model reports (AMRs), the disposition is a consolidated summary of how the FEP has been included and addressed in the TSPA-LA model, based on supporting technical analysis reports and model reports (collectively, AMRs) that describe the inclusion of the FEP. This approach works well for FEPs that focus on a particular process, interrelated processes, or a defined subsystem. By contrast, system-level FEPs are overarching and are not focused on a particular process or subsystem and, therefore, evaluation of the FEPs cannot be assigned or mapped to a specific AMR or set of AMRs. Consequently, in some cases the system-level FEP dispositions refer directly to the TSPA-LA or other higher-level supporting documentation, and no “roadmap” to supporting AMRs is provided. For system-level FEPs that are excluded from the TSPA-LA, this document provides the screening arguments identifying the bases for the screening decision (i.e., low probability, low consequence, or by regulation) and the technical basis supporting the decision is discussed. References to project and non-project information supporting the exclusion are provided.

In cases where a FEP covers multiple technical areas and is shared with other FEP AMRs, this analysis report provides only a partial technical basis for the screening decision as it relates to (generic name) concerns. The full technical basis for the shared FEPs is addressed, collectively, by all of the sharing FEP AMRs. Only one system-level FEP, FEP 1.1.11.00.0A, which addresses monitoring of the repository, is shared with another analysis report (Table 1-1).

An overview of the Yucca Mountain Project (YMP) FEP analysis and scenario development process is presented in *The Development of the TSPA-LA Features, Events, and Processes* (BSC 2004 [DIRS 168706], Sections 2.4, 3, and 4), describing the TSPA-LA FEP identification and screening process that led to the development of the LA FEP List (DIRS 170760). Changes in the FEP list, FEP names, and FEP descriptions can also be traced through that report. The FEPs addressed in this report are a subset of the revised LA FEP List. These FEPs are listed in Table 1-1, and shared FEPs are indicated.

The resulting system-level FEP list has been compared with the list of external hazards presented in *MGR External Events Hazards Screening Analysis* (BSC 2003 [DIRS 163999]), which deals with external events occurring within the operational and preclosure periods. Within the constraints of postclosure concerns, as opposed to preclosure considerations (e.g. FEPs do not address preclosure concerns, such as operations, unless they have a potential to influence postclosure conditions; timescales of concern for preclosure are on the order of 50 to 100 years, compared to the 10,000-year basis for postclosure considerations), the FEP lists were found to be consistent.

Direct inputs supporting the screening decisions are listed in Section 4. Indirect inputs supporting the screening decisions are listed in Section 6.1. The individual FEP discussions providing identification (FEP number, name, and description) and screening (screening decision, screening argument, or TSPA disposition) information are in Section 6.2. Appendix A is a glossary. Appendix B provides qualification of non-project specific meteorite data for intended use with this document. Appendix C addresses the analysis for the timing of human intrusion. Appendix D addresses meteorite impact probabilities.

Table 1-1. System-Level FEPs for TSPA-LA

FEP Number	FEP Name	Addressed in Section	Sharing FEP AMR
Assessment Basis and Modeling Requirement FEPs (Section 6.2.1)			
0.1.02.00.0A	Timescales of concern	6.2.1.1	—
0.1.03.00.0A	Spatial domain of concern	6.2.1.2	—
0.1.09.00.0A	Regulatory requirements and exclusions	6.2.1.3	—
0.1.10.00.0A	Model and data issues	6.2.1.4	—
1.1.07.00.0A	Repository design	6.2.1.5	—
1.1.13.00.0A	Retrievability	6.2.1.6	—
2.1.01.04.0A	Repository-scale spatial heterogeneity of emplaced waste	6.2.1.7	—
Process and Site-Control FEPs (Section 6.2.2)			
1.1.05.00.0A	Records and markers for the repository	6.2.2.1	—
1.1.08.00.0A	Inadequate quality control and deviations from design	6.2.2.2	—
1.1.09.00.0A	Schedule and planning	6.2.2.3	—
1.1.10.00.0A	Administrative control of the repository site	6.2.2.4	—
1.1.11.00.0A	Monitoring of the repository	6.2.2.5	Unsaturated Zone (UZ)
1.1.12.01.0A	Accidents and unplanned events during construction and operation	6.2.2.6	—
Human Intrusion FEPs (Section 6.2.3)			
1.4.02.01.0A	Deliberate human intrusion	6.2.3.1	—
1.4.02.02.0A	Inadvertent human intrusion	6.2.3.2	—
1.4.02.03.0A	Igneous event precedes human intrusion	6.2.3.3	—
1.4.02.04.0A	Seismic event precedes human intrusion	6.2.3.4	—
1.4.03.00.0A	Unintrusive site investigation	6.2.3.5	—
1.4.04.00.0A	Drilling activities (human intrusion)	6.2.3.6	—
1.4.04.01.0A	Effects of drilling intrusion	6.2.3.7	—
1.4.05.00.0A	Mining and other underground activities (human intrusion)	6.2.3.8	—
1.4.11.00.0A	Explosions and crashes (human activities)	6.2.3.9	—
3.3.06.01.0A	Repository excavation	6.2.3.10	—
Miscellaneous Geologic and Astronomic FEPs (Section 6.2.4)			
1.2.05.00.0A	Metamorphism	6.2.4.1	—
1.2.08.00.0A	Diagenesis	6.2.4.2	—
1.2.09.00.0A	Salt diapirism and dissolution	6.2.4.3	—
1.2.09.01.0A	Diapirism	6.2.4.4	—
1.5.01.01.0A	Meteorite impact	6.2.4.5	—
1.5.01.02.0A	Extraterrestrial events	6.2.4.6	—
1.5.03.01.0A	Changes in the earth’s magnetic field	6.2.4.7	—
1.5.03.02.0A	Earth tides	6.2.4.8	—
2.2.06.05.0A	Salt creep	6.2.4.9	—
2.3.13.03.0A	Effects of repository heat on the biosphere	6.2.4.10	—

1.3 SCIENTIFIC ANALYSIS LIMITATIONS

The intended use of this analysis report is to provide FEP screening information for a project-specific FEP database and to promote traceability and transparency for included and excluded FEPs. This analysis report is intended to be used as the source documentation for inclusion or exclusion of system-level FEPs for the TSPA-LA model. The following limitations apply to this analysis report:

- Because this analysis report cites other AMRs and controlled documents as direct input, the limitations of this analysis report inherently include the limitations and constraints described in the cited documents. In particular, the results of the waste package degradation analyses (BSC 2004 [DIRS 169996], Sections 6.5 and 7.2) result from the use of representative thermal hydrologic history files produced to allow model runs to be exercised in the cited report. The actual drip shield and waste package degradation profiles used in the TSPA-LA model will make use of the actual thermal hydrologic history files appropriate for the repository. Because representative histories were used, significant differences in the degradation profile generated for TSPA-LA are not expected.

- In the one case (Table 1-1) of a shared FEP (FEP 1.1.11.00.0A, Monitoring of the repository), the scope of this analysis report is focused on programmatic monitoring as described in the regulations. The full technical basis for this shared FEPs is addressed, collectively, by all of the sharing FEP AMRs.

- For screening, the mean values of probabilities, mean amplitude of events, or mean value of consequences (e.g., mean time to waste package degradation) are generally used in this analysis report as a basis for reaching include-exclude decisions. Mean values are determined based on the range of possible values.

- The results of the FEP screening presented here are specific to the repository design and processes for the YMP available at the time of the TSPA-LA. Changes in direct inputs (Section 4.1), baseline conditions used for this evaluation, or other subsurface conditions will need to be evaluated to determine whether the changes are within the limits stated in the FEP evaluations. Engineering and design changes are subject to evaluation to determine whether there are any adverse affects on safety, as codified at 10 CFR 63.73 and in Subparts F and G (DIRS 156605). See also the requirements at 10 CFR 63.44 (DIRS 156605).

2. QUALITY ASSURANCE

Development of this analysis report and the supporting analyses are subject to the Office of Civilian Radioactive Waste Management quality assurance program as identified in the *Technical Work Plan for: Regulatory Integration Team Revision of Features, Events, and Processes (FEPs) Analysis Reports* (BSC 2004 [DIRS 170408], Section 8.1).

The report contributes to the analysis and modeling used to support performance assessment. The system-level FEPs documented here involve investigations of items or barriers on the Q-list and have the potential to affect the calculation of the performance of the natural barriers and various engineered barrier system (EBS) components included on the Q-list. However, the system-level FEPs themselves do not qualify as "Q-list" items. The evaluations and conclusions do not directly affect engineered features important to safety, as defined in AP-2.22Q, *Classification Analyses and Maintenance of the Q-List*.

Approved quality assurance procedures were used to conduct and document the activities described in this analysis report (BSC 2004 [DIRS 170408], Section 4.1). This work constitutes an analysis report, and the documentation was prepared according to AP-SIII.9Q, *Scientific Analyses*, and in accordance with related procedures and guidance documents as outlined in the technical work plan. The technical work plan also identifies applicable controls for the electronic management of data (BSC 2004 [DIRS 170408], Section 8.4) during the analysis and documentation activities.

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3. COMPUTER SOFTWARE AND MODEL USAGE

This analysis report uses no computational software; therefore, this analysis is not subject to software controls. The analyses and arguments are based on guidance and regulatory requirements, on the results of analyses presented and documented in other analysis reports, and on other technical literature. Software and models used in the supporting documents are cited for traceability and transparency purposes, but no software and models were used in the development of this report.

This analysis report was developed using only commercial off-the-shelf software. Microsoft® Word 2000 used for word processing is exempt from qualification requirements in accordance with LP-SI.11Q-BSC, *Software Management*. The spreadsheet program Microsoft® Excel 2000 was used for calculations as described below.

Data cited from outside source are qualified within this report in accordance with AP-SIII.9Q (Appendix B), and the meteorite–related data are used in an analysis package (Appendix D) for determining the probability of meteorite impact and the resulting crater damage. The spreadsheets in Appendices B and D were written using the standard functions of commercial off-the-shelf software (Microsoft® Excel 2000) and, therefore, are not required to be qualified in accordance with LP-SI.11Q-BSC, Section 2.1.6. Microsoft® Excel 2000 was also used to graphically present the meteorite impact probability data and to provide equations and coefficients for a regression analysis using the standard graphical interface for adding trend lines to graphs. There were no applications (routines or macros) developed using this commercial off-the-shelf software. The information provided is sufficient to allow review and checking without recourse to the originator.

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4. INPUTS

AP-3.15Q, *Managing Technical Product Inputs*, categorizes technical product input usage as either direct input or indirect input. Direct input is used to develop the results or conclusions in a technical product. Indirect input is used to provide additional information that is not used in the development of results or conclusions. Direct inputs are addressed in this section. Indirect inputs are addressed in Section 6.1.3.

All direct inputs (data, parameters, and other information) used in this FEPs analysis are identified in Section 4.1. Direct inputs used in this analysis report were obtained from controlled source documents and other sources in accordance with AP-3.15Q. The FEP screening criteria (i.e., low probability, low consequence) described at 10 CFR 63 (DIRS 156605), along with the FEP screening criteria (i.e., by regulation) derived from the regulations, are identified in Section 4.2. Applicable codes and standards are identified in Section 4.3.

4.1 DIRECT INPUTS

The LA FEP List (DIRS 170760) was used as a direct input to provide the initial list of system-level FEPs for screening in this analysis report. An overview of the YMP FEP analysis and scenario development process is presented in *The Development of the TSPA-LA Features, Events, and Processes* (BSC 2004 [DIRS 168706]), which describes the TSPA-LA FEP identification and screening process. As part of that process, the LA FEP List (DTN: MO0407SEPFEPLA.000 [DIRS 170760]) was developed. This DTN was used as an initial input to this analysis. The list of system-level FEPs, presented in Table 1-1, was derived from DTN: MO0407SEPFEPLA.000 (DIRS 170760) with subsequent modifications. For each FEP, the LA FEP List identifies a FEP analysis report or a set of sharing FEP analysis reports. Subsequent changes from the LA FEP List (numbers, names, or descriptions) are reflected in the information provided in Section 6.2 and are documented in the "FEP History File" in the FEP database (BSC 2004 [DIRS 168706], Table 6-1). Other direct inputs used for the FEP screening analysis are listed in Table 4-1. Data from external sources are used as direct input and are listed in Table 4-1. Data from these sources have been justified per AP-SIII.9Q and are considered qualified for the intended use. These justifications are documented in Appendix B.

Table 4-1. Direct Inputs Used for System-Level FEP Screening

Source	Input	Input Category	Used In	Input Description
ASM International. 1990. Properties and Selection: Nonferrous Alloys and Special-Purpose Materials. Volume 2 of ASM Handbook. Formerly Tenth Edition, Metals Handbook. 5th Printing 1998. Materials Park, Ohio: ASM International. TIC: 241059. (DIRS 141615)	p. 621	Established Fact	Table C-2	Modulus of Elasticity for Titanium Grade 24
ASME (American Society of Mechanical Engineers) 1998. 1998 ASME Boiler and Pressure Vessel Code. 1998 Edition with 1999 and 2000 Addenda. New York, New York: American Society of Mechanical Engineers. TIC: 247429. (DIRS 145103)	Section II, Table 1	Established Fact	Table C-2	Tensile strength for Titanium Grade 24

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
Backman, M.E. and Goldsmith, W. 1978. "The Mechanics of Penetration of Projectiles into Targets." International Journal of Engineering Science, 16, (1), 1-99. New York, New York: Pergamon. TIC: 255605. (DIRS 167628)	p. 33	Data	Section 6.2.3.9; Tables B-1, B-3	Penetration depth as a function of penetrator diameter
	p. 38, Equation 6.2	Data	Section 6.2.3.9; Appendix B; Tables B-1, B-3	Poncelet Equation
Bourgoyne, A.T., Jr.; Millheim, K.K.; Chenevert, M.E.; and Young, F.S., Jr. 1986. "Rotary Drilling Bits." Applied Drilling Engineering. SPE Textbook Series Volume 2. Pages 190-245. Richardson, Texas: Society of Petroleum Engineers. TIC: 250085. (DIRS 155233)	Equation 5.19, Q1	Data	Sections 6.2.3.2, 6.2.3.6, 6.2.3.7; Appendices B and C; Tables B-1, B-2	Penetration rate is inversely proportional to the square of the compressive strength of material being drilled, all other factors being equal
Brakenridge, G.R. 1981. "Terrestrial Paleoenvironmental Effects of a Late Quaternary-Age Supernova." Icarus, 46, (1), 81-93. New York, New York: Academic Press. TIC: 255707. (DIRS 167873)	Entire	Data	Section 6.2.4.6; Appendix B; Table B-20	General reference to study of effects of past supernova explosion
	Figure 1; pp. 83, 85, and 86	Data	Section 6.2.4.6; Appendix B; Table B-1	Frequency, magnitude, and consequences of a supernova event
Bredehoeft, J.D. 1997. "Fault Permeability Near Yucca Mountain." Water Resources Research, 33, (11), 2459-2463. Washington, D.C.: American Geophysical Union. TIC: 236570. (DIRS 100007)	p. 2460	Data	Section 6.2.4.8; Appendix B; Tables B-1; B-22	Earth tide water level fluctuations in Well UE-25 p#1
BSC (Bechtel SAIC Company) 2003. Subsurface Geotechnical Parameters Report. 800-K0C-WIS0-00400-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040108.0001. (DIRS 166660)	Figure 8-45	Data	Figure C-1	Unconfined compressive strength and modulus of elasticity data for repository host horizon
BSC 2003. Total System Performance Assessment-License Application Methods and Approach. TDR-WIS-PA-000006 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031215.0001. (DIRS 166296)	pp. 71 and 73	Data	Section 6.2.1.7	Description of treatment of various waste forms as three generic waste form groups

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
BSC 2003. Total System Performance Assessment-License Application Methods and Approach. TDR-WIS-PA-000006 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031215.0001. (DIRS 166296) (Continued)	pp. 77, 78, and 81	Data	Section 6.2.1.7	Description of treatment of waste form types in conjunction with varying seepage and thermohydrologic conditions
	Section 3.3	Data	Section 6.2.1.4	TSPA-LA process for treating alternative conceptual models
	Section 3.4	Data	Section 6.2.1.4	TSPA-LA process for treating abstractions
	Section 3.5	Data	Section 6.2.1.4	TSPA-LA process for treating parameter uncertainty
	Section 5.1	Data	Sections 6.2.1.4, 6.2.4.10	Description of model components used to incorporate geologic, hydrologic, and geochemical data
	Section 5.1	Data	Sections 6.2.1.5, 6.2.1.6	Description of model components used to incorporate design elements, particularly models for EBS, Waste Form, and Waste Package
	Section 7	Data	Section 6.2.1.4	TSPA-LA process for model validation

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
BSC 2003. Total System Performance Assessment-License Application Methods and Approach. TDR-WIS-PA-000006 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031215.0001. (DIRS 166296) (Continued)	Section 8.1	Data	Section 6.2.1.4	TSPA-LA process for uncertainty analysis
	Sections 1.3 and 9.1	Data	Section 6.2.1.1	10,000- and 20,000- year periods used for TSPA-LA model.
	Sections 5.1 and 9.1	Data	Section 6.2.1.2	Description of TSPA-LA model with regard to spatial domain of concern with dose calculated at 18 km from the repository
BSC 2004. Characterize Framework for Igneous Activity at Yucca Mountain, Nevada. ANL-MGR-GS-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 169989)	Section 6.1	Data	Section 6.2.4.4	Form of igneous intrusion will be in dikes rather than large diapirs
	Table 7-1	Data	Section 6.2.3.3	Probability of igneous intersection of the repository
BSC 2004. *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada.* ANL-CRW-GS-000003 REV 00 Errata 001. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20000510.0175; DOC.20040223.0007. (DIRS 168030)	Section 6.3.1	Data	Section 6.2.4.4	Regional setting of Yucca Mountain is extensional
	Table 6	Data	Section 6.2.4.1	Local cumulative fault slip rates
BSC 2004. D&E / PA/C IED Interlocking Drip Shield and Emplacement Pallet. 800-IED-WIS0-00401-000-00D. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040503.0018. (DIRS 169220)	Directory; Table 5	Data	Appendix C, Table C-2	References to DTNs for material properties for titanium, including corrosion rates
BSC 2004. D&E / PA/C IED Subsurface Facilities. 800-IED-WIS0-00101-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040309.0026. (DIRS 164519)	Entire	Data	Sections 6.2.3.9, 6.2.4.5; Appendix D; Table D-6	Drift area design drawing, including drift end coordinates and thickness of overburden

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
BSC 2004. D&E / PA/C IED Typical Waste Package Components Assembly. 800-IED-WIS0-00201-000-00E. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040517.0007. (DIRS 169480)	Directory: Material Character-istics	Data	Table C-2	Reference to DTN for material properties for Stainless Steel Type 316N and Alloy 22
BSC 2004. *Drift Degradation Analysis.* ANL-EBS-MD-000027, Rev. 03. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 166107)	Tables E-6, E-7, E-8, E-9, E-10, E-14	Data	Section 6.2.3.4; Appendix C, Table C-1	Intact rock properties for host rock units
BSC 2004. Geologic Framework Model (GFM2000). MDL-NBS-GS-000002 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 170029)	Figure 6-1	Data	Section 6.2.4.5; Appendix D	Location of boreholes with respect to surface elevation and repository layout
	Table 6-2, Topopah Spring Tuff and Sections 6 and 6.5.1.4	Data	Sections 6.2.4.3; 6.2.4.9	Correlation of the repository host horizon with zones and subzones of the Topopah Spring Tuff and lithologic descriptions
BSC 2004. Seismic Consequence Abstraction. MDL-WIS-PA-000003 Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 169183)	Sections 6.3; 6.4; 6.5	Data	Section 6.2.3.4; Appendix C	Discussions of residual stress threshold and damage abstractions
BSC 2004. UZ Flow Models and Submodels. MDL-NBS-HS-000006 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 169861)	Figure 6.1-1	Data	Section 6.2.4.5; Appendix D	Grid cell size for the UZ flow model
	Sections 6.1.2; 6.2.2	Data	Section 6.2.4.5; Appendix D	Flow characteristics of the Paintbrush nonwelded tuff
	Table 6.1-2	Data	Section 6.2.4.10	Infiltration rates used in UZ flow modeling
BSC 2004. WAPDEG Analysis of Waste Package and Drip Shield Degradation. ANL-EBS-PA-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 169996)	Sections 6.5, 7.2	Data	Sections 1.3, 6.2.3.2, 6.2.3.6, 6.2.3.7; Appendix C	Mean time of failure for drip shields and waste packages based on representative, but surrogate, water chemistries
BSC 2004. Performance Confirmation Plan. TDR-PCS-SE-000001 Rev 04. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040825.0002. (DIRS 170505)	Entire	Data	Sections 6.2.1.5, 6.2.2.2, 6.2.2.5	General citation to performance confirmation plan

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
Canori, G.F. and Leitner, M.M. 2003. Project Requirements Document. TER-MGR-MD-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031222.0006. (DIRS 166275)	Entire	Data	Table 4-3; Sections 4.2.1; 6.2.1.3	Identifies and assigns requirements
Ceplecha, Z. 1992. "Influx of Interplanetary Bodies onto Earth." Astronomy and Astrophysics, 263, 361-366. New York, New York: Springer-Verlag. TIC: 246784. (DIRS 135242)	Figure 1	Data	Section 6.2.4.5; Appendix B Tables B-1, B-9, B-10; Appendix D	Log of mass (m) to the log of the cumulative number (N) of interplanetary bodies of a mass equal to or greater than m coming to the earth's atmosphere every year
	p. 362; Figure 1	Data	Section 6.2.4.5; Appendix B; Table B-1; Appendix D; Table D-1	Compilation of flux data from multiple studies
Ceplecha, Z. 1994. "Impacts of Meteoroids Larger than 1m into the Earth's Atmosphere." Astronomy and Astrophysics, 286, (3), 967-970. New York, New York: Springer-Verlag. TIC: 246761. (DIRS 135243)	Figure 2; Table 4	Data	Section 6.2.4.5; Appendix B; Tables B-1, B-11, B-13	Relative percent of different types of meteorite material
	pp. 967 to 969; Tables 1 and 3	Data	Section 6.2.4.5; Appendix B; Tables B-1, B-15	Bulk densities of meteorite materials
CRWMS M&O 1998. Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada. Milestone SP32IM3, September 23, 1998. Three volumes. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981207.0393. (DIRS 103731)	Section 4	Data	Section 6.2.4.5	Magnitude of earthquakes considered as part of the expert elicitation and implicitly included with the resulting data
Dence, M.R.; Grieve, R.A.F.; and Robertson, P.B. 1977. "Terrestrial Impact Structures: Principal Characteristics and Energy Considerations." Impact and Explosion Cratering, Planetary and Terrestrial Implications, Proceedings of the Symposium on Planetary Cratering Mechanics, Flagstaff, Arizona, September 13-17, 1976. Roddy, D.J.; Pepin, R.O.; and Merrill, R.B., eds. Pages 247-275. New York, New York: Pergamon Press. TIC: 247237. (DIRS 135253)	Figure 12	Data	Section 6.2.3.9; Appendix B; Tables B-1, B-3	Relation of crater diameter to energy release

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
Dence, M.R.; Grieve, R.A.F.; and Robertson, P.B. 1977. "Terrestrial Impact Structures: Principal Characteristics and Energy Considerations." Impact and Explosion Cratering, Planetary and Terrestrial Implications, Proceedings of the Symposium on Planetary Cratering Mechanics, Flagstaff, Arizona, September 13-17, 1976. Roddy, D.J.; Pepin, R.O.; and Merrill, R.B., eds. Pages 247-275. New York, New York: Pergamon Press. TIC: 247237. (DIRS 135253) (Continued)	p. 250	Data	Section 6.2.4.5; Appendix B; Table B-1	Depth of exhumation by meteorites
	p. 262	Data	Section 6.2.3.9; Appendix B; Tables B-1, B-3	Radius of overstress condition from Piledriver nuclear test
	pp. 261 to 264	Data	Section 6.2.4.5; Appendix B, Table B-1	Depth of fracture zones for meteorites
Ehlers, E.G. and Blatt, H. 1982. Petrology, Igneous, Sedimentary, and Metamorphic. New York, New York: W.H. Freeman and Company. TIC: 255657. (DIRS 167802)	p. 168, Figure 6-3	Data	Section 6.2.4.1; Tables B-1, B-5, B-6	Pressure gradient is 0.6 kbar/km; thermal gradient is 10ºC/km
	p. 566	Data	Section 6.2.4.1; Appendix B; Tables B-1, B-5, B-6	Conditions needed for onset of metamorphism include temperatures greater than 150ºC to 200ºC; pressure = 0.5-1 kbar; depth = 4-5 km
	pp. 684 and 685	Data	Section 6.2.4.1; Tables B-1, B-5, B-6	Geothermal gradient is 10ºC to 25ºC/km

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
Ferguson, C.D. 2002. "Mini-Nuclear Weapons and the U.S. Nuclear Posture Review." Monterey, California: Monterey Institute of International Studies, Center for Nonproliferation Studies. Accessed December 4, 2002. TIC: 253717. http://www.cns.miis.edu/pubs/week/020408.htm. (DIRS 160988)	Entire	Data	Section 6.2.3.9; Appendix B, Tables B-1, B-3	Limitations on weapons penetration depth
Forrestal, M.J.; Longcope, D.B.; and Norwood, F.R. 1981. "A Model to Estimate Forces on Conical Penetrators Into Dry Porous Rock." Journal of Applied Mechanics, 48, (1), 25-29. New York, New York: American Society of Mechanical Engineers. TIC: 255607. (DIRS 167630)	p. 28	Data	Section 6.2.3.9; Appendix B, Tables B-1, B-3	Penetration of 2.6 m into a welded tuff
Grieve, R.; Rupert, J.; and Therriault, A. 1995. "The Record of Terrestrial Impact Cratering." GSA Today, 5, (10), 194-196. Boulder, Colorado: Geological Society of America. TIC: 246688. (DIRS 135260)	p. 194	Data	Section 6.2.4.5; Appendix B, Tables B-1, B-8; Appendix D	Threshold for on-set of complex cratering.
Grieve, R.A.F. 1998. "Extraterrestrial Impacts on Earth: The Evidence and the Consequences." Meteorites: Flux with Time and Impact Effects. Grady, M.M.; Hutchinson, R.; McCall, G.J.H.; and Rothery, D.A., eds. Geological Society Special Publication No. 140. Pages 105-131. London, England: Geological Society. TIC: 254143. (DIRS 163385)	p. 113; Figure 8	Data	Section 6.2.4.5; Appendix B; Tables B-1, B-8; Appendix D	Crater diameter to depth relationships
Grieve, R.F. 1987. "Terrestrial Impact Structures." Annual Review of Earth and Planetary Sciences, 15, 245-269. Palo Alto, California: Annual Reviews. TIC: 246788. (DIRS 135254)	p. 248, p. 257 and Figure 8	Data	Section 6.2.4.5; Appendix B; Table B-1; Appendix D	Size-frequency distribution of earth impact structures
	pp. 246 and 249	Data	Section 6.2.4.5; Appendix B, Appendix D	Threshold diameters associated with simple and complex cratering
Hills, J.G. and Goda, P.M. 1993. "Fragmentation of Small Asteroids in the Atmosphere." The Astronomical Journal, 105, (3), 1114-1144. Woodbury, New York: American Institute of Physics. TIC: 246798. (DIRS 135281)	Figures 16 and 17	Data	Appendix B; Tables B-1, B-8, B-18, B-19; Figures B-4a, B-4b, B-4c; Appendix D; Table D-4; Figures D-2a, D-2b	Graphs of modeling results by others showing meteor radii, velocities, and resulting crater diameters.

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
Hills, J.G. and Goda, P.M. 1993. "Fragmentation of Small Asteroids in the Atmosphere." The Astronomical Journal, 105, (3), 1114-1144. Woodbury, New York: American Institute of Physics. TIC: 246798. (DIRS 135281) (Continued)	Figures 9, 12, 18	N/A	Appendix D	Figures indicating meteor radii and other "non-crater' consequences
	pp. 1140 and 1142, Figures 9, 16, 17, and 18	Data	Assumption 5.4; Section 6.2.4.5; Appendix D	Crater diameters and other consequences resulting from initial meteor radii for differing initial velocities and compositions
Kahraman, S.; Balci, C.; Yazici, S.; and Bilgin, N. 2000. "Prediction of the Penetration Rate of Rotary Blast Hole Drills Using a New Drillability Index." International Journal of Rock Mechanics and Mining Sciences, 37, (5), 729-743. New York, New York: Pergamon. TIC: 255709. (DIRS 167761)	Eq. 8, 12, and 14	Data	Appendix B, Tables B-1, B-2; Appendix C	Penetration rate inversely proportional to rock strength properties; Equations relating drillability, compressive strength, tensile strength and rate of penetration
	Equation 8	Data	Sections 6.2.3.2, 6.2.3.6, 6.2.3.7; Appendix B	Equation indicating inverse relationships of rate of penetration to material properties
Krystinik, L.F. 1990. "Early Diagenesis in Continental Eolian Deposits." Chapter 8 of Modern and Ancient Eolian Deposits: Petroleum Exploration and Production. Fryberger, S.G.; Krystinik, L.F.; and Schenk, C.J., eds. Denver, Colorado: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section. TIC: 247781. (DIRS 135295)	p. 8-1	Data	Section 6.2.4.2; Tables B-1, B-7; Appendix B	Rates of diagenetic processes
	p. 8-4	Data	Section 6.2.4.2; Appendix B; Tables B-1, B-7	Other cements include iron, aluminum, and silica; and cementation process is reversible
	pp. 8-2 and 8-3	Data	Section 6.2.4.2; Appendix B, Tables B-1, B-7	Increased diagenetic effects associated with deep burial

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
Lattman, L.H. 1973. "Calcium Carbonate Cementation of Alluvial Fans in Southern Nevada." Geological Society of America Bulletin, 84, (9), 3013-3028. Boulder, Colorado: Geological Society of America. TIC: 235904. (DIRS 129305)	p. 3015	Data	Section 6.2.4.2; Appendix B; Tables B-1, B-7	Specific reference for rates and process of calcium carbonate cementation in southern Nevada
Lattman, L.H. and Simonberg, E.M. 1971. "Case-Hardening of Carbonate Alluvium and Colluvium, Spring Mountains, Nevada." Journal of Sedimentary Petrology, 41, (1), 274-281. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists. TIC: 223189. (DIRS 129306)	p. 277	Data	Section 6.2.4.2; Appendix B; Tables B-1, B-7	Specific reference for rate of cementation
Lean, J. 1997. "The Sun's Variable Radiation and its Relevance for Earth." Annual Review of Astronomy and Astrophysics, 35, 33-67. Palo Alto, California: Annual Reviews. TIC: 255614. (DIRS 167639)	pp. 33 to 67	Data	Section 6.2.4.5; Tables B-1, B-20	List of linkages between solar activity and earth's atmospheric and climatic systems
Maynard, N.C. 1995. "Space Weather Prediction." Reviews of Geophysics (Supplement), 33, (Part 1), 547-557. Washington, D.C.: American Geophysical Union. TIC: 253729. (DIRS 160888)	pp. 547 to 557	Data	Section 6.2.4.6; Tables B-1, B-20	List of engineered systems potentially affected by space weather
MO0003RIB00071.000. Physical and Chemical Characteristics of Alloy 22. Submittal date: 03/13/2000. (DIRS 148850)	Alloy 22	Data	Section 6.2.3.4; Table C-2	Yield strength, tensile and modulus of elasticity
MO0003RIB00073.000. Physical and Chemical Characteristics of TI Grades 7 and 16. Submittal date: 03/13/2000. (DIRS 152926)	Titanium Grade 7 and 16	Data	Section 6.2.3.4; Table C-2	Yield strength, tensile strength, and modulus of elasticity
MO0003RIB00076.000. Physical and Chemical Characteristics of Type 316N Grade. Submittal date: 03/14/2000. (DIRS 153044)	Stainless Steel Type 316N	Data	Table C-2	Yield strength
MO0004QGFMPICK.000. Lithostratigraphic Contacts from MO9811MWDGFM03.000 to be Qualified Under the Data Qualification Plan, TDP-NBS-GS-000001. Submittal date: 04/04/2000. (DIRS 152554)	Depth of contacts for Paintbrush nonwelded unit (Tpp, Tpt, Tptrv3, Tptrv1)	Data	Section 6.2.4.5; Appendix D, Table D-7	Contacts for Paintbrush nonwelded unit
MO0311RCKPRPCS.003. Intact Rock Properties Data on Uniaxial and Triaxial Compressive Strength. Submittal date: 11/04/2003. (DIRS 166073)	Uniaxial compressive strength	Data	Section 6.2.3.4; Table C-1	Uniaxial compressive strength for host horizon units
MO0407SEPFEPLA.000. LA FEP List. Submittal date: 07/20/2004. (DIRS 170760)	Entire	Data	Sections 1.1, 1.2; Table 1-1; Sections 4.1, 6.1.1	Q source list for LA FEPs

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
Odenwald, S. 2003. "Earth - Magnetic Field" Poetry Space Science Education: Ask the Space Scientist http://image.gsfc.nasa.gov/poetry/ask/askmag.html. Washington, D.C.: National Aeronautics and Space Administration. Accessed February 25, 2003. TIC: 253712. (DIRS 160892)	Entire	Data	Section 6.2.4.7; Table B-1; Appendix B; Table B-21	Information regarding various space/earth phenomena and coupling mechanisms and probable effects
Patterson, W.J. 1974. "Results and Analysis of Three Instrumented Projectile Penetration Tests at the Watching Hills Blast Range, Suffield, Alberta, Canada." EOS, Transactions, 56, (12), 1197. Washington, D.C.: American Geophysical Union. TIC: 255677. (DIRS 167805)	Entire	Data	Section 6.2.3.9; Appendix B; Tables B-1, B-3	Penetration depths of 9.08 m; 14.7 m; 20.7 m into a glacial lake soil
Reeves, C.C. 1976. Caliche: Origin, Classification, Morphology and Uses. Lubbock, Texas: Estacado Books. TIC: 245928. (DIRS 104303)	p. 110	Data	Section 6.2.4.2; Appendix B; Tables B-1, B-7	Reduction in vertical infiltration rates associated with cementation
Shoemaker, E.M. 1983. "Asteroid and Comet Bombardment of the Earth." Annual Review of Earth and Planetary Sciences, 11, 461-494. Palo Alto, California: Annual Reviews. TIC: 246922. (DIRS 135308)	pp. 464 and 480	Data	Section 6.2.4.5; Table B-1; Appendix D	Composition and percentages of types of meteors - data for iron meteors
Stix, G. and Yam, P. 2001. "Facing a New Menace." Scientific American, 285, (5), 14-15. New York, New York: Scientific American. TIC: 254304. (DIRS 160994)	p. 15	Data	Section 6.2.3.9; Tables B-1, B-3	Energy release equivalents related to aircraft crashes
Taylor, E.M. 1986. Impact of Time and Climate on Quaternary Soils in the Yucca Mountain Area of the Nevada Test Site. Master's thesis. Boulder, Colorado: University of Colorado. TIC: 218287. (DIRS 102864)	Chapter 5, pp. 86 to 89	Data	Section 6.2.4.2; Tables B-1, B-7	Relation of cementation to climate factors
	Figure 9, p. 33	Data	Section 6.2.4.2; Appendix B; Tables B-1, B-2	Rates of SiO_2 and $CaCO_3$ accumulation
	pp. 31 to 33	Data	Section 6.2.4.2	Conditions at Yucca Mountain favor SiO_2 cementation over $CaCO_3$
	pp. 31 to 33, Figure 9, and Chapter 5	Data	Table B-1	Description of cementation processes in Yucca Mountain soils

Table 4-1. Direct Inputs Used for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
Wuschke, D.M.; Whitaker, H.H.; Goodwin, B.W.; and Rasmussen, L.R. 1995. Assessment of the Long-Term Risk of a Meteorite Impact on Hypothetical Canadian Nuclear Fuel Waste Disposal Vault Deep in Plutonic Rock. AECL-11014. Pinawa, Manitoba, Canada: Atomic Energy of Canada Limited, Whiteshell Laboratories. TIC: 221413. (DIRS 129326)	Figure 1	Data	Assumption 5.4; Section 6.2.4.5; Table B-1	Effects of meteorite impacts are spherical in nature
	p. 3	Data	Section 6.2.4.5; Appendix B; Table B-1; Appendix D	Extent of rock disruption produced by meteorite impact and diameter threshold for simple to complex cratering
	p. 44	Data	Appendix B, Appendix D	Cratering distribution curve
	pp. 4 and 26	Data	Section 6.2.4.5; Table B-1; Appendix D	Information and formula for calculating impact probabilities
Young, C.W. 1976. Status Report on High Velocity Soil Penetration Program. SAND76-0291. Albuquerque, New Mexico: Sandia Laboratories. ACC: MOL.20040407.0069. (DIRS 167806)	Table II	Data	Section 6.2.3.9; Appendix B, Tables B-1, B-3	Penetration depth of 67 m into hard playa soil

NOTE: All non-project specific sources used as direct input have been justified for use within this document, as documented in Appendix B, and are therefore considered as qualified.

The regulations at 10 CFR Part 63 (DIRS 156605) also provide direct inputs to the FEPs screening process. By specifying characteristics, concepts, and definitions, the regulations serve as de facto inputs used for FEPs screening. The regulatory definitions and elucidation of the regulatory concepts pertaining to the reference biosphere, geologic setting, reasonably maximally exposed individual (RMEI), and human intrusion are explained in BSC (2004 [DIRS 168706], Section 4.1.3). For system-level FEPs, the inputs of interest include the reference biosphere, the geologic setting, and the RMEI. These definitions and concepts have implications for defining the areal extent of the accessible environment and the controlled area, plus the spatial relationship between the repository and the RMEI. The related regulatory citations are listed in Table 4-2. The application of these definitions and descriptions are discussed below.

Table 4-2. Regulations Used as Direct Inputs for System-Level FEP Screening

Source	Input	Input Category	Used In	Input Description
10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available. (DIRS 156605)	10 CFR Part 63	Established Fact	Sections 6.2.1.3	Reference to pertinent NRC regulations
	10 CFR Subpart D	Established Fact	Section 6.2.2.6	Requirements for audits, inspections, and notifications.
	10 CFR 63 Subpart F	Established Fact	Sections 1.3, 6.1.6, 6.2.1.5, 6.2.2.2, 6.2.2.5; Assumption 5.5	Regulatory requirements and specifications for a performance confirmation program to confirm design parameters and to ensure that the NRC is informed of changes needed in the design to accommodate actual field conditions
	10 CFR 63 Subpart G	Established Fact	Sections 1.3, 6.1.6, 6.2.2.2; Assumption 5.5	Regulatory requirements for a quality assurance program
	10 CFR 63.2	Established Fact	Section 6.2.4.10	Regulatory definition for reference biosphere
	10 CFR 63.2	Established Fact	Sections 6.2.4.3, 6.2.4.4, 6.2.4.9	Regulatory definition of geologic setting

Table 4-2. Regulations Used as Direct Inputs for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available. (DIRS 156605) (Continued)	10 CFR 63.44	Established Fact	Sections 1.3, 6.1.6, 6.2.1.5, 6.2.2.2, 6.2.2.5 Assumption 5.5	Regulatory requirement pertaining to modifications and deviations from the design
	10 CFR 63.73 and 10 CFR 63.73(a)	Established Fact	Sections 1.3, 6.1.6, 6.2.2.2, 6.2.2.5, 6.2.2.6; Assumption 5.5	Regulatory requirement for reporting deficiencies of the site, design, or construction
	10 CFR 63.102(j)	Established Fact	Sections 6.2.2.3, 6.2.3.10	Regulatory concept for use of a performance assessment
	10 CFR 63.102(k)	Established Fact	Sections 6.2.2.1; 6.2.2.4; Assumption 5.2	Regulatory concept regarding consideration of institutional controls in performance assessment
	10 CFR 63.111(e)(1, 2, and 3)	Established Fact	Section 6.2.1.6	Regulatory requirement for repository design to allow for retrieval
	10 CFR 63.113(d)	Established Fact	Section 6.2.3.5	Regulatory requirement to evaluate human intrusion only through a stylized scenario
	10 CFR 63.114(a)	Established Fact	Table 4-3; Sections 6.2.1.4, 6.2.4.3, 6.2.4.4, 6.2.4.9	Regulatory requirement to include data that are related to the geology, hydrology, and geochemistry of Yucca Mountain and the surrounding region to the extent necessary and for the EBS
	10 CFR 63.114(b)	Established Fact	Table 4-3; Section 6.2.1.4	NRC requirement for performance assessment models pertaining to data, uncertainty, parameter ranges, probability distributions, and bounding values

Table 4-2. Regulations Used as Direct Inputs for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available. (DIRS 156605) (Continued)	10 CFR 63.114(c)	Established Fact	Section 6.2.1.4	NRC regulation pertaining to consideration of alternative conceptual models of FEPs
	10 CFR 63.114(d)	Established Fact	Table 4-3; Sections 4.2.3, 6.1.2, 6.1.2.1, 6.2.1.1	Regulatory basis for low probability exclusion
	10 CFR 63.114(e or f)	Established Fact	Table 4-3; Section 4.2.3, 6.1.2	Regulatory requirements to provide technical basis for exclusion based on low consequence
	10 CFR 63.114(g)	Established Fact	Section 6.2.1.4	Requirement to provide technical basis for models
	10 CFR 63.115(a)	Established Fact	Sections 6.2.4.3, 6.2.4.4, 6.2.4.9	Regulatory requirement to identify natural features of the geologic setting
	10 CFR 63.131; 10 CFR 63.131(c); 10 CFR 63.131(d)(1)	Established Fact	Sections 6.1.6, 6.2.2.5; Assumption 5.4	Regulatory requirements pertaining to performance confirmation program and site monitoring
	10 CFR 63.302	Established Fact	Section 6.2.3.5	Regulatory definition of human intrusion
	10 CFR 63.302	Established Fact	Sections 4.1, 6.2.1.2	Regulatory definitions for accessible environment and controlled area
	10 CFR 63.303	Established Fact	Sections 6.2.1.1; 6.2.1.3	Compliance to be based on mean of distribution of projected doses for 10,000 years after disposal

Table 4-2. Regulations Used as Direct Inputs for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available. (DIRS 156605) (Continued)	10 CFR 63.305(a)	Established Fact	Section 4.1	Regulatory requirement that FEPs describing the reference biosphere be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site
	10 CFR 63.305(b)	Established Fact	Section 4.1, 6.2.4.10	Regulatory requirement that the U.S. Department of Energy (DOE) should not project changes in the biosphere other than climate
	10 CFR 63.305(c)	Established Fact	Sections 6.2.1.1, 6.2.4.3, 6.2.4.4, 6.2.4.9; Assumption 5.3	Regulatory requirement that the DOE vary factors based upon cautious, but reasonable assumptions, consistent with present knowledge of factors that could affect Yucca Mountain over the next 10,000 years
	10 CFR 63.311(a)	Established Fact	Section 6.2.3.10	NRC preclosure exposure limits based on radiological exposure
	10 CFR 63.312(a), 63.315(b)	Established Fact	Sections 4.1; 6.2.1.2	Description of RMEI location
	10 CFR 63.321	Established Fact	Table 4-3; Sections 6.2.1.1, 6.2.3.2, 6.2.3.6, 6.2.3.7; Appendix C	NRC regulatory criteria under which human intrusion must be evaluated
	10 CFR 63.322 and 63.322(a, b, c, d, e)	Established Fact	Table 4-3; Sections 6.2.3.6, 6.2.3.7, 6.2.3.8, 6.2.3.9; Appendix C	Regulatory requirements pertaining to the stylized human intrusion scenario
	10 CFR 63.322(f)	Established Fact	Table 4-3; Sections 4.1, 6.2.3.1, 6.2.3.2, 6.2.3.7, 6.2.3.8, 6.2.3.10	Regulatory requirement that only radionuclides transported to the saturated zone (SZ) be considered

Table 4-2. Regulations Used as Direct Inputs for System-Level FEP Screening (Continued)

Source	Input	Input Category	Used In	Input Description
10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available. (DIRS 156605) (Continued)	10 CFR 63.341	Established Fact	Sections 6.2.1.1	Requirement to provide peak dose after 10,000 years
	10 CFR 63.342	Established Fact	Table 4-3; Sections 4.2.3, 6.2.3.3, 6.2.3.4; Appendix C	Limited exclusion for unlikely FEPs in conjunction with human intrusion and with the groundwater protection standard
66 FR 55732. Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, NV, Final Rule. 10 CFR Parts 2, 19, 20, 21, 30, 40, 51, 60, 61, 63, 70, 72, 73, and 75. Readily available. (DIRS 156671)	10 CFR Part 63, Supplementary information, 3.10 Human Intrusion Standard, p. 55761	Established Fact	Sections 6.2.3.1, 6.2.3.2, 6.2.3.7, 6.2.3.8, 6.2.3.10	NRC stated intent that risks to intruders and public from cuttings not be considered
66 FR 32074. 40 CFR Part 197, Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV; Final Rule. Readily available. (DIRS 155216)	40 CFR Part 197; Supplementary Information p. 32117	Established Fact	Section 6.2.1.2	U.S. Environmental Protection Agency (EPA) perspective on potential extent of controlled area
	Supplementary Information p. 32094	Established Fact	Section 6.2.1.2	EPA designation of the location of the RMEI

The definitions and concepts discussed in BSC (2004 [DIRS 168706], Section 4.1.3.3) indicate that the RMEI is located no closer than 18 km to the south of the repository in the direction of groundwater flow and over a contaminated groundwater plume (10 CFR 63.312 [DIRS 156605]), and that the limit of the controlled area is no greater than 5 km from the repository in any other direction (10 CFR 63.302 [DIRS 156605]). The location of the RMEI and the associated distance from the repository is of primary interest in evaluating potential exposure risks from potential releases at the repository. The location of the RMEI is also important for determining exposure, and it is part of the technical basis for the included FEPs. The location and characteristics of the RMEI for the nominal scenario class also are used for the disruptive scenario classes.

Furthermore, the reference biosphere must be consistent with present knowledge of conditions in the region, and changes in the biosphere (other than climate) from conditions at the time of license application submittal should not be projected (BSC 2004 [DIRS 168706], Section 4.1.3.1; 10 CFR 63.305(a) and (b) [DIRS 156605]). The geologic setting (geology, hydrology, and climate) may evolve based upon cautious, but reasonable assumptions, consistent with present knowledge of factors that could affect the system in the next 10,000 years (BSC 2004 [DIRS 168706], Section 4.1.3.2).

The NRC juxtaposed geologic and hydrologic factors in the subsection addressing required characteristics of the reference biosphere, and it is inferred that the listed regulatory constraint of changes in the reference biosphere may also be applicable to conditions that may occur at Yucca Mountain. This approach agrees with the statement at 10 CFR 63.102(i) (DIRS 156605):

> Characteristics of the reference biosphere and the reasonably maximally exposed individual are to be based on current human behavior and biospheric conditions in the region, as described in §63.305 and §63.312.

Specifically identified in the definition of the reference biosphere are changes to soil, topography, and flora. The application of this regulatory input specifically indicates that characteristics of the reference biosphere are to be based on biospheric conditions in the region. The restriction on consideration of changes in flora is applicable to discussions in Section 6.2.4.10 dealing with potential changes in ecological factors due to repository heat, and it provides a regulatory basis for excluding the consideration of changes. More strictly interpreted, this provision would only apply to the reference biosphere and not to the repository area.

Because of regulatory positions (10 CFR 63.102(k) [DIRS 156605]) regarding the unreliability of institutional controls (BSC 2004 [DIRS 168706], Section 4.1.3), for the system-level FEPs addressing administrative controls, and particularly their influence on the timing of human intrusion, the FEPs have been excluded by regulation from consideration in the human intrusion stylized analysis.

With regard to human intrusion related FEPs, rather than speculating on the nature and probability of future intrusion, the NRC required that human intrusion be evaluated via a human intrusion stylized analysis. With regard to the timing of the human intrusion, the use of active and passive institutional controls (such as markers and an information repository) will reduce the potential for future human activity. However, it is not possible to make scientifically sound forecasts of the long-term reliability of such controls as previously discussed under institutional controls, so the affect of such controls on the timing of the human intrusion is not further considered. Additionally, 10 CFR 63.322(f) (DIRS 156605) and 40 CFR 197.26(e) (DIRS 165519) require that only radionuclides transported to the SZ be considered, which precludes the consideration of FEPs related to the exposure of the public, drillers, or other human intruders from cuttings, circulated materials, or tailings. With regard to the motivation of a human intrusion being intentional and deliberate versus inadvertent and accidental, 10 CFR Part 63 (DIRS 156605) is silent. Similarly, 40 CFR Part 197 (DIRS 165519) does not directly address the motivation or intentionality of the intrusion. However, the NRC states in the supplementary information to 10 CFR Part 63 (66 FR 55732 [DIRS 156671], p. 55761) that the motives for a human intrusion are not likely to be economically motivated given knowledge of present conditions. The supplementary information for 40 CFR Part 197 (66 FR 32074 [DIRS 155216], p. 32127) clarifies that consideration of deliberate intrusion is not intended. Consequently, all deliberate human intrusion FEPs discussed in this analysis report are excluded based on the regulatory intent, and all inadvertent intrusions are considered within the context of the regulatory requirements. The requirement considers only the stylized human intrusion (i.e., based on drilling techniques related to groundwater use) and the timing of such an event, regardless of the specific motivation or intentionality of the intruders.

4.2 CRITERIA

Criteria relevant to the FEP screening process are discussed in this section. These criteria stem from applicable regulations at 10 CFR Part 63 (DIRS 156605) (and those incorporated from 40 CFR Part 197 [DIRS 155216]), as identified in the *Project Requirements Document* (PRD) (Canori and Leitner 2003 [DIRS 166275]). These criteria find expression as specific acceptance criteria presented by the NRC in the *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274], Sections 2.2.1.2, 2.2.1.4, and 2.2.1.4.2.3). Correlations between the regulations and the Yucca Mountain Review Plan (YMRP) acceptance criteria are listed in Table 4-3.

4.2.1 Project Requirements Document

The PRD (Canori and Leitner 2003 [DIRS 166275]) lists and categorizes regulatory requirements and other project requirements, and it provides a "crosswalk" to the YMP organizations responsible for ensuring that the criteria are addressed in the LA. The regulatory requirements include criteria relevant to performance assessment activities, in general, and to FEP-related activities as they pertain to performance assessment, in particular. A crosswalk between the regulatory requirements, the PRD, and the acceptance criteria in the YMRP (NRC 2003 [DIRS 163274], Sections 2.2.1.2.1.3 and 2.2.1.2.2.3) is presented in Table 4-3.

Table 4-3. Relationships of NRC Regulations to the PRD and Acceptance Criteria from the YMRP

Description of the Applicable Regulatory Requirement or Acceptance Criterion	10 CFR Part 63 (DIRS 156605)	PRD Canori and Leitner 2003 (DIRS 166275)	YMRP NRC 2003 (DIRS 163274)
	Regulatory Citation	Associated PRD	Associated Criteria in the YMRP
General Requirements and Scope Pertinent to FEP Screening			
Include data related to geology, hydrology, geochemistry, and geophysics	63.114(a)	PRD-002/ T-015	2.2.1.2.1.3 Acceptance Criterion 1
Include information of the design of the EBS used to define parameters and conceptual models	63.114(a)	PRD-002/ T-015	2.2.1.2.1.3 Acceptance Criterion 1
Account for uncertainties and variabilities in parameter values and provide the technical basis for parameter ranges, probability distributions, or bounding values	63.114(b)	PRD-002/ T-015	2.2.1.2.2.3 Acceptance Criteria 2 and 5
FEP Screening Criteria			
Provide the justification and technical basis for excluding FEPs specifically excluded by regulation.	Not Applicable	Not Applicable	2.2.1.2.1.3 Acceptance Criterion 2

Table 4-3. Relationships of NRC Regulations to the PRD and Acceptance Criteria from the YMRP (Continued)

Description of the Applicable Regulatory Requirement or Acceptance Criterion	10 CFR Part 63 (DIRS 156605)	PRD Canori and Leitner 2003 (DIRS 166275)	YMRP NRC 2003 (DIRS 163274)
	Regulatory Citation	**Associated PRD**	**Associated Criteria in the YMRP**
General Requirements and Scope Pertinent to FEP Screening			
FEP Screening Criteria (Continued)			
Provide the technical basis for either inclusion or exclusion of FEPs. Provide the justification and technical basis for those excluded based on probability.	63.114(d) 63.342	PRD-002/ T-015 PRD-002/ T-034	2.2.1.2.1.3 Acceptance Criterion 2 2.2.1.2.2.3 Acceptance Criteria 1 and 2
Provide the technical basis for either inclusion or exclusion of FEPs. Provide the justification and the technical basis for those excluded based on lack of significant change in resulting radiological exposure or release to the accessible environment.	63.114 (e and f) 63.342	PRD-002/ T-015 PRD-002/ T-034	2.2.1.2.1.3 Acceptance Criterion 2 2.2.1.2.2.3 Acceptance Criteria 1 and 2
Human Intrusion Criteria			
Time of earliest penetration without recognition and basis	63.321(a)	PRD-002/ T-029	2.2.1.4.2.3 Acceptance Criterion 1
Treatment if human intrusion results in RMEI exposure prior to 10,000 years	63.321(b)(1)	PRD-002/ T-029	2.2.1.4.2.3 Acceptance Criterion 2
Treatment if human intrusion results in RMEI exposure post-10,000 years	63.321 (b)(2)	PRD-002/ T-029	2.2.1.4.2.3 Acceptance Criterion 2
Required circumstances/ assumptions for human intrusion analysis	63.322 (a, b, c, d, e)	PRD-002/ T-030	2.2.1.4.2.3 Acceptance Criterion 2
Consideration only via groundwater pathway	63.322(f)	PRD-002/ T-030	2.2.1.4.2.3 Acceptance Criterion 2
No consideration of unlikely processes in combination with human intrusion	63.322(g)	PRD-002/ T-030	2.2.1.4.2.3 Acceptance Criterion 2

4.2.2 Yucca Mountain Review Plan

The NRC will be reviewing the LA. The basis of the review is described in the YMRP (NRC 2003 [DIRS 163274], Section 2.2.1.2), and the bases for acceptance are stated as acceptance criteria. In Table 4-3, YMRP acceptance criteria are correlated to the corresponding regulations and related PRD sections as they pertain to FEP-related criteria.

The cited YMRP criteria are listed in Table 4-4. The YMRP acceptance criteria for FEP screening echo the screening criteria of low probability and low consequence, but also allow for exclusion of a FEP if the process is specifically excluded by the regulations (Section 4.2.3).

4.2.3 FEPs Screening Criteria

The criteria for determining "low probability", "low consequence", and "by regulation" exclusions are described below.

Low Probability

The low-probability criterion is stated in 10 CFR 63.114(d) (DIRS 156605):

> Consider only events that have at least one chance in 10,000 of occurring over 10,000 years.

and supported by 10 CFR 63.342 (DIRS 156605):

> DOE's [The Department of Energy's] performance assessments shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal. DOE's assessments for the human-intrusion and ground-water protection standards shall not include consideration of unlikely features, events, and processes, or sequences of events and processes, i.e., those that are estimated to have less than one chance in 10 and at least one chance in 10,000 of occurring within 10,000 years of disposal.

The low probability criterion for very unlikely events is stated as less than one chance in 10,000 of occurring in 10,000 years ($10^{-4}/10^{4}$ yr). As noted in Assumption 5.1, the low-probability criterion for very unlikely events corresponds to an annual-exceedance probability of 10^{-8}. The criterion for unlikely events corresponds to an annual-exceedance probability of 10^{-5} to 10^{-8}.

Low Consequence

The low consequence criterion is stated in 10 CFR 63.114 (e and f) (DIRS 156605):

> (e) Provide the technical basis for either inclusion or exclusion of specific features, events, and processes in the performance assessment. Specific features, events, and processes must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, would be significantly changed by their omission.

Table 4-4. Relevant YMRP Acceptance Criteria

YMRP Criterion	Acceptance Criterion	Description
Scenario Analysis and Event Probability: Scenario Analysis (from YMRP [DIRS 163274], Section 2.2.1.2.1.3)	1. The Identification of a List of FEPs Is Adequate	The safety analysis report contains a complete list of FEPs related to the geologic setting or the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers), that have the potential to influence repository performance. The list is consistent with the site characterization data. Moreover, the comprehensive features, events, and processes list includes, but is not limited to, potentially disruptive events related to igneous activity (extrusive and intrusive); seismic shaking (high-frequency-low magnitude, and rare large-magnitude events); tectonic evolution (slip on existing faults and formation of new faults); climatic change (change to pluvial conditions); and criticality.
	2. Screening of the Initial List of FEPs Is Appropriate	The DOE has identified all FEPs related to either the geologic setting or to the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers) that have been excluded.
		The DOE has provided justification for those FEPs that have been excluded. An acceptable justification for excluding FEPs is that either the FEP is specifically excluded by regulation; probability of the FEP (generally an event) falls below the regulatory criterion; or omission of the feature, and process does not significantly change the magnitude and time of the resulting radiological exposures to the RMEI or radionuclide releases to the accessible environment.
		The DOE has provided an adequate technical basis for each FEP, excluded from the performance assessment, to support the conclusion that the FEP is specifically excluded by regulation, the probability of the FEP falls below the regulatory criterion, or omission of the FEP does not significantly change the magnitude and time of the resulting radiological exposures to the RMEI or radionuclide releases to the accessible environment.

Table 4-4. Relevant YMRP Acceptance Criteria (Continued)

YMRP Criterion	Acceptance Criterion	Description
Scenario Analysis and Event Probability: Identification of Events with Probability Greater than 10^{-8} per Year (from YMRP [DIRS 163274], Section 2.2.1.2.2.3)	1. Events Are Adequately Defined	Events or event classes are defined without ambiguity and used consistently in probability models, such that probabilities for each event or event class are estimated separately.
		Probabilities of intrusive and extrusive igneous events are calculated separately. Definitions of faulting and earthquakes are derived from the historical record, paleoseismic studies, or geological analyses. Criticality events are calculated separately by location.
	2. Probability Estimates for Future Events Are Supported by Appropriate Technical Bases.	Probabilities for future natural events are based on past patterns of the natural events in the Yucca Mountain region, considering the likely future conditions and interactions of the natural and engineered repository system. These probability estimates have specifically included igneous events, faulting and seismic events, and criticality events.
	5. Uncertainty in Event Probability Is Adequately Evaluated	Probability values appropriately reflect uncertainties. Specifically: a. The DOE provides a technical basis for probability values used, and the values account for the uncertainty in the probability estimates; and b. The uncertainty for reported probability values adequately reflects the influence of parameter uncertainty on the range of model results (i.e., precision) and the model uncertainty, as it affects the timing and magnitude of past events (i.e., accuracy).

Table 4-4. Relevant YMRP Acceptance Criteria (Continued)

YMRP Criterion	Acceptance Criterion	Description
Demonstration of Compliance with Post-closure Public Health and Environmental Standards Demonstration of Compliance with the Human Intrusion Standard (from YMRP [DIRS 163274], Section 2.2.1.4.2.3)	1. Evaluation of the Time of an Intrusion Event	The technical basis and associated analyses adequately support the selection of time of occurrence of human intrusion, as specified at 10 CFR 63.321.
	2. Evaluation of an Intrusion Event Demonstrates that the Annual Dose to the RMEI in Any Year during the Compliance Period Is Acceptable	The TSPA of human intrusion is performed separately from the overall TSPA, and meets the requirements for performance assessments, specified at 10 CFR 63.114.
		The TSPA for human intrusion is identical to the TSPA for individual protection, except that it assumes the occurrence of a postulated human intrusion event with characteristics, as defined at 10 CFR 63.322 and excludes the consideration of unlikely natural FEPs.
		A sufficient number of realizations [have] been run using the total system performance code, to ensure that the results of the calculations are statistically stable.
		The estimated repository performance is reasonable and consistent with the analysis of overall repository performance and with the characteristics of the postulated intrusion event.
		The annual dose curve for limited human intrusion confirms that the repository system meets performance objectives, specified at 10 CFR 63.321, for limited human intrusion events.

NOTES: The YMRP (NRC 2003 [DIRS 163274], Section 2.2.1.2.2.3) includes two additional criteria regarding the identification of events with probabilities greater than 10^{-8} per year. Acceptance Criteria 3 applies to probability models, which are not used for system-level FEP evaluations and the criterion is, therefore, not applicable. Acceptance Criteria 4 deals with probability model parameters, and is, therefore, not applicable.

The criterion related to identification of Events with Probability Greater than 10^{-8} per Year and for the Human Intrusion standard were identified as applicable during the preparation of this report, and were not previously identified within the techncial work plan. This identification is based on the the results of analysis identifiying that some FEPs have low probabilities, but greater than 10^{-8} per year, and because the justification for excluding human intrusion based on timing of such an event were added to this report in Appendix C.

(f) Provide the technical basis for either inclusion or exclusion of degradation, deterioration, or alteration processes of engineered barriers in the performance assessment, including those processes that would adversely affect the performance of natural barriers. Degradation, deterioration, or alteration processes of engineered barriers must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, would be significantly changed by their omission.

and supported by 10 CFR 63.342 (DIRS 156605):

> …DOE's performance assessments need not evaluate the impacts resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurrence if the results of the performance assessments would not be changed significantly.

Some FEPs have a beneficial effect on the TSPA, as opposed to an adverse effect. As identified in 10 CFR 63.102(j) (DIRS 156605), the concept of a performance assessment includes that:

> The features, events, and processes considered in the performance assessment should represent a wide range of both beneficial and potentially adverse effects on performance (e.g., beneficial effects of radionuclide sorption; potentially adverse effects of fracture flow or a criticality event). Those features, events, and processes expected to materially affect compliance with [10 CFR] 63.113(b) or be potentially adverse to performance are included, while events (event classes or scenario classes) that are very unlikely (less than one chance in 10,000 over 10,000 years) can be excluded from the analysis. …

The YMRP (NRC 2003 [DIRS 163274], Section 2.2.1) states that:

> In many regulatory applications, a conservative approach can be used to decrease the need to collect additional information or to justify a simplified modeling approach. Conservative estimates for the dose to the reasonably maximally exposed individual may be used to demonstrate that the proposed repository meets U.S. Nuclear Regulatory Commission regulations and provides adequate protection of public health and safety. …The total system performance assessment is a complex analysis with many parameters, and the U.S. Department of Energy may use conservative assumptions to simplify its approaches and data collection needs. However, a technical basis that supports the selection of models and parameter ranges or distributions must be provided.

Based on these statements, FEPs that are demonstrated to have only beneficial effects on the radiological exposures to the RMEI, or radionuclide releases to the accessible environment, can be excluded on the basis of low consequence because they have no adverse effects on performance.

By Regulation

The YMRP (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3, Acceptance Criterion 2) allows for exclusion of a FEP if the process is specifically excluded by the regulations. To wit:

> The DOE has provided justification for those FEPs that have been excluded. An acceptable justification for excluding FEPs is that either the FEP is specifically excluded by regulation; probability of the FEP (generally an event) falls below the regulatory criterion; or omission of the feature, and process does not significantly change the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment.

4.3 CODES, STANDARDS, AND REGULATIONS

Applicable codes and standards include direct inputs (shown in Table 4-1) used for material properties for the EBSs discussed in Appendix C. These include:

- ASM International (1990 [DIRS 141615], p. 621)
- ASME (1998 [DIRS 145103], Section II, Table 1).

The following source, which is used as indirect input and discussed in Appendix C, is pertinent to the evaluation of drilling technology used in groundwater exploration:

- IADC (1992 [DIRS 155232]).

The following applicable regulatory requirements are discussed in Sections 4.1 and 4.2:

- 10 CFR Part 63 (DIRS 156605)
- 40 CFR Part 197 (DIRS 165519).

Closely related discussions taken from the supplementary information sections of the following rule promulgations are used as direct input:

- 66 FR 55732 (DIRS 156671)
- 66 FR 32074 (DIRS 155216).

5. ASSUMPTIONS

Assumptions used in FEP screening for the system-level FEPs are addressed in this section. Five general assumptions were used in screening the system-level FEPs.

Assumption 5.1: For naturally occurring FEPs, it is assumed that regulations expressed as probability criterion can also be expressed as an annual exceedance probability, which is defined as the probability that a specified value (e.g., for ground motions or fault displacement) will be exceeded during one year. More specifically, a stated probability screening criterion of one chance in 10,000 in 10,000 years ($10^{-4}/10^{4}$ yr) is assumed equivalent to a 10^{-8} annual-exceedance probability. Likewise, the stated definition of unlikely events as having one chance in 10 in 10,000 years ($10^{-1}/10^{4}$ yr) of occurring, and as used in assessments of human intrusion and ground-water protection standards, is assumed equivalent to a 10^{-5} annual-exceedance probability.

Justification–The definition of annual exceedance probability, and the following justification for this assumption, is taken from BSC (2004 [DIRS 169881], Glossary).

The assumption of equivalence of annual-exceedance probability is appropriate if the possibility of an event is equal for any given year. This satisfies the definition of a Poisson distribution as "…a mathematical model of the number of outcomes obtained in a suitable interval of time and space, that has its mean equal to its variance…" (Merriam-Webster 1993 [DIRS 100468], p. 899). This is inferred to mean that naturally occurring, infrequent, and independent events, can be represented as stochastic processes in which distinct events occur in such a way that the number of events occurring in a given period of time depends only on the length of the time period. The use of this assumption is justified in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (BSC 2004 [DIRS 168030], Section 6.4.2), which indicates that assuming that the behavior of the earth is generally Poissonian or random is the underlying assumption in all probabilistic hazard analyses.

For example, all meteorite impacts are considered as independent events with regard to size, time, and location. Although there may be cases where sufficient data and information exist to depart from this assumption, the Poisson model is generally an effective representation of nature and represents a compromise between the complexity of natural processes, availability of information, and the sensitivity of results of engineering relevance. Consequently, for geologic processes that occur over long time spans, assuming annual equivalence over a 10,000-year period (a relatively short time span for geologic-related events) is reasonable and consistent with the basis of probabilistic hazard analyses. Therefore, no further confirmation is required.

Use–This assumption is used for FEPs:

Changes in the earth's magnetic field (1.5.03.01.0A)	Section 6.2.4.8
Meteorite impact (1.5.01.01.0A)	Section 6.2.4.10

Assumption 5.2: The analysis to determine the timing at which a human intrusion could occur without recognition by the drillers is based on physical principles and material properties (Appendix C). However, inherent in the analysis is the assumption that records and markers are lost, ignored, or otherwise ineffective in preventing or delaying the intrusion.

Justification–This assumption is intrinsic in the regulatory requirement to consider that a human intrusion occurs and for determining the earliest time for the intrusion. It is consistent with the regulatory requirement at 10 CFR 63.102(k) (DIRS 156605), which states "…it is not possible to make scientifically sound forecasts of the long-term reliability of institutional controls." It is also conservative and reasonable to assume that surface controls are lost at some time within the 10,000-year regulatory time span. No further confirmation is required.

Use–The assumption is used for FEPs:

Administrative control of the repository site (1.1.10.00.0A)	Section 6.2.2.3
Records and markers for the repository (1.1.05.00.0A)	Section 6.2.2.5
Inadvertent human intrusion (1.4.02.02.0A)	Section 6.2.3.2
Drilling activities (human intrusion) (1.4.04.00.0A)	Section 6.2.3.7
Mining and other underground activities (human intrusion) (1.4.05.00.0A)	Section 6.2.3.9

Assumption 5.3: It is assumed that potential naturally occurring events, but perhaps of different magnitude, have occurred at least once in the past within the geologic record used as the basis for determining that factors that could affect the Yucca Mountain disposal system over the next 10,000 years.

Justification–This assumption is justified because it is consistent with the regulations used as direct input. At 10 CFR 63.305(c) (DIRS 156605), the DOE is directed to "vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system over the next 10,000 years." The regulatory concepts for the reference biosphere and the geologic setting are discussed in Section 4.1.

The implication of this assumption is that any discernible affects or processes related to past events on the site setting are reflected in the present knowledge of natural processes that form the basis of the TSPA. If the subject FEP phenomena are not reflected or discernible in the data used to describe past settings, then they are either of low consequence or of low probability and can be excluded from consideration. Because it is consistent with the regulations, no further confirmation is necessary.

Use–This assumption is used throughout. It is particularly relevant to FEPs related to processes and phenomena that, speculatively, could affect future states of the system, but for which the magnitude or coupling to the effect on the repository is not well defined, or for which consequences in present time are known to be minor. These include FEPs such as:

Earth tides (1.5.03.02.0A)	Section 6.2.4.8
Changes in the earth's magnetic field (1.5.03.01.0A)	Section 6.2.4.9
Extraterrestrial events (1.5.01.02.0A)	Section 6.2.4.10

These types of events are known to occur. However, the effects of the phenomenon or the effects associated with varying magnitudes of the event type and probabilities are not well documented (e.g., effects of a supernova); the form of the coupling process is not well defined (e.g., changes in the earth's magnetic field); or the phenomenon has been shown to have no affect or insignificant affect at the present time (e.g., earth tides).

Assumption 5.4: For the meteorite impact analysis, it is assumed that the initial entry velocity of meteors is 15 to 20 km/sec, that the initial entry angle is vertical, and that fracturing beneath an impact crater is cylindrical with depth.

Justification–For the meteorite analysis (discussed in Section 6.2.4.5 and provided in Appendix D), assumptions are made to ensure that the analysis is conservative in nature and that the range of uncertainty in values is covered. The justification for each segment of the assumption is as follows:

Initial Entry Velocities Are 15 to 20 km/sec–A summary of velocity information from the reviewed literature is provided in Table 5-1 and supports the assumption. An assumption is necessary because the data are inadequate to develop a defensible distribution of velocities. Velocities of known meteoroids and comets range from 12.9 km/sec for meteorites (Chyba 1993 [DIRS 135248], Table 1a) to over 80 km/sec for long period comets (Marsden and Steel 1994 [DIRS 129308], pp. 233 to 236). However, the assumption of 15 to 20 km/sec, in addition to being conservative with respect to crater formation, are consistent with the average velocities of observed meteors (Chyba 1993 [DIRS 135248], Table 1a; Ceplecha 1994 [DIRS 135243], Table 2) with diameters of particular interest (i.e., producing craters with frequencies at or greater than the screening criterion). Because an equal weighting of occurrence of asteroidal and cometary compositions is assumed in Appendix D, the simple averaging shown in Table 5-1 is appropriate and self-consistent. The cited references are given in Table 5-1. Hills and Goda (1993 [DIRS 135281], p. 1116) also indicate that a velocity of 20 km/sec is typical of incoming meteors. These sources are used as direct input for the calculation presented in Appendix D. So the assumption of values of 15 km/sec and 20 km/sec would be consistent with the direct inputs. Therefore, no further confirmation of this assumption is necessary.

Initial entry velocities are assumed to be 15 to 20 km/sec, regardless of the meteor composition or size. The distribution between asteroidal and cometary materials is provided in Appendix D (Table D-2), and at large mass (10^8 kg) is assumed equivalent. The assumption of a velocity (velocities have been measured to range from a few km/sec to upwards of 80 km/sec) is necessary because there is insufficient data to develop a distribution for possible velocities. The assumed velocities are justified because they generally are conservative and in agreement with available entry velocity data. For fragmented meteors, higher initial velocities tend to result in smaller meteorite-impact crater diameters (Hills and Goda 1993 [DIRS 135281], p. 1140, Figure 17). The intuitive assumption of increased velocity leading to increased cratering is only correct if the metric is the equivalent radius of the crater produced if all of the impacting material were collected into a single body that hits the ground at a given impacted velocity (Hills and Goda 1993 [DIRS 135281], p. 1140, Figure 16). Ram pressures on the meteor are a function of the velocity squared. After ram pressures exceed material strength properties, the meteor fragments, and the fragments disperse over a wider area (Hills and Goda 1993 [DIRS 135281], Figures 3 and 9). Additionally, increased initial velocities also result in increased ablation in the atmosphere, resulting in a loss of mass (Hills and Goda 1993 [DIRS 135281], Figure 6). As a result, for a given meteor below a certain initial radius (which is composition dependent, but generally on the order of 100 m) increased initial velocity leads to decreased impact velocity

(Hills and Goda 1993 [DIRS 135281], Figure 10), and the mass of the largest resulting fragment markedly decreases for initial meteor radius of less than 100 m (Hills and Goda 1993 [DIRS 135281], Figure 11). Decreased velocity and decreased mass of the largest fragment in turn lead to decreased individual crater radius. Velocities less than 15 km/sec would result in larger crater diameters. However, lower velocities are not considered because they would not be consistent with corroborating information.

Table 5-1. Summary of Velocity Data from Reviewed Literature

Velocity (km/s)				
Asteroids	**Long Period Comets**	**Short Period Comets**	**Not Specified**	**Source**
			20.3	Brown et al. 1998 (DIRS 162569), p. 294.
20	60	40	- -	Chapman and Morrison 1994 (DIRS 135245), p. 34 and Figure 1.
			14.3	Chyba 1993 (DIRS 135248), p. 701. Average value (excluding object 1991-VG as human artifact).
			13.3	Chyba 1993 (DIRS 135248), p. 701. Median value.
20.8	45	38.5		Hughes 1998 (DIRS 162562), p. 35 and 37.
			20.7	Ceplecha 1994 (DIRS 135243), Table 2; Chyba 1993 (DIRS 135248), Table 1a. Derived average for 1 to 10 m.
			15.8	Ceplecha 1994 (DIRS 135243), Table 2; Chyba 1993 (DIRS 135248), Table 1a. Derived average for 11 to 60 m.
	58.2			Marsden and Steel 1994 (DIRS 129308), Table V.
			25	Grieve 1987 (DIRS 135254), p. 250.
20.1				Shoemaker 1983 (DIRS 135308), p. 468. Weighted by probability.
20.3	54.4	39.3	18.2	Average
0.36	6.7	0.75	4.1	Standard deviation
29.4				Average of all values regardless of type
15.9				Standard deviation

Initial Entry Angle Is Zero (Vertical)–The initial entry is at zenith angle zero, or vertical, for all meteoroids. Due to a longer path length, more kinetic energy is absorbed in the atmosphere from meteoroids entering at nonzero zenith angles (Hills and Goda 1998 [DIRS 135291]), which would result in smaller crater diameters. Vertical entry (zero entry angle) is an upper-bounding value because all material entering the atmosphere with vertical entry is implicitly considered to have the potential to impact the earth surface, and the path length through which atmospheric effects occur is minimized. This assumption is needed because there is no direct input available relating flux and angle of entry. This assumption is conservative and no further confirmation of this assumption is necessary.

Zone of Fracturing Is Cylindrical with Depth, Rather than Parabolic–For analysis purposes, the vertical extent of effects (e.g., exhumation or fracturing) is represented as a cylinder. The diameter of the cylinder is assumed to correspond to the crater diameter, and the depth corresponds to the depth of interest derived from the crater diameter. In reality, the effects are more likely parabolic in nature (inferred from Wuschke et al. 1995 [DIRS 129326], Figure 1). If a parabolic zone is used, however, the depth of the effect becomes shallower with distance from the centerline of the crater. Consequently, the volume of material affected by meteorites impacting outside the boundary of the repository (i.e., with the centerline of the crater outside the repository but with crater diameters overlapping the boundary of the repository) would be smaller, and located in shallower geologic units. By assuming a cylindrical zone, the maximum depth of the effect (exhumation or fracturing) is applied throughout the area below the crater diameter and, thereby, conservatively considers a larger volume of the material overlying the repository. Therefore, no further confirmation of this assumption is necessary because the assumption is conservative.

Use–This assumption is used in the meteorite impact analysis (Appendix D), which supports the discussion provided in:

Meteorite impact (1.5.01.01.0A)	Section 6.2.4.5

These assumptions are used in calculating the probability of forming a crater of a given diameter, and to determine the crater diameter occurring at a 10^{-8} annual exceedance frequency.

Assumption 5.5: It is assumed that the repository will be constructed, operated, and closed according to the regulatory requirements applicable to the construction, operation, and closure periods. Deviations from design will be detected and corrected.

Justification–Inherent in the approach to evaluating FEPs is the assumption that the repository will be constructed, operated, and closed according to the design used as the basis for the FEP screening and in accordance with NRC license requirements. This is inherent in performance evaluation of any engineering project, and design verification and performance confirmation are required as part of the construction and operation processes. Therefore, no further confirmation of the assumption is required

Engineering and design changes are subject to evaluation to determine if there are any adverse affects on safety as codified at 10 CFR 63.73 and in Subparts F and G (DIRS 156605). See also the requirements at 10 CFR 63.32, 10 CFR 63.44, and 10 CFR 63.131 (DIRS 156605).

These requirements require periodic and special reports regarding:

- Progress of construction
- Data about the site obtained during construction that are not within the predicted limits on which the facility design was based
- Deficiencies in design and construction that, if uncorrected, could adversely affect safety in the future
- Results of research and development programs conducted to resolve safety questions.

Use–Any changes in direct inputs listed in Section 4.1, in baseline conditions used for this evaluation, or in other subsurface conditions will be evaluated to determine if the changes are within the limits stated in the FEP evaluations. This assumption is specifically used in FEPs:

Repository design (1.1.07.00.0A)	Section 6.2.1.5
Inadequate quality control and deviations from design (1.1.08.00.0A)	Section 6.2.2.2
Monitoring of the repository (1.1.11.00.0A)	Section 6.2.2.5
Accidents and unplanned events during construction and operation (1.1.12.01.0A)	Section 6.2.2.6

6. ANALYSES

The system-level FEP analyses are discussed in this section. The methods and approach used for the FEP screening process are discussed in Section 6.1, and the screening documentation is presented in Section 6.2.

6.1 METHODS AND APPROACH

The identification and screening of a comprehensive list of FEPs potentially relevant to the postclosure performance of the Yucca Mountain repository is an ongoing, iterative process based on site-specific information, design, and regulations. FEP analysis uses the following definitions (NRC 2003 [DIRS 163274], Glossary):

- Feature–an object, structure, or condition that has a potential to affect disposal system performance.

- Event–a natural or human-caused phenomenon that has a potential to affect disposal system performance and that occurs during an interval that is short compared to the period of performance.

- Process–a natural or human-caused phenomenon that has a potential to affect disposal system performance and that operates during all or a significant part of the period of performance.

The FEP analysis for the TSPA-LA (BSC 2004 [DIRS 168706]) is summarized in the following sections.

6.1.1 System-Level FEPs Origin and Identification

The first step of FEP analysis is FEP identification and classification, which addresses Acceptance Criterion 1 of the YMRP (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3). The TSPA-LA FEP identification and classification process (BSC 2004 [DIRS 168706], Section 3) produced a version of the LA FEP List (DIRS 170760) that is used as direct input to this system-level FEP analysis. Except for editorial corrections to FEP descriptions, changes to the LA FEP List from the information shown for the Data Tracking Number (DTN): MO0407SEPFEPLA.000 (DIRS 170760) are discussed below.

As part of the TSPA-LA FEP evaluation (following TSPA-SR), FEP 3.2.10.00.0A (Atmospheric transport of contaminants) was removed from the system-level FEP list and reassigned elsewhere, and FEP 2.1.01.04.0A (Repository scale heterogeneity of waste) was assigned to the system-level FEP list. Two additional FEPs were added to the TSPA-LA FEP list. These two new FEPs address the effect of preceding disruptive events on determining the timing of human intrusion (1.4.02.03.0A, Igneous event precedes human intrusion; 1.4.02.04.0A, Seismic event precedes human intrusion). Consequently, 33 FEPs are identified as system-level FEPs for TSPA-LA, as noted and derived from the LA FEP List (DIRS 170760).

6.1.2 FEPs Screening Process

The second step of FEP analysis is FEP screening, which addresses Acceptance Criterion 2 of the YMRP (NRC 2003 [DIRS 163274], Section 2.2.1.2.1.3). The TSPA-LA FEP screening process is described in BSC (2004 [DIRS 168706], Section 4).

For FEP screening, each FEP is screened against the specified exclusion criteria (Section 4.2.3), summarized in the following three FEP screening statements:

1) FEPs having less than one chance in 10,000 of occurring over 10,000 years may be excluded (screened out) from the TSPA on the basis of low probability (10 CFR 63.114(d) and 10 CFR 63.342 [DIRS 156605]).

2) FEPs whose omission would not significantly change the magnitude and time of the resulting radiological exposures to the RMEI, or radionuclide releases to the accessible environment, may be excluded (screened out) from the TSPA on the basis of low consequence (10 CFR 63.114 (e and f) [DIRS 156605]).

3) FEPs that are inconsistent with the characteristics, concepts, and definitions specified at 10 CFR Part 63 (DIRS 156605) may be excluded (screened out) from the TSPA by regulation.

A FEP need only satisfy one of the exclusion screening criteria to be excluded from TSPA. A FEP that does not satisfy any of the exclusion screening criteria must be included (screened in) in the TSPA-LA model.

This analysis report documents the screening decisions for system-level FEPs. In cases where a FEP covers multiple technical areas and is shared with other FEP AMRs, this analysis report provides only a partial technical basis for the screening decision as it relates to system-level FEP issues. The full technical basis for the shared FEPs is addressed, collectively, by all of the sharing FEPs analysis reports.

Documentation of the screening for each FEP is provided in Section 6.2. The following standardized format is used. For some FEPs, an optional supplemental discussion section may be provided to address pertinent background information.

Section 6.2.*x* FEP Name (FEP Number)

FEP Description: This field describes the nature and scope of the FEP under consideration.

Screening Decision: Identifies the screening decision as one of:

- “Included”
- “Excluded – Low Probability”
- “Excluded – Low Consequence”
- “Excluded – By Regulation.”

In a few cases, a FEP may be excluded by a combination of two criteria (e.g., Low Probability and Low Consequence).

Screening Argument: This field is used only for excluded FEPs. It provides the discussion for why a FEP has been excluded from TSPA-LA.

TSPA Disposition: This field is used only for included FEPs. It provides the consolidated discussion of how a FEP has been included in TSPA-LA, making reference to more detailed documentation in other supporting technical AMRs, as applicable.

Supporting Reports: This field is only used for included FEPs. It provides the list of supporting technical AMRs that identified the FEP as an included FEP and contain information relevant to the implementation of the FEP within the TSPA-LA model. This list of supporting technical AMRs provides traceability of the FEP through the document hierarchy. For excluded FEPs, it is indicated as "Not Applicable."

6.1.3 Supporting AMRs and Inputs

Per AP-SIII.9Q (particularly, Attachment 2, Section 6), direct inputs used in this AMR are identified in Section 4. Corroborative information is also cited to support the direct inputs. The sources of corroborative information (i.e., indirect input) are listed in Table 6-1.

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening

Source	Input	Used In	Input Description
10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available. (DIRS 156605)	10 CFR 63.102(j)	Sections 4.2.3, 6.2.1.6	Regulatory concept for use of a performance assessment
	10 CFR 63.114	Tables 4-3, 4-4; Section 6.2.1.4	Regulatory requirements pertaining to models and model documentation for performance assessment
	10 CFR 63.121	Sections 6.2.2.1, 6.2.2.4	Regulatory requirements pertaining to land ownership and site control
	10 CFR 63.133(d)	Section 6.2.2.5	Regulatory requirement regarding confirmation of seals for boreholes, ramps, and shafts
	10 CFR 63.2	Sections 6.2.3.1, 6.2.3.6, 6.2.3.7, 6.2.3.8, 6.2.3.9	NRC definition of Performance Assessment including consideration of FEPs
	10 CFR 63.302	Sections 6.2.3.1, 6.2.3.6, 6.2.3.7, 6.2.3.8, 6.2.3.9	Regulatory definition for human intrusion

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
10 CFR 63. Energy: Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada. Readily available. (DIRS 156605) (Continued)	10 CFR 63.321(a)	Sections 6.2.3.2, 6.2.3.6, 6.2.3.7; Appendix C	Regulatory requirement to provide the analyses and the technical bases used to determine the time of occurrence of human intrusion
	10 CFR 63.321(b)(1)	Table 4-3; Sections 6.2.3.2, 6.2.3.6, 6.2.3.7; Appendix C	Regulatory requirement to provide the results of the analysis for human intrusion
	10 CFR 63.321(b)(2)	Table 4-3; Sections 6.2.3.2, 6.2.3.6, 6.2.3.7; Appendix C	Regulatory requirement to present the human intrusion dose analysis in the FEIS if it occurs post-10,000 years
	10 CFR 63.322(g)	Table 4-3; Appendix C	Regulatory exclusion of unlikely FEPs from the human intrusion scenario and groundwater protection standards
	10 CFR 63.51(a)(3)(i, ii, iii)	Sections 6.2.2.1, 6.2.2.4	Regulatory requirement for construction of markers, archiving records, and site control
	10 CFR 63.72(a) and (b)(1 through 11)	Sections 6.2.2.1; 6.2.2.4	Regulatory requirements for construction of markers, archiving records, and site control
40 CFR 197. Protection of Environment: Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada. Readily available. (DIRS 165519)	40 CFR 197.26	Sections 4.1, 6.2.3.5, 6.2.3.6, 6.2.3.7, 6.2.3.8	EPA-defined circumstances of human intrusion
	40 CFR 197.26(e)	Sections 4.1, 6.2.3.1, 6.2.3.2, 6.2.3.6, 6.2.3.7, 6.2.3.8, 6.2.3.10	EPA-specified condition that only release of radionuclides that occur as a result of the intrusion and that are transported through the resulting borehole to the SZ are projected

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
66 FR 32074. 40 CFR Part 197, Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV; Final Rule. Readily available. (DIRS 155216)	40 CFR Part 197, Supplementary Information, Item 3 " What is the Standard for Human Intrusion?" p. 32105	Sections 6.2.3.1, 6.2.3.2, 6.2.3.8, 6.2.3.9	EPA response to comments regarding the human intrusion scenario
	40 CFR Part 197; Psupplemenatry , Item 10. "Is the Single Borehole Scenario a Reasonable Approach to Judge the Resilience of the Yucca Mountain Disposal System Following Human Intrusion?" p. 32127	Sections 4.1, 6.2.3.1, 6.2.3.2, 6.2.3.8, 6.2.3.9	EPA perspective on consideration of deliberate human intrusion
66 FR 55732. Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, NV, Final Rule. 10 CFR Parts 2, 19, 20, 21, 30, 40, 51, 60, 61, 63, 70, 72, 73, and 75. Readily available. (DIRS 156671)	10 CFR Part 63, Supplementary information, 3.10 Human Intrusion Standard, p. 55761	Sections 6.2.3.6; 6.2.3.7	NRC stated intent that a stylized human intrusion scenario be used
	10 CFR Part 63, Supplementary information, III. Public Comments and Response, 2.2 Retrievability, Issue 2, p. 55743	Section 6.2.1.6	NRC statement that the retrievability requirement is not intended to facilitate recovery
	10 CFR Part 63, Supplementary information, p. 55761	Sections 4.1, 6.2.3.5; Appendix C	NRC statements regarding documents indicating lack of mineral resources in vicinity of Yucca Mountain
Abbas, H.; Paul, D.K.; Godbole, P.N.; and Nayak, G.C. 1996. "Aircraft Crash Upon Outer Containment of Nuclear Power Plant." Nuclear Engineering and Design, 160, (1-2), 13-50. New York, New York: Elsevier. TIC: 255604. (DIRS 167627)	Entire	Appendix B	General reference to aircraft hazard analysis for nuclear power plants
	Figures 9, 10, 11, and page 25	Appendix B; Tables B-3, B-4	Mass and velocity of three different aircraft

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Arakel, A.V. 1996. "Quaternary Vadose Calcretes Revisited." AGSO Journal of Australian Geology & Geophysics, 16, (3), 223-229. Canberra, Australia: Australian Government Public Service. TIC: 255481. (DIRS 167623)	p. 223	Appendix B; Table B-7	$CaCO_3$ initially plugs porosity and permeability
	p. 226	Appendix B; Table B-7	Rapid maturation of cemented soil profiles
Arnold, N.F. 2003. "Space Plasma Influences on the Earth's Atmosphere." Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 361, 127-132. London, England: Royal Society of London. TIC: 255613. (DIRS 167638)	Entire	Table B-20	General reference
	p. 127	Section 6.2.4.6; Appendix B	Discussion of cosmic ray influence on earth's atmosphere
Avallone, E.A. and Baumeister, T., III, eds. 1987. Marks' Standard Handbook for Mechanical Engineers. 9th Edition. New York, New York: McGraw-Hill. TIC: 206891. (DIRS 103508)	pp. 13-63 and 13-64	Appendix C	Description of types of metal milling and related equipment
Backman, M.E. and Goldsmith, W. 1978. "The Mechanics of Penetration of Projectiles into Targets." International Journal of Engineering Science, 16, (1), 1-99. New York, New York: Pergamon. TIC: 255605. (DIRS 167628)	Entire	Table 6-1; Appendix B; Tables B-1, B-3	General reference to missile impact study
	pp. 32 and 38	Sections 6.2.3.9; Appendix B; Tables B-1, B-3	Description of penetration into semi-infinite targets.
Bailey, M.E. and Emel'Yanenko, V.V. 1998. "Cometary Capture and the Nature of the Impactors." Meteorites: Flux with Time and Impact Effects. Grady, M.M.; Hutchison, R.; McCall, G.J.H.; and Rothery, D.A.; eds. Geological Society Special Publication No. 140. Pages 11-17. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162564)	Entire	Appendix B; Tables B-8; B-10, B-16b; Figure B-1	General reference
	p. 14	Tables 6-1; B-15, B-19; Figures B-4b, B-4c	Density of comets; Resulting crater radii
	p. 15, Eq. 3; Eq. 4; Eq. 10	Appendix B	Distribution equations

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Baldwin, B. and Butler, C.O. 1985. "Compaction Curve." American Association of Petroleum Geologists Bulletin, 69, (4), 622-626. Tulsa, Oklahoma: American Association of Petroleum Geologists. TIC: 255917. (DIRS 167871)	Figure 3	Appendix B; Table B-7	Reference to the Sclater-Christie sandstone compaction curve
Bates, R.L. and Jackson, J.A., eds. 1984. Dictionary of Geological Terms. 3rd Edition. Garden City, New York: Anchor Books/Doubleday. TIC: 206591. (DIRS 128109)	p. 137	Sections 6.2.4.1, 6.2.4.2	Definition of diagenesis
	p. 138	Section 6.2.4.4	Definition of diapirism
	p. 322	Section 6.2.4.1	Definition of metamorphism
Beer, F.P. and Johnston, E.R., Jr. 1981. Mechanics of Materials. New York, New York: McGraw-Hill. TIC: 255414. (DIRS 166708)	Entire	Table B-2	Reference to textbook on material properties, including brittle and ductile properties
	p. 37	Appendix B	Description of brittle and ductile relationship
	pp. 36, 68, 69, 101, and 584	Appendix C	Descriptions of characteristic strength relationships for brittle and ductile materials
Berner, R.A. 1980. Early Diagenesis: A Theoretical Approach. Princeton, New Jersey: Princeton University Press. TIC: 241522. (DIRS 128110)	Figure 3-2	Section 6.2.4.2	Porosity reduction with increasing compaction
Berry, L.G. and Mason, B. 1959. Mineralogy: Concepts, Descriptions, Determinations. San Francisco, California: W.H. Freeman and Company. TIC: 238767. (DIRS 135236)	p. 233	Section 6.2.4.2	Definition of diagenesis
	p. 240	Section 6.2.4.1	Description of conditions conducive to metamorphism
Bevan, A.W.R.; Bland, P.A.; and Jull, A.J.T. 1998. "Meteorite Flux on the Nullarbor Region, Australia." Meteorites: Flux with Time and Impact Effects. Grady, M.M.; Hutchison, R.; McCall, G.J.H., and Rothery, D.A.; eds. Geological Society Special Publication No. 140. Pages 59-73. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162565)	Entire	Tables 6-1; B-8	General reference
	Table 4	Tables 6-1; B-14	Percent iron meteorite finds
Biggin, A.J. and Thomas, D.N. 2003. "Analysis of Long-Term Variations in the Geomagnetic Polodial Field Intensity and Evaluation of Their Relationship with Global Geodynamics." Geophysical Journal International, 152, (2), 392-415. Oxford, England: Blackwell Publishing. TIC: 255680. (DIRS 167876)	Entire	Appendix B; Table B-21	General reference to study
	Figure 11	Section 6.2.4.7	Anti-correlation of variation and pole reversals
	pp. 409 to 412	Section 6.2.4.7	Frequency of pole reversals and intensity variations

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Bilgesu, H.I.; Tetrick, L.T.; Altmis, U.; Mohaghegh, S.; and Ameri, S. 1997. "A New Approach for the Prediction of Rate of Penetration (ROP) Values." 1997 SPE Eastern Regional Meeting held in Lexington, Kentucky, October 22-24, 1997. SPE 39231. Pages 175-179. Richardson, Texas: Society of Petroleum Engineers. TIC: 255661. (DIRS 167782)	Entire	Appendix B; Table B-2	Review of factors affecting penetration rate
Birkeland, P.W. 1974. Pedology, Weathering and Geomorphological Research. 1974. New York, New York: Oxford University Press. TIC: 241201. (DIRS 128113)	p. 234	Section 6.2.4.2	Relationship between depth of calcareous horizons and precipitation
Bland, P.A.; Conway, A.; Smith, T.B.; Berry, F.J.; Swabey, S.E.J.; and Pillinger, C.T. 1998. "Calculating Flux from Meteorite Decay Rates: A Discussion of Problems Encountered in Deciphering a 10^5-10^6 Year Integrated Meteorite Flux at Allan Hills and a New Approach to Pairing." Meteorites: Flux with Time and Impact Effects. Grady, M.M.; Hutchison, R.; McCall, G.J.H.; and Rothery, D.A.; eds. Geological Society Special Publication Mo. 140. Pages 43-58. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162563)	Entire	Appendix B; Table B-8	General reference
	Figure 1	Appendix B; Figure B-1; Tables B-9, B-10	Meteoroid flux data
	Figure 5	Appendix B; Table B-10; Figure B-1	Meteoroid flux data
Bourgoyne, A.T., Jr.; Millheim, K.K.; Chenevert, M.E.; and Young, F.S., Jr. 1986. "Rotary Drilling Bits." Applied Drilling Engineering. SPE Textbook Series Volume 2. Pages 190-245. Richardson, Texas: Society of Petroleum Engineers. TIC: 250085. (DIRS 155233)	Chapter 5	Appendix C; Table B-2	Relation of abrasiveness to drillability, operation principles of drill bit tooth, lateral forces on drill bit, factors affecting rate of penetration
	Entire	Appendix B; Tables B-1, B-2	General reference to text on applied drilling engineering
	Section 5.1	Appendix C	Discussion of type of bits used in rotary drilling
Boyer, H.E. and Gall, T.L., eds. 1984. Metals Handbook. Desk Edition. 10th Printing 1997. Metals Park, Ohio: American Society for Metals. TIC: 250192. (DIRS 155318)	Entire	Appendix C	Failure mechanisms for ductile material
Bredehoeft, J.D. 1997. "Fault Permeability Near Yucca Mountain." Water Resources Research, 33, (11), 2459-2463. Washington, D.C.: American Geophysical Union. TIC: 236570. (DIRS 100007)	Entire	Appendix B; Table B-22	General reference

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Brown, P.; Spalding, R.E.; ReVelle, D.O.; Tagliaferri, E.; and Worden, S.P. 2002. "The Flux of Small Near-Earth Objects Colliding with the Earth." Nature, 420, (6913), 294-296. London, England: Macmillan Journals. TIC: 254145. (DIRS 162569)	Entire	Appendix B; Table B-8; Figures B-1, B-3	General reference
	Figure 4 and Eq. 3	Appendix B; Tables B-9, B-10	Meteoroid flux data
	p. 294	Tables 5-1; B-15	Meteor velocities and densities
	p. 296	Appendix B	Meteor percent-by-type
BSC (Bechtel SAIC Company) 2003. Requirements Management Plan. PLN-MGR-AD-000004 REV 01 ICN 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031212.0002. (DIRS 168577)	Entire	Section 6.2.1.3	Management Plan
BSC 2003. Total System Performance Assessment-License Application Methods and Approach. TDR-WIS-PA-000006 REV 00 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20031215.0001. (DIRS 166296)	Entire	Sections 6.2.1.1, 6.2.1.2, 6.2.1.4, 6.2.4.10	Project document summarizing methods and approach for TSPA-LA model
	Section 5.1	Sections 6.2.1.2, 6.2.4.10	Method of modeling climate change
	Section 8.3 and Appendix D.3	Sections 6.2.2, 6.2.2.5, 6.2.2.6	TSPA-LA process for addressing multiple barrier analysis and barrier neutralization analysis examples
BSC 2003. Underground Layout Configuration. 800-P0C-MGR0-00100-000-00E. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20031002.0007. (DIRS 165572)	Figures 1 and B-4	Appendix D; Figures D-4a, D-4b	Minimum overburden above the repository layouts
	Section 7.1.8; Figure 1	Appendix D	Minimum depth of overburden in emplacement area
BSC 2004. Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada. ANL-CRW-GS-000003 REV 00 Errata 001. Las Vegas, Nevada: Bechtel SAIC Company. ACC: MOL.20000510.0175; DOC.20040223.0007. (DIRS 168030)	Section 6.4.2	Assumption 5.1	Justification for annual equivalence of 1×10^{-8}

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
BSC 2004. Configuration Management Plan. PLN-MGR-AD-000003 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040225.0010. (DIRS 168396)	Entire	Section 6.2.1.3	Management Plan
BSC 2004. D&E / PA/C IED Subsurface Facilities. 800-IED-WIS0-00103-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040309.0028. (DIRS 168370)	Entire	Appendix D	Drawing for subsurface facilities, including encompassed area
BSC 2004. Drift Degradation Analysis. ANL-EBS-MD-000027, Rev. 03. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 166107)	Section 6.4.2.4	Appendix C	General reference regarding drift collapse with time in the lithophysal unit.
BSC 2004. Geologic Framework Model (GFM2000). MDL-NBS-GS-000002 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 170029)	Table 6-2, Figures 6-8 and 6-14, and Section 6.5.1.3	Appendix D	Lithologic descriptions
BSC 2004. Initial Radionuclide Inventories. ANL-WIS-MD-000020 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 170022)	Sections 6.4.2 and 6.6	Section 6.2.1.7	Treatment of waste inventory heterogeneity
BSC 2004. Seismic Consequence Abstraction. MDL-WIS-PA-000003 Rev. 01. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 169183)	Entire	Appendix C	General reference to seismic damage abstraction
BSC 2004. WAPDEG Analysis of Waste Package and Drip Shield Degradation. ANL-EBS-PA-000001 REV 02. Las Vegas, Nevada: Bechtel SAIC Company. (DIRS 169996)	Section 6.3.8	Appendix C	Early time failures of waste packages due to manufacturing defects
BSC 2004. Yucca Mountain Site Description. TDR-CRW-GS-000001 REV 02 ICN 01. Two volumes. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040504.0008. (DIRS 169734)	Section 3.3.4	Sections 6.2.4.3, 6.2.4.9	Lithologic descriptions for Yucca Mountain
Ceplecha, Z. 1992. "Influx of Interplanetary Bodies onto Earth." Astronomy and Astrophysics, 263, 361-366. New York, New York: Springer-Verlag. TIC: 246784. (DIRS 135242)	Entire	Attachment B; Tables B-8, B-19; Figure B-1; Appendix D; Table D-2	General reference
	p. 361	Appendix B	Meteoroid by percent type
	p. 364	Figures B-4b, B-4c, Table B-19	Mass range where atmospheric shielding is partially or completely effective
	Tables 1 and 3	Appendix B	Meteor information sources

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Ceplecha, Z. 1994. "Impacts of Meteoroids Larger than 1m into the Earth's Atmosphere." Astronomy and Astrophysics, 286, (3), 967-970. New York, New York: Springer-Verlag. TIC: 246761. (DIRS 135243)	Entire	Appendix B; Tables B-8, D-2	Results of small meteoroid impact study
	Figure 3	Table B-19	Resulting impact velocities
	Table 2	Table 5-1; Assumption 5.4; Appendix B	Measured velocities of meteoroids
Chadwick, O.A.; Nettleton, W.D.; and Staidl, G.J. 1995. "Soil Polygenesis as a Function of Quaternary Climate Change, Northern Great Basin, USA." Geoderma, 68, (1-2), 1-26. New York, New York: Elsevier. TIC: 255603. (DIRS 167626)	Entire	Appendix B; Table B-7	Results of soil studies along a transect with significant elevation change, as a surrogate for climate variation
Chapman, C.R. and Morrison, D. 1994. "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard." Nature, 367, (6458), 33-40. New York, New York: Nature America. TIC: 246781. (DIRS 135245)	Entire	Tables B-8; Figure B-1	General reference
	Figure 1 and p. 34	Table 5-1; Appendix B, Table B-10	Meteor frequency and meteor velocities
	p. 33	Section 6.2.3.9	Energy of meteorite impacts and conversion factor for megatons to joules
	p. 34	Appendix B; Table B-15; Appendix D	Range in meteor densities
	pp. 33 and 34	Table B-19; Figure B-4b	Thresholds for atmospheric penetration
Chyba, C.F. 1993. "Explosions of Small Spacewatch Objects in Earth's Atmosphere." Nature, 363, (6431), 701-703. London, United Kingdom: Macmillan Journals. TIC: 246762. (DIRS 135248)	Entire	Table B-8	General reference
	p. 701	Table 5-1; Tables B-10, B-19; Figures B-1, B-4b; Appendix D	Meteor velocities and atmospheric penetration thresholds
	p. 703	Table B-14	Percentage of iron-nickel asteroids
	pp. 703 and 704	Table B-15, B-19	Densities of various types of meteorites
	Table 1a	Table 5-1; Assumption 5.4; Appendix D	Diameters and velocities of observed space objects

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Cole, D.G. 2003. "Space Weather: Its Effects and Predictability." Space Science Reviews, 107, (1-2), 295-302. Dordrecht, The Netherlands: Kluwer Academic. TIC: 255616. (DIRS 167641)	Entire	Appendix B; Table B-20	General reference to discussion of Earth's response to space weather
	pp. 299 to 301	Section 6.2.4.6; Appendix B	List of engineered systems potentially affected by space weather
CRWMS M&O 1999. Final Report: Plant and Soil Related Processes Along a Natural Thermal Gradient at Yucca Mountain, Nevada. B00000000-01717-5705-00109 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990513.0037. (DIRS 105031)	Entire	Section 6.2.4.10	General reference to plant survey information
	Executive Summary, Figure 9, Section 3.3	Section 6.2.4.10	Discussions of relationships of transpiration, percent shrub cover, and temperature to percent shrub cover
	Figure 8; p. 41	Section 6.2.4.10	Soil temperature increases of the magnitude predicted are probably within the adaptive range of some plant species now at Yucca Mountain
	p. 46	Section 6.2.4.10	Effects of repository heating on biosphere; concerns with transition from perennial to annual plant species
CRWMS M&O 2000. Site Recommendation Design Baseline. Technical Change Request T2000-0133. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000503.0159. (DIRS 150088)	Entire	Appendix D	Historical repository design information
CRWMS M&O 2000. Total System Performance Assessment for the Site Recommendation. TDR-WIS-PA-000001 REV 00 ICN 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20001220.0045. (DIRS 153246) (see footnote at end of table)	Entire	Appendix C	General reference to TSPA-SR work
	Figure 4.4-11	Appendix C	Plot of dose histories for human intrusion
	Section 3.4	Sections 6.2.3.2, 6.2.3.6, 6.2.3.7; Appendix C	Longevity of waste packages and drip shields for TSPA-SR
	Section 4.4	Appendix C	Discussion of stylized human intrusion analysis study
	Tables 4.4-1; 4.4-11; 4.4-12	Appendix C	Human intrusion analysis assumptions for TSPA-SR

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Day, W.C.; Dickerson, R.P.; Potter, C.J.; Sweetkind, D.S.; San Juan, C.A.; Drake, R.M., II; and Fridrich, C.J. 1998. *Bedrock Geologic Map of the Yucca Mountain Area, Nye County, Nevada.* Geologic Investigations Series I-2627. Denver, Colorado: U.S. Geological Survey. ACC: MOL.19981014.0301. (DIRS 100027)	Entire	Sections 6.2.4.3, 6.2.4.9	Geologic map of Yucca Mountain region showing formations and structural features
Dence, M.R.; Grieve, R.A.F.; and Robertson, P.B. 1977. "Terrestrial Impact Structures: Principal Characteristics and Energy Considerations." Impact and Explosion Cratering, Planetary and Terrestrial Implications, Proceedings of the Symposium on Planetary Cratering Mechanics, Flagstaff, Arizona, September 13-17, 1976. Roddy, D.J.; Pepin, R.O.; and Merrill, R.B., eds. Pages 247-275. New York, New York: Pergamon Press. TIC: 247237. (DIRS 135253)	Entire	Appendix B; Tables B-1, B-8	General reference
	p. 247 and p. 270	Appendix B	Resulting crater radius
	p. 270	Appendix B; Figure B-4a, Table B-19	Examples of crater diameters
DOE (U.S. Department of Energy) 1998. Introduction and Site Characteristics. Volume 1 of Viability Assessment of a Repository at Yucca Mountain. DOE/RW-0508. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19981007.0028. (DIRS 100548)	Section 6.1	Section 6.2.4.2	Discussion of natural diagenetic processes at Yucca Mountain
DOE 2002. Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada. DOE/EIS-0250. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20020524.0314; MOL.20020524.0315; MOL.20020524.0316; MOL.20020524.0317; MOL.20020524.0318; MOL.20020524.0319; MOL.20020524.0320. (DIRS 155970)	Entire	Section 6.2.1.1, 6.2.1.2, 6.2.3.2; Appendix C	General reference for treatment of potential for hazards to the environment
	Section 5.7.1	Sections 6.2.3.2, 6.2.3.6, 6.2.3.7; Appendix C	Human intrusion scenario
	Section 5.9; p. 5-41	Section 6.2.4.10	Effects of repository heat on biosphere
	Table 3-20	Section 6.2.4.2	Duripans present in soils at Yucca Mountain

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Driscoll, F.G. 1986. Groundwater and Wells. 2nd Edition. St. Paul, Minnesota: Johnson Filtration Systems. TIC: 217555. (DIRS 116801)	p. 281	Table 6-1, Appendix C	Discussion of the use of drill collars and stabilizers in the drill assembly
	p. 360	Appendix C	Description of the use of drilling additives to address lost circulation
	pp. 278 to 286	Appendix C	Discussion of direct rotary drilling methods and applicable conditions for use
	pp. 316 to 317; Figures 10.10 and 10.54	Appendix C	Description and figures of specialized drilling tools
Eghbal, M.K. and Southard, R.J. 1993. "Micromorphological Evidence of Polygenesis of Three Aridisols, Western Mohave Desert, California." Soil Science Society of America Journal, 57, (4), 1041-1050. Madison, Wisconsin: Soil Science Society of America. TIC: 255602. (DIRS 167625)	p. 1049	Appendix B; Table B-7	Description of aridisol pedogenesisis
Eghbal, M.K. and Southard, R.J. 1993. "Stratigraphy and Genesis of Durorthids and Haplargids on Dissected Alluvial Fans, Western Mojave Desert, California." *Geoderma, 59,* (1-4), 151-174. Amsterdam, The Netherlands: Elsevier. TIC: 255601. (DIRS 167624)	pp. 170 and 171	Appendix B; Table B-7	Field studies addressing duripan formation
Ehlers, E.G. and Blatt, H. 1982. Petrology, Igneous, Sedimentary, and Metamorphic. New York, New York: W.H. Freeman and Company. TIC: 255657. (DIRS 167802)	Entire	Appendix B	General reference to textbook on metamorphism
Fenelon, J.M. 2000. Quality Assurance and Analysis of Water Levels in Wells on Pahute Mesa and Vicinity, Nevada Test Site, Nye County, Nevada. Water-Resources Investigations Report 00-4014. Carson City, Nevada: U.S. Geological Survey. ACC: MOL.20030904.0304. (DIRS 160881)	Entire	Appendix B; Table B-22	Water level fluctuations due to earth tides at the Nevada Test Site
	p. 14	Section 6.2.4.8: Table B-22	Water level fluctuation in wells due to earth tides
Fridrich, C.J. 1999. "Tectonic Evolution of the Crater Flat Basin, Yucca Mountain Region, Nevada." Chapter 7 of Cenozoic Basins of the Death Valley Region. Wright, L.A. and Troxel, B.W., eds. Special Paper 333. Boulder, Colorado: Geological Society of America. TIC: 248054. (DIRS 118942)	p. 189	Section 6.2.4.1	Discussion of the locus of subsidence in the Yucca Mountain region

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Glasstone, S. and Dolan, P.J., eds. 1977. "Descriptions of Nuclear Explosions." Chapter II of The Effects of Nuclear Weapons. 3rd Edition. Pages 26-79. Washington, D.C.: U.S. Department of Defense and U.S. Department of Energy. ACC: MOL.20030925.0035. (DIRS 160992)	Section 2.104	Appendix B, Table B-3	Extent of effects of underground blast from the Rainer 1.7 kiloton blast
Grattan-Bellew, P.E. and Vijay, M.M. 1986. "Influence of Physical Properties of Rock on Rate of Penetration of a Water-Jet Drill." Canadian Mineralogist, 24, 323-328. Ottawa, Canada: Mineralogical Association of Canada. TIC: 255711. (DIRS 167786)	Entire	Appendix B, Table B-2	Commonly measured rock properties and relationship to water-jet drilling
Grieve, R.; Rupert, J.; and Therriault, A. 1995. "The Record of Terrestrial Impact Cratering." GSA Today, 5, (10), 194-196. Boulder, Colorado: Geological Society of America. TIC: 246688. (DIRS 135260)	Entire	Appendix B; Table B-16a; Figure B-2; Appendix D: Figures D-1, D-3	Review and update of terrestrial impact structures
	p. 196	Appendix B	Constant for distribution equation
Grieve, R.A.F. 1998. "Extraterrestrial Impacts on Earth: The Evidence and the Consequences." Meteorites: Flux with Time and Impact Effects. Grady, M.M.; Hutchinson, R.; McCall, G.J.H.; and Rothery, D.A., eds. Geological Society Special Publication No. 140. Pages 105-131. London, England: Geological Society. TIC: 254143. (DIRS 163385)	Entire	Appendix B; Table B-8; Appendix D	General reference for an updated meteor cratering study
Grieve, R.F. 1987. "Terrestrial Impact Structures." Annual Review of Earth and Planetary Sciences, 15, 245-269. Palo Alto, California: Annual Reviews. TIC: 246788. (DIRS 135254)	Entire	Section 6.2.4.5: Appendix B: Tables B-8, B-16a; Figure B-2; Appendix D; Figures D-1, D-3	General reference for impact cratering on earth
	p. 250	Table 5-1	Meteor velocities
Gronlund, L. and Wright, D. 2002. "Earth Penetrating Weapons" Global Security Cambridge, Massachusetts: Union of Concerned Scientists. Accessed December 10, 2002. TIC: 253714. http://www.ucsusa.org/global_security/nuclear_weapons/page.cfm?pageID=777 (DIRS 160989)	Entire	Appendix B, Table B-3	Information on penetration depth, current U.S. earth-penetrating weapons capabilities of Guided Bomb Unit series weapons.
Hagan, M.E. 1995. "Thermospheric Connections." Reviews of Geophysics (Supplement), 33, (Part 1), 729-735. Washington, D.C.: American Geophysical Union. TIC: 253731. (DIRS 160890)	Entire	Appendix B; Table B-20	Hypothetical complex coupling of the thermosphere, ionosphere, and magnetosphere

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Hartmann, W.K. 1966. Terrestrial and Lunar Flux of Large Meteorites Through Solar System History. Publication No. 3. Tempe, Arizona: Arizona State University, Center for Meteorite Studies. TIC: 254144. (DIRS 162567)	Entire	Table B-8	General reference
Hills, J.G. and Goda, P.M. 1993. "Fragmentation of Small Asteroids in the Atmosphere." The Astronomical Journal, 105, (3), 1114-1144. Woodbury, New York: American Institute of Physics. TIC: 246798. (DIRS 135281)	Entire	Appendix B; Table B-19; Appendix D; Figure D-3	General reference to work on meteor fragmentation and cratering
	Figure 1	Appendix B; Table B-15	Assumed densities for meteorites
	Figures 3, 6, 9, 10, and 11	Assumption 5.4	Supporting figures that corroborate with work of others
	Figures 4; 6; 10; 11; 12	Table B-19	Atmospheric effects on meteors
	p. 1116	Table 6-1; Assumption 5.4	Initial velocity of meteors
Hills, J.G. and Goda, P.M. 1998. "Damage from the Impact of Small Asteroids." Planetary and Space Science, 46, (2-3), 219-229. Oxford, United Kingdom: Elsevier. TIC: 246675. (DIRS 135291)	Entire	Assumption 5.4; Table B-8	General reference for impact cratering studies
	p. 224	Appendix B	Meteoroid composition
	p. 225; Figure 7	Table B-14	Iron meteors as percent of total
	p. 228	Appendix D	Dissipation of energy into atmosphere and relationship to velocity and entry angle
Hoffman, K.A. 1995. "How are Geomagnetic Reversals Related to Field Intensity?" Eos, Volume 76, July 18, 1995, p. 289. Washington, D.C.: American Geophysical Union. Accessed April 23, 2003. TIC: 253732. http://www.agu.org/sci-soc/hoffman.html (DIRS 160891)	Entire	Section 6.2.4.7; Appendix B, Table B-21	Alternative interpretations of available data suggesting that the magnetic reversal may not reach completion
Howarth, D.F.; Adamson, W.R.; and Berndt, J.R. 1986. "Correlation of Model Tunnel Boring and Drilling Machine Performances with Rock Properties." International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 23, (2), 171-175. New York, New York: Pergamon. TIC: 255620. (DIRS 167645)	Entire	Appendix B; Table B-2	Relationship of material strength properties to percussive drill performance
	Figure 2	Appendix B	Correlation of saturated compressive strength to rate of penetration

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Hughes, D.W. 1998. "The Mass Distribution of Crater-Producing Bodies." Meteorites: Flux with Time and Impact Effects. Geological Society Special Publication No. 140. Grady, M.M.; Hutchison, R.; McCall, G.J.H.; and Rothery, D.A.; eds. Pages 31-42. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162562)	Entire	Appendix B; Tables B-8, B-10, B-13, B-16b, B-19; Figure B-1	General reference
	Figure 3	Appendix B; Table B-3	Crater diameter - to - energy release relationships from work of others
	p. 31	Figure B-4c	Crater diameter related to size of meteor event
	p. 31 and p. 37	Table B-19	Relation of meteor diameters to resulting crater diameters
	p. 34	Appendix D	Crater diameter distribution curve
	p. 35 and p. 37	Table 6-1, Table 5-1; Assumption 5.4	Meteor velocities
	p. 37	Appendix B; Table B-19	Point cratering frequency from work of others
	p. 4, Equation 2	Appendix B	Cratering distribution and mass flux equations
	pp. 34 and 40	Table B-15	Meteor densities
	Table 2	Appendix B; Table B-12	Source of distribution information from other authors
Humphrey, J.D.; Ransom, K.L.; and Matthews, R.K. 1986. "Early Meteoric Diagenetic Control of Upper Smackover Production, Oaks Field, Louisiana." The American Association of Petroleum Geologists Bulletin, 70, (1), 70-85. Tulsa, Oklahoma: American Association of Petroleum Geologists. TIC: 246098. (DIRS 118461)	pp. 77 and 78	Section 6.2.4.2; Appendix B; Table B-7	Rates of diagenetic processes in the vadose zone
Hyndman, D.W. 1972. Petrology of Igneous and Metamorphic Rocks. International Series in the Earth and Planetary Sciences. New York, New York: McGraw-Hill. TIC: 248141. (DIRS 150295)	Entire	Tables B-5, B-6	General reference for metamorphic petrology text
	pp. 270 to 272	Tables B-5, B-6; Appendix B	Conditions necessary for metamorphism and temperature and lithostatic gradients
IADC (International Association of Drilling Contractors) 1992. Drilling Manual. 11th Edition. Houston, Texas: International Association of Drilling Contractors. TIC: 232344. (DIRS 155232)	Entire	Appendix C	Classification chart for selection of roller bits

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Kahraman, S. 2002. "Correlation of TBM and Drilling Machine Performances with Rock Brittleness." Engineering Geology, 65, (4), 269-283. New York, New York: Elsevier. TIC: 255618. (DIRS 167643)	Entire	Appendix B; Table B-2	Correlation of rock brittleness properties to drill performance
Kahraman, S.; Balci, C.; Yazici, S.; and Bilgin, N. 2000. "Prediction of the Penetration Rate of Rotary Blast Hole Drills Using a New Drillability Index." International Journal of Rock Mechanics and Mining Sciences, 37, (5), 729-743. New York, New York: Pergamon. TIC: 255709. (DIRS 167761)	Entire	Appendix B; Tables B-1, B-2	General reference to a materials properties study
	Eq. 12; Eq 14; and Table 2	Appendix B	Equations indicating relationship of compressive and tensile strength of rock properties
Karam, P.A. 2002. "Gamma and Neutrino Radiation Dose from Gamma Ray Bursts and Nearby Supernovae." Health Physics, 82, (4), 491-499. Philadelphia, Pennsylvania: Lippincott Williams & Wilkins. TIC: 255918. (DIRS 167872)	Entire	Section 6.2.4.6; Appendix B; Table B-20	General reference to paper addressing dose from extraterrestrial events
	pp. 491 and 492	Appendix B	Magnitude and frequency of extraterrestrial events
	Table 1	Section 6.2.4.6; Appendix B	Dose calculation for extraterrestrial events
Kies, A.; Majerus, J.; and de Lantremange, N.D. 1999. "Underground Radon Gas Concentrations Related to Earth Tides." Il Nuovo Cimento della Società Italiana di Fisica, 22C, (3-4), 287-293. Bologna, Italy: Editrice Compositori. TIC: 253721. (DIRS 160882)	Entire	Section 6.2.4.8; Appendix B	Relationship of gas flux to earth tides and of small magnitude
Krystinik, L.F. 1990. "Early Diagenesis in Continental Eolian Deposits." Chapter 8 of Modern and Ancient Eolian Deposits: Petroleum Exploration and Production. Fryberger, S.G.; Krystinik, L.F.; and Schenk, C.J., eds. Denver, Colorado: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section. TIC: 247781. (DIRS 135295)	Entire	Section 6.2.4.2; Appendix B, Table B-7	General reference for early diagenetic rates and processes in eolian deposits
	p. 8-8, Table 2	Section 6.2.4.2; Appendix B	Cementation processes and associated minerals
Lachenbruch, A.H. and Sass, J.H. 1978. "Models of an Extending Lithosphere and Heat Flow in the Basin and Range Province." Chapter 9 of Cenozoic Tectonics and Regional Geophysics of the Western Cordillera. Smith, R.B. and Eaton, G.P., eds. Memoir 152. Pages 209-250. Boulder, Colorado: Geological Society of America. TIC: 225059. (DIRS 142990)	pp. 212 and 246	Section 6.2.4.4	Yucca Mountain south of areas with high heat flux

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Lattman, L.H. 1972. "Relation of Caliche (Calcrete) Horizons to Alluvial Fan Processes in Southern Nevada." Abstracts with Programs - Geological Society of America, 4, (7), 574. Boulder, Colorado: Geological Society of America. TIC: 255828. (DIRS 167813)	Entire	Appendix B; Table B-7	Caliche formation and destruction is climate related
Lattman, L.H. 1973. "Calcium Carbonate Cementation of Alluvial Fans in Southern Nevada." Geological Society of America Bulletin, 84, (9), 3013-3028. Boulder, Colorado: Geological Society of America. TIC: 235904. (DIRS 129305)	Entire	Section 6.2.4.2; Table B-7	General reference rates and processes of calcium carbonate cementation in Southern Nevada
	pp. 3014 and 3022	Section 6.2.4.2	Specific references for rates and process of calcium carbonate cementation in southern Nevada
Lattman, L.H. 1983. "Effect of Caliche on Desert Processes." Chapter 4 of Origin and Evolution of Deserts. Wells, S.G. and Haragan, D.R., eds. 1st Edition. Albuquerque, New Mexico: University of New Mexico Press. TIC: 255700. (DIRS 167815)	Entire	Appendix B; Table B-7	General reference to chapter on caliche
	pp. 107 and 108	Appendix B, Table B-7	Net effect of cementation on infiltration and soil stability
Lean, J. 1997. "The Sun's Variable Radiation and its Relevance for Earth." Annual Review of Astronomy and Astrophysics, 35, 33-67. Palo Alto, California: Annual Reviews. TIC: 255614. (DIRS 167639)	Entire	Section 6.2.4.6; Appendix B; Table B-20	General reference to solar linkage study and review
	pp. 57 to 61	Section 6.2.4.6; Appendix B	List of systems affected by space weather
Lennox, D. and Rees, A., eds. 1990. Jane's Air-Launched Weapons. Alexandria, Virginia: Jane's Information Group. TIC: 255862. (DIRS 167804)	Entire	Appendix B, Table B-3	Specifications (mass, length, diameter, mass of warhead) for various air-launched weapons
Machette, M.N. 1982. "Morphology, Age, and Rate of Accumulation of Pedogenic $CaCO_3$ in Some Calcareous Soils and Pedogenic Calcretes of Southwestern United States." Abstracts with Programs - Geological Society of America, 14, (4), 182-183. Boulder, Colorado: Geological Society of America. TIC: 209942. (DIRS 167814)	Entire	Appendix B; Table B-7	$CaCO_3$ accumulation rates in the southwestern United States

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Marsden, B.G. and Steel, D.I. 1994. “Warning Times and Impact Probabilities for Long-Period Comets.” Hazards Due to Comets and Asteroids. Gehrels, T., ed. 221-237. Tucson, Arizona: University of Arizona Press. TIC: 246879. (DIRS 129308)	Entire	Table B-8	General reference to asteroid probability impact study
	p. 235, Figure 4	Appendix D	Calculated impacted probabilities for observed objects
	pp. 233 to 236	Assumption 5.4	Velocity of meteoroids
	Table V	Table 5-1	Meteor velocity
Maynard, N.C. 1995. “Space Weather Prediction.” Reviews of Geophysics (Supplement), 33, (Part 1), 547-557. Washington, D.C.: American Geophysical Union. TIC: 253729. (DIRS 160888)	Entire	Section 6.2.4.6; Appendix B; Table B-20	Description of various effects on earth from various space-related phenomena
Melosh, H.J. 1989. Impact Cratering: A Geologic Process. New York, New York: Oxford University Press. TIC: 247750. (DIRS 146025)	p. 35	Appendix B	Hugoniot elastic limit for granodiorite
Merriam-Webster. 1993. Merriam-Webster’s Collegiate Dictionary, 10th Edition. Springfield, Massachusetts: Merriam-Webster. TIC: 8883. (DIRS 100468)	p. 899, Poisson Distribution	Assumption 5.1	Definition of a Poisson Distribution.
Nelson, R.W. 2001. “Low-Yield Earth-Penetrating Nuclear Weapons.” FAS Public Interest Report, 54, (1), 1-5. Washington, D.C.: Federation of American Scientists. TIC: 253719. (DIRS 160996)	Entire	Sections 6.2.3.9; Appendix B; Table B-3	Information on long rod penetration
Neukum, G. and Ivanov, B.A. 1994. “Crater Size Distributions and Impact Probabilities on Earth from Lunar, Terrestrial-Planet, and Asteroid Cratering Data.” Hazards Due to Comets and Asteroids. Gehrels, T., ed. 359-416. Tucson, Arizona: The University of Arizona Press. TIC: 246879. (DIRS 121510)	Entire	Appendix B, Table B-8; Figures B-1, B-2; Appendix D; Figures D-1, D-3	General reference for planetary cratering studies
	p. 404; Figure 24	Appendix B	Discussion of lower bound of Grieve’s distribution
	Table IV	Appendix B; Figure B-3; Tables B-9, B-10, B-16b, B-17; Appendix D	Impact rates based on lunar data and adjusted for gravity differences
Novotna, D. and Vitek, V. 1991. “The Atmospheric Mean Energetic Level and External Forcing.” Studia Geophysica et Geodaetica, 35, (1), 33-38. Prague, Czechoslovakia: Geophysical Institute of the Czechoslovak Academy of Sciences. TIC: 255610. (DIRS 167634)	Entire	Table B-20	General reference
	p. 35	Section 6.2.4.6; Appendix B	Discussion of potential climate forcing mechanisms

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
NRC (U.S. Nuclear Regulatory Commission) 2003. Yucca Mountain Review Plan, Final Report. NUREG-1804, Rev. 2. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards. TIC: 254568. (DIRS 163274)	Entire	Sections 4.2; 6.2.1.3	NRC Review plan and associated Acceptance Criteria
	Glossary	Section 6	Definitions of FEPs
	Section 2.2.1	Section 4.2.3	NRC perspective on use of conservative approach for modeling
	Section 2.2.1.2.1.3; Acceptance Criterion 1	Tables 4-3, 4-4; Section 6.1.1	Applicable acceptance criteria and relevant to performance assessment and/or FEPs considerations
	Section 2.2.1.2.1.3; Acceptance Criterion 2	Tables 4-3, 4-4; Sections 4.2.3, 6.1.2, 6.1.2.3	Criterion allowing exclusion “by regulation”
	Section 2.2.1.2.2.3; Acceptance Criteria 1, 2, 5	Tables 4-3, 4-4	Applicable acceptance criteria and relevant to performance assessment and/or FEPs considerations
	Section 2.2.1.2.2.3; Acceptance Criteria 3, 4	Table 4-4	Criteria relevant to probabilistic model, but not relevant to FEPs evaluations per se
	Section 2.2.1.4.2.3; Acceptance Criteria 1, 2	Tables 4-3, 4-4	Criteria relevant to the human intrusion stylized analysis
	Sections 2.2.1.2; 2.2.1.4	Section 4.2, 4.2.2	General reference to sections of the review plan with applicable criteria
Palmer, S.N. and Barton, M.E. 1987. “Porosity Reduction, Microfabric and Resultant Lithification in UK Uncemented Sands.” Geological Society Special Publication, 36, 29-40. Oxford, United Kingdom: Blackwell Scientific Publications. TIC: 246095. (DIRS 118483)	pp. 32 and 39; Figure 3	Section 6.2.4.2; Appendix B; Table B-7	Discussion of porosity reduction of sands due to compaction during burial

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Pechala, F. 1985. "The Effect of Extraterrestrial Interactions on Change of Tropospheric Circulation in the Polar Regions of the Earth." Studia Geophysica et Geodaetica, 29, (4), 405-412. Prague, Czechoslovakia: Geophycial Institute of the Czechoslovak Academy of Sciences. TIC: 255609. (DIRS 167633)	Entire	Sections 6.2.4.7; Appendix B; Tables B-20, B-21	General reference
	p. 406	Section 6.2.4.7	Extraterrestrial event may trigger energy redistributions in the troposphere
Press, F. and Siever, R. 1978. Earth. 2nd Edition. San Francisco, California: W.H. Freeman and Company. TIC: 255856. (DIRS 167965)	Entire	Appendix B, Tables B-5, B-6	General reference to geology text book
	p. 296	Section 6.2.4.1; Appendix B, Tables B-5, B-6	Geothermal and pressure gradients, and conditions needed for onset of metamorphism (about 300 degrees C)
Putot, C.J.M.; Guesnon, J.; Perreau, P.J.; and Constantinescu, A. 2000. "Quantifying Drilling Efficiency and Disruption: Field Data vs. Theoretical Model." SPE Drilling & Completion, 15, (2), 118-125. Richardson, Texas: Society of Petroleum Engineers. TIC: 255897. (DIRS 167791)	p. 118	Appendix C	Description of conditions that would cause a driller to adjust drilling parameters or stop drilling
	p. 123	Appendix C	Description of relations between rate of penetration and degradation of drilling conditions in shale
Reeves, C.C. 1976. Caliche: Origin, Classification, Morphology and Uses. Lubbock, Texas: Estacado Books. TIC: 245928. (DIRS 104303)	Entire	Section 6.2.4.2; Appendix B	General reference
	pp. 7, 28, 29, 84 to 87, and 110; Figure 4-10	Section 6.2.4.2	Specific references for physical, chemical, and climatological factors affecting caliche formation
Reid, G.C. 1995. "The Sun-Climate Question: Is There a Real Connection?" Review of Geophysics (Supplement), 33, (Part 1), 535-538. Washington, D.C.: American Geophysical Union. TIC: 253730. (DIRS 160889)	Entire	Appendix B, Table B-20	Discussion of relationship of solar cycles to long-term and short-term weather and climate patterns

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Retallack, G.J. 1991. "Untangling the Effects of Burial Alteration and Ancient Soil Formation." Annual Review of Earth and Planetary Sciences. 19. 183-206. Palo Alto, California: Annual Reviews. TIC: 255912. (DIRS 167870)	Entire	Tables B-5, B-6	General reference to paper addressing burial of paleosoils
	p. 200	Appendix B; Tables B-5, B-6	Conditions needed for metamorphism
Richardson, J. and Bedient, J. 2001. "Frequently Asked Questions (FAQ) About Fireballs and Meteorite Dropping Fireballs." Geneseo, New York: American Meteor Society. Accessed April 22, 2003. TIC: 254120. http://www.amsmeteors.org/fireball/faqf.html (DIRS 162571)	Entire	Appendix B; Tables B-8, B-13	General reference
	FAQs 15 and 16	Appendix B	Percent-by-type meteor data
	FAQs 15 and 16	Tables B-14, B-15	Meteor densities
Rozelot, J.P. 2001. "Possible Links Between the Solar Radius Variations and the Earth's Climate Evolution Over the Past Four Centuries." Journal of Atmospheric and Solar-Terrestrial Physics, 63, (4), 375-386. New York, New York: Pergamon. TIC: 255615. (DIRS 167640)	Entire	Appendix B, Table B-20	General reference to study of solar activity - earth climate linkages.
Ruderman, M.A. 1974. "Possible Consequences of Nearby Supernova Explosions for Atmospheric Ozone and Terrestrial Life." Science, 184, 1079-1081. Washington, D.C.: American Association for the Advancement of Science. TIC: 255914. (DIRS 167875)	Entire	Section 6.2.4.6; Appendix B; Table B-20	Potential for supernova event to affect the ozone layer
Salem, A.M.K.; Abdel-Wahab, A.; and McBride, E.F. 1998. "Diagenesis of Shallowly Buried Cratonic Sandstones, Southwest Sinai, Egypt." Sedimentary Geology, 119, (3-4), 311-335. New York, New York: Elsevier. TIC: 255708. (DIRS 167869)	Entire	Appendix B, Table B-7	General reference to diagenesis paper on shallow buried sandstone
	pp. 319 to 331	Appendix B; Table B-7	Diagenetic history of a shallow-buried sandstone
Sass, J.H.; Lachenbruch, A.H.; Dudley, W.W., Jr.; Priest, S.S.; and Munroe, R.J. 1988. Temperature, Thermal Conductivity, and Heat Flow Near Yucca Mountain, Nevada: Some Tectonic and Hydrologic Implications. Open-File Report 87-649. Denver, Colorado: U.S. Geological Survey. TIC: 203195. (DIRS 100644)	pp. 38 and 39	Section 6.2.4.1	Geothermal gradients in deep boreholes

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Satchwell, R.M. 1994. An Experimental Study of the Effect of Bedding Plane Anisotrophy on the Rate of Penetration. Ph.D. dissertation. Laramie, Wyoming: University of Wyoming, Department of Chemical and Petroleum Engineering. TIC: 255659. (DIRS 167952)	Eq. 6.4-1	Appendix B; Table B-2	Equation for torque on drill string, including rock strength, and showing inverse relationship
Savage, J.C.; Svarc, J.L.; and Prescott, W.H. 1999. "Strain Accumulation at Yucca Mountain, Nevada, 1983-1998." Journal of Geophysical Research, 104, (B8), 17627-17631. Washington, D.C.: American Geophysical Union. TIC: 245645. (DIRS 118952)	p. 17627	Section 6.2.4.1	Strain accumulation rate at Yucca Mountain
Shoemaker, E.M. 1983. "Asteroid and Comet Bombardment of the Earth." Annual Review of Earth and Planetary Sciences, 11, 461-494. Palo Alto, California: Annual Reviews. TIC: 246922. (DIRS 135308)	p. 468	Table 5-1	Meteor velocity
	p. 470	Table B-19; Figure B-4a	Resulting crater diameters
	p. 473	Figure B-4b; Table B-19	Resulting crater diameters
	p. 475	Figure B-4c; Table B-19	Limit for non-fragmenting meteors
	p. 479	Figures B-4c; Table B-19	Limits for non-fragmenting meteors
	p. 480	Table B-14	Composition and percent-by-type for iron
Siddiqui, N.A. and Abbas, H. 2002. "Mechanics of Missile Penetration into Geo-Materials." Structural Engineering and Mechanics, 13, (6), 639-652. Taejon, Korea: Techno-Press. TIC: 255608. (DIRS 167631)	Entire	Appendix B, Table B-3	Rework of Forrestal et al. (1981 [DIRS 167630]). Suggests penetration depth of 2.9 m
Smith, R.P.; Jackson, S.M.; and Hackett, W.R. 1998. "Magma Intrusion and Seismic-Hazards Assessment in the Basin and Range Province." Proceedings Volume, Basin and Range Province (BRP) Seismic-Hazards Summit, Reno, Nevada, May 13-15, 1997. Miscellaneous Publication 98-2, 155-166. Salt Lake City, Utah: Utah Geological Survey. TIC: 246749. (DIRS 118967)	p. 155; Figure 2	Section 6.2.4.4	Mechanisms and effects of dike formation in igneous intrusion
Solomon, K.A.; Erdmann, R.C.; and Okrent, D. 1975. "Estimate of the Hazards to a Nuclear Reactor from the Random Impact of Meteorites." Nuclear Technology, 25, 68-71. La Grange Park, Illinois: American Nuclear Society. TIC: 241714. (DIRS 103697)	Entire	Appendix B; Table B-8	General reference to article addressing meteorite impact hazard at nuclear facilities
	Table I	Appendix B, Tables B-9, B-10; Figure B-1	Meteoroid flux information
Stix, G. and Yam, P. 2001. "Facing a New Menace." Scientific American, 285, (5), 14-15. New York, New York: Scientific American. TIC: 254304. (DIRS 160994)	Entire	Appendix B	General reference including energy release from cruise missile

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Stuart, J.S. 2001. "A Near-Earth Asteroid Population Estimate from the LINEAR Survey." Science, 294, (5547), 1691-1693. Washington, D.C.: American Association for the Advancement of Science. TIC: 254146. (DIRS 162568)	Entire	Appendix B; Table B-8	General reference
Taylor, E.M. 1986. Impact of Time and Climate on Quaternary Soils in the Yucca Mountain Area of the Nevada Test Site. Master's thesis. Boulder, Colorado: University of Colorado. TIC: 218287. (DIRS 102864)	Entire	Appendix B	General reference to Master's thesis done on Yucca Mountain soils
Thrush, P.W., ed. 1968. Dictionary of Mining, Mineral, and Related Terms. Chicago, Illinois: Maclean Hunter Publishing Company. TIC: 207966. (DIRS 106989)	pp. 30, 320, and 699	Section 6.2.4.2	Definitions of diagenesis, alteration, and metamorphism
Warren, T.M. 1984. "Factors Affecting Torque for a Roller Cone Bit." Journal of Petroleum Technology, 36, (10), 1500-1508. Dallas, Texas: Society of Petroleum Engineers of AIME. TIC: 255859. (DIRS 167788)	Entire	Appendix B; Table B-2	Factors affecting torque on drill bit including rock properties
Warren, T.M. 1987. "Penetration-Rate Performance of Roller-Cone Bits." Drilling. SPE Reprint Series No. 22. Richardson, Texas: Society of Petroleum Engineers. TIC: 250084. (DIRS 155234)	Entire	Appendix C	Principles of drill bit operation for roller cone bit; Penetrate rate is inversely proportion to the square of the compressive strength of the material being drilled
Wernicke, B.; Davis, J.L.; Bennett, R.A.; Elosegui, P.; Abolins, M.J.; Brady, R.J.; House, M.A.; Niemi, N.A.; and Snow, J.K. 1998. "Anomalous Strain Accumulation in the Yucca Mountain Area, Nevada." Science, 279, 2096-2100. New York, New York: American Association for the Advancement of Science. TIC: 235956. (DIRS 103485)	Entire	Section 6.2.4.1	General reference for strain accumulation rate at Yucca Mountain
Williams, N.H. 2001. "Contract No. DE-AC08-01RW12101 - Total System Performance Assessment - Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain - Input to Final Environmental Impact Statement and Site Suitability Evaluation REV 00 ICN 02." Letter from N.H. Williams (BSC) to J.R. Summerson (DOE/YMSCO), December 11, 2001, RWA:cs-1204010670, with enclosure. ACC: MOL.20011213.0056. (DIRS 157307)	Section 6.2	Appendix C	TSPA-SR maximum mean dose assuming intrusion at 100 years postclosure.
	Section 6.4	Appendix C	TSPA-SR sensitivity analysis for human intrusion

Table 6-1. Indirect Inputs Used in the Analysis of System-Level FEP Screening (Continued)

Source	Input	Used In	Input Description
Wu, C. 2000. "Powerful Explosive Blasts Onto Scene" Science News Online. Washington, D.C.: Science Service. Accessed March 25, 2004. TIC: 255698. http://www.sciencenews.org/articles/20000122/fob6.asp. (DIRS 167812)	Entire	Appendix B; Table B-3	New explosive (octanitrocubane) may have twice the yield of trinitrotoluene (TNT)
Wuschke, D.M.; Whitaker, H.H.; Goodwin, B.W.; and Rasmussen, L.R. 1995. Assessment of the Long-Term Risk of a Meteorite Impact on Hypothetical Canadian Nuclear Fuel Waste Disposal Vault Deep in Plutonic Rock. AECL-11014. Pinawa, Manitoba, Canada: Atomic Energy of Canada Limited, Whiteshell Laboratories. TIC: 221413. (DIRS 129326)	Entire	Section 6.2.4.5; Appendix B; Table B-8; Figure B-2; Appendix D; Figures D-1, D-3	General reference
	Equation 3	Table B-16a	Cratering distribution equation
	p. 26, Table 1	Appendix D	Information for calculating impact probabilities
Yaalon, D.H. 1967. "Factors Affecting the Lithification of Eolianite and Interpretation of Its Environmental Significance in the Coastal Plain of Israel." Journal of Sedimentary Petrology, 37, (4), 1189-1199. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists. TIC: 255600. (DIRS 167622)	Entire	Appendix B, Table B-7	Rate of diagenesis in coastal eolian deposits
	p. 1189	Appendix B; Table B-7	Percent $CaCO_3$ needed to initiate lithification
	p. 1194	Table B-7	Rate of lithification
Zolensky, M. 1998. "The Flux of Meteorites to Antarctica." Meteorites: Flux with Time and Impact Effects. Geological Society Special Publication No. 140. Grady, M.M.; Hutchison, R.; McCall, G.J.H., and Rothery, D.A.; eds. Pages 93-104. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162566)	Entire	Table B-8	General reference

NOTE: DIRS 153246 was cancelled due to development of the TSPA-LA. The referenced document is the source of information generated for Site Recommendation and is therefore an appropriate historical reference.

6.1.4 Qualification of Direct Inputs

Because the system-level FEPs are overarching in nature and address processes and events that are not specific to the YMP, direct inputs were obtained from literature searches of peer-reviewed journals, other widely recognized scientific periodicals, compendiums of technical articles, and other sources such as technical handbooks and textbooks. Direct inputs from non-YMP sources are listed in Table 4-1. Evaluation and justification for the use of such direct inputs, per AP-SIII.9Q, is discussed in Appendix B, along with a description of the result of literature searches and discussions that substantiate and corroborate the input used in the various FEP discussions. Appendix B is divided based on subject matter and is used to provide the procedurally required information.

6.1.5 Assumptions and Simplifications

For included FEPs, TSPA dispositions may include statements regarding assumptions made to implement the FEP within the TSPA-LA model. Such statements describe the manner in which the FEP has been included; they are not used as the basis of the screening decision to include the FEP with the TSPA-LA model.

Because individual FEPs are specific in nature, any discussion of applicable mathematical formulations, equations, algorithms, numerical methods, or idealizations or simplifications are provided within the discussions in Section 6.2 and subsections.

6.1.6 Intended Use and Limitations

The intended use of this analysis report is to provide system-level FEP screening information for a project-specific FEP database and to promote traceability and transparency regarding FEP screening. This analysis report is intended to be used as the source documentation for the FEP database (BSC 2004 [DIRS 168706]). For included FEPs, this document summarizes and consolidates the method of implementing the FEP in TSPA-LA in the form of TSPA disposition statements. For excluded FEPs, this document provides the technical basis for the exclusion in the form of screening arguments.

Inherent in this evaluation approach is the limitation that the repository will be constructed, operated, and closed according to the design used as the basis for the FEP screening and in accordance with NRC license requirements. This is inherent in the performance evaluation of any engineering project, and design verification and performance confirmation are required as part of the construction and operation processes. The results of the FEP screening presented here are specific to the repository design evaluated in this analysis report for TSPA-LA, particularly for FEPs related to explosions and meteorite impacts.

Changes in the direct inputs (Section 4.1), in baseline conditions used for this evaluation, or in other subsurface conditions will need to be evaluated to determine if the changes are within the limits stated in the FEP evaluations. Engineering and design changes are subject to evaluation to determine if there are any adverse affects on safety as codified at 10 CFR 63.73 and in Subparts F and G (DIRS 156605). See also the requirements at 10 CFR 63.44 and 10 CFR 63.131 (DIRS 156605).

6.2 SYSTEM-LEVEL FEPS SCREENING AND ANALYSES

The 33 system-level FEPs for TSPA-LA are addressed in this section. The FEPs are organized into four groups: assessment basis and modeling requirement FEPs (Section 6.2.1), process and site control FEPs (Section 6.2.2), human intrusion FEPs (Section 6.2.3), and miscellaneous geologic and astronomic FEPs (Section 6.2.4). Within each group, the FEPs are addressed in numeric order based on FEP number.

There are four appendices to this analysis report. Appendix A is a glossary. Appendix B documents data qualification for the direct inputs being qualified and intended for use within this document. Appendix C is an analysis of the timing of human intrusion without recognition by the intruder. Appendix D is an expanded discussion of meteorite-related FEPs, including the mathematical formulation for determining the probability of impacts and cratering effects.

6.2.1 Assessment Basis and Modeling Requirement FEPs

This set of FEPs is related to the regulatory framework, modeling, and design basis used for the performance assessment. All direct inputs used in this section originated from YMP-controlled sources or NRC regulations and are listed in Section 4. No further discussion beyond that provided in Section 4 is required.

These assessment basis and modeling requirement FEPs are overarching and capture issues (a) common to multiple spatial regions or to the system in general, and/or (b) related to the assessment strategy or design in general rather than to a specific nominal and/or disruptive event/process. Therefore, the inclusion of these FEPs in TSPA-LA, as described in the respective TSPA Dispositions, is typically incorporated as part of general model conceptualization (e.g., temporal or spatial discretization method, parameter selection method) rather than as a specific parameter value or distribution, as is more typical of other, nonsystem-level FEPs.

In particular, FEPs 0.1.09.00.0A (Regulatory requirements and exclusions) and 0.1.10.00.0A (Model and data issues) are not dispositioned in the TSPA as are other FEPs. Their inclusion in the analysis cannot be captured by a parameter, submodel, or calculation. Rather, they specify an approach that is to be used to define the overall methodology in development of the TSPA model. As such, their disposition in the TSPA is actually defined in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296]), especially in Section 9. That document provides the top-level method and approach for conducting the TSPA-LA model development and analyses. It describes the upper-level approach and processes for developing and testing of the TSPA-LA model and its documentation. It also describes the systematic approach to collecting and utilizing information from the supporting organizations.

6.2.1.1 Timescales of Concern (0.1.02.00.0A)

FEP Description:	This FEP addresses the timescales of concern over which the disposal system may present a significant health or environmental hazard.
Screening Decision:	Included
Screening Argument:	Not Applicable
TSPA Disposition:	“Timescales of concern” is included in the TSPA–LA by analyzing performance for a 10,000-year period, as required by the NRC.

The timescale of concern has been set by the NRC at (10 CFR 63.303 [DIRS 156605]). That regulation states that compliance is to be based on the mean of the distribution of projected doses of DOE's performance assessments, which project the performance of the Yucca Mountain disposal system for 10,000 years after disposal.

A 10,000-year timescale is consistent with the criteria established for "low probability" at (10 CFR 63.114(d) [DIRS 156605]). It is also consistent with 10 CFR 63.305(c) (DIRS 156605), which states that the DOE must vary factors relating to the geology, hydrology, and climate that could affect the Yucca Mountain disposal system in the next 10,000 years.

A 10,000-year period is also specified as a basis of consideration at for treatment of the human intrusion stylized analysis (10 CFR 63.321 [DIRS 156605]).

The NRC also requires that in the environmental impact statement, DOE provide peak dose information after 10,000 years following disposal (10 CFR 63.341 [DIRS 156605]). The regulation specifically states that no regulatory standard applies to the results of this analysis.

As stated in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296], Section 1.3), "[t]he regulatory time period of analysis for the compliance evaluation is 10,000 years. However, the TSPA analyses are intended to extend beyond 10,000 to 20,000 years. This is intended to provide a basis for evaluating whether uncertainties in results after 10,000 years affect compliance during the regulatory performance period. Likewise, the FEPs for these analyses will not go beyond 10,000 years." Furthermore, "[c]urrent plans are to analyze simulations up to 20,000 years, and to utilize 300 realizations per analysis. These plans may be modified for various reasons as the analyses progress" (BSC 2003 [DIRS 166296], Section 9.1). The TSPA for the FEIS evaluated doses over time periods up to one million years (DOE 2002 [DIRS 155970]).

Supporting AMRs: None

6.2.1.2 Spatial Domain of Concern (0.1.03.00.0A)

FEP Description: This FEP addresses the spatial domain of concern over which the disposal system may present a significant health or environmental hazard.

Screening Decision: Included

Screening Argument: Not Applicable

TSPA Disposition: "Spatial domain of concern" is included in the TSPA–LA by specifying the spatial boundary conditions for the various models used in the performance assessment and those used in the environmental impact statement.

The spatial domain of concern is a function of the analysis being performed. The model-specific spatial domain considered in the TSPA–LA model differs according to the phenomenon being considered. For instance, the spatial domain of concern for a regional groundwater flow model and the geologic setting is bounded on a regional scale, while the analysis of waste package damage occurs at the scale of a single waste package, with specific corrosion phenomena being considered at the fracture and pitting level. Individual model domains are described in the documentation of each component of the TSPA model and in individual AMRs.

The spatial domain encompassed and evaluated explicitly in the TSPA model extends from the land surface through the UZ, through the repository, into the SZ, and laterally away from the repository to the location of the RMEI. This encompasses the eight primary model components and submodels described and illustrated in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296], Section 5.1).

Significant health or environmental hazards may not be present throughout the entire area, but the entire area is considered to be within the domain of spatial concern of the performance assessment. The potential for environmental impact has been addressed in the FEIS (DOE 2002 [DIRS 155970]) and is not further addressed in the TSPA-LA. From a regulatory standpoint, the spatial domain of concern wherein there is a potential for a significant health or environmental hazard is primarily defined by the location of the RMEI.

In practical application, this spatial domain could extend approximately 18 km in the direction of groundwater flow (generally to the south) and extends no more than 5 km from the repository footprint in any other direction (i.e., the spatial domain defines the extent of the controlled area to the location of the RMEI). As described in Section 4.1, and as specified at 10 CFR 63.312(a) (DIRS 156605), the RMEI is located at 18 km, and:

> Lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination

The accessible environment is defined at 10 CFR 63.302 (DIRS 156605) by the definition of the controlled area:

> Accessible environment means any location outside the controlled area.

The controlled area is defined as (10 CFR 63.302 [DIRS 156605]):

(1) The surface area, identified by passive institutional controls, that encompasses no more than 300 km^2. It must not extend farther:

    South than 36° 40′ 13.6661″ north latitude, in the predominant direction of groundwater flow; and

    Than 5 km from the repository footprint in any other direction; and

(2) The subsurface underlying the surface area.

The supplementary information in the regulations for 40 CFR Part 197 (66 FR 32074 [DIRS 155216], p. 32117) states that:

> If fully employed by DOE, and based on current repository design, the controlled area could extend approximately 18 km in the direction of ground water flow (presently believed to be in a southerly direction) and extend no more than 5 km from the repository footprint in any other direction.

The EPA indicates that the location of the RMEI would be 18 km south of the repository footprint (66 FR 32074 [DIRS 155216], p. 32094). Accordingly, the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296], Section 9.1) states that, "[t]he probabilistic simulations of the total system will be evaluated to determine the key factors contributing to the dose at 18 km." The basis for assuming the RMEI is located at 18 km is described in the preceding text.

Supporting AMRs: None

6.2.1.3 Regulatory Requirements and Exclusions (0.1.09.00.0A)

FEP Description: This FEP addresses regulatory requirements and guidance specific to the Yucca Mountain repository.

Screening Decision: Included

Screening Argument: Not Applicable

TSPA Disposition: "Regulatory requirements and exclusions" is intrinsically Included in the TSPA–LA due to the governing nature of the federal regulations and the mandated licensing process.

Federal regulations applicable to the long-term performance of the disposal system are described at 10 CFR Part 63 (DIRS 156605) and incorporate the requirements of 40 CFR Part 197 (DIRS 165519). Regulatory requirements and exclusions provide the framework within which the TSPA is conducted. They define the performance criteria and provide assumptions that must be used in the evaluation (e.g., timescale of concern, characteristics of the reference biosphere, specification of a human-intrusion stylized analysis, limits on release to the accessible environment). They provide guidance on the FEPs that must be considered (i.e., exclusion of low-probability and low-consequence events and processes) and limit the range of conditions that must be considered (e.g., "consistent with present knowledge of natural processes").

The various aspects of the repository (including design, construction, operation, and preclosure and postclosure performance) must be shown to comply with regulatory requirements. If not, the repository will not be licensed, construction may be prohibited, operations may be halted until deficiencies are corrected, or further operations or closure activities will be delayed until deficiencies are corrected.

The NRC is responsible for determining compliance "based upon the mean of the distribution of projected doses of DOE's performance assessments which project the performance of the Yucca Mountain disposal system for 10,000 years after disposal" (10 CFR 63.303 [DIRS 156605]). The DOE must demonstrate a reasonable expectation that the postclosure individual-protection standard, human-intrusion standard, and ground-water protection standard will not be exceeded. Evaluation of compliance to these standards is a primary objective of the TSPA.

The criteria and assumptions to be used in making the evaluation are provided in the various referenced sections at 10 CFR Part 63 (DIRS 156605) and at 40 CFR Part 197 (DIRS 165519) and, as applicable to FEP screening, are listed in Section 4.2. These criteria and assumptions are regulatory requirements and have been incorporated into the TSPA model either using specified characteristics to guide selection of input parameters (such as the characteristics of the RMEI) or by consideration of a range of possible climatic and geologic settings consistent with present knowledge of natural processes. This approach is described in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296]).

In a more general sense, compliance with regulatory requirements has been identified in the PRD (Canori and Leitner 2003 [DIRS 166275]). The PRD was developed as part of Configuration Management as described in the YMP *Configuration Management Plan* (BSC 2004 [DIRS 168396]). The PRD is used to implement the *Requirements Management Plan* (BSC 2003 [DIRS 168577]). The PRD documents and categorizes the regulatory requirements and other project requirements, and it lists the various YMP organizations responsible for ensuring that the criteria have been addressed in the LA. The regulatory requirements include criteria relevant to performance assessment activities, and the regulatory requirements have been linked to specific technical activities being performed for the LA. These criteria find expression as specific acceptance criteria presented by the NRC in the YMRP (NRC 2003 [DIRS 163274]), which will be used by the NRC during the licensing process to evaluate whether regulatory requirements have been adequately addressed.

Supporting AMRs: None

6.2.1.4 Model and Data Issues (0.1.10.00.0A)

FEP Description: This FEP addresses issues related to modeling of the disposal system. Model and data issues are general (i.e., methodological) issues affecting the modeling process and data usage. Model issues include the approach and assumptions associated with the selection of conceptual models, the mathematical implementation of conceptual models, model geometry and dimensionality, models of coupled processes, and boundary and initial conditions. Data issues include the derivation of data values and correlations.

Screening Decision: Included

Screening Argument: Not Applicable

TSPA Disposition: Model and data requirements are addressed specifically at 10 CFR 63.114 (DIRS 156605) and are included in the TSPA-LA as described in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296]).

The specifications at 10 CFR 63.114 (a, b, c, and g) (DIRS 156605) pertinent to this FEP include the following clauses:

"(a) Include data related to the geology, hydrology, and geochemistry (including disruptive processes and events) of the Yucca Mountain site, and the surrounding region to the extent necessary, and information on the design of the engineered barrier system, used to define parameters and conceptual models used in the assessment."

"(b) Account for uncertainties and variability in parameter values." Several kinds of uncertainties are distinguished and receive somewhat different treatments. In general, the TSPA–LA has grouped these as parameter uncertainty and model form uncertainty. The TSPA recognizes and accounts for parameter uncertainty, where appropriate, and intends to provide the regulators with a basis for a "reasonable expectation" of compliance.

"(c) Consider alternative conceptual models of features and processes." In many of the subsystems of the overall TSPA system, there are plausible alternative models or assumptions, which result in model form uncertainty. In some cases, these alternative models form a continuum, and sampling from the continuum of assumptions fits naturally within the Monte Carlo framework of sampling from probability distributions. In other cases, the assumptions or models are based on discrete choices. Two possible approaches to incorporating alternative models within the TSPA include 1) weighting all models into one comprehensive Monte Carlo simulation (lumping), or 2) keeping the discrete models separate and performing multiple Monte Carlo simulations for each discrete model (splitting). There are advantages and disadvantages to both approaches. A combination of the two approaches is being used.

"(g) Provide the technical basis for models used in the performance assessment such as comparisons made with outputs of detailed process-level models and/or empirical observations." Each of the models used in developing the TSPA has been documented according to project-specific quality assurance procedures for model development, validation, and use. Model selection, use, verification, and inputs are addressed in the individual modeling reports.

The *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296]) outlines the use of various model components that consider the geologic, hydrologic, and geochemical data (Section 5.1), parameter uncertainty (Section 3.5), alternative conceptual models (Section 3.3), and abstractions (Section 3.4). The TSPA–LA model validation approach is outlined in Section 7, and the approach for uncertainty analysis is provided in Section 8.1 of that document.

Additionally, each of the models used in developing the TSPA is documented in a stand-alone modeling report per project-specific quality assurance procedures. The modeling reports address model selection, model development, verification, validation, inputs, and use. These modeling reports were prepared per the guidelines for model documentation and the specific guidance and criteria for the consideration of alternative conceptual models (including relationships to FEPs) and the treatment of uncertainty. The list of regulatory specifications for the performance assessment germane to model and data issues requires the consideration of data on the geology, hydrology, and geochemistry (including disruptive processes and events), consideration of uncertainty, the consideration of alternative conceptual models, and providing the technical basis of any models used.

Supporting AMRs: None

6.2.1.5 Repository Design (1.1.07.00.0A)

FEP Description: This FEP addresses the consideration of the design of the repository and the ways in which the design contributes to long-term performance. The performance assessment must account for design features, material characteristics, and the ways in which the design influences the evolution of the in-drift environment.

Screening Decision: Included

Screening Argument: Not Applicable

TSPA Disposition: "Repository design" and potential design modifications are Included in the TSPA–LA because the repository design is the basis of the models used for the performance assessment.

Examples of the approach for including design elements are outlined in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296], Section 5.1). Particularly applicable to this FEP are the model components for the EBS, waste package and drip shield degradation, waste form degradation and mobilization, and EBS flow and transport. These model components take into account the physical dimensions, material characteristics, and evolution of the in-drift environment, all of which stem directly from design considerations. The design elements are included as nominal-scenario class parameters used to define the physical dimensions, characteristics, and long-term behavior of the waste form, waste packages, and EBS. Design modifications are required to be analyzed for potential affects.

The incorporation of repository design information into the framework of the TSPA-LA model components has been accomplished using of a series of information exchange drawings (IEDs), which are cited as needed in the individual model AMRs. The drawings include information regarding material characteristics and properties, component dimensions, and component performance under various conditions (e.g., corrosion rates, seismic response, and damage areas). The use of design drawings is discussed in the model AMRs as applicable.

Inherent in the performance assessment modeling of engineered systems is that there are failure rates, or times-to-failure, associated with the systems, and that the engineered systems interact with the natural systems. Such baseline failure rates are identified in the related FEP 2.1.03.08.0A (Early failure of waste packages) and specifically include the consideration of manufacturing and welding defects within the waste package degradation analysis. Deficiencies beyond those specifically included in the cited FEP are addressed under FEP 1.1.08.00.0A (Inadequate quality control and deviations from design).

Furthermore, 10 CFR Part 63 Subpart F (DIRS 156605) provides a list of specifications for a performance confirmation program to provide data related to conditions encountered and changes in those conditions, functioning of the natural engineered systems, and monitoring and testing. A performance confirmation plan is documented in BSC (2004 [DIRS 170505]). Modifications and deviations from the TSPA-LA design are subject to regulatory requirements that address deliberate changes and modifications. The manner in which the DOE must address changes, and by which the NRC is informed of the changes, is codified at 10 CFR 63.44 (DIRS 156605). As indicated in 10 CFR 63.142 (d) (DIRS 156605), deviations from quality standards must be controlled.

Supporting AMRs: None

6.2.1.6 Retrievability (1.1.13.00.0A)

FEP Description: This FEP addresses design, emplacement, operational, or administrative measures that might be applied or considered to enable or ease retrieval of waste. There may be a requirement to retrieve all or part of the waste stored in the repository, for example, to recover valuable fissile materials or to replace defective waste packages.

Screening Decision: Included

Screening Argument: Not Applicable

TSPA Disposition: "Retrievability" is a performance objective of the repository as specified at 10 CFR 63.111(e)(1, 2, and 3) (DIRS 156605), and features are included in the design to allow for retrievability.

The regulation specifies that the repository be designed in such a way that it preserves "…the option of waste retrieval throughout the period during which wastes are being emplaced…so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated…" (10 CFR 63.111(e) (1, 2, and 3) [DIRS 156605]). This precludes further FEP consideration for resource recovery and retrieval past 50 years after waste emplacement (limitations are discussed in the supplemental discussion below). Regardless, the repository design is part of the basis of the postclosure evaluation, and aspects of the repository design related to waste retrievability are, therefore, implicitly considered as part of the basis for the TSPA modeling and have been included, as noted in FEP 1.1.07.00.0A (Repository design). The design elements related to retrievability include dimensions of the drifts, design of the emplacement system, and waste package design. The incorporation of repository design information into the framework of the various TSPA-LA model components has been accomplished using of a series of IEDs, which are cited as needed in the individual model AMRs. The drawings contain information regarding material characteristics and properties, component dimensions, and component performance under various conditions (e.g., corrosion rates, seismic response, damage areas).

Examples of the approach for including design elements is further outlined in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296], Section 5.1). Particularly applicable to this FEP are the model components for the EBS, waste package and drip shield degradation, waste form degradation and mobilization, and EBS flow and transport. Retrievability is thereby implicitly "Included" in the TSPA.

Supporting AMRs: None

Supplemental Discussion:

The objective of the performance assessment is to evaluate compliance with postclosure performance objective per 10 CFR 63.102(j) (DIRS 156605). The operational and administrative considerations of retrievability are a preclosure consideration and are, therefore, beyond the scope of the performance assessment. Furthermore, postclosure retrieval of wastes or other repository-system components for resource recovery was addressed by the NRC in the supplementary information for 10 CFR Part 63 (66 FR 55732 [DIRS 156671], p. 55743, Section III, Public Comments and Response, 2.2 Retrievability, Issue 2). To wit:

> As for longer retrieval periods [>50 years]…the Commission has previously noted that its retrieval provision is not intended to facilitate recovery. Waste retrieval is intended to be an unusual event only to be undertaken to protect public health and safety.

6.2.1.7 Repository-Scale Spatial Heterogeneity of Emplaced Waste (2.1.01.04.0A)

FEP Description: Waste placed in Yucca Mountain will have physical, chemical, and radiological properties that will vary spatially, resulting in variation in the mass of radionuclides available for transport from different parts of the repository.

Screening Decision: Included

Screening Argument: Not Applicable

TSPA Disposition: Heterogeneity of the waste inventory is further discussed under FEP 2.1.01.03.0A. Heterogeneity is greater for DOE spent nuclear fuel (SNF) and high-level radioactive waste (HLW) glass inventories than it is for commercial SNF (CSNF).

At the repository scale, waste form degradation and mobilization in the TSPA-LA model is addressed using three generic waste forms: CSNF (which for modeling purposes also addresses naval SNF), DOE-owned SNF (DSNF), and DOE-owned HLW (DHLW) glass. These categories of waste will be placed in and disposed of in two types of waste packages: CSNF waste packages and codisposal waste packages, with the latter containing DSNF and DHLW glass.

For scenarios in which only a few packages breach, package-to-package heterogeneity could be important in quantifying exposure of the RMEI. For the postclosure TSPA, however, these "few-package" scenarios are not significant to performance because only scenarios with many packages breached show calculated releases that approach the exposure limit. For multiple-package breach scenarios, package-to-package heterogeneity is directly addressed in the TSPA-LA using uncertainty parameters for the average inventory within the CSNF and codisposal packages (BSC 2004 [DIRS 170022], Sections 6.4.2 and 6.6).

At the repository-scale, radionuclide dissolution and release depend more directly on infiltration than on the specific location within the repository, and therefore, waste forms are treated as generic categories (BSC 2003 [DIRS 166296], pp. 71 to 73). Within the TSPA-LA model, the generic waste types are coupled to spatial variations in infiltration properties rather than to a specific location (BSC 2003 [DIRS 166296], pp. 77 to 78). More specifically, the process of waste form degradation will be modeled by equations using empirical degradation rate formulas for the three generic waste form types: CSNF, DSNF, and DHLW. Output will be the mass of waste form exposed versus time and the volume of water in contact with the waste form versus time, which will be used to populate several waste form cells in the model that correspond to different waste form types and seepage cases. The amount of inventory that can ultimately enter each waste form cell will be a linear function of the number of packages emplaced for each generic waste type, seepage, and thermal hydrologic environment (BSC 2003 [DIRS 166296], p. 81).

The potential effect of waste heterogeneity at the drift-scale is addressed by including various seepage and thermal hydrologic environments at the repository scale. Because repository-scale heterogeneities are addressed in the above manner, this FEP is considered as explicitly included.

6.2.2 Process and Site-Control FEPs

This set of FEPs addresses quality control processes, site-control and institutional-control related issues, and site operational concerns that may affect postclosure performance. All direct inputs used in this section originated from YMP-controlled sources or NRC regulations (Section 4). No further discussion beyond that provided in Section 4 is required.

6.2.2.1 Records and Markers for the Repository (1.1.05.00.0A)

FEP Description: This FEP addresses the retention of records of the contents of the repository and markers constructed to inform future humans of the location and contents of the repository. Performance assessments must consider the potential effects of human activities that might take place within the controlled area at a future time when institutional controls and/or knowledge of the presence of a repository cannot be assumed.

Screening Decision: Excluded – By Regulation

Screening Argument: "Records and Markers for the Repository" is excluded from the TSPA–LA by regulation. At 10 CFR 63.102(k) (DIRS 156605), the regulation addresses the use of institutional controls. The regulation requires that both passive and active institutional controls are to be maintained, but also indicates that it is not possible to make sound forecasts regarding their long-term reliability.

The requirements for constructing monuments, preserving and archiving records, and oversight are listed at 10 CFR 63.51(a)(3)(i-iii), 10 CFR 63.72(a), and 10 CFR 63.72(b)(1-11) (DIRS 156605). Land ownership and control requirements are specified by 10 CFR 63.121 (DIRS 156605). The markers and repository archives will persist for some portion of the regulatory period, but for the analyses, they are assumed ineffective, in accordance with the regulatory requirements (Assumption 5.2).

At 10 CFR 63.102(k) (DIRS 156605), the NRC recognizes that institutional controls are expected to reduce significantly, but not eliminate, the potential for human activity that causes or accelerates the release of radioactive material. To eliminate further speculation on how to address the effectiveness of these controls the regulation states:

> However, because it is not possible to make scientifically sound forecasts of the long-term reliability of institutional controls, it is not appropriate to include consideration of human intrusion into a fully risk-based performance assessment for purposes of evaluating the ability of the geologic repository to achieve the performance objective.

Accordingly, for the FEPs addressing administrative controls, and particularly their influence on human intrusion, the FEPs have been excluded, by regulation, from consideration in the human intrusion stylized analysis.

The consideration of the timing of occurrence of human intrusion without recognition (Appendix C) is based only on the physical properties of the drip shields and waste packages past 10,000 years, rather than on any consideration of effectiveness of administrative control, planning restrictions, repository markers, or an information repository. Although these institutional controls will be implemented, they do not influence the calculated timing or determination of the likelihood of a human intrusion presented in Appendix C, and therefore there presence or absence makes no difference to the calculation of the resulting dose to the RMEI or to the release of radionuclides to the accessible environment as addressed by the TSPA–LA model.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.2.2 Inadequate Quality Control and Deviations from Design (1.1.08.00.0A)

FEP Description: This FEP addresses issues related to inadequate quality assurance and control procedures and inadequate testing during the design, construction, and operation of the repository. It also includes inadequacy in the manufacture of the waste forms, waste packages, and engineered features. Lack of quality control could result in a poorly designed repository, unmodeled design features, deviations from design, material defects, faulty waste package fabrication, and faulty or non-design standard construction. All of these may lead to reduction in the effectiveness of the engineered barriers.

Screening Decision: Excluded – Low Consequence

Screening Argument: "Inadequate Quality Control and Deviations from Design" is excluded from the TSPA–LA based on low consequence because the regulatory requirements for performance confirmation (10 CFR 63 Subpart F [DIRS 156605]) and quality assurance (10 CFR Subpart G [DIRS 156605]) require that any deviation from design be evaluated for potential impact, and that significant deviations which are detected during the operational period be corrected (10 CFR 63.73a [DIRS 156605]).

This FEP description is focused on the lack of quality control processes. As discussed in Section 6.1.6, inherent in the FEPs evaluation approach is the limitation that the repository will be constructed, operated, and closed according to the design used as the basis for the FEP screening and in accordance with NRC license requirements. This is an inherent limitation for performance evaluation of any engineering project, and design verification and performance confirmation are required as part of the construction and operation processes. Design verification during the operational period is the subject of an extensive *Performance Confirmation Plan* (BSC 2004 [DIRS 170505]). Furthermore, 10 CFR Part 63 (DIRS 156605) provides a list of requirements that have been incorporated into the performance confirmation program to provide data related to encountered subsurface conditions, functioning of the natural and engineered systems, and monitoring and testing.

Modifications and deviations from the TSPA-LA design are subject to regulatory requirements and review that address deliberate changes and modifications. The manner in which the DOE must address changes, and by which the NRC is informed of the changes, is codified at 10 CFR 63.44 (DIRS 156605). As indicated in 10 CFR Subpart G (DIRS 156605), the quality control program (including design control, procurement and materials control, inspections, and handling, storage, and shipping controls) is to be applied to all systems, structures, and components important to safety and to design and characterization of barriers important to waste isolation. Furthermore, deviations from quality standards and the design basis must be controlled.

At 10 CFR 63.73(a) (DIRS 156605), the NRC requires prompt notification if there is a significant deficiency found in (1) the characteristics of the Yucca Mountain site, or (2) the design and construction of the geologic repository area, including significant deviations from the design criteria and design bases stated in the application. Significant deviations that are detected during the operational period will be evaluated, and as needed, corrected. Any residual defects or fabrication or construction deficiencies, therefore, will be of a minor nature and will not lead to significant effects on the repository performance. Compliance with these requirements ensures a low consequence (it is unlikely that there will be significant effects from undetected deviations) in the event that the design is not followed.

Regardless of the requirements of the quality assurance and performance confirmation programs, the TSPA allows for the possibility that engineered systems may not perform entirely as designed for the full 10,000 years through the probabilistic treatment of waste-package and drip shield degradation. Some qualitative understanding of the effect of deficiencies can be taken from the multiple barrier analyses to be performed as part of the TSPA–LA modeling activities (BSC 2003 [DIRS 166296], Section 8.3). The qualitative understanding can be further supplemented with a quantitative measure provided by barrier neutralization analyses as described in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296], Appendix D.3).

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.2.3 Schedule and Planning (1.1.09.00.0A)

FEP Description: This FEP addresses the sequences of events and activities occurring during construction, operation, and closure of the repository. Deviations from the design, construction, or waste emplacement schedule may affect the long-term performance of the disposal system.

Screening Decision: Excluded – By Regulation

Screening Argument: "Schedule and Planning" is excluded from the TSPA–LA by regulation because the stated regulatory objective is postclosure performance assessment, whereas scheduling and planning are preclosure operational issues (10 CFR 63.102(j) [DIRS 156605]).

Events related to changes in the construction, operation, or closure schedules are outside the scope of the TSPA and would need to be evaluated as design modifications, should they occur.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.2.4 Administrative Control of the Repository Site (1.1.10.00.0A)

FEP Description: Administrative control can reduce the potential for detrimental or unplanned human activities within the controlled area that could inadvertently cause or accelerate the release of radioactive material.

Screening Decision: Excluded – By Regulation

Screening Argument: "Administrative control of the repository site" is excluded from the TSPA–LA by regulation. At 10 CFR 63.102(k) (DIRS 156605), the regulations address the use of institutional controls. The regulations require that both passive and active institutional controls be maintained, but not relied upon for performance.

The requirements for constructing monuments, preserving and archiving records, and oversight are listed at 10 CFR 63.51(a)(3)(i-iii), 10 CFR 63.72(a), and 10 CFR 63.72(b)(1-11) (DIRS 156605). Land ownership and control requirements are specified at 10 CFR 63.121 (DIRS 156605). The markers and repository archives will persist for some portion of the regulatory period, but for the analyses, they are assumed ineffective (Assumption 5.2) in accordance with regulatory requirements.

At 10 CFR 63.102(k) (DIRS 156605), the NRC recognizes that institutional controls are expected to reduce significantly, but not eliminate, the potential for human activity that causes or accelerates the release of radioactive material. To eliminate further speculation on how to address the effectiveness of these controls the regulation states:

> However, because it is not possible to make scientifically sound forecasts of the long-term reliability of institutional controls, it is not appropriate to include consideration of human intrusion into a fully risk-based performance assessment for purposes of evaluating the ability of the geologic repository to achieve the performance objective.

Accordingly, for the FEPs addressing administrative controls, and particularly the influence on human intrusion, the FEPs are excluded, by regulation, from consideration in the human intrusion stylized analysis.

On that basis, the consideration of the timing of occurrence of human intrusion without recognition (Appendix C) is evaluated only on the physical properties of the drip shields and waste packages past 10,000 years, rather than on any consideration of administrative control, planning restrictions, repository markers, or an information repository. Although these institutional controls will be implemented, they do not influence the calculated timing or determination of the likelihood of a human intrusion, and, therefore, make no difference to determining the resulting dose to the RMEI or to the release of radionuclides to the accessible environment as addressed by the TSPA–LA model.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.2.5 Monitoring of the Repository (1.1.11.00.0A)

FEP Description: Monitoring that is carried out during or after operations, for either operational safety or verification of long-term performance, has the potential to detrimentally affect long-term performance. For example, monitoring boreholes could provide enhanced pathways between the surface and the repository.

Screening Decision: Excluded – Low Consequence

Screening Argument: "Monitoring of repository" is excluded from the TSPA–LA based on low consequence stemming from the regulatory requirements that monitoring activities must not adversely affect the ability of the repository to meet the performance objectives and requirements for seal confirmation.

The repository will be constructed, operated, and closed according to NRC license requirements during the preclosure period. Modifications and deviations from the design are subject to regulatory requirements that address deliberate changes and modifications (10 CFR 63.44 [DIRS 156605]). Furthermore, at 10 CFR 63.73(a) (DIRS 156605), the NRC specifies prompt notification if there is a significant deficiency found in (1) the characteristics of the Yucca Mountain site, or (2) the design and construction of the geologic repository area, including significant deviations from the design criteria and design bases stated in the application. Significant deviations that are detected during the operational period will be evaluated and corrected, as needed. Any residual defects or fabrication or construction deficiencies, therefore, will be of a minor nature and will not lead to significant effects on the repository performance.

Regulation 10 CFR Part 63, Subpart F (DIRS 156605) provides a list of requirements for a performance confirmation program to confirm design parameters and to ensure that the NRC is informed of changes needed in the design to accommodate field conditions. The *Performance Confirmation Plan* (BSC 2004 [DIRS 170505]) precludes significant effects from monitoring activities. A performance confirmation program is a regulatory requirement as specified at 10 CFR 63.131 (DIRS 156605). The provisions of the requirement include 10 CFR 63.131(c) (DIRS 156605), which states that the program must include in situ monitoring, field and laboratory testing, and in situ experiments, as may be appropriate to provide the data required by paragraph (a) of the section. Consequently, the use of in situ monitoring and experimentation is anticipated. However, the regulation also states that any monitoring program must be implemented so that it "does not adversely affect the ability of the geologic and engineered elements of the geologic repository to meet the performance objectives" (10 CFR 63.131(d)(1) [DIRS 156605]).

All boreholes and monitoring wells will be drilled and sealed in accordance with regulatory requirements effective during the preclosure period. Confirmation that an adequate seal can be achieved is a regulatory requirement (10 CFR 63.133(d) [DIRS 156605]), which states that "tests must be conducted to evaluate the effectiveness of borehole, shaft, and ramp seals, before full scale operation proceeds to seal boreholes, shafts, and ramps." When properly sealed, there should be no pathway for unevaluated effect on groundwater flow systems, and boreholes should have no effect (i.e., are of low consequence) on the repository performance.

Some qualitative understanding of the effect of any residual deficiencies can be taken from the multiple barrier analysis to be performed as part of the TSPA–LA modeling activities (BSC 2003 [DIRS 166296], Section 8.3). This qualitative understanding can be supplemented with a quantitative measure provided by barrier neutralization analyses performed, as described in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296], Appendix D.3).

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.2.6 Accidents and Unplanned Events during Construction and Operation (1.1.12.01.0A)

FEP Description: The long-term performance of the disposal system might be seriously affected by unplanned or improper activities that take place during construction, operation, and closure of the repository

Screening Decision: Excluded – Low Consequence

Screening Argument: "Accidents and unplanned events during construction and operation" is excluded from the TSPA–LA based on low consequence because regulatory requirements for performance confirmation and quality assurance require evaluation of any such events should they occur.

The history of the development of this FEP indicates that the intent and scope of the FEP is to include the effects of unplanned events during the preclosure phase that have a long lasting effect, such as improper operation, handling accidents, and some aspects of sabotage. The objective of the TSPA is to evaluate postclosure compliance. Events related to changes in the construction, operation, or closure schedule are outside the scope of the TSPA.

Operations will be conducted according to procedures acceptable to the NRC. At 10 CFR 63.73 (DIRS 156605), the NRC requires prompt notification if there is a significant deficiency found in the characteristics, design, and construction of the geologic repository operations area that, were it to remain uncorrected, could adversely affect safety in the future. This includes significant deviations from the design criteria and design bases stated in the application, construction authorization, or the license. If the repository does not meet regulatory criteria, it will not be licensed and waste will not be emplaced. Quality control procedures and performance confirmation are designed to detect operational events resulting in deviations from the repository design that might affect long-term performance. Any significant deviations would be detected during regulator audits and inspections per 10 CFR Part 63 Subpart D (DIRS 156605) and corrected before further work in the repository would be allowed to continue. Therefore, accidents and unplanned events during the operational phase would not have a significant effect on long-term performance and are excluded from the TSPA–LA based on low consequence.

Sabotage is a form of deliberate human intrusion and has been excluded. Sabotage is more fully addressed in the FEPs 1.4.02.01.0A (Deliberate human intrusion) and 1.4.11.00.0A (Explosions and crashes [human activities]). Regardless of the type or cause of the event, some qualitative understanding of the potential effect of accidents and unplanned events can be taken from the multiple barrier analysis to be performed as part of the TSPA–LA modeling activities (BSC 2003 [DIRS 166296], Section 8.3). This qualitative understanding can be supplemented with a quantitative measure provided by barrier neutralization analyses performed, as described in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2002 [DIRS 166296], Appendix D.3).

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3 Human Intrusion FEPs

This set of FEPs is related to the potential for human intrusion into the repository. Direct inputs used in this section originating from YMP-controlled sources or NRC regulations are listed in Section 4 and its subsections and no further discussion beyond that provided in Section 4 is required for such sources. Non-YMP sources of direct input are also cited in Section 4. Such sources and corroborating information are discussed in Appendix B.

6.2.3.1 Deliberate Human Intrusion (1.4.02.01.0A)

FEP Description: Humans could deliberately intrude into the repository. Without appropriate precautions, intruders could experience high radiation exposures. Moreover, containment may be left damaged, which could increase radionuclide release rates to the biosphere. Motivation for deliberate human intrusion includes mining, waste retrieval, site remediation/improvement, archaeology, sabotage, and acts of war.

Screening Decision: Excluded – By Regulation

Screening Argument: "Deliberate Human Intrusion" is excluded from the TSPA-LA human intrusion stylized analysis by regulation, which indicates that analysis of deliberate human intrusion and exposure of the intruders does not serve the intended purpose of the analysis (10 CFR Part 63, 66 FR 55732 [DIRS 156671], p. 55761, Supplementary Information, 3.10 Human Intrusion Standard), and that exposure of the intruder is not to be considered (10 CFR 63.322(f) [DIRS 156605]).

Human intrusion is defined as (10 CFR 63.302 [DIRS 156605]):

> Human intrusion means breaching any portion of the Yucca Mountain disposal system, within the repository footprint, by any human activity.

This is an important concept in that "any" human activity that has the potential to breach the disposal system is included within the regulatory intent regarding human intrusion.

Performance assessment is defined (10 CFR 63.2 [DIRS 156605]) as an analysis that:

> Identifies the features, events, and processes (except human intrusion), and sequences of events and processes (except human intrusion), that might affect the Yucca Mountain disposal system and their probabilities of occurring during 10,000 years after disposal.

From this statement stems a regulatory basis for excluding all FEPs that address human intrusion from consideration in the TSPA–LA model, although other regulations provide the conditions for which human intrusion must be considered.

With regard to the motivation of a human intrusion being intentional and deliberate or inadvertent and accidental, regulation 10 CFR Part 63 (DIRS 156605) is silent. Similarly, 40 CFR Part 197 (DIRS 165519) does not directly address the motivation or intentionality of the intrusion. However, supplemental discussions for 40 CFR Part 197 (DIRS 155216) clarify that consideration of deliberate intrusion is not intended. In the supplementary information to 40 CFR Part 197 (66 FR 32074 [DIRS 155216], p. 32105, Item 3), the EPA, in response to comments regarding the human intrusion stylized analysis, states:

> Comments we received proposing alternative drilling frequencies and intentions, such as deliberately drilling into the repository, did not provide a sufficient rationale to abandon the NAS [National Academy of Science] recommendations and we therefore retained our original framing for the scenario.

The EPA amplifies this at 66 FR 32127 (66 FR 32074 [DIRS 155216], p. 32127, Item 10). The EPA explicitly states that:

> Some comments suggested that there is a strong possibility for deliberate intrusion into the repository to access its content as possible resources. We believe that there is no useful purpose to assessing the consequences of deliberate

> intrusions because in that case the intruders would be aware of the risks and consequences and would have decided to assume the risks. This is consistent with NAS's [the National Academy of Science] conclusion regarding intentional intrusion (NAS Report, p. 14).

Additionally, specifications at 10 CFR 63.322(f) (DIRS 156605) and 40 CFR 197.26(e) (DIRS 165519) indicate that only radionuclides transported to the SZ need to be considered, precluding the consideration of FEPs related to the exposure of the public, drillers, or other human intruders from cuttings, circulated materials, or tailings. The supplementary information to 10 CFR Part 63 (66 FR 55732 [DIRS 156671], p. 55761, Supplementary Information, 3.10 Human Intrusion Standard) is clear with the intent of the NRC:

> Human intrusion has the potential for releasing particulate HLW to the surface with drill cuttings or providing a fast pathway for radionuclides to be transported to the SZ by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the SZ). NAS [National Academy of Science] concluded, and the Commission agrees, that analysis of the risk to the public or the intruders (i.e., drilling crew) from radioactive drill cuttings left unattended at the surface for subsequent dispersal into the biosphere would not fulfill the purpose of the human intrusion calculation because it would not show how well a particular repository site and design would protect the public at large. Rather, an analysis of the hazard of particulate HLW left on the surface would be dominated by assumptions subject to significant speculation and uncertainty regardless of the particular site or design under evaluation. Additionally, the release to the surface represents a one-time release with no long-term effect on the repository barriers.

Consequently, all deliberate human intrusion FEPs are excluded based on regulatory intent and all inadvertent intrusions are considered within the context of the regulatory requirements to consider only the human intrusion stylized analysis and the timing of such an event (Appendix C).

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3.2 Inadvertent Human Intrusion (1.4.02.02.0A)

FEP Description: Humans could accidentally intrude into the repository. Without appropriate precautions, intruders could experience high radiation exposures. Moreover, containment may be left damaged, which could increase radionuclide release rates to the biosphere. Inadvertent human intrusion might occur during scientific, mineral or geothermal exploration.

Screening Decision: Excluded – By Regulation

Screening Argument: "Inadvertent Human Intrusion" is excluded from the TSPA–LA based on regulation (10 CFR 63.321 [DIRS 156605]) because inadvertent human intrusion without recognition by drillers before 10,000 years is not credible, and by regulatory intent, exposure to the intruders need not be considered.

With regard to the motivation of a human intrusion being intentional and deliberate or inadvertent and accidental, 10 CFR Part 63 (DIRS 156605) is silent. Similarly, 40 CFR Part 197 (DIRS 165519) does not directly address the motivation or intentionality of the intrusion. However, the supplemental discussions for 40 CFR Part 197 (DIRS 155216) clarify that consideration of deliberate intrusion is not intended. In the supplementary information to 40 CFR Part 197 (66 FR 32074 [DIRS 155216], p. 32105, Item 3), the EPA, in response to comments regarding the human intrusion stylized analysis, states:

> Comments we received proposing alternative drilling frequencies and intentions, such as deliberately drilling into the repository, did not provide a sufficient rationale to abandon the NAS [National Academy of Science] recommendations and we therefore retained our original framing for the scenario.

The EPA amplifies this at 66 FR 32127 (66 FR 32074 [DIRS 155216], p. 32127, Item 10). The EPA explicitly states that:

> Some comments suggested that there is a strong possibility for deliberate intrusion into the repository to access its content as possible resources. We believe that there is no useful purpose to assessing the consequences of deliberate intrusions because in that case the intruders would be aware of the risks and consequences and would have decided to assume the risks. This is consistent with NAS's [National Academy of Science] conclusion regarding intentional intrusion (NAS Report, p. 14).

Consequently, all deliberate human intrusion FEPs discussed in this analysis report are excluded based on regulatory intent, and all inadvertent intrusions are considered within the context of the regulatory requirements to consider only human intrusion stylized analysis and the timing of such an event.

At 10 CFR 63.321 (DIRS 156605), the NRC specifies the criteria under which human intrusion must be evaluated:

> DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers.

Furthermore, by way of explanation and corroboration, per 10 CFR 63.321(a) (DIRS 156605), the DOE must:

> Provide the analyses and its technical bases used to determine the time of occurrence of human intrusion (see 10 CFR 63.322) without recognition by the drillers.

If complete waste package penetration is projected to occur before or at the 10,000-year performance period, then the DOE is to provide a demonstration (10 CFR 63.321(b)(1) [DIRS 156605]) that:

> [T]here is a reasonable expectation that the reasonably maximally exposed individual receives no more than an annual dose of 0.15 mSv (15 mrem) as a result of a human intrusion, at or before 10,000 years after disposal.

and, per 10 CFR 63.321(b)(2) (DIRS 156605),

> If the exposure of the RMEI occurs after 10,000 years, or if the intrusion is projected to occur after 10,000 years, the results of the analysis and the bases of the analysis are to be provided in the environmental impact statement for Yucca Mountain.

The drip shield and waste package barrier capability are based on the physical properties of the drip shield and waste packages. Degradation of these components with time (BSC 2004 [DIRS 169996], Sections 6.5 and 7.2) indicate that:

- Because of the low corrosion rate of titanium alloy used for the drip shields, the initial breaches of the drip shields are not expected to occur until well after 10,000 years; more specifically, the modeling indicates approximately 40,000 years, with the median estimate of the mean time to initial breaching of drip shields at approximately 300,000 years.

- Because the corrosion rates of Alloy 22 (UNS N06022) used for the waste packages are so low, it is not expected that any waste packages will be breached by general corrosion during the first 10,000 years; models indicate that the time to initial breaching of the waste packages due to general corrosion is on the order of 100,000 years.

The results of the waste package degradations analyses cited from BSC (2004 [DIRS 169996], Sections 6.5 and 7.2) result from the use of representative thermal hydrologic history files produced to allow model runs to be exercised in the cited report. The actual drip shield and waste package degradation profiles used in the TSPA-LA model will make use of the actual thermal hydrologic history files appropriate for the repository. Because representative histories were used, however, significant differences in the degradation profile generated for TSPA-LA are not expected. While general corrosion occurs gradually over time up to the time of failure, the oxidation process is a surface phenomenon, and the underlying metal retains its integrity and resistance to drilling. Although results show the potential for failures at early time, these failures are the result of localized corrosion and, although modeled in TSPA-LA as a patch, are not associated with degradation of a significant surface area with respect to potential interaction with a rotary drill bit (Appendix C). Similarly, during the first 10,000 years, the material performance of the waste package would not be significantly degraded by stress corrosion cracking. Regardless of the localized corrosion effects or potential for stress corrosion cracking, the overall structural integrity of the waste package or drip shield, and the resistance, to drilling is maintained. This is corroborated by the TSPA-SR drip shield and waste package studies, which indicate long lifetimes for these components, with the first drip shield failures occurring after about 20,000 years (CRWMS M&O 2000 [DIRS 153246], Section 3.4). The first failures of the waste package outer material, Alloy 22, by general corrosion occurred after approximately 30,000 years.

Based on DOE analyses (Appendix C), the compressive strength and ductility of the metals from which the drip shields and waste package are fabricated differ significantly from the rock surrounding them and will remain largely intact through the 10,000-year regulatory period. Drillers would notice these differences in properties based on the rate of penetration. Rates of penetration range from inversely proportional to the square of the compressive strength of the material being drilled, to inversely proportional, all other factors being equal (Bourgoyne et al. 1986 [DIRS 155233], Eq. 5-19; Kahraman et al. 2000 [DIRS 167761], Equation 8). The compressive strength of the materials differ by a factor of two (Appendix C), suggesting that at a minimum, the rate of penetration would decrease by half or possibly to one fourth as the bit moved from the rock material to the engineered barrier, if in fact, the drill bit could penetrate the engineered barrier. Other effects would also be noticeable. A full discussion is provided in Appendix C. The drillers, therefore, should recognize that they have attempted to drill into some material other than rock for at least as long as the drip shields or waste packages are intact.

Based on these analyses, and in accordance with 10 CFR 63.321(b)(2) (DIRS 156605), the dose analysis of the stylized human intrusion case is not required for TSPA-LA because the human intrusion without recognition cannot occur prior to 10,000 years. Because the dose from the human intrusion was expected to occur after the 10,000-year regulatory compliance period, the human intrusion dose analysis for TSPA-SR was previously presented in the FEIS (DOE 2002 [DIRS 155970], Section 5.7.1). Documentation of the human intrusion stylized analysis for the LA will include a description of the technical basis and analyses to support the determination of the time of occurrence of the human intrusion and an update to the human intrusion stylized analysis exposure determination.

The requirements at 10 CFR 63.322(f) (DIRS 156605) and 40 CFR 197.26(e) (DIRS 165519), indicating that only radionuclides transported to the SZ need to be considered, preclude consideration of FEPs related to the exposure of the public, drillers, or other human intruders from cuttings, circulated materials, or tailings. The supplementary information to 10 CFR Part 63 (66 FR 55732 [DIRS 156671], p. 55761, Supplementary Information, 3.10 Human Intrusion Standard) is clear with the intent of the NRC:

> Human intrusion has the potential for releasing particulate HLW to the surface with drill cuttings or providing a fast pathway for radionuclides to be transported to the SZ by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the SZ). NAS [The National Academy of Science] concluded, and the Commission agrees, that

> analysis of the risk to the public or the intruders (i.e., drilling crew) from radioactive drill cuttings left unattended at the surface for subsequent dispersal into the biosphere would not fulfill the purpose of the human intrusion calculation because it would not show how well a particular repository site and design would protect the public at large. Rather, an analysis of the hazard of particulate HLW left on the surface would be dominated by assumptions subject to significant speculation and uncertainty regardless of the particular site or design under evaluation. Additionally, the release to the surface represents a one-time release with no long-term effect on the repository barriers.

Consequently, consideration of exposure to the intruders is specifically excluded.

Therefore, consideration of inadvertent human intrusion is excluded from the TSPA–LA. Because the dose from human intrusion is expected to occur after the 10,000-year regulatory compliance period, the human intrusion stylized analysis is not required for TSPA-LA.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3.3 Igneous Event Precedes Human Intrusion (1.4.02.03.0A)

FEP Description: An igneous event, such as a dike, could intersect the repository and significantly alter the material and structural properties of a drip shield and/or waste package. Because of the change in properties, an intruder, using groundwater exploration drilling techniques, may not be able to recognize that something other than naturally-occurring materials have been encountered.

Screening Decision: Excluded – By Regulation

Screening Argument: The probability of a dike intruding the repository has been determined to have a mean annualized probability of 1.7×10^{-8} (BSC 2004 [DIRS 169989], Table 7-1), but in no estimates reviewed to date has the probability of igneous activity within the repository footprint been calculated to be as high as 1×10^{-5}. Therefore, it is an unlikely event, as defined in 10 CFR 63.342 (DIRS 156605), and need not be further considered in conjunction with human intrusion.

The NRC indicates that unlikely FEPs (those estimated to have less than one chance in 10 and at least one chance in 10,000 years of occurring within 10,000 years of disposal, or roughly an annualized probability of 1×10^{-5} to 1×10^{-8}) and very unlikely events (those with an annualized probability of less than 1×10^{-8}) are to be excluded from the assessments for the human intrusion and groundwater protection standards (10 CFR 63.342 [DIRS 156605]). Consequently, this FEP is excluded based on the regulation.

Furthermore, the existing disruptive events scenario class allows for an igneous event to occur, but assumes that all waste packages within an intruded drift are damaged such that the drip shield and waste package provide no further protection. Thus, all waste packages in the intruded drift can contribute radionuclides to a groundwater release pathway, using the nominal scenario groundwater transport mechanism. Under the requirements of the human intrusion analysis, it is assumed that only one package is penetrated and that transport occurs to the SZ via the borehole. Because of the increased source term associated with the igneous intrusion, the existing disruptive scenario probability weighted exposure to the RMEI is likely conservative compared to the release from a single waste package release postulated for the human intrusion stylized analysis. Although, the release through the borehole may provide for a decreased transport time from the UZ to the SZ, the potential source term for the human intrusion stylized analysis is many times less than that associated with just the naturally occurring igneous event.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3.4 Seismic Event Precedes Human Intrusion (1.4.02.04.0A)

FEP Description: A seismic event could occur at the repository and significantly alter the material and structural properties of a drip shield and/or waste package. Because of the change in properties, an intruder, using groundwater exploration drilling techniques, may not be able to recognize that something other than naturally-occurring materials have been encountered.

Screening Decision: Excluded – Low Consequence and By Regulation

Screening Argument: The regulation requires that events with at least a 1 in 10 chance in 10,000 years of occurring (i.e., roughly an annualized of 1×10^{-5} or greater) be considered as part of the human intrusion assessment, but events with less of a chance not be considered (10 CFR 63.342 [DIRS 156605]).

Seismic events with an annualized probability of 1×10^{-5} are associated with the potential for onset of seismic-related damage to the drip shields and waste packages (BSC 2004 [DIRS 169183], Sections 6.3, 6.4, and 6.5). The onset of such events is associated with the potential for damage of limited surface areas on the engineered barriers (such as initiation of cracking or development of corrosion sites), although such sites will be filled with mineral precipitates and prevent advective flow. However, this does not necessarily indicate that the material properties (such as compressive strength) have been significantly altered or that the structural strength of the barriers has been significantly altered with respect to the potential for intrusion by drilling without recognition of the driller. As long as the materials retain their basic material characteristics (i.e., compressive strength in particular), the reaction of the drilling assembly will be such that a change in conditions will be recognized by a change in drilling conditions. As the damaged barrier is encountered, the drill bit will tend to “seize” or “catch” on any fractures or cracks in the surface, and the operation will produce "chatter" at the surface, or at the extreme, result in the drill bit being unable to rotate as it entangles with the metals and alloys of the engineered barriers. Under these conditions, the difference in shear strengths and modulus of elasticity will be the determining factors in being able to determine the difference between naturally occurring materials and the engineered barrier materials. The difference in these properties for rock and the metals and alloys used in the engineered barriers are significant (Appendix C).

The mean tensile strength and mean ultimate strength of the rock units range from 11.6 MPa to 23.8 MPa, or approximately 7 to 50 percent of the corresponding mean compressive strength (BSC 2003 [DIRS 166107], Tables E-6 through E-10 and E-14; and MO0311RCKPRPCS.003 [DIRS 166073]). These rock tensile strengths are, at a minimum, a factor of 14 less than those of the engineered barrier materials. Even conservatively assuming an equivalence of the yield strength of a ductile material to tensile or ultimate strength of brittle material generates a difference of a factor of much greater than 1.6 (i.e., the threshold for recognition of a change in penetration rates, as explained in Appendix C). Material properties for the engineered barriers are taken from MO0003RIB00071.000 (DIRS 148850), MO0003RIB00073.000 (DIRS 152926), and MO0003RIB00076.000 (DIRS 153044). The yield strength assigned to the engineered barrier materials is reported to range from 240 to 450 MPa for the stated offsets. A comparison of the ultimate and tensile strength to the rock units represents a minimum factor of 20 in material properties. Similarly, the mean modulus of elasticity for the rock materials is on the order of 6.9 to 33 GPa. Correspondingly, the reported shear modulus for the repository host horizon ranges from 0.42 to 8.21 GPa (or no greater than 1/3 of the maximum reported modulus of elasticity). By contrast, for the ductile alloys, the modulus of elasticity ranges from 106 to 206 GPa, representing a minimum factor of 3.2 difference from the rock properties.

Thus, the seismic events that must be considered (i.e., with annualized probabilities of 1×10^{-5} or greater) are of low consequence because they would not induce significant changes in the material properties of the host rock or the engineered barrier materials, and the penetration of such materials would still be recognizable.

The NRC indicates that unlikely FEPs (those estimated to have less than one chance in 10 and at least one chance in 10,000 of occurring within 10,000 years of disposal, or roughly an annualized probability of between 1×10^{-5} and 1×10^{-8}) and very unlikely events (those with an annualized probability of less than 1×10^{-8}) are to be excluded from the assessments for the human intrusion and groundwater protection standards (10 CFR 63.342 [DIRS 156605]). Consequently, other seismic events of greater magnitude, which may occur less frequently but have the potential to result in increased damage, are excluded based on the regulatory proscription of considering such events.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3.5 Unintrusive Site Investigation (1.4.03.00.0A)

FEP Description: This FEP addresses airborne, geophysical, or other surface-based investigations of a repository site after its closure.

Screening Decision: Excluded – By Regulation and Low Consequence

Screening Argument: "Unintrusive site investigation" is excluded from the TSPA–LA based on the regulatory definition and requirements for the human intrusion analysis and on low consequence of unintrusive activities.

By definition, unintrusive activities will have no discernible effect (i.e., are of low consequence) on the performance of the system. Human intrusion is defined as "…breaching of any portion of the Yucca Mountain disposal system, within the repository footprint, by any human activity" (10 CFR 63.302 [DIRS 156605]). Because the methodologies listed in the description are unintrusive, there are no mechanisms for the activities of this FEP to breach the disposal system or negatively affect repository performance, and the FEP is, therefore, excludable by regulation and low consequence.

Alternately, any human activity (including surface-based site investigations) or human-induced activity that has a significant negative affect (breach) on the barrier system is, by definition, human intrusion. The regulations at 10 CFR 63.113(d) (DIRS 156605) and 40 CFR 197.26 (DIRS 165519) stipulate that human intrusion shall be considered only through the consideration of the human intrusion stylized analysis.

Furthermore, the NRC, in the discussion regarding the timing and frequency of human intrusion (10 CFR Part 63, 66 FR 55732 [DIRS 156671], p. 55761, Supplementary Information), states that "some evaluations of the resource potential suggest that Yucca Mountain and the area around it does not represent an active candidate for either systematic or random exploratory drilling at this time." A list of citations for those studies is available in the regulation.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3.6 Drilling Activities (Human Intrusion) (1.4.04.00.0A)

FEP Description: This FEP addresses any type of drilling activity in the repository environment. These activities may be taken with or without awareness of the presence of the repository and with or without consent of the repository licensee. Drilling activities may be associated with natural resource exploration (water, oil and gas, minerals, geothermal energy), waste disposal (liquid), fluid storage (hydrocarbon, gas), or reopening existing boreholes.

Screening Decision: Excluded – By Regulation

Screening Argument: "Drilling activities (human intrusion)" is excluded from the TSPA-LA based on regulation because consideration of only a stylized human intrusion is mandated at 10 CFR 63.322 and 10 CFR 63.321 (DIRS 156605).

Human intrusion is defined as (10 CFR 63.302 [DIRS 156605]):

> Human intrusion means breaching any portion of the Yucca Mountain disposal system, within the repository footprint, by any human activity.

This is an important concept in that "any" human activity that has the potential to breach the disposal system is included within the regulatory intent regarding human intrusion.

Performance assessment is defined (10 CFR 63.2 [DIRS 156605]) as an analysis that:

> Identifies the features, events, and processes (except human intrusion), and sequences of events and processes (except human intrusion), that might affect the Yucca Mountain disposal system and their probabilities of occurring during 10,000 years after disposal.

From this statement stems a regulatory basis for excluding all FEPs that address human intrusion from consideration in the TSPA–LA model. However, there are specific regulatory provisions regarding consideration of human intrusion and drilling activities. To wit (10 CFR 63.322 [DIRS 156605]):

> For the purposes of the analysis of human intrusion, DOE must make the following assumptions:
>
> (a) There is a single human intrusion as a result of exploratory drilling for ground water;
>
> (b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository;
>
> (c) The drillers use the common techniques and practices that are currently employed in exploratory drilling for ground water in the region surrounding Yucca Mountain;
>
> (d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole;
>
> (e) No particulate waste material falls into the borehole;

(f) The exposure scenario includes only those radionuclides transported to the SZ by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the SZ); and

(g) No releases are included which are caused by unlikely natural processes and events.

This is similar to the requirements at 40 CFR 197.26 (DIRS 165519), except that the EPA regulation does not specify item (e) and item (f) is replaced with the following language (40 CFR 197.26(e) [DIRS 165519]):

> Only releases of radionuclides that occur as a result of the intrusion and that are transported through the resulting borehole to the SZ are projected;

Several concepts in this set of regulations are important to the evaluation of human intrusion FEPs. First, rather than speculating on the nature and probability of future intrusion, the NRC has required that human intrusion be evaluated via a human intrusion stylized analysis. Secondly, the regulation specifies that the stylized analysis must assume the intrusion is the result of exploring for groundwater. This is emphasized with the statement “DOE must make the following assumptions” (10 CFR 63.322 [DIRS 156605]). Therefore, all other types of drilling activities, by default, are excluded due to the regulatory-specified assumption.

Additionally, the supplementary information to 10 CFR Part 63 ([DIRS 156605], p. 55761, Supplementary Information, 3.10 Human Intrusion Standard) indicates that the NRC intended the analysis to be based on a stylized analysis. Accordingly, the NRC specifies the criteria under which human intrusion must be evaluated (10 CFR 63.321 [DIRS 156605]):

> DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers.

Furthermore, by way of explanation and corroboration, DOE must (10 CFR 63.321(a) [DIRS 156605]):

> Provide the analyses and its technical bases used to determine the time of occurrence of human intrusion (see 10 CFR 63.322) without recognition by the drillers.

And if complete waste package penetration is projected to occur before or at the 10,000-year performance period, then the DOE is to demonstrate that (10 CFR 63.321(b)(1) [DIRS 156605]):

> [T]here is a reasonable expectation that the reasonably maximally exposed individual receives no more than an annual dose of 0.15 mSv (15 mrem) as a result of a human intrusion, at or before 10,000 years after disposal.

And, per 10 CFR 63.321(b)(2) (DIRS 156605):

> If the exposure of the RMEI occurs after 10,000 years, or if the intrusion is projected to occur after 10,000 years, the results of the analysis and the bases of the analysis are to be provided in the environmental impact statement for Yucca Mountain.

The drip shield and waste package barrier capability are based on physical properties of drip shields and waste packages. Degradation of these components with time is discussed in BSC (2004 [DIRS 169996], Sections 6.5 and 7.2), and the analyses indicate that:

- Because of the low corrosion rate of titanium alloy used for the drip shields, the initial breaches of the drip shields are not expected to occur until well after 10,000 years; more specifically the modeling indicates approximately 40,000 years with the median estimate of the mean time to initial breaching of drip shields at approximately 300,000 years.

- Because the corrosion rates of Alloy 22 (UNS N06022) used for the waste packages are so low, it is not expected that any waste packages will be breached by general corrosion during the first 10,000 years; models indicate that the time to initial breaching of the waste packages due to general corrosion is on the order of 100,000 years.

The results of the waste package degradations analyses cited from BSC (2004 [DIRS 169996], Sections 6.5 and 7.2) result from the use of representative thermal hydrologic history files produced to allow model runs to be exercised in the cited report. The actual drip shield and waste package degradation profiles used in the TSPA-LA model will make use of the actual thermal hydrologic history files appropriate for the repository. Because representative histories were used, however, significant differences in the degradation profile generated for TSPA-LA are not expected. While general corrosion occurs gradually over time up to the time of failure, the oxidation process is a surface phenomenon, and the underlying metal retains its integrity and resistance to drilling. Although results show the potential for failures at early time, these failures are the result of localized corrosion and, although modeled in TSPA-LA as a patch, are not associated with degradation of a significant surface area with respect to potential interaction with a rotary drill bit (Appendix C). Similarly, during the first 10,000 years, the material performance of the waste package would not be significantly degraded by stress corrosion cracking. Regardless of the localized corrosion effects or potential for stress corrosion cracking, the overall structural integrity of the waste package and drip shield, and the resistance to drilling, is maintained. This is corroborated by the TSPA-SR drip shield and waste package studies that indicate long lifetimes for these components, with the first drip shield failures occurring after about 20,000 years (CRWMS M&O 2000 [DIRS 153246], Section 3.4). The first failures of the waste package outer material, Alloy 22, by general corrosion occurred after approximately 30,000 years.

Based on DOE analyses (Appendix C), the compressive strength and ductility of the metals from which the drip shields and waste package are fabricated differ significantly from the rock that would surround them and remain largely intact through the 10,000-year regulatory period. Drillers would notice these differences in properties based on the rate of penetration. Rate of penetration ranges from inversely proportional to the square of the compressive strength of the material being drilled, to inversely proportional, all other factors being equal (Bourgoyne et al. 1986 [DIRS 155233], Eq. 5-19; Kahraman et al. 2000 [DIRS 167761], Equation 8). The compressive strength of the materials differ by a factor of two (Appendix C), suggesting the at a minimum, the rate of penetration would decrease by half or possibly to one fourth as the bit moved from the rock material to the engineered barrier, if in fact, the drill bit could penetrate the engineered barrier. Other effects would also be noticeable. A full discussion is provided in Appendix C. The drillers, therefore, should recognize that they have attempted to drill into some material other than rock for at least as long as the drip shields or waste packages are intact.

Based on these analyses, and in accordance with 10 CFR 63.321(b)(2) (DIRS 156605), dose analysis of the stylized human intrusion case is not required for TSPA-LA because the human intrusion without recognition cannot occur prior to 10,000 years. Because the dose from the human intrusion was expected to occur after the 10,000-year regulatory compliance period, the human intrusion dose analysis for TSPA-SR was previously presented in the FEIS (DOE 2002 [DIRS 155970], Section 5.7.1). Documentation of the human intrusion stylized analysis for the LA will include a description of the technical basis and analyses to support the determination of the time of occurrence of the human intrusion and an update to the human intrusion stylized analysis exposure determination.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3.7 Effects of Drilling Intrusion (1.4.04.01.0A)

FEP Description: Drilling activities that intrude into the repository may create new release pathways to the biosphere and alter existing pathways. Possible effects of a drilling intrusion include interaction with waste packages, increased saturation in the repository leading to enhanced radionuclide transport to the SZ, changes to groundwater and EBS chemistry, and waste brought to the surface.

Screening Decision: Excluded – By Regulation

Screening Argument: “Effects of Drilling Intrusion” is excluded from the TSPA-LA based on regulation because consideration of only a stylized human intrusion is mandated (10 CFR 63.322 and 10 CFR 63.321 [DIRS 156605]).

Human intrusion is defined as (10 CFR 63.302 [DIRS 156605]):

> Human intrusion means breaching any portion of the Yucca Mountain disposal system, within the repository footprint, by any human activity.

This is an important concept in that any human activity that has the potential to breach the disposal system is included within the regulatory intent regarding human intrusion.

Performance assessment is defined (10 CFR 63.2 [DIRS 156605]) as an analysis that:

> Identifies the features, events, and processes (except human intrusion), and sequences of events and processes (except human intrusion), that might affect the Yucca Mountain disposal system and their probabilities of occurring during 10,000 years after disposal.

From this statement stems a regulatory basis for excluding all FEPs that address human intrusion from consideration in the TSPA–LA model. The NRC specifies the criteria under which human intrusion must be evaluated (10 CFR 63.321 [DIRS 156605]):

> DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers.

Furthermore, by way of exploration and corroboration, the DOE must (10 CFR 63.321(a) [DIRS 156605]):

> Provide the analyses and its technical bases used to determine the time of occurrence of human intrusion (see 63.322) without recognition by the drillers.

If complete waste package penetration is projected to occur before or at the 10,000-year performance period, then the DOE is to demonstrate that (10 CFR 63.321(b)(1) [DIRS 156605]):

> [T]here is a reasonable expectation that the reasonably maximally exposed individual receives no more than an annual dose of 0.15 mSv (15 mrem) as a result of a human intrusion, at or before 10,000 years after disposal.

And, per 10 CFR 63.321(b)(2) (DIRS 156605):

> If the exposure of the RMEI occurs after 10,000 years, or if the intrusion is projected to occur after 10,000 years, the results of the analysis and the bases of the analysis are to be provided in the environmental impact statement for Yucca Mountain.

Additionally, the requirements at 10 CFR 63.322(f) (DIRS 156605) and 40 CFR 197.26(e) (DIRS 165519), indicating that only radionuclides transported to the SZ need to be considered, preclude the consideration of FEPs related to the exposure of the public, drillers, or other human intruders from cuttings, circulated materials, or tailings. The supplementary information to 10 CFR Part 63 (66 FR 55732 [DIRS 156671], p. 55761, Supplementary Information, 3.10 Human Intrusion Standard) is clear with the intent of the NRC:

> Human intrusion has the potential for releasing particulate HLW to the surface with drill cuttings or providing a fast pathway for radionuclides to be transported to the SZ by water (e.g., water enters the waste package, releases radionuclides,

> and transports radionuclides by way of the borehole to the SZ). The NAS [National Academy of Science] concluded, and the Commission agrees, that analysis of the risk to the public or the intruders (i.e., drilling crew) from radioactive drill cuttings left unattended at the surface for subsequent dispersal into the biosphere would not fulfill the purpose of the human intrusion calculation because it would not show how well a particular repository site and design would protect the public at large. Rather, an analysis of the hazard of particulate HLW left on the surface would be dominated by assumptions subject to significant speculation and uncertainty regardless of the particular site or design under evaluation. Additionally, the release to the surface represents a one-time release with no long-term effect on the repository barriers.

The drip shield and waste package barrier capability are based on the physical properties of the drip shield and waste packages. Degradation of these components with time is discussed in BSC (2004 [DIRS 169996], Sections 6.5 and 7.2), and the analysis indicates that:

- Because of the low corrosion rate of titanium alloy used for the drip shields, the initial breaches of the drip shields are not expected to occur until well after 10,000 years; more specifically, the modeling indicates approximately 40,000 years, with the median estimate of the mean time to initial breaching of drip shields at approximately 300,000 years.

- Because the corrosion rates of Alloy 22 (UNS N06022) used for the waste packages are so low, it is not expected that any waste packages will be breached by general corrosion during the first 10,000 years; models indicate that the time to initial breaching of the waste packages due to general corrosion is on the order of 100,000 years.

The results of the waste package degradations analyses cited from BSC (2004 [DIRS 169996], Sections 6.5 and 7.2) result from the use of representative thermal hydrologic history files produced to allow model runs to be exercised in the cited report. The actual drip shield and waste package degradation profiles used in the TSPA-LA model will make use of the actual thermal hydrologic history files appropriate for the repository. Because representative histories were used, however, significant differences in the degradation profile generated for TSPA-LA are not expected. While general corrosion occurs gradually over time up to the time of failure, the oxidation process is a surface phenomenon, and the underlying metal retains its integrity and resistance to drilling. Although results show the potential for failures at early time, these failures are the result of localized corrosion and, although modeled in TSPA-LA as a patch, are not associated with degradation of a significant surface area with respect to potential interaction with a rotary drill bit (Appendix C). Similarly, during the first 10,000 years, the material performance of the waste package would not be significantly degraded by stress corrosion cracking. Regardless of these localized corrosion effects or potential for stress corrosion cracking, the overall structural integrity of the waste package and drip shield, and the resistance to drilling, is maintained. This is corroborated by the TSPA-SR drip shield and waste package studies that indicate long lifetimes for these components, with the first drip shield failures occurring after about 20,000 years (CRWMS M&O 2000 [DIRS 153246], Section 3.4). The first failures of the waste package outer material, Alloy 22, by general corrosion occurred after approximately 30,000 years (this general corrosion duration did not consider the 5 cm of stainless steel beneath the Alloy 22).

Based on DOE analyses (Appendix C), the compressive strength and ductility of the metals from which the drip shields and waste package are fabricated differ significantly from the rock that would surround them and would remain largely intact through the 10,000-year regulatory period. Drillers would notice these differences in properties based on the rate of penetration. Rates of penetration range from inversely proportional to the square of the compressive strength of the material being drilled, to inversely proportional, all other factors being equal (Bourgoyne et al. 1986 [DIRS 155233], Eq. 5-19; Kahraman et al. 2000 [DIRS 167761], Equation 8). The compressive strength of the materials differ by a factor of two (Appendix C), suggesting the at a minimum, the rate of penetration would decrease by half or possibly to one fourth as the bit moved from the rock material to the engineered barrier, if in fact, the drill bit could penetrate the engineered barrier. Other effects would also be noticeable. A full discussion is provided in Appendix C. The drillers, therefore, should recognize that they have attempted to drill into some material other than rock for at least as long as the drip shields or waste packages are intact.

Based on these analysis, and in accordance with 10 CFR 63.321(b)(2) (DIRS 156605), dose analysis of the stylized human intrusion case is not required for TSPA-LA because the human intrusion without recognition cannot occur prior to 10,000 years. Because the dose from the human intrusion was expected to occur after the 10,000-year regulatory compliance period, the human intrusion dose analysis for TSPA-SR was previously presented in the FEIS (DOE 2002 [DIRS 155970], Section 5.7.1). Documentation of the human intrusion stylized analysis for the LA will include a description of the technical basis and analyses to support the determination of the time of occurrence of the human intrusion and an update to the human intrusion stylized analysis exposure determination.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3.8 Mining and Other Underground Activities (Human Intrusion) (1.4.05.00.0A)

FEP Description: Mining and other underground human activities (e.g., tunneling, underground construction, quarrying) could disrupt the disposal system.

Screening Decision: Excluded – By Regulation

Screening Argument: "Mining and other underground activities (human intrusion)" is excluded from the TSPA–LA and the human-intrusion stylized analysis based on regulation because consideration of only a stylized human intrusion is mandated at 10 CFR 63.322 (DIRS 156605).

Human intrusion is defined as (10 CFR 63.302 [DIRS 156605]):

> Human intrusion means breaching any portion of the Yucca Mountain disposal system, within the repository footprint, by any human activity.

This is an important concept in that any human activity that has the potential to breach the disposal system is included within the regulatory intent regarding human intrusion.

Performance assessment is defined (10 CFR 63.2 [DIRS 156605]) as an analysis that:

> Identifies the features, events, and processes (except human intrusion), and sequences of events and processes (except human intrusion), that might affect the Yucca Mountain disposal system and their probabilities of occurring during 10,000 years after disposal.

From this statement stems a regulatory basis for excluding all FEPs that address human intrusion from consideration in the TSPA–LA model. However, there are specific regulatory provisions regarding consideration of human intrusion. To wit (10 CFR 63.322 [66 FR 55732 (DIRS 156671)]):

> For the purposes of the analysis of human intrusion, DOE must make the following assumptions:
>
> (a) There is a single human intrusion as a result of exploratory drilling for groundwater;
>
> (b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository;
>
> (c) The drillers use the common techniques and practices that are currently employed in exploratory drilling for ground water in the region surrounding Yucca Mountain;
>
> (d) Careful sealing of the borehole does not occur, instead natural degradation processes gradually modify the borehole;
>
> (e) No particulate waste material falls into the borehole;
>
> (f) The exposure scenario includes only those radionuclides transported to the SZ by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the SZ); and
>
> (g) No releases are included which are caused by unlikely natural processes and events.

This is similar to the requirements at 40 CFR 197.26 (DIRS 165519), except that the EPA regulation does not specify item (e) and item (f) is replaced with the following language (40 CFR 197.26(e) [DIRS 165519]):

> Only releases of radionuclides that occur as a result of the intrusion and that are transported through the resulting borehole to the SZ are projected.

Several concepts in this set of regulations are important to the evaluation of human intrusion FEPs. First, rather than speculating on the nature and probability of future intrusion, the NRC has required that human intrusion be evaluated via a human intrusion stylized analysis. Secondly, the regulation specifies that the stylized analysis assume the intrusion is the result of exploration for groundwater. This is emphasized in regulations with the statement that "DOE must make the following assumptions" (10 CFR 63.322 [DIRS 156605]). Therefore, all other types of intrusion, including mining, by default, are excluded due to the regulatory-specified assumption.

With regard to the motivation of a human intrusion being intentional and deliberate or inadvertent and accidental, 10 CFR Part 63 (DIRS 156605) is are silent. Similarly, the regulations at 40 CFR Part 197 (DIRS 165519) does not directly address the motivation or intentionality of the intrusion. However, the supplemental discussions for 40 CFR Part 197 clarify that consideration of deliberate intrusion is not intended. In the supplementary information to 40 CFR Part 197 (66 FR 32074 [DIRS 155216], p. 32105, Item 3), the EPA, in response to comments regarding the human intrusion stylized analysis, states:

> Comments we received proposing alternative drilling frequencies and intentions, such as deliberately drilling into the repository, did not provide a sufficient rationale to abandon the NAS [National Academy of Science] recommendations and we therefore retained our original framing for the scenario.

The EPA amplifies this (66 FR 32074 [DIRS 155216], p. 32127, Item 10), explicitly stating that:

> Some comments suggested that there is a strong possibility for deliberate intrusion into the repository to access its content as possible resources. We believe that there is no useful purpose to assessing the consequences of deliberate intrusions because in that case the intruders would be aware of the risks and consequences and would have decided to assume the risks. This is consistent with NAS's [National Academy of Science] conclusion regarding intentional intrusion (NAS Report, p. 14).

Additionally, the requirements at 10 CFR 63.322(f) (DIRS 156605) and 40 CFR 197.26(e) (DIRS 165519), indicating that only radionuclides transported to the SZ must be considered, preclude the consideration of FEPs related to the exposure of the public, drillers, or other human intruders from cuttings, circulated materials, or tailings. The supplementary information to 10 CFR Part 63 (66 FR 55732 [DIRS 156671], p. 55761, Supplementary Information, 3.10 Human Intrusion Standard) is clear with the intent of the NRC:

> Human intrusion has the potential for releasing particulate HLW to the surface with drill cuttings or providing a fast pathway for radionuclides to be transported

> to the SZ by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the SZ). NAS [National Academy of Science] concluded, and the Commission agrees, that analysis of the risk to the public or the intruders (i.e., drilling crew) from radioactive drill cuttings left unattended at the surface for subsequent dispersal into the biosphere would not fulfill the purpose of the human intrusion calculation because it would not show how well a particular repository site and design would protect the public at large. Rather, an analysis of the hazard of particulate HLW left on the surface would be dominated by assumptions subject to significant speculation and uncertainty regardless of the particular site or design under evaluation. Additionally, the release to the surface represents a one-time release with no long-term effect on the repository barriers.

Consequently, all deliberate human intrusion FEPs discussed in this analysis report are excluded based on the regulatory intent, and all inadvertent intrusions are considered within the context of the regulatory requirements to consider only the stylized human intrusion and the timing of such an event (see also Assumption 5.2 regarding the loss of records and ineffectiveness of repository markers).

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3.9 Explosions and Crashes (Human Activities) (1.4.11.00.0A)

FEP Description: Explosions or crashes resulting from future human activities may affect the long-term performance of the repository. Explosions may result from nuclear war, underground nuclear testing, or resource exploitation.

Screening Decision: Excluded – By Regulation and Low Consequence

Screening Argument: "Explosions and Crashes (Human Activities)" is excluded from the TSPA–LA based on regulation and low consequence because the type of phenomena listed primarily would have surficial effects, unless the repository was deliberately targeted, which is a specific form of deliberate human intrusion as is therefore excluded (10 CFR 63.322 [DIRS 156605]). Resource exploration, in the form of groundwater exploitation, is addressed as part of the human intrusion stylized analysis.

The development history for this FEP indicates that several possible cases are covered by this FEP. These include surface detonation of nuclear or conventional weapons, aircraft crashes, subsurface explosion related to resource recovery, and nuclear detonation nearby in the subsurface.

Human intrusion is defined as (10 CFR 63.302 [DIRS 156605]):

> Human intrusion means breaching any portion of the Yucca Mountain disposal system, within the repository footprint, by any human activity

This is an important concept in that any human activity that has the potential to breach the disposal system is included within the regulatory intent regarding human intrusion.

Performance assessment is defined (10 CFR 63.2 [DIRS 156605]) as an analysis that:

> Identifies the features, events, and processes (except human intrusion), and sequences of events and processes (except human intrusion), that might affect the Yucca Mountain disposal system and their probabilities of occurring during 10,000 years after disposal.

From this statement stems a regulatory basis for excluding all FEPs that address human intrusion, including explosions and crashes, from consideration in the TSPA–LA model. However, there are specific regulatory provisions regarding consideration of human intrusion as a stylized analysis based on exploratory drilling for groundwater (10 CFR 63.322 [DIRS 156605]).

With regard to the motivation of a human intrusion being intentional and deliberate or inadvertent and accidental, 10 CFR Part 63 (DIRS 156605) is silent. Similarly, 40 CFR Part 197 (DIRS 165519) does not directly address the motivation or intentionality of the intrusion. However, the supplemental discussions for 40 CFR Part 197 clarify that consideration of deliberate intrusion is not intended. In the supplementary information to 40 CFR Part 197 (66 FR 32074 [DIRS 155216], p. 32105, Item 3), the EPA, in response to comments regarding the human intrusion stylized analysis, states:

> Comments we received proposing alternative drilling frequencies and intentions, such as deliberately drilling into the repository, did not provide a sufficient rationale to abandon the NAS [National Academy of Science] recommendations and we therefore retained our original framing for the scenario.

The EPA amplifies this (66 FR 32127 [66 FR 32074 (DIRS 155216), p. 32127, Item 10]) stating that:

> Some comments suggested that there is a strong possibility for deliberate intrusion into the repository to access its content as possible resources. We believe that there is no useful purpose to assessing the consequences of deliberate intrusions because in that case the intruders would be aware of the risks and consequences and would have decided to assume the risks. This is consistent with NAS's [the National Academy of Science] conclusion regarding intentional intrusion (NAS Report, p. 14).

Consequently, all deliberate human intrusion FEPs discussed in this analysis report are excluded based on the regulatory intent, and all inadvertent intrusions are considered within the context of the regulatory requirements to consider only the human intrusion stylized analysis and the timing of such an event.

With regard to explosions and crashes, the depth of the repository suggests that such events are of low consequence to repository performance. The minimum depth of the TSPA-LA repository (distance from the emplacement area to the overlying surface) is approximately 200 m. The overburden thickness from emplacement area to topographic surface is 215 m (BSC 2004 [DIRS 164519]). A depth of 200 m will be used in the calculation to provide a small margin of conservatism.

With regard to potential consequences of airplane crashes, surface detonation, and subsurface detonation, the results of the evaluation of meteorite impact cratering (Appendix C) are relevant, and direct inputs to the discussion are addressed in Appendix B. To be of consequence, the detonation or impact must be sufficient to exhume the waste, create fracturing to depth, or create a significant increase in fracturing over a widespread area such that infiltration patterns and rates are significantly altered. The analysis presented in Appendix D suggests that impacts resulting in craters with diameters on the scale of 80 to 100 m (262 to 328 feet) might be sufficient to lead to fracturing of the geologic units overlying the repository sufficient to increase infiltration. A crater with a diameter on the order of 300 m (984 feet) is needed to initiate fracturing to the depth of the repository, and a crater with a diameter on the order of 1 km (3,280 feet) is needed to exhume waste directly to the surface. Based on Dence et al. (1977 [DIRS 135253], Figure 12), such crater diameters, respectively, are associated with energy release on the scale of 10^{12} to 10^{17} joules (200 tons to 20 megatons trinitrotoluene (TNT) equivalent based on a relationship of 1 megaton TNT = 4.2×10^{15} joules (J) per Chapman and Morrison (1994 [DIRS 135245], p. 33).

Such large-scale energy releases are not associated with surface impact of an aircraft or surface detonation of conventional ordnance because of insufficient energy release to the subsurface. By way of comparison, Stix and Yam (2001 [DIRS 160994], p. 15) suggest that kinetic energy of a Boeing 767 is on the order of 1 to 2 tons TNT. Stix and Yam also indicate that the potential explosive energy release from fuel on board a large jet passenger aircraft is on the order of 90 tons TNT (or 180 tons for two jets) , though this would not all be focused into the subsurface. With regard to more conventional ordinance, Ferguson (2002 [DIRS 160988]) suggests that the conventional yield of a GBU-28 "bunker buster" bomb is on the order of 2 tons and with a limitation on penetration depth of approximately 30 m. With regard to earth-penetrating weapons, available direct inputs suggest that a penetration depth of 30 m is a reasonable maximum estimate. Backman and Goldstein (1978 [DIRS 167628], pp. 32 and 38) provide two direct inputs. For a 5,000-psi concrete (34.5 MPa), which is at the lower end of the range in rock compressive strengths at Yucca Mountain, the maximum penetration depth is given as 25 penetrator diameters. If one assumes a 1-m diameter, then the maximum penetration depth is 25 m. Backman and Goldstein (1978 [DIRS 167628], p. 38, Equation 6.2) also present the Poncelet equation that, for a 150 kg mass and entrance velocity of 400 m/sec, yields a maximum penetration depth of about 38 m. Other direct inputs include the empirical results of Patterson (1974 [DIRS 167805]), who reports maximum penetration depth of 20.7 m in an old glacial lake bed for a projectile with a 20.3 cm diameter and velocity of 150.9 m/sec; the results from Young

(1976 [DIRS 167806], Table II), who reports 67 m in hard dry playa lake soils, and those of Forrestal et al. (1981 [DIRS 167630], p. 28), who report 2.6 m into a welded tuff.

Dence et al. (1977 [DIRS 135253], p. 262) suggest that in the 64-kt pile driver test, stresses at about 100 m (328 feet) were slightly less than that needed to propagate fractures in granodiorite.

Consequently, energy releases of the magnitude required to induce fracturing to depths of interest (i.e., 80 to 100 m, 262 to 328 feet) or over a wide portion of the repository, would require intentional and targeted, deep penetrating, high-yield detonations. By regulatory definition, this is considered as deliberate human intrusion and is excluded under other FEPs. For generic, smaller scale crashes and explosions, the energy release is insufficient to significantly affect repository performance, and are, therefore, excluded based on low consequence.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.3.10 Repository Excavation (3.3.06.01.0A)

FEP Description: Excavation of the repository and/or its contents may result in the production of tailings, which may subsequently release toxic contaminants.

Screening Decision: Excluded – By Regulation and Low Consequence

Screening Argument: "Repository Excavation" is excluded from the TSPA–LA based on regulation because the handling of excavation spoils during construction is primarily a preclosure operational concern, whereas the regulatory focus is on postclosure assessment. Furthermore, future mining of the repository for its waste content constitutes human intrusion and postclosure excavation of repository contents would constitute deliberate human intrusion. Additionally, the surface facilities will be removed and the surface restored prior to closure.

By explanation of the concept of performance assessment, the NRC clarifies that a performance assessment is to demonstrate compliance with *postclosure* performance objectives (10 CFR 63.102(j) [DIRS 156605]). Given that excavation of the repository host horizon will occur at the outset of the construction phase, the creation and handling of excavation spoils is a preclosure concern.

The NRC indicates that the preclosure requirement is to be based on protecting the RMEI against radiation exposures and releases of radioactive material (10 CFR 63.311(a) [DIRS 156605]). The regulation does not specify chemical toxicity as a preclosure performance criterion, nor does it require the estimation of health effects resulting from non-radiological toxicity. This is consistent with exclusion of FEP 3.3.07.00.0A (Non-radiological toxicity/ effects).

Furthermore, future mining of the repository for its waste content constitutes human intrusion, and postclosure excavation of repository contents would constitute deliberate human intrusion, and is therefore excluded. The regulations at 10 CFR 63.322(f) (DIRS 156605) and 40 CFR 197.26(e) (DIRS 165519), indicating that only radionuclides transported to the SZ must be considered, preclude the consideration of human-intrusion FEPs related to the exposure of the public, drillers, or other human intruders from cuttings, circulated materials, or tailings. The supplementary information to 10 CFR Part 63 (66 FR 55732 [DIRS 156671], p. 55761, Supplementary Information, 3.10 Human Intrusion Standard) states:

> Human intrusion has the potential for releasing particulate HLW to the surface with drill cuttings or providing a fast pathway for radionuclides to be transported to the SZ by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the SZ). NAS [National Academy of Science] NAS concluded, and the Commission agrees, that analysis of the risk to the public or the intruders (i.e., drilling crew) from radioactive drill cuttings left unattended at the surface for subsequent dispersal into the biosphere would not fulfill the purpose of the human intrusion calculation because it would not show how well a particular repository site and design would protect the public at large. Rather, an analysis of the hazard of particulate HLW left on the surface would be dominated by assumptions subject to significant speculation and uncertainty regardless of the particular site or design under evaluation. Additionally, the release to the surface represents a one-time release with no long-term effect on the repository barriers.

Within context, this statement is strictly directed towards concern with excavated waste rather than initial excavation tailings. However, the reasoning that materials left at the surface represent a one-time release with no long-term effect on the repository barriers is equally applicable to the initial excavation spoils. This is because spoils resulting from excavation of the repository would consist of naturally occurring materials. No chemical additives or chemical-based slurrying of the spoils will be used during excavation, and no organic materials (aside from the potential for trace amounts of machinery-related fluids such as lubrication oils, grease, or hydraulic fluids) will be introduced to the spoils and organic contaminants are, therefore, not of concern. Furthermore, the geologic materials at Yucca Mountain are not a economically feasible source of extractable metals or other mineral resources, and therefore the potential for leachate concentrations is not comparable to the potential to mine tailings associated with commercially viable mineral deposits. The spoils will be similar in mineralogic composition to naturally occurring alluvial materials already present in the washes and drainage channels existing at Yucca Mountain. Repository excavation is therefore excluded based on regulations and low consequence.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.4 Miscellaneous Geologic and Astronomic FEPs

This set of FEPs is related to effects of heat on the biosphere, to the geologic setting, or to extraterrestrial processes and events. Direct inputs used in this section originating from YMP-controlled sources or NRC regulations are listed in Section 4, and no further discussion beyond that provided in Section 4 is required for such sources. Non-YMP sources of direct input are also cited in Section 4. Such sources and corroborating information are discussed in Appendix B. Non-YMP originating source information related to various FEPs such as diagenesis, extraterrestrial events, and earth tides are discussed in Appendix B. Source information specifically related to meteorite-impact analyses are specifically addressed in Appendix D.

6.2.4.1 Metamorphism (1.2.05.00.0A)

FEP Description:	Regional metamorphism has the potential to affect the long-term performance of the repository if it occurs. Metamorphic activity is defined as solid state recrystallization changes to rock properties and geologic structures through the effects of heat and/or pressure.
Screening Decision:	Excluded – Low Probability and Low Consequence
Screening Argument:	"Metamorphism" is excluded from the TSPA–LA based on low probability because the conditions and time required for metamorphic process near Yucca Mountain are such that metamorphism is not credible within a 10,000-year period, and based on low consequence because contact metamorphism may occur only over a limited area and at a low probability.

For purposes of the FEP screening, the discussion is limited to regional scale and contact metamorphism. The definition of regional metamorphism applied herein refers to the processes by which rocks are changed by the action of heat and pressure at depths of a few kilometers beneath the surface of the earth (i.e., the onset of metamorphic conditions correspond to temperatures of 150°C to 200°C, pressures of 0.5 to 1 kilobars, and depths of 4 to 5 km (Ehlers and Blatt 1972 [DIRS 167802], p. 566). Alternately, metamorphism may occur near magmatic activity (referred to as contact metamorphism). Changes in sediments and rocks at lesser conditions are referred to as diagenesis. See FEP 1.2.08.00.0A Diagenesis, in Section 6.2.4.2. See also Bates and Jackson (1984 [DIRS 128109], pp. 137 and 322) and Berry and Mason (1959 [DIRS 135236], p. 240) for additional definitions.

Regional metamorphism depends on regional tectonic deformation at Yucca Mountain and is, therefore, dependent on the strain accumulation rates and slip rates. Savage et al. (1999 [DIRS 118952], p. 17627) present an evaluation of the strain accumulation rate at Yucca Mountain during 1983 to 1998. Savage et al. (1999 [DIRS 118952], p. 17627) indicate that the strain rate in the Yucca Mountain area is low, equivalent to 2 nanostrain/yr. Savage et al. (1999 [DIRS 118952]) also addressed alternative interpretations indicating higher strain rates on the order of 50 nanostrain/yr (Wernicke et al. 1998 [DIRS 103485]). Regardless of which strain rates are used, the strain rate has resulted in cumulative fault slip rates of 0.001 to 0.03 mm/yr (BSC 2004 [DIRS 169881], Table 6). The strain rates and the local cumulative fault slip rates suggest that mechanisms leading to metamorphic activity (particularly deep burial) will occur at a slow rate.

Conditions conducive to metamorphism include temperatures of 150ºC to 200ºC, pressures on the order of 0.5 to 1 kilobar, and depths of 4 to 5 km. The geothermal gradient at convergent plate boundaries may range from 10 to 25ºC per km (Ehlers and Blatt 1982 [DIRS 167802], pp. 684 and 685), while at Yucca Mountain, an extensional terrane, the geothermal gradient, measured in 300- to 600-m-deep borings at Yucca Mountain is approximately 30°C/km (Sass et al. 1988 [DIRS 100644], pp. 38 and 39), which agrees with the temperature gradient indicated by Press and Siever (1978 [DIRS 167965], p. 298). A typical value for pressure gradients from geostatic loading is about 0.6 kilobar/km (Ehlers and Blatt (1982 [DIRS 167802], p. 169, Figure 6-3), although Press and Siever (1978 [DIRS 167965], p. 298) indicate a pressure gradient on the order of 0.2 bar/km. This suggests that at Yucca Mountain, the metamorphic regime may be present at depths of approximately 4 to 5 km. The rate of subsidence (vertical movement leading to deep burial) is controlled by movement along block-bounding faults and, at maximum, approximates the cumulative rate of fault slip at Bare Mountain and Yucca Mountain. The local cumulative fault slip rate is 0.001 to 0.03 mm/yr (BSC 2004 [DIRS 169881], Table 6). A slip rate of 0.03 mm/yr would result in a vertical movement of approximately 0.3 m (1 foot) in 10,000 years. A 0.3-m (1-foot) vertical movement is insufficient to result in pressure and temperature conditions conducive to regional metamorphism at the repository elevation, which is much shallower than 5 km below the ground surface. Additionally, the locus of subsidence has moved to the southwest corner of the basin, away from Yucca Mountain (Fridrich 1999 [DIRS 118942], p. 189). Because the repository block itself will not be significantly affected by the present subsidence rates within 10,000 years, this FEP is excluded based on low consequence.

Contact metamorphism is by definition associated with igneous activity, which at Yucca Mountain is a localized rather than regional phenomenon. Further discussion is, therefore, beyond the scope of this FEP. Contact metamorphism is more fully addressed as part of the disruptive events FEP evaluation (FEP 1.2.04.02.0A, Igneous activity changes rock properties).

In summary, regional metamorphism requires greatly increased pressure (generally resulting from burial on the order of kilometers), increased temperatures (greater than 150°C to 200°C), and long periods of geologic time (millions of years). At Yucca Mountain, development of these conditions depends on the rate of active tectonism and would require several million years to develop and is, therefore, of low probability within the next 10,000 years. Because the repository block will not be significantly affected, metamorphism does not provide a mechanism to affect dose within the repository performance period (10,000 years). Therefore, "Metamorphism" is excluded from the TSPA–LA based on low consequence. Contact metamorphism is addressed in a related FEP.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.4.2 Diagenesis (1.2.08.00.0A)

FEP Description:	This FEP addresses natural processes that alter the mineralogy or other properties of rocks after the rocks have formed under temperature- and pressure-conditions normal to the upper few kilometers of the earth's crust. Diagenesis includes chemical, physical, and biological processes that take place in rocks after formation but before eventual metamorphism or weathering. This FEP refers to natural diagenetic processes only.
Screening Decision:	Excluded – Low Consequence
Screening Argument:	"Diagenesis" is excluded from the TSPA–LA based on low consequence because the diagenetic effects are generally favorable with regard to infiltration, reversible in nature, and occur over a prolonged time-scale.

The time required for complete diagenesis in the shallow environment (extending from the surface to the downward limit of evapotranspiration) is potentially within the 10,000-year timescale of concern for the repository performance assessment (Lattman and Simonberg 1971 [DIRS 129306], p. 277; and Krystinik 1990 [DIRS 135295], p. 8-1). Thus, diagenesis cannot be excluded based on low probability.

The two primary mechanisms for early and shallow diagenetic changes are compaction and cementation. Initial compaction may reduce eolian sediments by as much as 20 to 30 percent (Krystinik 1990 [DIRS 135295], p. 8-2), but after the initial compaction, "compaction does not become and important factor in diagenesis until the onset of grain deformation and pressure solution during deeper burial diagenesis" (Krystinik 1990 [DIRS 135295], p. 8-3). The geologic setting of Yucca Mountain, however, is one of minimal subsidence rates (as discussed for FEP 1.2.05.00.0A, Metamorphism). Consequently, deep burial and significant compaction is not a credible diagenetic mechanism at Yucca Mountain within the 10,000-year repository performance period.

Cementation, however, may be of interest. The predominance of SiO_2 cements at Yucca Mountain is documented in Taylor (1986 [DIRS 102864], Figure 9), who indicates that the accumulation rate of $CaCO_3$, while occurring, is significantly less that that for SiO_2. This is reflected in statements indicating that carbonate is primarily derived from airborne dust and the opaline SiO_2 from in-place weathering of the parent material and that the cementation by opaline SiO_2 is common in the study area and that opaline SiO_2 accumulation in the soils is favored over that of $CaCO_3$ (Taylor 1986 [DIRS 102864], pp. 31 to 33). Taylor (1986 [DIRS 102864]) also indicates SiO_2 cementation, with $CaCO_3$ as accessory cement, is common in the study area. Furthermore, the presence of cements other than $CaCO_{3,}$ such as SiO_2 in arid environments, is documented in Krystinik (1990 [DIRS 135295], p. 8-4).

The net effects of shallow diagenesis and associated cementation are to stabilize the surface environment and decrease the net vertical infiltration rate (Reeves 1976 [DIRS 104303], p. 110). Whereas Reeves work focused primarily on $CaCO_3$, but also addressed silicious cements, cementation in rhyolitic tuffs, absent a carbonate source, is not a significant process (Lattman 1973 [DIRS 129305], p. 3015). The predominance of SiO_2 cements at Yucca Mountain is an important consideration because Taylor (1986 [DIRS 102864]) indicates that in the soils studied, in the absence of effective precipitation or drainage to remove newly dissolved silica, it is precipitated elsewhere within the calcrete horizon, or $CaCO_3$ preferentially precipitates after opaline silica bonds adjacent soil grains. Taylor (1986 [DIRS 102864]) notes that this process may occur without necessarily plugging intervening pore spaces, as suggested by Reeves (1976 [DIRS 104303]). Taylor (1986 [DIRS 102864], Chapter 5) also suggests that the cementation process, particularly for $CaCO_3$ is reversible, and that the material can be redissolved and moved deeper into the soil profile. Modeling results discussed by Taylor (1986 [DIRS 102864]) suggest that increased precipitation in the future may translocate $CaCO_3$ accumulations to greater depths, where precipitation is greater. Thus, for Yucca Mountain alluvial material, it can be concluded that the net effect of infiltration is either minimal or infiltration is likely decreased.

Because the time frame of interest is 10,000 years, the potential for effects of climate change on shallow diagenesis must be considered. As direct input, Taylor (1986 [DIRS 102864], Chapter 5) indicates silts that formed in alluvium and eolian fines of Holocene to early Pleistocene or late Pliocene age near Yucca Mountain are characterized by distinctive trends in the accumulation of secondary clay, $CaCO_3$, and opaline SiO_2 that correspond with the ages of the surficial deposits. However, there is no macro- or micromorphological evidence to suggest that silica cementation occurred under climatic conditions cooler and wetter than those of present climate. In contrast, Taylor (1986 [DIRS 102864]) also states that accumulation rates of these materials during the Holocene can be attributed to several possible climatic scenarios associated with the Holocene-Pleistocene climate change, but suggest that precipitation has not been a limiting factor, and that climatic change was not sufficient to greatly decrease rates of accumulation.

Consequently, climate change can be assumed to affect the rate and location of shallow diagenesis due to changes in temperature, precipitation, vegetation, and other less critical factors that control the rate and distribution of diagenetic changes such as cementation. The net effect, however, will be to vary the depth of the cemented horizons (due to dissolution and reprecipitation), change the composition of the cement materials (due to differing equilibrium conditions), and otherwise drive the diagenetic processes to differing endpoints and redistribute the areas affected, rather than eliminating the net effects of diagenesis. However, the effect of variability in rates and location of infiltration is already addressed in TSPA-LA by varying the infiltration rates associated with varying climatic conditions. The net effect of past diagenesis in the host rocks is included implicitly in the TSPA–LA through the assignment of models and parameters for flow and transport in the UZ and SZ. Mineralogic changes, if any, induced by the repository and occurring over the period of several hundreds of years due to thermal loading, would be of greater consequence at the repository depth than changes resulting near the surface from naturally occurring diagenetic processes in the vadose zone. Repository-induced changes (e.g., geochemical and thermal processes) are addressed by other FEPs and are beyond the scope of the naturally occurring process that is the focus of this FEP. Although the changes might be similar due to increased temperatures, the naturally occurring changes at depth would occur over a period on the order of several thousand years rather than in several hundreds of years. Furthermore, uncertainty in rates and location of infiltration are already addressed in the TSPA-LA by varying the infiltration rates associated with the varying climatic conditions, which tends to dominate other flow rate uncertainties. This FEP, therefore, is excluded based on low consequence.

A brief overview of some of the above listed information is provided in the Supplemental Discussion at the end of this section.

TSPA Disposition: Not Applicable

Supporting AMRs: None

Supplemental Discussion:

Introduction–Bates and Jackson (1984 [DIRS 128109], p. 137) define two types of diagenesis. Mineralogically, diagenesis is defined as "the geochemical processes or transformations that affect clay minerals before burial in the marine environment." Sedimentologically, it is defined as "all the changes undergone by a sediment after its initial deposition, exclusive of weathering and metamorphism. It includes those processes (such as compaction, cementation, replacement) that occur under conditions of pressure and temperature that are normal in the outer portion of the earth's crust, and according to most United States geologists it includes changes occurring after lithification." Bates and Jackson (1984 [DIRS 128109], p. 137) further state "[t]here is no universally accepted definition of the term, and no delimitation, e.g., with metamorphism." A prelithification definition has been used by Thrush (1968 [DIRS 106989], p. 320) and Berry and Mason (1959 [DIRS 135236], p. 233). Post-lithification changes in rock that change grain size, develop new minerals, or destroy previously existing minerals are typically considered to be alteration (Thrush 1968 [DIRS 106989], p. 30) or metamorphism (Thrush 1968 [DIRS 106989], p. 699) rather than diagenesis, although the terms are sometimes used interchangeably or in conjunction.

Most of the literature on diagenesis focuses on sedimentary deposits and diagenetic processes that have occurred in clastic or carbonate sedimentary environments. The history of the studied deposits typically is characterized as fluvial or marine deposition (either as clastic deposition or chemical precipitation) during and followed by an extended period of deep burial (>1 km). The geologic system at Yucca Mountain, however, is characterized by erosion and exhumation of lithified igneous materials, rather than deposition and burial of clastic or carbonate sedimentary sequences. Consequently, for the evaluation of Yucca Mountain FEPs, diagenesis is expanded to include alteration of volcanic rocks at pressures and temperatures below metamorphic conditions and lithification processes that may occur in surficial deposits.

Diagenesis of the volcanic rocks at Yucca Mountain is discussed in the *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998 [DIRS 100548], Section 6.1). The host rock unit at Yucca Mountain is a welded tuff. Diagenesis has modified these rocks in the past, and will continue to do so in the future. Diagenesis has resulted in the formation of secondary zeolite and clay minerals. Much of this change occurred shortly after deposition of the volcanic rocks.

Change has continued at a slower rate throughout the last 10 million years, subsequent to deposition of the tuffs, and the products of past diagenesis in the welded tuffs are included implicitly in the TSPA–LA through the assignment of models and parameters for flow and transport in the UZ and SZ.

Surficial Quaternary deposits occur at the Yucca Mountain site and in the region. These deposits result from the weathering of parent geologic material (rhyolitic tuffs), and subsequent erosion and redeposition. On Yucca Mountain, these surficial deposits are present as alluvial and colluvial fans and fan remnants and as deposits in stream channels. In the Amargosa Desert, they are present as valley-fill material. The primary lithification processes affecting these surficial deposits are compaction and cementation, which in turn decrease infiltration rates. The variance in infiltration rates based on soil types is currently incorporated into the infiltration model for the Yucca Mountain region.

Compaction/Consolidation–The primary diagenetic processes of concern at Yucca Mountain include compaction and cementation. Compaction due to burial can result in a decrease in porosity with time. Palmer and Barton (1987 [DIRS 118483], Figure 3 and pp. 32 and 39) indicate that compaction due to burial of uncemented Tertiary-age sands reduced the in situ porosity by about 12 to 13 percent of the initial porosity, while Berner (1980 [DIRS 128110], Figure 3.2) suggests that a 40 to 50 percent decrease is possible, assuming a consistent and continuing burial process.

Cementation–A second diagenetic process of concern is cementation. In most arid and semi-arid environments, cementation occurs due to formation of calcium carbonate or other carbonate cements (Reeves 1976 [DIRS 104303], p. 7; Lattman 1973 [DIRS 129305], p. 3014). This may be expressed as formation of layers or fracture infills in the near-surface environment. However, the formation of carbonate cements depends on the presence of a source of the carbonate ion. Lattman (1973 [DIRS 129305]) conducted studies on fan deposits near Las Vegas, Nevada. The results indicate that alluvial fans in Nevada that consist of silicic igneous materials (such as those composed of rhyolite and rhyolitic tuffs) are “almost always very poorly cemented, showing little more than a few scattered, coated pebbles in weak calcic horizons. Even where, as in Las Vegas Basin, large quantities of calcareous dust are available, the cementation is very weak” (Lattman 1973 [DIRS 129305], p. 3022).

Krystinik (1990 [DIRS 135295], p. 8-8), however, discusses the role of other cementitious materials during diagenesis of surficial (eolian) deposits in arid environments, and notes that weathering can reverse the previous effects of diagenesis by removing earlier cements and allowing deflation to occur (Krystinik 1990 [DIRS 135295], p. 8-3). Krystinik (1990 [DIRS 135295], p. 8-4) indicates for eolian deposits, that in dry sand, diagenesis on the surface of active dunes occurs “in the form of minor chemical degradation of grains, rock-flour mortar, and as amorphous silica, iron, and aluminum oxy-hydroxide grain coatings.” Krystinik (1990 [DIRS 135295]) also notes that observed cements in damp sand included amorphous iron silica, aluminum, and lesser percentages of calcite, smectite, and sodium carbonate. Krystinik (1990 [DIRS 135295], pp. 8-4, 8-8, and Table 2) also notes that the solutes in water associated with these cements are “remarkably similar” to examples of water from granitic and igneous source terranes documented by others.

Reeves (1976 [DIRS 104303], p. 28) indicates that indurated soil horizons, due principally to silica cementation, are termed "duripans" in the U.S. and silcrete or silcrust in Australia and other countries. Reeves (1976 [DIRS 104303], p. 29) also mentions that near-surface silica hardpans occur in granitic alluvium in the San Joaquin Valley, discusses the factors that favor silica versus carbonate cementation, and mentions that many carbonate caliches contain measurable quantities of silica.

Duripans, or petrocalcic layers, are common in the soil descriptions presented in the FEIS (DOE 2002 [DIRS 155970], Table 3-20). It is possible that these deposits could experience additional cementation. The cementation of deposits mantling Yucca Mountain could affect future rates of moisture infiltration and cementation in deposits composing the alluvial aquifer downgradient of Yucca Mountain. As indicated above, however, increases in cementation tend to decrease the porosity and permeability of deposits. Thus, it is unlikely that cementation will significantly increase infiltration or flow rates.

Rate of Diagenesis of Shallow Deposits–Studies of the diagenesis and carbonate cementations of the Smackover Formation of Louisiana indicate that the rates of mineralogic stabilization were found to differ in the various diagenetic environments (Humphrey et al. 1986 [DIRS 118461], pp. 77 to 78). For the materials studied on various carbonate islands, however, "mineralogic stabilization in the meteoric phreatic zone goes to completion within a few thousand years" (Humphrey et al. 1986 [DIRS 118461]). They further state that rates of mineralogic stabilization in the shallow vadose zone (i.e., the downward limit of the zone of evapotranspiration) may be comparable to those of the meteoric phreatic environment. By contrast, Humphrey et al. (1986 [DIRS 118461], p. 78) also cite studies from carbonate sequences that indicate incomplete diagenesis in the deep vadose zone even after 200,000 years. Although these rates are for geologic materials, environments of deposition, and climate significantly different than the alluvial materials in an arid environment present at Yucca Mountain, the study does provide an "order of magnitude" estimate for the timescale of concern.

Dependence on Climate–The ideal environment for caliche formation appears to be neither excessively arid nor excessively humid, and caliche formation can occur over a wide range of climatic conditions (Reeves 1976 [DIRS 104303], pp. 84 to 87). Reeves (1976 [DIRS 104303], p. 86) further states that:

> Certainly, the vast mineralogical differences between calcium carbonate and silica, yet the juxtaposition of both minerals in caliche, is prima facie evidence of significant changes in soil chemistry… Because soil chemistry is affected by so many variables, such as temperature, parent material, vegetation, time and topography, it is impossible to describe a singular causative environmental factor for caliche formation.

In addition, the depth to calcareous horizons (i.e., pedocals) is closely related to the amount and timing of precipitation, where increased precipitation generally results in a greater depth to the calcic horizon (Birkeland 1974 [DIRS 128113], p. 234; Reeves 1976 [DIRS 104303], Figure 4-10).

6.2.4.3 Salt Diapirism and Dissolution (1.2.09.00.0A)

FEP Description: This FEP addresses geologic processes primarily relevant to repositories located in salt deposits. Salt diapirism refers to the tendency of salt to flow under lithostatic loading when density and viscosity contrasts with surrounding strata are favorable. Salt domes are the best-known example of salt diapirism. Salt dissolution can occur when any soluble mineral is removed by flowing water. Large-scale dissolution is a potentially important process in rocks that are composed predominantly of water-soluble evaporite minerals, such as salt.

Screening Decision: Excluded – By Regulation

Screening Argument: "Salt Diapirism and Dissolution" is excluded from the TSPA–LA based on regulatory requirements because salt deposits and evaporite deposits are not a geologic feature near the repository.

The definition of geologic setting is "the geologic, hydrologic, and geochemical systems of the region in which the geologic repository is or may be located" (10 CFR 63.2 [DIRS 156605]). Inclusion of this FEP would be outside the scope and intent stated at 10 CFR 63.21(c)(1) (DIRS 156605), which specifies consideration and description of "features, events, and processes outside of the site to the extent the information is relevant and material to safety or performance of the geologic repository." Furthermore, at 10 CFR 63.114(a) and 10 CFR 63.115(a) (DIRS 156605), the regulatory requirements are to "include data that are related to the geology, hydrology, and geochemistry (including disruptive events) of the Yucca Mountain Site, and the surrounding region to the extent necessary …" and to "identify … natural features of the geologic setting, that are considered barriers important to waste isolation." At 10 CFR 63.305(c) (DIRS 156605), the DOE is directed to "…vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system over the next 10,000 years."

Evaporite deposits of sufficient volume to develop a diapir or to be of concern for dissolution have not been reported near Yucca Mountain. Rather, Yucca Mountain is located in the southwestern Nevada volcanic field and consists of tilted fault blocks composed of layered sequences of ash flow, ash-fall, and bedded tuffs of Miocene age (BSC 2004 [DIRS 170029], Sections 6 and 6.5.1.4, and Table 6-2), as corroborated by BSC (2004 [DIRS 169734], Section 3.3.4) and as shown by Day et al. (1998 [DIRS 100027]). Voluminous evaporite deposits do not exist near Yucca Mountain, and the repository is not planned for a salt dome or cavern. This feature and related process of lithologic flow are, therefore, inconsistent with the present knowledge of the geologic setting for Yucca Mountain. Therefore, "Salt diapirism and dissolution" is excluded from the TSPA–LA based on the regulation.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.4.4 Diapirism (1.2.09.01.0A)

FEP Description: The process by which plastic, low density rocks (most commonly evaporites) may flow under lithostatic loading when density and viscosity contrasts with surrounding strata are favorable. Such a process would modify the groundwater flow regime and affect radionuclide transport.

Screening Decision: Excluded – By Regulation

Screening Argument: "Diapirism" is excluded from the TSPA–LA based on regulatory requirements because geologic conditions suitable to diapirism are not present near the repository.

In the broadest sense, diapirism encompasses "the piercing or rupturing of domed or uplifted rocks by mobile core material, by tectonic stresses as in anticlinal folds, by the effect of geostatic load in sedimentary strata as in salt domes or shale diapirs, or by igneous intrusions, forming diapiric structures such as plugs" (Bates and Jackson 1984 [DIRS 128109], p. 138). The concept of diapirism is usually applied to salt structures resulting from geostatic loading. FEP 1.209.00.0A (Salt diapirism) is addressed in Section 6.2.4.3 and is excluded by regulation. There is no past evidence of other forms of diapirism within the geologic setting at Yucca Mountain.

Current tectonic stresses in the region are extensional (BSC 2004 [DIRS 168030], Section 6.3.1), and an extensional stress regime is not conducive to compression-related anticlinal folding and doming associated with diapirism. The geologic materials at Yucca Mountain are brittle (particularly the welded tuffs), and have exhibited deformation by faulting and jointing, or formation of breccias rather than diapirism. The volcanic rocks present at the site are not capable of ductile flow under the stresses and at the temperatures expected to result at the site due to geostatic loading and waste emplacement. In general, ductile behavior is associated with increased temperatures and increased hydrostatic pressures and is expected at deep levels of the crust of the earth and in the mantle. However, Yucca Mountain is located in an area of only moderate heat flow in the Southern Great Basin; it lies south of the regions that might be more conducive to diapirism as indicated by relatively high crustal heat flow (Lachenbruch and Sass 1978 [DIRS 142990], pp. 212 and 246).

Therefore, further consideration of diapirism related to tectonic stresses and geostatic loading is precluded at 10 CFR 63.2, 10 CFR 63.21(c)(1), 10 CFR 63.114(a), 10 CFR 63.115(a), and 10 CFR 63.305(c) (DIRS 156605) because the necessary geologic materials and stress environment do not occur at Yucca Mountain.

Diapirism related to igneous intrusion is relevant to the disruptive scenario for igneous intrusion. Because of the stress regime at Yucca Mountain, an igneous event is most likely to be in the form of a dike(BSC 2003 [DIRS 169989], Section 6.1). Dikes would be oriented subparallel to the direction of existing groundwater flow and faults and fractures (and, therefore, have minimal effect on groundwater flow systems), as opposed to significant vertical changes due to uplift or doming events related to igneous-induced diapirism. By way of corroboration, Smith et al.

(1998 [DIRS 118967], p. 155) point out that extension is accommodated in the upper crust by intrusion of vertical dikes perpendicular to the extension direction, with surface deformation possibly including open fissures, monoclines, normal faults, and grabens, and with surface uplift being approximately a few meters (Smith et al. 1998 [DIRS 118967], Figure 2). Therefore, the igneous aspect of diapirism is excluded based on low consequence. The potential for hydrologic response to igneous activity is more fully evaluated in the FEP 1.2.10.02.0A (Hydrologic response to igneous activity), which is shared by multiple FEPs AMRs.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.4.5 Meteorite Impact (1.5.01.01.0A)

FEP Description: Meteorite impact close to the repository site might disturb or remove rock so that radionuclide transport to the surface is accelerated. Possible effects include alteration of flow patterns (faults, fractures), changes in rock stress, cratering, and exhumation of waste.

Screening Decision: Excluded – Low Probability and Low Consequence

Screening Argument: "Meteorite impact" is excluded from the TSPA–LA based on low probability and low consequence.

The FEP analysis depends on the probability of occurrence of various size impact craters, the area and relative dimensions of the repository footprint, and the depth of the repository below the ground surface. The probability of an impact crater of a given size occurring directly over or adjacent to the repository depends on the total flux of meteorites to the earth surface and the repository footprint area (or target area). The size of the crater of interest is determined by the depth from ground surface to the top of the repository, the depth of any intervening geologic layers of particular interest due to their physical or hydrologic properties, and the spatial relationship of crater diameter to the associated exhumation depth and fracture depth. The annualized probability threshold for consideration is 10^{-8} (Assumption 5.1).

Detailed probability calculations, and a thorough discussion of meteorite impact probability and cratering information provide the technical basis for exclusion. These calculations and related detailed discussion are provided in Appendix D. The analysis is based on direct input for meteorite characteristics and cratering statistics, all of which were taken from published literature (Appendix B).

The initial evaluation indicated that only simple cratering effects needed to be considered, due to the low probability of large crater diameters associated with complex cratering (Grieve 1987 [DIRS 135254], p. 249; Grieve et al. 1995 [DIRS 135260], p. 184; Wuschke et al. 1995 [DIRS 129326], p. 3). The relationship of energy release, crater diameter, and the spatial relationship of crater diameter to extent and depth of cratering effects was derived from a variety of sources, including: Dence et al. (1977 [DIRS 135253], pp. 250 and 261 to 264), Grieve (1998 [DIRS 163385], p. 113 and Figure 3), and Wuschke et al. (1995 [DIRS 129326], p. 3 and

Figure 1). Cratering rate distributions for the repository area were developed based on distributions and equations presented by Grieve (1987 [DIRS 135254], pp. 249, 257, and Figure 8) and Wuschke et al. (1995 [DIRS 129326], pp. 4 and 26). Meteorite flux mass and size information was derived from Ceplecha (1992 [DIRS 135242], p. 362 and Figure 1), and these data were further refined by type of material and related densities (Ceplecha 1994 [DIRS 135243], p. 967, Tables 1, 3, and 4, Figure 2; Shoemaker 1983 [DIRS 135308], pp. 464 and 480). This was coupled with other data (Hills and Goda 1993 [DIRS 135281], pp. 1140 and 1142, Figures 9, 16, 17, and 18) to translate initial meteor radius to resulting crater radius and other effects to produce a distribution of crater diameters based on meteoroid flux to earth.

These calculations are also based on a minimum depth to the repository of approximately 200 m (656 feet). The overburden thickness from the emplacement area to the topographic surface is 215 m (705 feet) (BSC 2004 [DIRS 164519]). A depth of 200 m (656 feet) is used in the calculation to provide a small margin of conservatism. Also of interest is the minimum depth to a key geohydrologic unit, the Paintbrush non-wleded tuff. In the easternmost portion of the repository, the depth of the unit is approximately 60 m (196 feet) (Appendix D). This unit, however, is considerably deeper over the remainder of the repository due to topographic changes to the west. The unit outcrops west of the ridgeline of Yucca Mountain, but at a location not overlying the repository footprint.

This FEP is excluded based on low probability for exhumation and fracturing to repository depth and based on low consequence for increased infiltration in the UZ that could result from a meteorite impact in the repository area or outcrop area adjacent to the waste emplacement area. Based on the TSPA-LA footprint design and using conservative assumptions for meteor entry velocity, the crater diameter (i.e., 20 to 80 m or 65 to 262 feet) that corresponds to the 10^{-8} annualized exceedance probability is of insufficient size to exhume waste or produce a crater with fractures that reach the repository depth (Appendix D). Larger crater diameters occur less frequently and are of lower probability, and therefore are excluded from the TSPA–LA. Smaller crater diameters occur more frequently, but these are of insufficient size to result in direct exhumation or fracturing to the depth of the repository; therefore, these smaller craters are excluded for exhumation and fracturing to repository depth based on low consequence.

Groundwater movement through specific rock units differ based on hydrogeologic properties of the rock units (BSC 2004 [DIRS 169861], Sections 6.1.2 and 6.2.2). Water that infiltrates into the Tiva Canyon welded unit can be transported rapidly through fractures as deep as the underlying Paintbrush nonwelded unit. Due to high porosity and low fracture density, the Paintbrush unit tends to slow and divert the downward velocity of water flow compared to highly fractured units such as the Tiva Canyon unit. However, isotopic analysis of ^{36}Cl has identified isolated pathways that provide relatively rapid water movement for small amounts of water through the Paintbrush nonwelded unit to the top of the underlying Topopah Spring welded unit. Due to increased fracturing in the Topopah Spring welded unit, water has the potential to travel more rapidly through the unit. Consequently, fracturing of the geologic units above the repository is of concern from the standpoint of altering flow paths because increased fracturing of the Paintbrush nonwelded unit could result in increased downward groundwater flux.

Particular zones of interest include the Pah Canyon and Topopah Spring subzones of the Paintbrush nonwelded tuff. For this analysis, the depths of these units were obtained from MO0004QGFMPICK.000 (DIRS 152554) based on borehole locations within the repository area (BSC 2004 [DIRS 170029], Figure 6-1). Depths are presented provided in Appendix D. The Paintbrush unit is present across the repository footprint and, generally, at depths substantially greater than 60 m at locations overlying the repository footprint. However, in the extreme eastern portion of the repository, the top of this unit can be at a depth of less than 60 m, and it outcrops to the west of the repository.

Appendix D provides four similar probability curves (based on multiple sources) in the two figures, Figures D-7 (for the TSPA-LA emplacement area only) and Figure D-8 (for the Paintbrush nonwelded unit outcrop area). Similar curves are provided for corroborative purposes on Figures D-9 and D-10 for the TSPA-LA siting area and TSPA-SR repository footprint area The curves in the figures are based in part on the modeling results given in Hills and Goda (1993 [DIRS 135281], pp. 1140 and 1142, Figures 16 and 17). On each figure, one of the curves represents the annualized exceedance probability for crater diameters resulting from the largest meteorite fragment stemming from a meteor with an atmospheric entry velocity of 15 km/sec and a vertical atmospheric entry angle. Increased entry velocities and angles tend to dissipate more energy and mass into the atmosphere and thus result in decreased crater diameters, as explained in Appendix D. A distribution of entry velocities and angles is likely the reality, but the distribution of velocity and entry angles is currently not quantifiable. Therefore, an entry velocity of 15 km/sec and vertical entry angle are conservative and used as the basis for the FEP evaluation. The curve for an entry velocity of 15 km/sec indicates resulting crater diameters of about 80 m (262 feet) at the threshold probability, and smaller crater diameters at greater probability.

The degree of conservatism in using a curve for an entry velocity of 15 km/sec and the largest resulting fragment can be qualitatively assessed by examining the remaining curves on Figure D-7. The remaining curves are for an atmospheric entry velocity of 20 km/sec; the Grieve's curve (1987 [DIRS 135254]) and the Wuschke et al. curve (1995 [DIRS 129326]) are based on observed earth cratering diameter distributions. The curves indicate that cratering diameters ranging from 20 to 60 m (66 to 197 feet) occur at the threshold probability.

The induced fracture depth from an 80-m (262-feet) diameter cratering event (i.e., a conservative estimate of the largest crater likely at the threshold probability of 10^{-8} events per year) would extend no deeper than about 60 meters (197 feet) based on fracture depth to crater diameter ratio of 0.76, which is discussed in Appendix D. More realistic crater diameters of 20 to 60 m (66 to 197 feet) suggest extended fracturing to depths of 45 m (148 feet) or less. Depths of less than 60 m (197 feet) would be of low consequence to inflow because they are too shallow to fracture the top of the units of interest. More frequent, but smaller diameter cratering events would correspondingly result in shallower fracturing depths. For most of the TSPA-LA repository footprint, the fracturing of the Paintbrush nonwelded unit can therefore, be excluded based on low probability because the probability of fracturing to depths of 60 m (197 feet) or greater (i.e., to the top of the unit) is less than 10^{-8} per year.

For the easternmost portion of the repository, where the units of interest are shallower, the effects of meteorite impact are excluded on low consequence. As long as the consequences associated with 80-m-diameter or smaller craters (that is, the effects from a crater diameter occurring at an annualized exceedance probability equal to or greater than 10^{-8}) are insignificant, this FEP can be excluded based on low consequence. To that end, an 80-m diameter crater encompasses an area of about 0.005 km^2 compared to the total repository area (14 km^2) used for the basis of the probability calculation, or approximately 0.04 percent of the land surface above the repository, with more frequent but smaller crater diameters encompassing lesser areas. Additionally, the smallest model grid block in the eastern part of the repository encompasses an area of approximately 0.01 km^2 (BSC 2004 [DIRS 169861], Figure 6.1-1). Thus, the diameter of the meteorite crater coincident with a 10^{-8} annualized exceedance probability encompasses about one-half of a model grid block. Because only the eastern portion of the repository site is subject to such effects, because the curve for an entry velocity of 15 km/sec is a conservative assumption with regard to entry velocity and angle, and because of the minimal land surface affected (particularly as modeled for UZ flow), it is concluded that additional fracturing from meteorite impact occurring at an annual exceedance probability of 10^{-8} or greater would not significantly alter the modeled UZ flow conditions used for TSPA-LA. More frequent, but smaller-diameter cratering events would result in shallower fracturing depths. Because the depths do not extend to the top of the geologic units of interest, the more frequent events are also excluded based on low consequence.

At an annualized probability of 10^{-8}, the corresponding crater diameter resulting from impact of the largest meteor fragment is likely to range from about 0.02 km to about 0.08 km (20 to 80 m [66 to 262 feet]) (Appendix D). The radius of the associated debris swarm (i.e., the degree of scatter of all fragments, but with lesser cratering effects, if any, than the largest fragment) is about 0.4 to 0.5 km for a meteorite causing an 80-m (262-feet) diameter crater (Hills and Goda 1993 [DIRS 135281], Figure 9). This suggests a debris field with a total encompassing cratering area of approximately 0.5 to 0.8 km^2, but with a pock-marked surface where some portion of the area is affected, and some portion is not, depending on the number and size of fragments. Furthermore, some of the debris field may fall beyond the repository area, and many of the craters would be too shallow to significantly affect infiltration. Such an event would only be of concern for the easternmost portions of the repository because of the shallower depth of the units of concern. At most, consideration of a 0.5 to 0.8 km^2 debris field or crater field, if totally encompassed within the repository footprint, would involve no more than 4 to 6 percent of the 14 km^2 surface area, or an equivalent of 50 to 80 of the more than 2,000 surface grid blocks (BSC 2004 [DIRS 169861], Figure 6.1-1) used for the UZ infiltration modeling. This suggests that an argument for exclusion based on low consequence is appropriate, even if the entire debris field and crater field, rather than just the crater resulting from the largest fragment, is considered.

Fracturing of the Paintbrush nonwelded unit above the repository is, therefore, excluded in part on low probability (for crater diameters larger than 80-m-diameter for most of the repository) and in part based on low consequence (for the easternmost portion of the repository and for crater diameters occurring with probability greater than the threshold probability).

With regard to the Paintbrush hydrologic unit outcrop area on the western edge of the repository area, the probability threshold (Figure D-9) indicates that resulting crater diameters from the largest fragment at the threshold probability would be less than 0.02 km (20 m or 66 ft). This decreased diameter at the threshold probability is due to the decrease in target area of the outcrop compared to that of the repository footprint. A 0.02-km diameter represents a surface area of about 0.0003 km^2, or less than 0.002 percent, of the repository surface area and much less than a single UZ model grid block. With regard to a debris field, the width (i.e., the narrow dimension) of the outcrop area is no greater than 0.1 km, thus limiting the affected outcrop area to no more than 0.03 km^2 as an upper bound for an event of any size. This would represent about 0.2 percent of the repository surface area used for the calculation. Accordingly, meteorite impact in the outcrop area can also be excluded based on low consequence.

Meteors that result in crater diameters of 80-m (corresponding with the threshold annual probability of 10^{-8}) could trigger earthquakes with magnitudes ranging from Magnitude 5 to slightly less than Magnitude 7 (Hills and Goda 1993 [DIRS 135281], Figure 18). Existing seismic analyses cover this range of magnitude (CRWMS M&O 1998 [DIRS 103731], Section 4). Therefore, a meteorite-caused earthquake is excluded based on low consequence because it would not provide a significant contribution to the earthquake hazard. Earthquake hazards are already included and probabilistically weighted in the TSPA-LA. The effects of changes in rock stress, such as those caused by seismic activity, are addressed in multiple FEP AMRs for FEPs 2.2.06.01.0A (Seismic activity changes porosity and permeability of rock); 2.2.06.02.0A (Seismic activity changes porosity and permeability of faults); and 2.2.06.02.0B (Seismic activity changes porosity and permeability of fractures).

Given that the FEP screening addresses postclosure issues, the effects of a near-surface explosion associated with a meteorite are also excluded based on low consequence because above-surface effects are not of concern for the subsurface postclosure repository.

Because infiltration is not significantly affected and no fracturing or exhumation occurs down to the repository depth, there is no mechanism for the meteorite impact at the threshold annual probability or greater to affect groundwater flux through the repository horizon. Therefore, the dose and radionuclide release of radionuclides are not significantly changed. The hydrology aspects of the FEP, therefore, are excluded from the TSPA–LA based on low consequence.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.4.6 Extraterrestrial Events (1.5.01.02.0A)

FEP Description: Extraterrestrial events (e.g., supernova, solar flare, gamma-ray burster, alien life forms) may affect long-term performance of the disposal system.

Screening Decision: Excluded – Low Consequence

Screening Argument: “Extraterrestrial events” are excluded from the TSPA–LA based on low consequence because the only identified mechanisms for affecting the repository (climate change and, hypothetically, microbial activity) are currently addressed in the TSPA-LA evaluation.

Potential mechanisms linking the effect of extraterrestrial events to changes in behavior of engineered and natural systems of an underground repository are not well documented in the scientific literature. In the absence of reputable published work identifying specific mechanisms, evaluating the effect of such events on the postclosure repository performance requires speculation and conceptualization of possible linkages between the event and repository performance.

In studies of the potential effects of Late Quaternary-Age supernova on the terrestrial paleoenvironment, over 120 radio-emitting galactic supernova remnants were cataloged (Brakenridge 1981 [DIRS 167873]). Using a value of 120 events in the past 15,000 years suggests a rate of approximately one event per 100 years. The largest of these peak fluxes was for the Vela supernova, which was calculated to have a peak flux of about 40,000 ergs/cm^2. Supernova events release on the order of 10^{49} to 10^{50} ergs of gamma radiation, and Brackenridge asserts that such an event has the potential to cause ozone depletion in the atmosphere for two to six years and can create nitrogen-rich environments at the surface of the earth (Brakenridge 1981 [DIRS 167873]). Observable effects are suggested to include kerogen rich sediments at 11 sites worldwide. Short-term terrestrial effects (i.e., on the scale of 1,000 years), speculatively, would have included global cooling. Brackenridge asserts that such events could result in increased ultraviolet-light penetration due to ozone layer depletion, increasing ultraviolet-light intensity by as much as 2 to 10 times the present level (Brakenridge 1981 [DIRS 167873]). Aside from potential effects on ^{14}C dating, no other effects are discussed, and no subsurface effects are mentioned. This work is corroborated with regard to nitrogen enrichment and ozone depletion (Ruderman 1974 [DIRS 167875]) and climate linkage (Arnold 2003 [DIRS 167638]; Novotna and Vitek 1991 [DIRS 167634], p. 35). The frequency and energy release is corroborated by Karam (2002 [DIRS 167872]), who also addresses the effects of gamma ray bursters and calculates doses for supernovae and gamma ray bursters. Karam (2002 [DIRS 167872]) also substantiates the lack of subsurface effects due to shielding and indicates that there is a 10^{-8} reduction in "typical dose" within the top 20 mm of rock (Karam 2002 [DIRS 167872], Table 1).

Solar-related effects and correlation to changes in natural systems on earth are summarized in a conceptual statement by Lean (1997 [DIRS 167639]): "Numerous associations are evident between solar variability and terrestrial parameters that range from the Earth's surface to hundreds of kilometers above it, on the time scales from days to centuries." In particular, Lean (1997 [DIRS 167639]) points out the decadal cycles in sun activity are evident in temperatures at the earth surface and through the atmosphere. Lean (1997 [DIRS 167639]) also indicates that there is an apparent association of surface temperature with overall solar activity, but it is unclear whether variable solar radiation is responsible. According to Lean (1997 [DIRS 167639]), least certain is the extent to which tenths-percent changes in visible and infrared radiation modify global surface temperature and climate. There is a current inability to adequately quantify all climate and ozone forcings, which adds ambiguities to assessments of global change (Lean 1997 [DIRS 167639], pp. 33 to 67).

Some of the listed examples of extraterrestrial events (supernovae, solar flares, gamma-ray bursters) are credible and could result in an influx of solar radiation, space radiation, or cosmic rays onto the magnetosphere. Collectively, this can be referred to as "space weather." Maynard (1995 [DIRS 160888]), in discussing the uses of "space weather" prediction, which is primarily focused on solar effects, lists several existing and potential customers and the basis of their need for such information. The discussion of the type of operations affected and the problems encountered includes spacecraft operations, satellite operations, GPS-locating operations (which are satellite based), space object tracking, over-the-horizon radar operations, high frequency communications, telecommunications such as transatlantic fiber optic communications, geomagnetically induced currents in power transmission lines and transformers, applied direct currents for pipeline corrosion mitigation, and semi-conductor manufacturing (likely related to power line fluctuations). This list of systems is corroborated by Lean (2001 [DIRS 167639], pp. 57 to 61) and Cole (2003 [DIRS 167641], pp. 299 to 301). While these effects may be pertinent during operation of the repository or performance confirmation activities, they are unlikely to directly affect long-term performance of the postclosure repository.

The effect of such past events is assumed (Assumption 5.3) to be reflected through the range of climatic properties, which were determined from field studies and observations that are included in the TSPA-LA. Because the existing data set includes the range of effects that have occurred in the past, the effects of future changes would be no greater than those already considered, and therefore, the initiating extraterrestrial events are considered to be of low consequence and are excluded.

This FEP definition also includes the potential effects of alien life forms. Aside from the hypothetical potential for microbial influx via meteorites, the presence of alien life forms has not been verified or documented in the scientific literature, is considered to be overly speculative, and is not further evaluated. The potential for effects from alien life forms (other than microbial activity) is judged to be of low probability (not credible) based on the absence of verification of any such life forms in the scientific literature. If the extraterrestrial transfer of microbes is presumed, then introduction into the repository could be postulated, although assumptions of stoichiometry would be speculative. However, terrestrial microbial effects on the cladding, waste package, and drip shield are considered under a separate set of FEPs (2.1.02.14.0A, 2.1.03.05.0A, 2.1.03.05.0B), and are assumed equivalent to potential extraterrestrial effects. As a result, the introduction of extraterrestrial microbes is excluded based on low consequence.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.4.7 Changes in the Earth's Magnetic Field (1.5.03.01.0A)

FEP Description: Changes in the earth's magnetic field could affect the long-term performance of the repository.

Screening Decision: Excluded – Low Consequence

Screening Argument: "Changes in the earth's magnetic field" is excluded from the TSPA–LA based on low consequence because no effect on the repository can be identified.

Changes and fluctuations in the earth's magnetic field are relatively common in geologic history. During the last 20 million years, the geomagnetic record shows at least 60 reversals, and the periodicity of the reversal is on the scale of a few hundred thousand years (Odenwald 2003

[DIRS 160892]). There has been a decrease in the earth's magnetic intensity in the last few thousand years, and there is some evidence that a reversal may occur sometime during the next few to several thousand years (Odenwald 2003 [DIRS 160892]). The frequency of pole reversals, and the variation in field intensity with time, is corroborated by Biggin and Thomas (2003 [DIRS 167876], Figure 11) and Hoffman (1995 [DIRS 160891]). This suggests that this FEP, while unlikely, cannot be excluded based on low probability (Assumption 5.1).

The potential mechanisms to link the effects of magnetic field changes to changes in behavior of engineered and natural systems are not well documented in the scientific literature. In the absence of reputable published work identifying specific mechanisms, evaluating the effect of changes on the postclosure repository performance requires speculation and conceptualization of possible linkages between the event and repository performance.

From an operational and performance confirmation standpoint, difficulties with location positioning, communications, and electrical circuitry could be affected, but the timeframe of any reversal is well beyond the operational period. Odenwald (2003 [DIRS 160892]) indicates that there are no identifiable fossil mutations or extinctions associated with the previous reversals. No corroborating information regarding the possible effects of a pole reversal or intensity fluctuations was found in the literature search. Only two linkages to natural systems on earth were found. Pechala (1985 [DIRS 167633], p. 406) discusses the linkage between the magnetic field and tropospheric circulation, and indicates that some authors use the relationship as a basis for explaining past changes in climate. Biggin and Thomas (2003 [DIRS 167876], pp. 409 to 412) suggest that changes in the magnetic field result from global-scale tectonic processes such as slab subduction and mantel processes.

Among the longer-term possible effects of changes in the magnetic field, only climate change has a reasonable possibility of affecting the repository. This hypothetically occurs through the complex coupling of the thermosphere, ionosphere, and magnetosphere (Pechala 1985 [DIRS 167633]). However, no clear evidence exists that long-term climate change is connected with magnetic reversals, and, therefore, no basis exists for evaluating the range of possible future effects. As noted, changes in the magnetic field are common in geologic history. The effect of such past events is assumed (Assumption 5.3) to be reflected in the range of climatic properties, determined from field studies and observations, and such changes are included in the TSPA-LA. Because the existing data set includes the range of effects that have occurred in the past, the effects of future changes would presumably be no greater than those already considered, and therefore, they are of low consequence.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.4.8 Earth Tides (1.5.03.02.0A)

FEP Description: Small changes of the gravitational field due to celestial movements (sun and moon) cause earth tides and may, in turn, cause pressure variations in the groundwater flow systems.

Screening Decision: Excluded – Low Consequence

Screening Argument: "Earth tides" is excluded from the TSPA–LA based on low consequence because the magnitude of water level fluctuations is insignificant and effects are implicit in existing water level records.

Earth tides are an ongoing phenomenon and are reflected as rhythmic, measurable pressure increases and decreases. At Yucca Mountain, the magnitude of the effect on water levels is on the order of centimeters. Earth tide fluctuations in borehole UE-25 p#1 are cited in non-YMP sources, and indicate a fluctuation of 2.05 cm (Bredehoeft 1987 [DIRS 100007], p. 2460). This is corroborated by water levels in boreholes at Paiute Mesa (on the Nevada Test Site). These water levels were analyzed for earth tide effects and the fluctuation due to earth tides was on the order of several hundredths of a foot (Fenelon 2000 [DIRS 160881], p. 14). Consequently, individual fluctuations are of low magnitude. Additional corroboration is from Kies et al. (1999 [DIRS 160882]) who state: "tidal forces deform the earth; effects induced on fluids near the surface of the earth are documented by the observations of water level changes in wells. These changes are driven by alterations of the pore pressure induced by tidal deformation of porous and fluid-saturated crustal material." These pressure changes can result in related effects such as fluctuations in underground gas concentrations (Kies et al. 1999 [DIRS 160882]) and water level fluctuation in wells (Fenelon 2000 [DIRS 160881], p. 14). As noted by Kies et al. (1999 [DIRS 160882]), the strain variations induced by earth tides are small (less than on the order of 10^{-8}), and their appearances are periodic and of known magnitude. Therefore, any significant cumulative effects of earth tides are reflected in the existing data for the hydrogeologic system (Assumption 5.3). Earth tides are of such a small magnitude that any effect on the flow system is of low consequence because the fluctuations are accounted for in the water level data used as the basis for the TSPA.

TSPA Disposition: Not Applicable

Supporting AMRs: None

6.2.4.9 Salt Creep (2.2.06.05.0A)

FEP Description: Salt creep may lead to changes in the stress field, compaction of the waste packages, and consolidation of the long-term components of the sealing system.

Screening Decision: Excluded – By Regulation

Screening Argument: "Salt creep" is excluded from the TSPA–LA based on regulatory requirements to consider data that are related to the geology of the site. Large volume salt and evaporite deposits are not present near the repository and, therefore, are not related to the geology of the site.

The geologic setting is defined as (10 CFR 63.2 [DIRS 156605]): "the geologic, hydrologic, and geochemical systems of the region in which the geologic repository is or may be located." Consideration of this FEP is outside the scope and intent stated at 10 CFR 63.21(c)(1) (DIRS 156605), which specifies consideration and description of "features, events, and processes outside of the site to the extent the information is relevant and material to safety or performance of the geologic repository." Furthermore, at 10 CFR 63.114(a) and 10 CFR 63.115(a) (DIRS 156605), the regulatory requirements are to "include data that are related to the geology, hydrology, and geochemistry (including disruptive events) of the Yucca Mountain Site, and the surrounding region to the extent necessary …". The regulation further requires the project to "identify … natural features of the geologic setting that are considered barriers important to waste isolation." At 10 CFR 63.305(c) (DIRS 156605), DOE is directed to "…vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system over the next 10,000 years."

Evaporite deposits of sufficient volume to result in salt creep have not been reported near Yucca Mountain. Rather, Yucca Mountain is located in the southwestern Nevada volcanic field and consists of tilted fault blocks composed of layered sequences of ash flow, ash-fall, and bedded tuffs of Miocene age (BSC 2004 [DIRS 170029], Sections 6 and 6.5.1.4 and Table 6-2). This is corroborated by BSC (2004 [DIRS 169734], Section 3.3.4) and Day et al. (1998 [DIRS 100027]). Voluminous evaporite deposits do not exist near Yucca Mountain, and the repository is not planned for a salt dome or cavern. This feature and related process of salt creep are, therefore, inconsistent with the present knowledge of the geologic setting for Yucca Mountain. There are no rocks in the repository that are sufficiently plastic to creep in a manner similar to salt. Salt creep, therefore, is excluded based on regulations.

TSPA Disposition:	Not Applicable
Supporting AMRs:	None

6.2.4.10 Effects of Repository Heat on the Biosphere (2.3.13.03.0A)

FEP Description:	Heat released from radioactive decay of the waste may increase the temperatures at the surface above the repository. This could result in local or extensive changes in the ecological characteristics.
Screening Decision:	Excluded – By Regulation and Low Consequence
Screening Argument:	"Effect of repository heat on the biosphere" is excluded from the TSPA–LA based on regulation and low consequence because the regulations preclude consideration of changes in flora and fauna and any such changes would likely have minimal impact on infiltration rates.

The FEP description does not specify how a change in ecological factors at the ground surface might affect the performance of a repository located 200 m (656 feet) below ground surface. One feasible conceptual mechanism might be a change in infiltration due to a change in plant species. The effects of repository heat on the biosphere are summarized in the FEIS (DOE 2002 [DIRS 155970], Section 5.9 and p. 5-41) based on work chiefly related to concerns with transition from perennial to annual plant species (CRWMS M&O 1999 [DIRS 105031], p. 46). However, at 10 CFR 63.305(b) (DIRS 156605), the NRC states that:

> DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all the analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of submission of the license application.

The definition of reference biosphere at 10 CFR 63.2 (DIRS 156605) specifically identifies flora as being a component of the reference biosphere.

> Reference biosphere means the description of the environment inhabited by the reasonably maximally exposed individual. The reference biosphere comprises the set of specific biotic and abiotic characteristics of the environment, including, but not necessarily limited to, climate, topography, soils, flora, fauna, and human activities.

By implication, the DOE should not project changes in the biosphere (more specifically, flora) and must assume that the flora remains constant. Therefore, the effects of repository heat on the biosphere are excluded based on regulation. More strictly interpreted, these regulatory provisions would only apply strictly to the reference biosphere and not to the repository area. The effect of repository heat on the geosphere is addressed in FEP 2.2.10.12.0A (Geosphere dryout due to waste heat). The effects of climate change (FEP 1.3.01.00.0A) also are addressed separately.

Furthermore, changes in infiltration due to changes in ecological factors are expected to be small in comparison to differences in infiltration resulting from use of the bounding infiltration cases resulting from changes in climate state, particularly if the ecological factor is primarily a shift in species rather than a shift in entire ecosystems. The range of average infiltration values considered is from 1.25 mm/year for the lower bound for present day climate to as much as 31.69 mm/year for the upper bound of the glacial transition climate (BSC 2004 [DIRS 169861], Table 6.1-2), which is an approximately 25 times increase between the lower bounding case and the upper bounding case used in the TSPA-LA. For the climate states considered, mean infiltration rates range from 4.43 to 17.02 mm/year, or an approximate increase of four times. Climate change and the effects on infiltration are addressed in the TSPA-LA as outlined in the *Total System Performance Assessment-License Application Methods and Approach* (BSC 2003 [DIRS 166296], Section 5.1), and infiltration rates include consideration of upper-bound, mean, and lower-bound rates. This FEP may also be excluded based on low consequence because the resulting change in infiltration rates are likely to be less than the range in infiltration rates due to climate changes that are already considered. This is because the shift in species would be transient, and would potentially reverse as the repository cooled with time. This is corroborated by pre-1998 studies indicating that resulting temperature changes are within the adaptive range of some plant species now at Yucca Mountain (CRWMS M&O 1999 [DIRS 105031], Figure 8 and p. 41).

By way of corroborating the exclusion of this FEP, a potential effect of the repository heat is a shift in species at the surface, which could conceivably change the water infiltration rate. However, changes in infiltration rates are potentially affected by a number of factors (e.g., increases and decreases in vegetation and vegetation type, climate changes, slope, aspect, total precipitation, air temperature, runoff, solar heating, and characteristics of the soil matrix). The degree of the change in species due to change in temperature is discussed in *Final Report: Plant and Soil Related Processes along a Natural Thermal Gradient at Yucca Mountain, Nevada* (CRWMS M&O 1999 [DIRS 105031]) and is used as the basis for this corroborative argument and is as follows.

During active transpiration periods, shrubs removed about 31 percent of the total precipitation that fell during the period studied (with a range of 12 to 54 percent at the seven study locations having a full range of plant species) (CRWMS M&O 1999 [DIRS 105031], Executive Summary), and total shrub cover at the sites ranged from about 8 to 16 percent (CRWMS M&O 1999 [DIRS 105031], Figure 9). An analysis of percent cover of shrubs and of soil temperature at a depth of 45 cm suggests that for each 1°C increase in temperature, the percent cover of shrubs decreases by 1.2 percent and that the percent cover of annual grasses increases 5.5 percent (CRWMS M&O 1999 [DIRS 105031], Section 3.3). The percent cover of the only grass species currently found at each of the study sites (*Bromus rubens*) increased by 2.3 percent with every 1ºC increase in temperature. The results of various analyses of the effects of repository heat on the near-surface soil layer of the biosphere are presented in the FEIS (DOE 2002 [DIRS 155970], Table 5-15 and p. 5-41). These results predict that the soil temperature near the root zone of the shrub increases by a maximum of 0.4°C in wet soils and 3°C in dry soils. Further, they predict that at a soil depth of 2 m (7 feet), the soil temperature can increase by a maximum of 0.8°C in wet soils and 6°C in dry soils. Consequently, the temperature shift of concern can range between 0.4°C and 6°C. The resulting percent cover of shrubs could decrease by about 0.5 percent to 7.2 percent (i.e., 1.2 percent change/°C, multiplied by the temperature change).

As part of this corroborative analysis, these reported values (as shown in Table 6-2) are used to calculate the reduction in evapotranspiration based on existing evapotranspiration, shrub cover, and thermally driven changes in shrub cover. As shown in Table 6-2, dividing the evapotranspiration values (12 to 54 percent) by the range of existing shrub cover (8 to 16 percent) yields a ratio for percent evapotranspiration to percent shrub cover. Multiplying this ratio by the bounding values of the range in percent change in shrub cover (0.5 to 7.2 percent) yields a percent change in evapotranspiration due to potential change in the shrub cover. The reported values and calculations are consolidated in Table 6-2.

Table 6-2. Approximate Percent Change in Evapotranspiration Due to Shift in Plant Species

Percent Evapotranspiration from Shrubs (Range for Existing Conditions	Percent Shrub Cover (Existing)	Percent Evapotranspiration Divided by Percent Shrub Cover	Change in Percent Shrub Cover	Approximate Change in Percent Evapotranspiration
12 (low)	8	1.5	0.5	0.8
31 (mean)	8	3.9	0.5	2.0
54 (high)	16	3.4	0.5	1.7
12 (low)	8	1.5	7.2	11
31 (mean)	16	1.9	7.2	14
54 (high)	16	3.4	7.2	25

This suggests that a shift away from shrub species could result in less than 1 percent to at most a 25-percent decrease in transpiration of total precipitation, and the potential for a similar increase in infiltration due to the loss of shrub cover. These values are conservative in that they do not account for an offsetting contribution to evapotranspiration from the increase in annual grass percentages (i.e., 2.3 percent increase in annual grasses for each 1˚C in temperature). Additionally, the variation in surface soil temperatures at Yucca Mountain that are caused by elevation, slope, aspect, and other natural attributes suggest that soil temperature increases of the magnitude predicted are probably within the adaptive range of some plant species now at Yucca Mountain (CRWMS M&O 1999 [DIRS 105031], Figure 8 and p. 41). Thus, increases in infiltration likely would be less than those stated.

TSPA Disposition: Not Applicable

Supporting AMRs: None

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7. CONCLUSIONS

The system-level FEP screening decisions, and the basis for the Exclude decisions, are summarized in Table 7-1.

Table 7-1. Summary of System-Level FEP Screening Decisions

FEP Number	FEP Name	Screening Decision	Decisions Basis for Exclude	Addressed in Section
0.1.02.00.0A	Timescales of concern	Included	—	6.2.1.1[a]
0.1.03.00.0A	Spatial domain of concern	Included	—	6.2.1.2[a]
0.1.09.00.0A	Regulatory requirements and exclusions	Included	—	6.2.1.3[a]
0.1.10.00.0A	Model and data Issues	Included	—	6.2.1.4[a]
1.1.05.00.0A	Records and markers for the repository	Excluded	By Regulation	6.2.2.1[b]
1.1.07.00.0A	Repository design	Included	—	6.2.1.5[a]
1.1.08.00.0A	Inadequate quality control and deviations from design	Excluded	Low Consequence	6.2.2.2[b]
1.1.09.00.0A	Schedule and planning	Excluded	By Regulation	6.2.2.3[b]
1.1.10.00.0A	Administrative control of the repository site	Excluded	By Regulation	6.2.2.4[b]
1.1.11.00.0A	Monitoring of the repository	Excluded	Low Consequence	6.2.2.5[b]
1.1.12.01.0A	Accidents and unplanned events during construction and operation	Excluded	Low Consequence	6.2.2.6[b]
1.1.13.00.0A	Retrievability	Included	—	6.2.1.6[a]
1.2.05.00.0A	Metamorphism	Excluded	Low Probability Low Consequence	6.2.4.1[d]
1.2.08.00.0A	Diagenesis	Excluded	Low Consequence	6.2.4.2[d]
1.2.09.00.0A	Salt diapirism and dissolution	Excluded	By Regulation	6.2.4.3[d]
1.2.09.01.0A	Diapirism	Excluded	By Regulation	6.2.4.4[d]
1.4.02.01.0A	Deliberate human intrusion	Excluded	By Regulation	6.2.3.1[c]
1.4.02.02.0A	Inadvertent human intrusion	Excluded	By Regulation	6.2.3.2[c]
1.4.02.03.0A	Igneous event precedes human intrusion	Excluded	By Regulation	6.2.3.3[c]
1.4.02.04.0A	Seismic event precedes human intrusion	Excluded	Low Consequence By Regulation	6.2.3.4[c]
1.4.03.00.0A	Unintrusive site investigation	Excluded	Low Consequence By Regulation	6.2.3.5[c]
1.4.04.00.0A	Drilling activities (human intrusion)	Excluded	By Regulation	6.2.3.6[c]
1.4.04.01.0A	Effects of drilling intrusion	Excluded	By Regulation	6.2.3.7[c]
1.4.05.00.0A	Mining and other underground activities (human intrusion)	Excluded	By Regulation	6.2.3.8[c]
1.4.11.00.0A	Explosions and crashes (human activities)	Excluded	By Regulation Low Consequence	6.2.3.9[c]
1.5.01.01.0A	Meteorite impact	Excluded	Low Probability Low Consequence	6.2.4.5[d]
1.5.01.02.0A	Extraterrestrial events	Excluded	Low Consequence	6.2.4.6[d]

Table 7-1. Summary of System-Level FEP Screening Decisions (Continued)

FEP Number	FEP Name	Screening Decision	Decisions Basis for Exclude	Addressed in Section
1.5.03.01.0A	Changes in the earth's magnetic field	Excluded	Low Consequence	6.2.4.7[d]
1.5.03.02.0A	Earth tides	Excluded	Low Consequence	6.2.4.8[d]
2.1.01.04.0A	Repository-scale spatial heterogeneity of emplaced waste	Included	—	6.2.1.7[a]
2.2.06.05.0A	Salt creep	Excluded	By Regulation	6.2.4.9[d]
2.3.13.03.0A	Effects of repository heat on the biosphere	Excluded	By Regulation Low Consequence	6.2.4.10[d]
3.3.06.01.0A	Repository excavation	Excluded	By Regulation Low Consequence	6.2.3.10[c]

[a] Assessment Basis and Modeling Requirement FEPs (Section 6.2.1).
[b] Process and Site Control FEPs (Section 6.2.2).
[c] Human Intrusion FEPs (Section 6.2.3).
[d] Miscellaneous Geologic and Astronomic FEPs (Section 6.2.4).

The conclusions from this document (FEP screening decisions and supporting rationale) are considered "technical product output" with no assigned DTN. The FEP screening decision, TSPA-LA disposition (for included FEPs), or screening argument (for excluded FEPs), and any changes to the FEP name, number, and descriptions, will be incorporated in the Yucca Mountain TSPA-LA FEP database. This database will contain all Yucca Mountain FEPs considered for TSPA-LA with FEP number, name, description, and relevant FEP AMRs where specific FEPs are screened. The FEP database will also document screening decisions (include or exclude), screening arguments, and TSPA dispositions quoted from this and all other FEP AMRs. Documentation of the FEP database will be given in a separate technical (AP-3.11Q) report (BSC 2004 [DIRS 168706]). All FEP information, including the 33 system-level FEPs considered in this report, will be submitted to technical data management system by the Yucca Mountain FEP database team as a final LA FEP DTN. These final data will be qualified as Technical Product Output from the AP-3.11Q report (BSC 2004 [DIRS 168706]). The final FEP DTN will supersede all of the previous DTNs. It will then be citable by any downstream documents, such as the safety analysis report or AMR revisions.

The relevant YMRP Acceptance Criteria and how they are addressed for the system-level FEPs AMR is shown in Table 7-2.

Table 7-2. Relevant YMRP Acceptance Criteria and the System-Level FEPs AMR

YMRP Criterion	Acceptance Criterion	Description	How Addressed in this Analysis Report
Scenario Analysis and Event Probability: Scenario Analysis (from YMRP [DIRS 163274], Section 2.2.1.2.1.3)	1. The Identification of a List of FEPs Is Adequate	The safety analysis report contains a complete list of FEPs related to the geologic setting or the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers), that have the potential to influence repository performance. The list is consistent with the site characterization data. Moreover, the comprehensive features, events, and processes list includes, but is not limited to, potentially disruptive events related to igneous activity (extrusive and intrusive); seismic shaking (high-frequency-low magnitude, and rare large-magnitude events); tectonic evolution (slip on existing faults and formation of new faults); climatic change (change to pluvial conditions); and criticality.	The list of system-level FEPs is presented in Section 1.2, and FEP descriptions are presented in Section 6.2. Description and origin of the system-level FEP list and descriptions are presented in Section 6.1.1. This analysis report does not address disruptive events or climatic change.
	2. Screening of the Initial List of FEPs Is Appropriate	The DOE has identified all FEPs related to either the geologic setting or to the degradation, deterioration, or alteration of engineered barriers (including those processes that would affect the performance of natural barriers) that have been excluded.	The excluded system-level FEPs are listed in Table 7-1.
		The DOE has provided justification for those FEPs that have been excluded. An acceptable justification for excluding FEPs is that either the FEP is specifically excluded by regulation; probability of the FEP (generally an event) falls below the regulatory criterion; or omission of the feature, and process does not significantly change the magnitude and time of the resulting radiological exposures to the RMEI or radionuclide releases to the accessible environment.	See the method and approach discussion provided in Section 6.1.2 and the individual justification (by regulation, low probability, low consequence) for excluding FEPs. The justification is also included in Table 7-1.
		The DOE has provided an adequate technical basis for each FEP, excluded from the performance assessment, to support the conclusion that the FEP is specifically excluded by regulation, the probability of the FEP falls below the regulatory criterion, or omission of the FEP does not significantly change the magnitude and time of the resulting radiological exposures to the RMEI or radionuclide releases to the accessible environment.	The individual FEP screening decisions and supporting technical bases are discussed in Section 6.2.

Table 7-2. Relevant YMRP Acceptance Criteria and the System-Level FEPs AMR (Continued)

YMRP Criterion	Acceptance Criterion	Description	How Addressed in this Analysis Report
Scenario Analysis and Event Probability: Identification of Events with Probability Greater than 10^{-8} per Year (from YMRP [DIRS 163274], Section 2.2.1.2.2.3)	1. Events Are Adequately Defined	Events or event classes are defined without ambiguity and used consistently in probability models, such that probabilities for each event or event class are estimated separately.	See the FEP Description provided for each FEP in Section 6.2 and the cited supporting AMRs.
		Probabilities of intrusive and extrusive igneous events are calculated separately. Definitions of faulting and earthquakes are derived from the historical record, paleoseismic studies, or geological analyses. Criticality events are calculated separately by location.	This analysis report does not address igneous, seismic or criticality FEPs. This criterion is not applicable to this analysis report.
	2. Probability Estimates for Future Events Are Supported by Appropriate Technical Bases.	Probabilities for future natural events are based on past patterns of the natural events in the Yucca Mountain region, considering the likely future conditions and interactions of the natural and engineered repository system. These probability estimates have specifically included igneous events, faulting and seismic events, and criticality events.	Other future naturally occurring events (such as meteorite impact) are addressed in this analysis report. See FEP discussions in Section 6.2.4 for a list of naturally occurring FEPs that are addressed. This analysis report does not address igneous, seismic or criticality FEPs.
	5. Uncertainty in Event Probability Is Adequately Evaluated	Probability values appropriately reflect uncertainties. Specifically: a. The DOE provides a technical basis for probability values used, and the values account for the uncertainty in the probability estimates: and b. The uncertainty for reported probability values adequately reflects the influence of parameter uncertainty on the range of model results (i.e., precision) and the model uncertainty, as it affects the timing and magnitude of past events (i.e., accuracy).	The technical basis and discussion of uncertainties used for exclusion of system-level FEPs are discussed in the subsections of Section 6.2 for the individual FEPs.

Table 7-2. Relevant YMRP Acceptance Criteria and the System-Level FEPs AMR (Continued)

YMRP Criterion	Acceptance Criterion	Description	How Addressed in this Analysis Report
Demonstration of Compliance with Post-closure Public Health and Environmental Standards Demonstration of Compliance with the Human Intrusion Standard (from YMRP [DIRS 163274], Section 2.2.1.4.2.3)	1. Evaluation of the Time of an Intrusion Event	The technical basis and associated analyses adequately support the selection of time of occurrence of human intrusion, as specified at 10 CFR 63.321.	See the technical justification of timing as provided in Appendix C. See Section 6.2.3 for a discussion of human intrusion-related FEPs.
	2. Evaluation of an Intrusion Event Demonstrates that the Annual Dose to the RMEI in Any Year during the Compliance Period Is Acceptable	The TSPA of human intrusion is performed separately from the overall TSPA, and meets the requirements for performance assessments, specified at 10 CFR 63.114.	See the technical justification of timing of earliest occurrence of human intrusion without recognition by the driller, provided in Appendix C. See Section 6.2.3 for a discussion of human intrusion-related-FEPs consistent with the requirements of 10 CFR 63.321 and 10 CFR 63.322. A human intrusion analysis has been provided for a post-10,000 year human intrusion in the final environmental impact statement (FEIS) (DOE 2002 [DIRS 155970], Section 5.7.1).
		The TSPA for human intrusion is identical to the TSPA for individual protection, except that it assumes the occurrence of a postulated human intrusion event with characteristics, as defined at 10 CFR 63.322 and excludes the consideration of unlikely natural FEPs.	
		A sufficient number of realizations [have] been run using the total system performance code, to ensure that the results of the calculations are statistically stable.	
		The estimated repository performance is reasonable and consistent with the analysis of overall repository performance and with the characteristics of the postulated intrusion event.	
		The annual dose curve for limited human intrusion confirms that the repository system meets performance objectives, specified at 10 CFR 63.321, for limited human intrusion events.	

NOTE: The YMRP (NRC 2003 [DIRS 163274], Section 2.2.1.2.2.3) includes two additional criteria regarding the identification of events with probabilities greater than 10^{-8} per year. Acceptance Criteria 3 applies to probability models, which are not used for system-level FEP evaluations and the criterion is, therefore, not applicable. Acceptance Criteria 4 deals with probability model parameters, and is, therefore, not applicable.

The criterion related to identification of Events with Probability Greater than 10^{-8} per Year and for the Human Intrusion standard were identified as applicable during the preparation of this report, and were not previously identified within the techncial work plan. This identification is based on the the results of analysis identifiying that some FEPs have low probabilities, but greater than 10^{-8} per year, and because the justification for excluding human intrusion based on timing of such an event were added to this report in Appendix C.

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40 CFR 197. Protection of Environment: Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada. Readily available. 165519

66 FR 32074. 40 CFR Part 197, Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV; Final Rule. Readily available. 155216

66 FR 55732. Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, NV, Final Rule. 10 CFR Parts 2, 19, 20, 21, 30, 40, 51, 60, 61, 63, 70, 72, 73, and 75. Readily available. 156671

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MO0003RIB00073.000. Physical and Chemical Characteristics of Ti Grades 7 and 16. Submittal date: 03/13/2000. 152926

MO0003RIB00076.000. Physical and Chemical Characteristics of Type 316N Grade. Submittal date: 03/14/2000. 153044

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MO0407SEPFEPLA.000. LA FEP List. Submittal date: 07/20/2004. 170760

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APPENDIX A

GLOSSARY

Alluvial Fan	A cone-shaped deposit of alluvium made by a stream where it runs out onto a level plain or meets a slower stream. The fans generally form where streams issue from mountains upon the lowland.
Annual Exceedance Probability	The probability that a specified value (such as ground motion or fault displacement) will be exceeded during one year.
Asteroid	A small planet with a diameter from a fraction of a mile to nearly 500 miles.
Astronomical Unit	A measure for distance within the solar system equal to the mean distance between earth and sun, that is, about 92,956,000 miles (149,598,000 km).
Bolide	A meteor that show signs of explosion or fragmentation.
Caliche	A calcareous soil component typically forming a friable to hard, off-white, crudely layered interval near the surface of stony desert soils; several cm or more thick; old, thick caliche intervals (calcrete) have the texture and hardness of concrete aggregate.
Colluvial Slope	A hill slope mantled with loose, heterogeneous soil and rock fragments that are the result of weathering and accumulation by creep and unchanneled snowmelt or runoff.
Comet	A celestial body that consists of a fuzzy head usually surrounding a bright nucleus, that often, with the part of its orbit near the sun, develops a long tail which points away from the sun and that has an orbit varying in eccentricity between nearly round and parabolic.
Diagenesis	Processes involving physical and chemical changes in sediment after deposition that convert it to consolidated rock; includes compaction, cementation, recrystallization, and perhaps replacement.
Diapir	A dome or anticlinal fold, the overlying rocks of which have been ruptured by squeezing out of the plastic core material. Diapirs in sedimentary strata usually contain cores of salt or shale. Igneous intrusions may also show diapiric structure.
Dike	A tabular intrusion of magma that is at a high angle to layering in the intruded strata (i.e., vertical or subvertical at Yucca Mountain).

Disruptive Event Scenario Classes The scenario class, or set of related scenario classes, that describes the behavior of the system if perturbed by disruptive events. The disruptive scenario classes contain all disruptive FEPs that have been retained for analysis.

Disruptive FEP An included FEP that has a probability of occurrence during the period of performance less than 1.0 (but greater than the cutoff of $10^{-4}/10^{4}$ year).

Event A natural or human-caused phenomenon that has a potential to affect disposal system performance and that occurs during an interval that is short compared to the period of performance.

Excluded FEP A FEP that is identified by the FEP-screening process as requiring no further analysis in the quantitative TSPA, based on low probability, low consequence, or regulation.

Expected FEP An included FEP that, for the purposes of the TSPA, is assumed to occur with a probability equal to 1.0 during the period of performance.

Faulting Process of fracture and attendant slip along the fracture plane, or recurrent slip along such a plane.

Feature An object, structure, or condition that has a potential to affect disposal system performance.

Fireball A bright meteor with luminosity that equals or exceeds that of the brightest planets (generally magnitude of –3 or brighter).

Folding Formation of folds expressed by geometric features that include fold limbs, fold axes, and axial planes. Large or systematic compressive and drag folds are results of tectonic activity.

Fracture A brittle crack in rock. Groups of fractures in more or less regular orientation and spacing are joints. Fractures form by bending (shear joints) or tension or principal stress reduction (extension joints). Cooling joints are formed by tension exerted by contraction as a volcanic rock cools.

Future A single, deterministic representation of the future state of the system. An essentially infinite set of futures can be imagined for any system.

Gamma Ray Burst	A burst of gamma rays from space lasting from a fraction of a second to many minutes. There is no clear scientific consensus as to their cause or even their distance.
Geodetic Strain Rate	Regional strain rate determined at the earth's surface by repeated measurement of displacements of precisely located landmarks (monuments) embedded in the deforming medium.
Graben	A block, generally long compared to its width, that has been downthrown along faults relative to the rocks on either side.
Gray	A unit of radiation dose equal to 1 joule of energy deposited in 1 kg of tissue or other material. The gray (Gy) is a Systeme International (SI) unit and is equal to 100 rad.
Igneous Activity	Any process associated with the generation, movement, emplacement, or cooling of molten rock within the earth or exterior to the earth's surface.
Included FEP	A FEP that is identified by the FEP screening process as requiring analysis in the quantitative TSPA.
Intrusive Event (with respect to repository performance)	An igneous intrusion (such as a dike, dike system, or other magmatic body in the subsurface) that intersects the repository footprint at the repository elevation.
Metamorphism	Process by which consolidated rocks are altered in composition and texture, or internal structure, by conditions and forces not resulting simply from burial and weight of subsequently accumulated overburden. Pressure, heat, and the introduction of new chemical substances are the principal causes, and the resulting changes, which generally include the development of new minerals, are a thermodynamic response to a greatly altered environment. Diagenesis has been considered to be incipient metamorphism.
Meteor	One of the small particles of matter in the solar system observable directly only when it falls into the earth's atmosphere where friction may cause its temporary incandescence.
Meteorite	A meteor that reaches the surface of the earth without being completely vaporized.
Meteoroid	A meteor particle itself without relation to the phenomena it produces when entering the earth's atmosphere.

Nominal Scenario Class	The scenario class, or set of related scenario classes, that describes the expected or nominal behavior of the system as perturbed only by the presence of the repository. The nominal scenario class contains all expected FEPs that have been retained for analysis.
Nonwelded Unit	A volcanic ash, or tuff, that is crumbly or easily excavated because the component glass shards did not weld together during compaction of relatively cool ash, or ash having relatively sparse glass content.
Paleoseismic Slip	The amount of fault slip indicated by buried offset strata. Individual paleoearthquakes are indicated by discrete amounts of offset.
Potentiometric Surface	A notional surface representing the total head of groundwater as defined by the level at which such water stands in a well. The water table is a particular potentiometric surface.
Process	A natural or human-caused phenomenon that has a potential to affect disposal system performance and that operates during all or a significant part of the period of performance.
Radionuclide	Radioactive type of atom with an unstable nucleus that spontaneously decays, usually emitting ionizing radiation in the process. Radioactive elements are characterized by their atomic mass and atomic number.
Seismic Activity	Seismicity; the recurrence and distribution of earthquakes associated with a specified seismic source.
Strain Rate	The rate at which a unit of length is shortened or lengthened under a stress load, usually given in terms of inverse seconds. Strain rate is often expressed in units of mm/yr where an actual length difference, rather than a ratio, is calculated.
Stylized Analysis	An analysis using specified assumptions and requirements in lieu of speculation on the nature and probability of a subject event.
Supernova	A stellar explosion that takes place late in the life of a massive star.
Tectonic Activity	The dynamic manifestation of stress loads generated within the earth’s crust (e.g., igneous intrusion, earthquakes, uplift).

Tectonic Deformation The suite of geological structures generated by body stresses exerted within the earth's crust; such structures range in scale from microscopic (e.g., mylonite fabric) to regional (e.g., overthrust belts). Also, the process by which such structures together are formed.

Tectonic Extension Stretching or extension of the crust as a result of deep-seated tectonic stress, such as back-arc spreading.

Tectonic Process The dynamic evolution of structure generated through the buildup and relaxation of regional stress.

Tectonism All movement of the crust at small scale produced by tectonic processes, including mountain building (orogeny), regional uplift, and subsidence; the general expression of tectonic processes through time and space.

Water Table The surface of unconfined groundwater at which the pressure is equal to that of the atmosphere.

Welded Unit A volcanic ash, or tuff, that is strongly indurated because hot glass shards partially melted together (welded) during compaction of the ash bed while the ash was still hot.

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APPENDIX B

SUITABILITY DEMONSTRATION FOR DATA FROM OUTSIDE SOURCES USED AS DIRECT INPUTS TO SYSTEM-LEVEL FEPS

B1. INTRODUCTION

This appendix demonstrates the suitability of previously unqualified data for use in Section 6.2 and Appendices C and D of this analysis report. It is not intended as stand-alone documentation separate from the main document. The data justified herein is intended for use only for features, events, and processes (FEPs) screening and, more specifically, for use within this work product.

Data from external sources that do not meet the definition of "Established Fact" have been used as direct input to this document. The inputs from these sources are justified for use in this appendix and are considered qualified for intended use within the document using the criteria found in AP-SIII.9Q, *Scientific Analyses*. Accordingly, these data are assigned a Q status of "qualified" in the project's Document Input Reference System (DIRS) database. The evaluation criteria used for the following justification represent a subset of the methods and attributes required for qualification of data per AP-SIII.2Q, *Qualification of Unqualified Data.* The following information is provided for each source: the full reference citation, a description of the data that were used from the source, and the extent to which the data demonstrate the properties of interest. In addition, one or more of the following criteria is also addressed:

- Reliability of data source
- Qualifications of personnel or organizations generating the data
- Prior uses of the data
- Availability of corroborating data.

The criteria described above meet the requirements of AP-SIII.9Q and are provided as justification that the data that have been used from these sources are considered to be qualified for intended use.

Section B2 of this appendix identifies the direct inputs, Section B3 addresses the methods used to demonstrate suitability, and Section B4 discusses the appropriate criteria. Accordingly, Section B5 provides the evaluation of the data, and contains the discussion wherein the direct inputs are corroborated and shown suitable for use.

B2. DATA SETS FOR USE WITHIN THIS TECHNICAL PRODUCT

The direct inputs being evaluated are identified in Table B-1. The table has been subdivided by FEP or FEP grouping, which will be treated separately within Section B5 of this appendix. Each item in the following table has been assigned an Item designator (Q) to facilitate traceability to the sources and factors tables that appear in Section B5 of this appendix. The tables in Section B5 of this appendix also address the corroborating information in tables presented in Section B5. Corroborating information has been identified in those tables with an Item designator (C), denoting that the item is being used for corroboration.

The source column in Table B-1 provides the citation as it appears in the DIRS database and provides traceability through the Technical Information Center (TIC) number or DIRS numbers. The description column in the Table B-1 provides a brief description of the data being evaluated, by equation number, numeric value, or statement of the concept being used as the direct input. The direct input used in formulating a screening decision is listed along with the originating citation or information is given in normal type immediately below the input. This information is repeated in the last column in the tables in Section B5. The citations provided in Table B-1 also appear within Table 4-5 of the main body of the report. The tables in Section B5 of the main body identify the associated sections of the main body of the report that utilize the input, so that information is not repeated here.

The information used for direct input is also identified in Section 4 of the main body of this document, and supporting references are clearly identified in the various subsections of Section 6.2, as needed to provide the technical basis for exclusion of the FEP.

Table B-1. Data Sets for Use within this Technical Product

Item	Source	Description of Direct Input
Timing of Human Intrusion Analysis		
Q1	Bourgoyne, A.T., Jr.; Millheim, K.K.; Chenevert, M.E.; and Young, F.S., Jr. 1986. "Rotary Drilling Bits." *Applied Drilling Engineering.* SPE Textbook Series Volume 2. Pages 190-245. Richardson, Texas: Society of Petroleum Engineers. TIC: 250085. (DIRS 155233)	The rate of drill penetration may range from inversely proportional to the square of the compressive strength to inversely proportional to the compressive strength of the rock. Equation 5-19 directly relates the square of the formation compressive strength to the rate of penetration and therefore allows a comparison of drilling behavior based on material properties.
Q2	Kahraman, S.; Balci, C.; Yazici, S.; and Bilgin, N. 2000. "Prediction of the Penetration Rate of Rotary Blast Hole Drills Using a New Drillability Index." *International Journal of Rock Mechanics and Mining Sciences, 37,* (5), 729-743. New York, New York: Pergamon. TIC: 255709. (DIRS 167761)	The rate of drill penetration may range from inversely proportional to the square of the compressive strength to inversely proportional. Equation 8 addresses the rate of penetration in terms of a drillability index, but provides a correlation of the index to unconfined compressive strength and to tensile strength in Equations 14 and 15.
Explosions and Crashes		
Q3	Backman, M.E. and Goldsmith, W. 1978. "The Mechanics of Penetration of Projectiles into Targets." *International Journal of Engineering Science, 16,* (1), 1-99. New York, New York: Pergamon. TIC: 255605. (DIRS 167628)	The maximum penetration depth of earth penetrating weapons is approximately 30 m. The relationships and equations giving depth of penetration are taken from p. 32, which provides information for a monobloc round-ended steel projectile with a length-to-diameter ratio of 8, striking normally at 150 m/s. The stated relationship is a penetration depth into sand of 350 diameters, and for high-strength concrete (5,000 psi strength), a penetration depth of 25 diameters. A maximum penetration depth can be calculated by assuming a penetrator with a maximum diameter. The Poncelet equation (Equation 6.2 on p. 38) and factors from Table 2 for hard soils (95 percent sand and, 5 percent silt $a_8 = 15.7$, $a_{10} = 24.7$) are provided and can be used to determine a maximum penetration depth. A maximum depth can be determined by assuming the mass associated with the penetrator with a maximum diameter.

Table B-1. Data Sets for Use within this Technical Product (Continued)

Item	Source	Description of Direct Input
Explosions and Crashes (Continued)		
Q4	Dence, M.R.; Grieve, R.A.F.; and Robertson, P.B. 1977. "Terrestrial Impact Structures: Principal Characteristics and Energy Considerations." *Impact and Explosion Cratering, Planetary and Terrestrial Implications, Proceedings of the Symposium on Planetary Cratering Mechanics, Flagstaff, Arizona, September 13-17, 1976.* Roddy, D.J.; Pepin, R.O.; and Merrill, R.B., eds. Pages 247-275. New York, New York: Pergamon Press. TIC: 247237. (DIRS 135253)	The energy release required to create a crater with a diameter sufficient to fracture to 60 m or 200 m (i.e., the depths of interest) is on the order of 10^{12} to 10^{17} Joule. Figure 12 is used to relate energy release to crater diameter and hence to fracturing and cratering depth. The energy release from underground nuclear detonations results in fracturing to distances on the order of 100 meters or less. p. 262 indicates that the 64-kt Pile Driver test produced stresses at about 100 meters (328 feet) that were slightly less than those needed to propagate fractures in granodiorite.
Q5	Ferguson, C.D. 2002. "Mini-Nuclear Weapons and the U.S. Nuclear Posture Review." Monterey, California: Monterey Institute of International Studies, Center for Nonproliferation Studies. Accessed December 4, 2002. TIC: 253717. http://www.cns.miis.edu/pubs/week/020408.htm (DIRS 160988)	The energy yield of conventional weapons is on the order of 2 tons or less. This is based on direct input from this citation stating that an explosive capability of 2 tons is given for the GBU-28 explosive ordnance.
Q6	Forrestal, M.J.; Longcope, D.B.; and Norwood, F.R. 1981. "A Model to Estimate Forces on Conical Penetrators Into Dry Porous Rock." *Journal of Applied Mechanics, 48,* (1), 25-29. New York, New York: American Society of Mechanical Engineers. TIC: 255607. (DIRS 167630)	The maximum penetration depth of earth penetrating weapons is approximately 30 m. Direct input from this paper indicate that experimental test results at the Sandia, Tonopah Test Range, Nevada indicate a penetrator; 1.52 m long, with outer diameter of 0.165 m and mass of 182 kg, with an initial velocity of 411 m/s penetrated to a depth of 2.6 m in unsaturated welded tuff
Q7	Patterson, W.J. 1974. "Results and Analysis of Three Instrumented Projectile Penetration Tests at the Watching Hills Blast Range, Suffield, Alberta, Canada." *EOS, Transactions, 56,* (12), 1197. Washington, D.C.: American Geophysical Union. TIC: 255677. (DIRS 167805)	The maximum penetration depth of earth penetrating weapons is approximately 30 m. Provides empirical information on rock penetrations tests. Penetrators with a diameter of 15.24 cm and mass of 181.4 kg were fired with impact velocities of 93 m/sec, 122.8 m/s and 150.9 m/sec and achieved penetration depths of 9.08 m, 14.7 m, and 20.7 m respectively. The target material was an old glacial lake bed.
Q8	Stix, G. and Yam, P. 2001. "Facing a New Menace." *Scientific American, 285,* (5), 14-15. New York, New York: Scientific American. TIC: 254304. (DIRS 160994)	Kinetic energy for jet aircraft is approximately 2 tons TNT equivalent or less. This information provides energy release associated with a large jetliner (Boeing 767) crash.
Q9	Young, C.W., 1976. *Status Report on High Velocity Soil Penetration Program.* SAND76-0291. Albuquerque, New Mexico: Sandia National Laboratories. (DIRS 167806)	The maximum penetration depth of earth penetrating weapons is approximately 30 m. Provides empirical information on soil penetration tests, Table II indicates that a penetrator with a weight of 320 lbs, and 6.0 inch diameter impacting with a speed of 2316 feet per second penetrated 220.5 feet (67 m) into a dry playa soil.

Table B-1. Data Sets for Use within this Technical Product (Continued)

Item	Source	Description of Direct Input
Metamorphism		
Q10	Ehlers, E.G. and Blatt, H. 1982. *Petrology, Igneous, Sedimentary, and Metamorphic.* New York, New York: W.H. Freeman and Company. TIC: 255657. (DIRS 167802)	The minimum conditions needed for onset of metamorphism are: T> 150-200ºC P = 0.5-1 kbar Depth = 4-5 km The range in geothermal gradients is 10 to 25ºC and the pressure gradient is approximately 0.6 kbar/km. From p. 566, the text states "the minimum temperature at which typical regional metamorphic processes begin in sediments is about 150 – 200 degrees C, with pressures on the order of 0.5-1 kbar and depth within the crust of about 4-5 km. At these pressures and temperatures diagenetic processes are complete." From p. 684-685, the range in geothermal gradients at convergent plate junctions is inferred typically to be between 10 and 25 degrees C/km. From p 168, Figure 6-3, in the top 200 km of the crust, the pressure gradient is approximately 1 mbar per 1500 km (or about 0.6 kbar per km) and the temperature gradient is approximately 1000 degrees C per 100 kilometer or 10 degrees per kilometer.
Diagenesis		
Q11	Krystinik, L.F. 1990. "Early Diagenesis in Continental Eolian Deposits." Chapter 8 of *Modern and Ancient Eolian Deposits: Petroleum Exploration and Production.* Fryberger, S.G.; Krystinik, L.F.; and Schenk, C.J., eds. Denver, Colorado: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section. TIC: 247781. (DIRS 135295)	The time required for diagenesis is less than 10,000 years. p. 8-1 indicates that shallow diagenesis may achieve lithification within 5,000 years. Compaction does not generally become significant until deep burial has occurred. pp. 8-2 and 8-3 indicate that initial compaction can reduce porosity by 20-30 percent, but additional compaction is not significant prior to deep burial. Cements other than carbonate may develop in arid environments p. 8-4 indicates that iron, aluminum, and silica may be cementing agents in arid environments.
Q12	Lattman, L.H. and Simonberg, E.M. 1971. "Case-Hardening of Carbonate Alluvium and Colluvium, Spring Mountains, Nevada." *Journal of Sedimentary Petrology, 41,* (1), 274-281. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists. TIC: 223189. (DIRS 129306)	The time required for diagenesis is less than 10,000 years. p. 277 provides a bound on the rate of case-hardening and formation of calcretes in southeastern Nevada and suggests rates on the order of tens of years.
Q13	Lattman, L.H. 1973. "Calcium Carbonate Cementation of Alluvial Fans in Southern Nevada." *Geological Society of America Bulletin, 84,* (9), 3013-3028. Boulder, Colorado: Geological Society of America. TIC: 235904. (DIRS 129305)	Cementation by $CaCO_3$ is not a significant process in rhyolitic tuffs. p. 3015 of this paper discusses the role of carbonate cements for rhyolitic tuffs and indicates that carbonate cementation is not significant if a source of carbonate is not present.

Table B-1. Data Sets for Use within this Technical Product (Continued)

Item	Source	Description of Direct Input
		Diagenesis (Continued)
Q14	Reeves, C.C. 1976. *Caliche: Origin, Classification, Morphology and Uses.* Lubbock, Texas: Estacado Books. TIC: 245928. (DIRS 104303)	The net effect of cementation is to decrease infiltration rates. p. 110 indicates that a caliche horizon impedes the movement of both infiltration and capillary water and cites several supporting studies.
Q15	Taylor, E.M. 1986. *Impact of Time and Climate on Quaternary Soils in the Yucca Mountain Area of the Nevada Test Site.* Master's thesis. Boulder, Colorado: University of Colorado. TIC: 218287. (DIRS 102864)	p. 86 SiO_2 cementation is not dependent on climatic conditions, but does exhibit distinctive trends that correspond with the ages of the surficial deposits. p. 87 Accumulation rates are attributable to several climatic scenarios, but changes were insufficient to decrease the rate of accumulation. p. 89 Modeling suggests that $CaCO_3$ may translocate to greater depth with onset of greater precipitation. The preceding statements are taken from Chapter 5 of the citation. p. 33, Figure 9, accumulation rates for Yucca Mountain favor SiO_2 over $CaCO_3$, which is an accessory cement, and the cementation process is reversible. The preceding statements are taken from pp. 31-33, Figure 9, pp 86 to 89, and Chapter 5 of the citation.
		Meteorite Impact
Q16	Ceplecha, Z. 1992. "Influx of Interplanetary Bodies onto Earth." *Astronomy and Astrophysics, 263,* 361-366. New York, New York: Springer-Verlag. TIC: 246784. (DIRS 135242)	Source of flux information for full range of masses p. 362 and Figure 1
Q17	Ceplecha, Z. 1994. "Impacts of Meteoroids Larger than 1m into the Earth's Atmosphere." *Astronomy and Astrophysics, 286,* (3), 967-970. New York, New York: Springer-Verlag. TIC: 246761. (DIRS 135243)	Source of flux data based on percent composition and related densities. p. 967-969, Tables 1, 3, 4, Figure 2
Q18	Dence, M.R.; Grieve, R.A.F.; and Robertson, P.B. 1977. "Terrestrial Impact Structures: Principal Characteristics and Energy Considerations." *Impact and Explosion Cratering, Planetary and Terrestrial Implications, Proceedings of the Symposium on Planetary Cratering Mechanics, Flagstaff, Arizona, September 13-17, 1976.* Roddy, D.J.; Pepin, R.O.; and Merrill, R.B., eds. Pages 247-275. New York, New York: Pergamon Press. TIC: 247237. (DIRS 135253)	Energy to crater diameter and cratering depth relationships. p. 250, pp. 261-264

Table B-1. Data Sets for Use within this Technical Product (Continued)

Item	Source	Description of Direct Input
Meteorite Impact (Continued)		
Q19	Grieve, R.F. 1987. "Terrestrial Impact Structures." *Annual Review of Earth and Planetary Sciences, 15,* 245-269. Palo Alto, California: Annual Reviews. TIC: 246788. (DIRS 135254)	Cratering rate distribution based on observed earth cratering (i.e., proportional to $D_{crater}^{-1.8}$) and threshold size for onset of complex cratering (4 km). p. 248, p. 257, Figure 8
Q20	Grieve, R.; Rupert, J.; and Therriault, A. 1995. "The Record of Terrestrial Impact Cratering." *GSA Today, 5,* (10), 194-196. Boulder, Colorado: Geological Society of America. TIC: 246688. (DIRS 135260)	Onset of complex cratering occurs with crater diameters of 4 km. p. 194
Q21	Grieve, R.A.F. 1998. "Extraterrestrial Impacts on Earth: The Evidence and the Consequences." *Meteorites: Flux with Time and Impact Effects.* Grady, M.M.; Hutchinson, R.; McCall, G.J.H.; and Rothery, D.A., eds. Geological Society Special Publication No. 140. Pages 105-131. London, England: Geological Society. TIC: 254143. (DIRS 163385)	Crater diameter to depth of effect relationships. Depth of exhumation is approximately 0.28 D_{crater}. p. 113, Figure 8
Q22	Hills, J.G. and Goda, P.M. 1993. "Fragmentation of Small Asteroids in the Atmosphere." *The Astronomical Journal, 105,* (3), 1114-1144. Woodbury, New York: American Institute of Physics. TIC: 246798. (DIRS 135281)	Modeling results demonstrating a variety of effects from meteorite impact including resulting crater diameters and related consequences. Figures 16 and 17 provide key meteor radius to crater diameter relationship information.
Q23	Shoemaker, E.M. 1983. "Asteroid and Comet Bombardment of the Earth." *Annual Review of Earth and Planetary Sciences, 11,* 461-494. Palo Alto, California: Annual Reviews. TIC: 246922. (DIRS 135308)	Contribution of iron meteors to the total flux is about 5 percent. pp. 464 and 480
Q24	Wuschke, D.M.; Whitaker, H.H.; Goodwin, B.W.; and Rasmussen, L.R. 1995. *Assessment of the Long-Term Risk of a Meteorite Impact on Hypothetical Canadian Nuclear Fuel Waste Disposal Vault Deep in Plutonic Rock.* AECL-11014. Pinawa, Manitoba, Canada: Atomic Energy of Canada Limited, Whiteshell Laboratories. TIC: 221413. (DIRS 129326)	Spatial relationships of crater diameter to extents and depth of fracturing (0.76 D_{crater}) and exhumation (0.14 D_{crater}). pp. 3 Spatial extent of fracturing is assumed to be spherical. Figure 1 Cratering rate data for the Canadian shield and application to a hypothetical Canadian repository. pp. 4 and 26
Extraterrestrial Events		
Q25	Brakenridge, G.R. 1981. "Terrestrial Paleoenvironmental Effects of a Late Quaternary-Age Supernova." *Icarus, 46,* (1), 81-93. New York, New York: Academic Press. TIC: 255707. (DIRS 167873)	Frequency of supernova event (1 event per 100 years), magnitude (10^{50} ergs), and potential consequences of the event (nitrogen enrichments, ozone depletion, global cooling) due to a supernova event. p. 81-93

Table B-1. Data Sets for Use within this Technical Product (Continued)

Item	Source	Description of Direct Input
Extraterrestrial Events (Continued)		
Q26	Lean, J. 1997. "The Sun's Variable Radiation and its Relevance for Earth." *Annual Review of Astronomy and Astrophysics, 35,* 33-67. Palo Alto, California: Annual Reviews. TIC: 255614. (DIRS 167639)	Relationships exist between the decadal sun cycle, and overall solar activity and the earth's surface temperature, and possible link from changes in IR and visible and IR radiation to changes in earth's temperatures and climate. p. 33-67
Q27	Maynard, N.C. 1995. "Space Weather Prediction." *Reviews of Geophysics (Supplement), 33,* (Part 1), 547-557. Washington, D.C.: American Geophysical Union. TIC: 253729. (DIRS 160888)	List of engineered systems potentially affected by space weather. p. 547-557
Earth's Magnetic Field		
Q28	Odenwald, S. 2003. "Earth - Magnetic Field" Poetry Space Science Education: Ask the Space Scientist http://image.gsfc.nasa.gov/poetry/ask/askmag.html. Washington, D.C.: National Aeronautics and Space Administration. Accessed February 25, 2003. TIC: 253712. (DIRS 160892)	The periodicity of pole reversals is on the scale of a few hundred thousand years to once every million years. There has been a decrease in the earth's magnetic intensity in the last few thousand years, and some evidence that a reversal may occur sometime during the next few to several thousand years. There is no identifiable fossil evidence (such as mutation or extinctions) stemming from magnetic field changes. These statements are made within the citation.
Earth Tides		
Q29	Bredehoeft, J.D. 1997. "Fault Permeability Near Yucca Mountain." *Water Resources Research, 33,* (11), 2459-2463. Washington, D.C.: American Geophysical Union. TIC: 236570. (DIRS 100007)	Earth tides cause fluctuations in water levels at Yucca Mountain that are on the order of a few centimeters. p. 2460 give a value of 2.05 cm.

B3. DEMONSTRATION OF SUITABILITY USING THE CORROBORATIVE METHOD

The data to be evaluated have been extracted from nonproject specific sources and will be justified for use by the corroborating data approach. The corroborating data approach may be used when subject matter data comparisons can be shown to substantiate or confirm parameter values and may include comparisons of unqualified to unqualified data. The use of the corroborative data approach seems most feasible for judging correctness and reliability by comparing independently developed but related, data sets. This approach is also useful for justifying use of direct inputs and demonstrating suitability for use in the analysis.

In this appendix, the indirect input is also referred to as "corroborative-use-only" information to help differentiate it from the direct input being justified for use. In some cases, a single source may provide both direct and indirect input.

B4. EVALUATION CRITERIA

The following criteria are established for qualifying these data through corroboration:

1. Is there a sufficient quantity of corroborating data available for comparison?

   Table B-1 is organized by type of information to be evaluated, and each of the sources of data to be evaluated is listed. For each subject area, at least two, and preferably three or more, independent sources of information will be considered for corroboration.

2. Can inferences drawn to corroborate these data be clearly identified, justified, and documented?

   For each source of information to be evaluated, the discussion will include a brief statement regarding the original purpose of the study, the method used to acquire the data, and any limitations germane to the corroboration of the data. Additionally, the basis for assuming adequacy for comparison (e.g., similar type study, update to previous study, compared to previous studies in related fields) will be stated.

For quantitative inputs, corroboration will be shown either by graphical representation of the various data sets, or in table or text format, comparing the various values from the various sources. Corroboration will be considered acceptable, if "singular" values (e.g., mean velocity or percent by composition) are shown to be within two standard deviations of the mean value, with the mean and deviations developed by equal weighting of reported mean values from each source. This standard was chosen based on assuming a normal distribution of data. In a normal distribution, about 95 percent of the values should be within two standard deviations of the mean. In the case of probability distributions or equations based on probability distributions (e.g., mass flux or cratering rates), corroboration will be considered acceptable if the resulting probability distributions fall within two orders of magnitude for any given point in the distribution (e.g., for the probability of crater diameter of a given size). This large range of values is consistent with recognizing the large degree of uncertainty associated with small number of observations of extraterrestrial bodies known to date.

For qualitative inputs addressing key concepts of an FEP, one or more corroborative information sources will be used to substantiate the direct input. The source(s) should not conflict with the direct input, and should be in general agreement. This standard may also be used when corroborating boundary conditions that define the conditions necessary for the initiation of an FEP (e.g., temperature and pressure conditions associated with the onset of metamorphism). For cases with only one available source of information, the appropriateness for use as direct input will be justified.

Therefore, the use of "broad" acceptance criteria is justified, and in lieu of corroboration, a bounding or conservative value (with respect to inclusion of the FEP) may be recommended and considered as qualified under this exercise. Consistent with the intended use, some latitude is taken in applying these criteria and an adequate explanation or justification for variance from the above criteria is provided.

For each FEP-specific data set within Section B3, the evaluation criteria to be applied (i.e., quantitative or qualitative) will be identified.

B5. EVALUATION OF THE TECHNICAL CORRECTNESS OF THE DATA

The technical correctness of the data (and the corroborating information) and hence its suitability to use was evaluated based on the factors listed in AP-SIII.9Q, Section 5.2.1 l), and discussed previously in the introduction to this appendix.

Section B5 has been subdivided with direct input for each subject FEP (or grouping of FEPs) being accorded an individual subsection. The discussion of technical correctness for each FEP-specific data set is addressed in four parts.

The first part (Section B5.x.1 Literature Search) discusses the scope of the literature review. The literature review involved a keyword search, and the number of returns or "citations" is given. The term "citation" is used in the generic sense and is not specific to either direct inputs or indirect inputs. Preliminary screening of citations based on title and available abstract information was done to help limit the number of citations to be evaluated, and goes to limiting further review to those citations that are related to the properties of interest. The direct inputs to be used were chosen after reviewing the list of selected citations and review of the technical content of the citations.

The second part (Section B5.x.2 Evaluation of Factors) addresses the technical correctness of both the data being evaluated, and the corroborating information. The technical correctness of the data and corroborating information was evaluated based on the previous list of factors. In the summary tables, direct input citations are listed first and are followed by the corroborative citations. A single cited paper might serve as the source for multiple types of direct input and reference only information. The designator "Q" within the item identifier indicates the item is to be justified for use. If a direct item is also used to corroborate a different direct input, the "Q" value is listed as corroborating information for that use rather than assigning a "C" number and having a single citation with two designators. In some cases "Q" information is mutually corroborating (i.e., if there is little difference in the listed information) and in some cases a citation may be direct input in one instance, but is used only in a corroborative sense for other information. A "C" designator in the item identifier column indicates the item is used only to corroborate one or more data sets.

The first column of the evaluation table addresses the factor "Demonstrates Properties of Interest." For each source, the evaluation includes a brief statement regarding the original purpose of the study, its applicability, and any limitations germane to use of the information. The factor of "Prior Use by Others" is documented in column 2 of the table. Where possible, this was accomplished by checking against citations in the SciSearch® database or Science Citation Index, which provide the number of other citations which cite back to the subject document. In some instances, the subject document was not found in the SciSearch® database and the number of citations is not known. This is to be expected, as many of these particular articles (such as those related to drill performance) are directed towards technology or engineering application or the citation did not initially appear in publications routinely included in the SciSearch® database (such as thesis and textbooks). The factor of reliability of the data source is addressed in the third column (Prior Peer or Other Professional Review) by noting the type of originating document, with peer-reviewed journals being specifically noted. Items listed as “technical journal” denote that the use of peer-review prior to publishing has not been established. Textbooks are noted as such and are typically subject to an editorial and fact checking. Citations denoted as “articles” rather than “papers” denote information extracted from “reputable” sources, but the reported information has not been subjected to technical review. The reliability of the data source is also considered in Column 4 of the tables (Extent and Reliability of Documentation). This is a subjective evaluation, which was used in part to determine whether a citation should be used as a direct input, with preference as direct input given to those citations with moderate to high documentation levels. If information on equipment and procedures is provided in the citation, it is noted in this column. The fifth column (Importance of the Data) designates the citation as direct input or indirect input, based on its importance to the FEP analysis.

By addressing the above listed factors for the corroborative information, the fourth factor (availability of corroborating data) is also addressed. However, the comparison of the direct input to the corroborative information requires more detail and it is specifically addressed under the third subsection (Section B5.x.3 Discussion) for each FEP-specific dataset. The discussions for each FEP may be subdivided by topic to facilitate corroboration of the direct inputs.

The fourth part of each section (Section B5.x.4 Data Status and Limitations) provides recommendations regarding status of the direct input and any associated limitations and relates to suitability for use.

B5.1 SUITABILITY DEMONSTRATION FOR TIMING OF HUMAN INTRUSION-RELATED FEPS

The difference in material properties of rock and the engineered barrier system and the effect on drilling parameters may allow recognition of penetration of the engineered barriers. The relationship being evaluated is that:

> The rate of drill penetration may range from inversely proportional to the square of the compressive strength to inversely proportional to the compressive strength of the rock.

This range in relationship is documented in the direct inputs noted as Items Q1 and Q2 in Table B-1. The data are in the form of equations or functional relationships and are qualitative in nature. Therefore, the qualitative criteria for general agreement will be applied. Multiple sources corroborate the data.

B5.1.1 Literature Search

A literature search was performed using SciSearch® and the GeoRef® databases and was focused on recent papers and updates, and on information directly relevant and applicable to the analysis. The intent of the search was to identify potential citations that addressed factors that would differentiate between drilling in naturally occurring materials and penetration of an engineered barrier. The keyword and subject based-searches utilized various “AND” combinations for the keywords “drilling,” “rate,” “penetration,” and “factors” in various combinations. The SciSearch® database (limited to publication dates for 1980 to 2004) returned a total of three records and the GeoRef® databases (based on all records, including 2004) returned 46 records. Duplicate citations between the two databases were noted, and 12 citations were judged be potentially pertinent for the intended use and further evaluation. Based on existing references used for *Total System Performance Assessment for the Site Recommendation* (TSPA-SR), an electronic search of the eLibrary for the Society of Professional Engineers was also performed using the SPE Intelligent Search function with the input question of "what factors affect rate of penetration and drilling parameters." The query was set at a 50 percent match and for a return of 200 citations, and no publication date limitation was imposed. From the list of returned citations, four additional citations were marked for further consideration. Additionally, previous discussions of the topic in the final environmental impact statement (FEIS) and TSPA-SR documentation were reviewed and citations in those sources were added to the list.

Citations from these sources not selected for evaluation were discarded because they dealt with drilling techniques that are unlikely to be used in groundwater exploration, as required by the regulations. Some other reasons for discarding a citation is that the citation dealt with rock types that are not present at Yucca Mountain above the repository (e.g., shales and limestones), or the paper dealt with specific drilling conditions that were not of interest for shallow conditions.

B5.1.2 Evaluation of Factors

For each of the sources to be used in the evaluation (whether as direct input, or as indirect input and corroboration of the direct input), the pertinent factors are evaluated in tabular form in Table B-2.

Table B-2. Sources and Factors Evaluation for Direct Inputs to the Timing of Human Intrusion

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q1	Q2, C2, C3, C4, C6	Bourgoyne, A.T., Jr.; Millheim, K.K.; Chenevert, M.E.; and Young, F.S., Jr. 1986. "Rotary Drilling Bits." *Applied Drilling Engineering.* SPE Textbook Series Volume 2. Pages 190-245. Richardson, Texas: Society of Petroleum Engineers. TIC: 250085. (DIRS 155233)	This textbook specifically addresses drilling engineering principles and application of the principles. Chapter 5 specifically addresses the use of rotary drill bits and principles of operations, selection, and factors affecting their operation. Chapter 5 is directly applicable to techniques and practices commonly used in groundwater exploration drilling, which is a regulatory criterion for determining the timing of an intrusion without recognition.	Not found in SciSearch®	Textbook written by two authors in petroleum engineering academia and two authors from the petroleum industry. This is a standard text for petroleum engineering curriculum.	Moderate to High – This text provides a thorough discussion of rotary drill bit performance and provides a variety of equations used in industry to determine the rate of drill bit penetration.	Direct Input – The rate of drill penetration may range from inversely proportional to the square of the compressive strength to inversely proportional to the compressive strength of the rock. Equation 5-19 directly relates the square of the formation compressive strength to rate of penetration and therefore allows a comparison of behavior based on material properties. Indirect Input - Chapter 5 also provides several discussions regarding drilling principles and practices that are useful for understanding the concepts behind drilling operations. These are discussed in Appendix C of this analysis report and are not further considered herein.

Table B-2. Sources and Factors Evaluation for Direct Inputs to the Timing of Human Intrusion (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q2	Q1 and C1 through C7	Kahraman, S.; Balci, C.; Yazici, S.; and Bilgin, N. 2000. "Prediction of the Penetration Rate of Rotary Blast Hole Drills Using a New Drillability Index." *International Journal of Rock Mechanics and Mining Sciences, 37,* (5), 729-743. New York, New York: Pergamon. TIC: 255709. (DIRS 167761)	Addresses the interaction of rotary drilling to rock properties. This paper precedes the paper by the same author and used as indirect input. The rock property used for correlation is the 'drillability index', which can be defined in terms of tensile strength and unconfined compressive strength.	Six citations in SciSearch®	Technical journal	Moderate to High – A discussion of previous studies, field studies, and laboratory studies is provided. A schematic of the laboratory equipment is provided, and laboratory results are provided in graphical form. The mathematical development of the proposed model using the drillability index is provided.	Direct Input – The rate of drill penetration may range from inversely proportional to the square of the compressive strength to inversely proportional to the compressive strength of the rock. Eq. 8 of this paper addresses the rate of penetration in terms of a drillability index, but provides a correlation of the index to unconfined compressive strength and to tensile strength in Equations 14 and 15.
C1	Not Applicable	Beer, F.P. and Johnston, E.R., Jr. 1981. *Mechanics of Materials.* New York, New York: McGraw-Hill. TIC: 255414. (DIRS 166708)	This is a standard engineering text addressing mechanics of materials.	Not found in SciSearch®	Textbook	Moderate – This is a standard engineering text.	Indirect Input – This text provides information on the relationship of brittle and ductile materials and the respective strength parameters.

Table B-2. Sources and Factors Evaluation for Direct Inputs to the Timing of Human Intrusion (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C2	Not Applicable	Bilgesu, H.I.; Tetrick, L.T.; Altmis, U.; Mohaghegh, S.; and Ameri, S. 1997. "A New Approach for the Prediction of Rate of Penetration (ROP) Values." *1997 SPE Eastern Regional Meeting held in Lexington, Kentucky, October 22-24, 1997.* SPE 39231. Pages 175-179. Richardson, Texas: Society of Petroleum Engineers. TIC: 255661. (DIRS 167782)	The paper provides a description of a neural network developed to estimate rates of penetration. It does not specifically link penetration rates to formation properties. It shows the rate of penetration rates based on neural networks of parameters, one of which is formation properties.	Paper not listed in SciSearch®	Proceedings paper – not peer-reviewed	Moderate – The paper does not provide any independent validation of the approach used for modeling.	Indirect Input – This paper provides corroboration of the factors affecting rate of penetration.

Table B-2. Sources and Factors Evaluation for Direct Inputs to the Timing of Human Intrusion (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C3	Not Applicable	Grattan-Bellew, P.E. and Vijay, M.M. 1986. "Influence of Physical Properties of Rock on Rate of Penetration of a Water-Jet Drill." *Canadian Mineralogist, 24,* 323-328. Ottawa, Canada: Mineralogical Association of Canada. TIC: 255711. (DIRS 167786)	Addresses water-jetting drilling techniques, rather than rotary drilling. However, links performance to rock properties.	Paper not listed in SciSearch®	Technical journal	Moderate to Low – This paper provides a limited discussion of laboratory methods and provides optical micrographs to support the conclusions.	Indirect Input – This paper indicates that commonly measured properties such as compressive strength, tensile strength, and porosity do not correlate with rate of water-jet penetration. This may limit the applicability of material properties being a defining factor for recognition to rotary drilling methods.
C4	Not Applicable	Howarth, D.F.; Adamson, W.R.; and Berndt, J.R. 1986. "Correlation of Model Tunnel Boring and Drilling Machine Performances with Rock Properties." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 23,* (2), 171-175. New York, New York: Pergamon. TIC: 255620. (DIRS 167645)	This paper provides a link between rock material properties and drilling/tunneling machine performance. Provides correlation of rate of penetrations to three rock properties (compressive strength, saturated density, and P-wave velocity) and for three types of equipment (tunnel boring machine, diamond drilling and percussive drilling).	13 citations in SciSearch®	Technical journal	Moderate-This paper provides a cursory summary of testing equipment and methods, and provides testing results in table and graphical format.	Indirect Input – This paper does not address material property strength on rotary drilling, but does confirm that the properties are germane to diamond and percussive drilling.

Table B-2. Sources and Factors Evaluation for Direct Inputs to the Timing of Human Intrusion (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C5	Not Applicable	Kahraman, S. 2002. "Correlation of TBM and Drilling Machine Performances with Rock Brittleness." *Engineering Geology, 65,* (4), 269-283. New York, New York: Elsevier. TIC: 255618. (DIRS 167643)	This paper provides a link between a rock material property to drilling/tunneling machine performance and rotary drilling. It does confirm the relationships of rock properties to drilling performance. However, the definitions and assumptions regarding brittleness prevent its use for comparison to penetration rates in ductile materials.	Six citations in SciSearch®	Peer-reviewed journal paper	Moderate to High– This paper provides laboratory test data to support correlation of rate of penetration to various rock properties and cites to supporting papers that provide the laboratory methods.	Indirect Input – Figure 5 provides correlation of three brittleness indices to rate of penetration. Adequate correlation is shown for factors based on compressive strength and tensile strength. This can be used to corroborate other papers using compressive strength as a key factor.
C6	Not Applicable	Kahraman, S.; Bilgin, N.; and Feridunoglu, C. 2003. "Dominant Rock Properties Affecting the Penetration Rate of Percussive Drills." *International Journal of Rock Mechanics & Mining Sciences, 40,* (5), 711-723. New York, New York: Pergamon. TIC: 255619. (DIRS 167644)	This paper provides a link between rock material properties and performance of an alternate drilling method. While not directly applicable to rotary bit operation, it does confirm the relationships of rock properties to drilling performance.	One citation in SciSearch®	Technical journal	Moderate to High - A discussion of previous studies and experimental studies are provided. Laboratory results are provided in tabular and graphical form along with a statistical analysis of the results.	Indirect Input – This paper describes material property correlation to percussive drilling, rather than rotary drilling. However, the rate of penetration is correlated to the uniaxial compressive strength and tensile strength, but poorly correlated to the elasticity modulus for percussive drilling.

Table B-2. Sources and Factors Evaluation for Direct Inputs to the Timing of Human Intrusion (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C7	Not Applicable	Satchwell, R.M. 1994. *An Experimental Study of the Effect of Bedding Plane Anisotrophy on the Rate of Penetration.* Ph.D. dissertation. Laramie, Wyoming: University of Wyoming, Department of Chemical and Petroleum Engineering. TIC: 255659. (DIRS 167952)	This work addresses the deviation effect of bedding plane anisotropies for three different bit types, including roller cone bits.	Dissertations not listed in SciSearch®	Doctoral Dissertation	Moderate – The documentation satisfies the requirements for a dissertation.	Indirect Input – provides a summary overview of background information. Provides an equation (cited to Warren) that relates torque to rock strength and rate of penetration. This is used to corroborate the inverse proportionality of rock strength to rate of penetration.
C8	Not Applicable	Warren, T. M. 1984. "Factors Affecting Torque for a Roller Cone Bit." *Journal of Petroleum Technology, 36*, (10), 1500-1508. Dallas, Texas: Society of Petroleum Engineers. TIC: 255859 (DIRS 167788)	This paper provides description relating torque to roller bit performance including the tendency for bit deviation from the vertical.	Seven citations in SciSearch®	Technical journal	Moderate - The paper provides and equation and supporting discussions only.	Indirect Input – This is used to corroborate the inverse proportionality of rock strength to rate of penetration.

B5.1.3 Discussion

The information being justified for use is that:

> The rate of drill penetration may range from inversely proportional to the square of rock strength, to inversely proportional to the rock strength.

This stems from the two equations cited as direct input. Items Q1 and Q2 are mutually corroborating, and Items C1 through C7 provide corroborating information for both direct inputs.

Bourgoyne et al. (1986 [DIRS 155233], Equation 5-19) (Q1) indicates that the relationship of rate of penetration is inversely proportional to the square of compressive strength of the formation. The equation is given as:

$$R = \frac{K}{S^2}\left[\frac{W_o}{d_b} - \left(\frac{W}{d_b}\right)_t\right]^2 N \qquad \text{(Eq. B-1)}$$

where K = constant of proportionality, S = compressive strength of the rock, W = bit weight, W_0 = threshold bit weight, d_b = bit diameter, all at time t, and N = rotary speed. All other factors being equal, this indicates that the rate of penetration (R) is affected in a manner inversely proportional to the square of the compressive strength. Bourgoyne et al. (1986 [DIRS 155233]) (Q1) cites to another author that indicates that the rate of penetration is directly proportional to K, which is a constant of proportionality that includes the effect of rock strength, although it does not indicate whether an inverse square relationship is represented in the value for K.

Kahraman et al. (2000 [DIRS 167761], Equation 8) (Q2) mutually corroborates with Bourgoyne et al. (1986 [DIRS 155233]) (Q1). The equation used by Kahraman stems from the same source as that used by Bourgoyne et al. However, Kahraman expresses the equation in terms of a drillability index, which is then shown to have an inverse proportionality to compressive strength and tensile strength, rather than an inverse square relationship. The corroborating equation is given by Kahraman as:

$$PR = 3.20\frac{NW}{\alpha D} \qquad \text{(Eq. B-2)}$$

where PR = penetration rate, N = rotation speed, W = bit weight, α = the drillability index and D = the bit diameter. The drillability index, α is then expressed in terms of compressive strength, σ_c. Eq. 12 of Kahraman et al. (2000 DIRS [167761]) (Q2):

$$\sigma_c = 3.09\alpha + 14.13 \qquad \text{(Eq. B-3)}$$

A simple substitution of terms generates an equivalent equation:

$$PR = 3.20 \frac{NW}{\left(\dfrac{\sigma_c - 14.13}{3.09}\right) D} \qquad \text{(Eq. B-4)}$$

Similarly, Eq. 14 of the same paper provides a correlation to tensile strength, in the form of

$$\sigma_T = 0.22\alpha + 2.11 \qquad \text{(Eq. B-5)}$$

A simple substitution of terms generates an equivalent equation:

$$PR = 3.20 \frac{NW}{\left(\dfrac{\sigma_T - 2.11}{0.22}\right) D} \qquad \text{(Eq. B-6)}$$

Thus from Bourgoyne et al. (1986 [DIRS 155233], Equation 5-19) (Q1), the relationship is shown to be inversely proportional to square of the compressive strength, and from Kahraman et al. (2000 [DIRS 167761], Equation 8) (Q2), the relationship is shown to be only inversely proportional to either the compressive strength or the tensile strength. How is it then that these two equations are considered mutually corroborative?

Based on Equation B-4, a doubling of compressive strength from 20 to 40 MPa, and then from 40 MPa to 80 MPa would, in the first instance, result in an approximate 4.4 times decrease in the rate of penetration (i.e., the inverse square relationship as suggested by Bourgoyne et al.). However, with progressive doubling from 40 MPa to 80 MPa, Equation B-4 gives about a 2.5 times decrease in penetration rates. A third doubling of strength from 80 MPa to 160 MPa would result in a decrease of about 2.1 times, and a fourth doubling from 160 MPa to 320 MPa indicates a decrease of about 2.1 times. Similar relationships can be seen for the tensile strength. Based on Equation B-6, and assuming tensile strengths of 4, 8, 16, and 32 MPa, then the decrease in penetration rate, respectively, are factors of 3.1, 2.4, and 2.2.

This suggests that the correlation proposed by Kahraman et al. (2000 [DIRS 167761], Equation 8) (and Equation B-2) is not a linear relationship throughout the range of possible values, and at lower values may approach an inverse square relationship. Kahraman notes that the proposed inverse relationship is based on a coefficient value for data points with compressive strengths greater than 40 MPa, because of poor correlation with experimental results at lower compressive strengths. If this equation were then applied to lower compressive strength materials, it would be expected that the estimated penetration rates would be understated. Bourgoyne does not discuss any upper limitations on the applicability of the equation based on rock strength. Thus, the two relationships are not contradictory and are mutually corroborative at least for the lower range of unconfined compressive strength and for tensile strength. Additionally, as discussed in Appendix C, Table C-1, the compressive strength of the repository host horizons is greater than 40 MPa, which better fits the conditions tested by Kahraman. Assuming the linear relationship from Kahraman is likely conservative because increases in compressive strengths would not decrease penetration rates as significantly as assuming the inverse-squared relationship.

The two equations (Eq. B-3 and B-5) from Kahraman are corroborated from four sources (Items C1, C5, C7, and C8). First, if the relationships are correct, then the ratio for compressive strength and tensile strength should be between a factor of ten and twenty. This is based on the general assumption that for brittle materials, that tensile strength should be about 10 to 20 percent of the compressive strength. In general, brittle materials are significantly stronger in compression than in tension (Beer and Johnston 1981 [DIRS 166708], p. 37) (C1). For example, the tensile strength of concrete is about 10 to 20 percent of its compressive strength, and rock properties at the site (see Appendix C) also indicate a ratio of 10 to 20 for compressive strength to tensile strength. Assuming a hypothetical drillability index of one, and substituting into Equations B-3 and B-5, yields a ratio of $\sigma_c/\sigma_T = 17.22/2.33 = 7.4$. Assuming a drillability index of 100 yields a ratio of $\sigma_c/\sigma_T = 323.13/24.11 = 13.4$. Therefore, the relationship between the equations is at least reasonable and internally consistent with the rock property used as the basis for the conclusions in Kahraman (2000 [DIRS 167761], Table 2) (Q2).

A second line of corroboration is the relationships based on brittleness also proposed by Kahraman (2002 [DIRS 167643]) (C5). Because the data set is the same as that used for Kahraman (2000 [DIRS 167761]) (Q2), but the principles used to develop the relationships in the data are different, the later paper can be used to corroborate the first. In Kahraman (2002 [DIRS 167643]) (C5), the developed equations relate the rate of penetration to parameter values that incorporate both compressive strength and tensile strength of a material. Kahraman (2002 [DIRS 167643]) (C5) indicates the rate of penetration is correlatable to the brittleness B_1, which is defined as the ratio of the compressive strength to the tensile strength; and to B_2, which is the ratio of compressive strength minus tensile strength to the compressive strength plus the tensile strength. The equations developed use the ratio of parameters involving both the unconfined compressive strength and the tensile strength. Given that they are shown to correlate to penetration rates lends support to the appropriateness of the original equations (Equations B-3 and B-5), wherein the compressive strength and the tensile strength are related to the drillability coefficient and hence to the penetration rate.

Thirdly, Satchwell (1994 [DIRS 167952], Equation 6-4-1) (C7), citing to Warren (1984 [DIRS 167788]) (C8) indicates that the bit torque is proportional to the penetration rate and to the rock strength:

$$T = \frac{\left(\frac{1}{\alpha}\right)\left(\frac{\pi}{4}\right)\left(D^2 ER - WR\right)}{2\pi N} \qquad \text{(Eq. B-7)}$$

Isolation of the variable for penetration rate (R) indicates that the penetration rate (R) is inversely proportional to rock strength (E), rather than inversely proportional to the square of the rock strength (E). This further corroborates the results from Kahraman (2000 [DIRS 167761], Equation 8) (Q2).

Further general corroboration for the direct input taken both Bourgoyne et al. (1986 [DIRS 155233]) and for Kahraman (2000 [DIRS 167761]) (Q2) stem from the remaining corroborative sources (C2, C3, C4, C6). Bilgesu et al. (1997 [DIRS 167782]) (C2) indicates that key factors in determining rate of penetration include weight on bit, rotary speed, pump rates, bit type, and formation hardness. Bilgesu et al. expresses the formation characteristics as formation drillability and formation abrasiveness. Grattan-Bellew and Vijay (1986 [DIRS 167786]) (C3), in evaluating water jetting, indicate that "though not applicable to water-jet drilling, commonly measured physical properties of rock, for example, compressive strength, tensile strength, specific gravity, and porosity, do not correlate water-jet penetration." They indicate, however, that the mechanics of water jet drilling are different from rotary drilling (i.e., fracture propagation rather than cratering and chip formation), so the lack of correlation is to be expected.

The dependency of rotary drill penetration on unconfined compressive strength also is corroborated from other multiple sources, though these are not directly applicable to rotary drilling. Howarth et al. (1986 [DIRS 167645], Figure 2) (C4) indicate that for percussion drilling, a doubling of the saturated compressive strength from 50 MPa to 100 MPa, the penetration rate fits a nonlinear curve and decreases from 100 mm/min to 50 mm/min. Howarth et al., however, demonstrated that there was no significant correlation to dry compressive strength for percussion drilling. Kahraman (2002 [DIRS 167643]) (C5) provides a list 10 papers by other authors to indicate that uniaxial compressive strength is the most widely used parameter for predicting the performance of tunneling machines and drilling rigs, though the exact relationship is not given or further discussed. Kahraman (2003 [DIRS 167644]) (C6), in contrast to Howarth et al. (1986 [DIRS 167645]) (C4), indicates that for percussive drills the relation of penetration rate to uniaxial compressive strength is a linear relationship.

B5.1.4 Data Status and Limitations

The stated relationship that the rate of drill penetration may range from inversely proportional to the square of the compressive strength to inversely proportional to the compressive strength of the rock stems from the two direct input sources listed in Section B5.1.2. The equations from those two direct inputs have been adequately corroborated from multiple sources, and all sources evaluated are in general agreement. Thus, the qualitative criteria for general agreement have been met. Corroboration of the direct input provides the required level of confidence that the data are suitable for their intended use, which is for FEP screening. The status of the stated relationship and the related direct inputs evaluated above should be considered as qualified for use within this technical product. However, limitations apply.

The direct inputs are entirely adequate, based on compressive strength and tensile strength properties, to support a conceptual argument that significant changes in drill performance would occur and be recognized if a bit penetrates the drift wall or crown (naturally occurring material) and then encounters a metallic or alloy material used for the engineered barrier system. The exact relationship of unconfined compressive strength on the penetration rate, however, is not entirely certain. The relationship does not appear to be an inverse square relationship as suggested by Bourgoyne et al. (1986 [DIRS 155233]) (Q1) for greater material strengths, but does appears to be something less that that relationship. However, the corroborative information clearly suggests that an inverse square relationship likely represents the upper bound in the range of relationship. A more supportable position is that the relationship is inversely proportional.

Accordingly, a limitation on use of the data is imposed: the upper bound of an inverse square relationship shown from Bourgoyne et al. (1986 [DIRS 155233]) (Q1) may be mentioned, but the FEP screening decision should be determined based on the better substantiated, but less dramatic change in rate of penetration suggested by Kahraman (2000 [DIRS 167761]) (Q2). As will be discussed in Appendix C of this analysis report, the rock and engineered barrier material strength unconfined compressive strengths are significantly greater than 40 MPa. Although both direct input relationships have been corroborated, the more linear relationship suggested by Kahraman for greater material strengths better addresses site conditions, and is more conservative. That is, a greater difference in material properties is required to induce a similar and noticeable change in drilling conditions and, thus, creates a more stringent threshold to use in FEPs screening.

B5.2 SUITABILITY DEMONSTRATION FOR DIRECT INPUTS FOR FEP 1.4.11.00.0A EXPLOSIONS AND CRASHES (HUMAN ACTIVITY)

This section addresses direct inputs related to the energy released and depth of effects resulting from explosions and crashes. The five following statements, and the supporting direct inputs, are being justified for use.

- The energy release required to create a crater with a diameter sufficient to fracture to 60 m or 200 m (i.e., the depths of interest) is on the order of 10^{12} to 10^{17} Joules. This information is taken from Item Q4 in Table B-1.

- Kinetic energy for jet aircraft is approximately 2 tons TNT equivalent or less. This is taken from Item Q8 in Table B-1.

- The energy yield of conventional weapons is on the order of 2 tons or less. This is taken from Item Q5 in Table B-1.

- The maximum penetration depth of earth penetrating weapons is approximately 30 m. This information is drawn from Items Q3, Q6, Q7, and Q9 in Table B-1.

- The energy release from underground nuclear detonations results in fracturing to distances on the order of 100 meters or less. This information is taken from Item Q4 in Table B-1.

The direct input being justified is in the form of equations or functional relationships, or they are empirical data. The objective is to justify input representing the maximum possible effects (i.e., upper bound of possible conditions) against a theoretical threshold of significance (i.e., minimum depth or energy release needed to be of significance). Therefore, the quantitative criteria will be applied, but conservative values will be recommended.

B5.2.1 Literature Search

A literature search was performed using SciSearch® and the GeoRef® databases and was focused on recent papers and updates directly relevant and applicable to the analysis. The intent of the search was to identify potential citations that addressed factors that would identify the magnitude of various explosion and crash scenarios, and their effect in the subsurface. Various key-word searches based on the terms "earth penetrating weapons," "subsurface effects," "explosions," and "crashes" were performed. In total, the SciSearch® database (limited to publication dates for 1980 to 2004) returned no pertinent records and the GeoRef® databases (based on all records including 2004) returned five pertinent records. Because of the sparse amount of information, the reference lists for these five citations were then reviewed to identify any other pertinent papers, and an Internet search was performed. The resulting citation list is provided in Table B-3.

B5.2.2 Evaluation of Factors

For each of the sources to be used in the evaluation (whether as direct input or reference only and corroboration of the direct input), pertinent factors are evaluated in tabular form in Table B-3.

Table B-3. Sources and Evaluation for Direct Input to Explosions and Crashes

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q3	Q6, Q7, Q9 and Q5, C11, C13, C14	Backman, M.E. and Goldsmith, W. 1978. "The Mechanics of Penetration of Projectiles into Targets." *International Journal of Engineering Science, 16,* (1), 1-99. New York, New York: Pergamon. TIC: 255605. (DIRS 167628)	Applicable – The entire paper is concerned with terminal ballistics and the penetration mechanics for various categories of targets and types of penetrators. Earth materials are discussed as semi-infinite targets and various factors are discussed. Equations for determining depth of penetration are provided.	160 citations in SciSearch®	Peer-reviewed Technical journal	High – This is a summary work addressing a variety of projectile characteristics, target characteristics, and equations from a wide variety of sources. Extensively cited and extensive bibliography provided.	Direct Input – The maximum penetration depth of earth penetrating weapons is approximately 30 m. The relationships and equations giving depth of penetration are taken from: p. 32, for steel projectile with a length-to-diameter ratio of 8, striking normally at 150 m/s. Penetration depth into sand of 350 diameters, and for high-strength concrete (5,000 psi strength), a penetration depth of 25 diameters. The Poncelet equation (Equation 6.2 on p. 38) and factors from Table 2 for hard soils (95 percent sand and, 5 percent silt a_8 = 15.7, a_{10} = 24.7).

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q4	C10, C11, C12	Dence, M.R.; Grieve, R.A.F.; and Robertson, P.B. 1977. "Terrestrial Impact Structures: Principal Characteristics and Energy Considerations." *Impact and Explosion Cratering, Planetary and Terrestrial Implications, Proceedings of the Symposium on Planetary Cratering Mechanics, Flagstaff, Arizona, September 13-17, 1976.* Roddy, D.J.; Pepin, R.O.; and Merrill, R.B., eds. Pages 247-275. New York, New York: Pergamon Press. TIC: 247237. (DIRS 135253)	Figure 12 of this paper relates energy release to crater diameter. Diameter can then be equated to excavation and fracturing depth, which are of direct interest.	The effects addressed in this paper have been used in other repository design considerations regarding meteorite impact. The energy release equations are often cited in other works in the subject area. Science Citation Index indicate 17 citations	This paper was extracted from an edited compendium of related works.	Moderate – This paper provides a summary of characteristics of craters and respective dimension and compares cratering effects to those of nuclear testing. No information on procedures or quality control is provided.	Direct Input – The energy release required to create a crater with a diameter sufficient to fracture to 60 m or 200 m (i.e., the depths of interest) is on the order of 1012 to 1017 Joule. Figure 12 is used to relate energy release to crater diameter and hence to fracturing and cratering depth. The energy release from underground nuclear detonations results in fracturing to distances on the order of 100 meters or less. p. 262 indicates that the 64-kt Pile Driver test produced stresses at about 100 meters (328 feet) that were slightly less than those needed to propagate fractures in granodiorite.

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q5	Q8, C13, C16.	Ferguson, C.D. 2002. "Mini-Nuclear Weapons and the U.S. Nuclear Posture Review." Monterey, California: Monterey Institute of International Studies, Center for Nonproliferation Studies. Accessed December 4, 2002. http://www.cns.miis.edu/pubs/week/020408.htm. TIC: 253717. (DIRS 160988)	This paper mentions and briefly discusses existing conventional and potential nuclear earth penetrating weapons.	Article not listed in SciSearch®	This is essentially an editorial article from a public policy institute rather than a scientifically-oriented or technical article.	Low – article provides a brief discussion of various weapons capability, but citations are primarily to policy and position papers rather than to technical papers. Weapons capabilities are provided only as attributed quotes.	Direct Input – The energy yield of conventional weapons is on the order of 2 tons. This is based on direct input from this citation stating that an explosive capability of 2 tons is given for the GBU-28 explosive ordnance. Indirect Input – The depths stated in the paper may be biased to understating the potential depth of penetration. However, they do provide a minimum or lower bound of possible penetration depths. Used to corroborate depth of penetrations calculated based on Backman and Goldsmith and results of experimental test data from Forrestal et al., from Young, and from Patterson.

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	**Corroborating Items**	**Source**	**1. Demonstrates Properties of Interest**	**2. Prior Use by Others**	**3. Type of Publication and Review**	**4. Extent and Reliability of Documentation**	**5. Proposed Input Status**
Q6	Q3, Q7, Q8, Q9 and Q5 C11, C14, C15	Forrestal, M.J.; Longcope, D.B.; and Norwood, F.R. 1981. "A Model to Estimate Forces on Conical Penetrators Into Dry Porous Rock." *Journal of Applied Mechanics, 48,* (1), 25-29. New York, New York: American Society of Mechanical Engineers. TIC: 255607. (DIRS 167630)	This journal paper develops a model to predict the forces exerted on conical-nosed penetrators for normal impact into dry rock targets. Results of an experimental test into a tuff unit are cited as corroboration to the model results. The experimental results are directly applicable.	14 citations in SciSearch®	Peer-reviewed journal paper	Moderate – Experimental test results for a conical penetrator into tuff are provided and a citation to a correspondence is given. Information on the projectile characteristics and the target material are provided and are adequate to judge comparability to Yucca Mountain geomaterials.	Direct Input – The maximum penetration depth of earth penetrating weapons is approximately 30 m. Direct input from this paper (p. 28) indicates that experimental test results at the Sandia, Tonopah Test Range, Nevada indicate a penetrator; 1.52 m long, with outer diameter of 0.165 m and mass of 182 kg, with an initial velocity of 411 m/s penetrated to a depth of 2.6 m. in an unsaturated, welded tuff.

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q7	Q3, Q6, Q8, Q9 and Q5, C11, C14	Patterson, W.J. 1974. "Results and Analysis of Three Instrumented Projectile Penetration Tests at the Watching Hills Blast Range, Suffield, Alberta, Canada." *EOS, Transactions, 56,* (12), 1197. Washington, D.C.: American Geophysical Union. TIC: 255677. (DIRS 167805)	This abstract provides results of experimental data for penetrators into geomaterials and the information is directly applicable.	Abstract not listed in SciSearch®	This is information provide only in abstract form and was presumably not subject to peer-review	Low – the nature of the publication and its presentation only in abstract form provides only the barest of documentation.	Direct Input – The maximum penetration depth of earth penetrating weapons is approximately 30 m Provides empirical information on rock penetrations tests. Penetrators with a diameter of 15.24 cm and mass of 181.4 kg were fired with impact velocities of 93 m/sec, 122.8 m/s and 150.9 m/sec and achieved penetration depths of 9.08 meters, 14.72 meters, and 20.7 m respectively. The target material was an old glacial lake bed.

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q8	C9	Stix, G. and Yam, P. 2001. "Facing a New Menace." *Scientific American, 285,* (5), 14-15. New York, New York: Scientific American. TIC: 254304. (DIRS 160994)	This paper addresses airline security and screening issues. However, a sidebar column provides the results of calculations for various energies related to airliner impacts.	One citation in SciSearch®	This article is extracted from a respected scientific journal, but is nontechnical in content and likely not peer reviewed.	Moderate – The calculation results in the sidebar are straightforward calculations and the bases for the calculations are given. They are adequate for use in FEPs screening.	Direct Input – Kinetic energy for jet aircraft is approximately 2 tons TNT equivalent or less. This information provides energy release associated with a large jetliner (Boeing 767) crash.
Q9	Q3, Q7, Q9 and C11, C14	Young, C.W., 1976. *Status Report on High Velocity Soil Penetration Program.* SAND76-0291. Albuquerque, New Mexico: Sandia National Laboratories. ACC: MOL.20040407.0069 (DIRS 167806)	This is an investigation report prepared for Sandia Laboratories regarding earth penetration. It is applicable because it provides experimental data for the depth of penetration in soils.	Paper not listed in SciSearch®	National laboratory report	Moderate – Experimental results are discussed and provided. In particular, description of penetrators and targets are provided.	Direct Input – The maximum penetration depth of earth penetrating weapons is approximately 30 m. Provides empirical information on soil penetration tests. Table II indicates that a penetrator with a weight of 320 lbs, and 6.0 inch diameter impacting with a speed of 2316 feet per second penetrated 220.5 feet (67 m) into a hard playa soil.

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C9	Not Applicable	Abbas, H.; Paul, D.K.; Godbole, P.N.; and Nayak, G.C. 1996. "Aircraft Crash Upon Outer Containment of Nuclear Power Plant." *Nuclear Engineering and Design, 160,* (1-2), 13-50. New York, New York: Elsevier. TIC: 255604. (DIRS 167627)	This paper addresses aircraft impact on aboveground structures – particularly containment buildings for nuclear power plants. Paper considers the linear mass density and crushing strength of a Boeing 707-320, FB-111 jet fighter, and the F4 Phantom jet fighter.	Three citations in SciSearch®	Peer-reviewed journal paper	Moderate - This paper develops the equations needed to analyze reaction forces and stresses within a cylindrical containment building and provides a comparison to other similar types of studies. However, the reference list appears limited, and citations for the aircraft characteristics are not provided.	Indirect Input – Figures 9, 10, and 11 and p. 25 provide linear mass densities for three types of aircraft. This can be used to calculate approximate kinetic energy of various aircraft. Input data by aircraft type include: Boeing 707-320: Velocity of 102.8 m/s, linear mass density of 9,000 kg/m, total length of 40 m. FB-111: Velocity of 108.2 m/sec, linear mass density of 9000 kg/m, total length of 22 m. F4 Phantom: Velocity of 215.8 m/sec, linear mass density of 3500 kg/m, total length of 16 m. Provides corroboration for calculations cited from Stix and Yam.
C10	Not Applicable	Glasstone, S. and Dolan, P.J., eds. 1977. "Descriptions of Nuclear Explosions." Chapter II of *The Effects of Nuclear Weapons.* 3rd Edition. Pages 26-79. Washington, D.C.: U.S. Department of Defense and U.S. Department of Energy. ACC: MOL.20030925.0035. (DIRS 160992)	This document provides and overview of the effects of nuclear weapons, including effects of underground detonations.		This is a government-sponsored document and was developed through interagency cooperation.	Moderate – This document is a thorough overview of the topic, and technical discussion is provided. It summarizes the results of underground nuclear testing.	Indirect Input – Section 2.104 provides a description of fracturing related to the RAINIER test.

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C11	Not Applicable	Gronlund, L. and Wright, D. 2002. "Earth Penetrating Weapons" Global Security Cambridge, Massachusetts: Union of Concerned Scientists. Accessed December 10, 2002. TIC: 253714. (DIRS 160989) http://www.ucsusa.org/global_security/nuclear_weapons/page.cfm?pageID=777	This paper mentions and briefly discusses existing conventional and potential nuclear earth penetrating weapons.	Article not listed in SciSearch®	This is essentially an editorial article from a public policy institute rather than a scientifically-oriented or technical article.	Low – article provides a brief discussion of various weapons capabilities, but citations are primarily to policy and position papers rather than to technical papers. Weapons capabilities are provided only as attributed quotes.	Indirect Input – The penetration depths stated in the paper may be biased to understating the potential depth of penetration. However, they do provide a minimum or lower bound of possible penetration depths. Containment depths for subsurface explosions are stated. Used to corroborate depth of penetrations calculated based on Backman and Goldsmith and results of experimental test data from Forrestal et al., from Young, and from Patterson, (i.e., reported penetrations of 6 m of concrete and 30 m of earth). Also used to indicate the depths required to contain an explosion (60 meters for a one-kiloton explosion, and 300 meters for a 100-kiloton explosion).

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C12	Not Applicable	Hughes, D.W. 1998. "The Mass Distribution of Crater-Producing Bodies." *Meteorites: Flux with Time and Impact Effects.* Geological Society Special Publication No. 140. Grady, M.M.; Hutchison, R.; McCall, G.J.H.; and Rothery, D.A.; eds. Pages 31-42. Bath, England: Geological Society of London. TIC: 254143.	This paper is directed to addressing factors that define basic relationships of meteor flux to cratering rates. However, the author takes an energy-based equation approach and provides a figure that summarizes the results of multiple studies that link energy releases to crater diameters.	Paper not listed in SciSearch®	This paper was extracted from an edited and refereed compendium of the London Geologic Society (31 referees, including two whom are routinely cited in meteorite impact work).	Moderate – Paper provides a good summary of preceding work by others and performs an evaluation of these various sets and ranges of equation. The figure of interest provides citations to the original source documentation of works by others.	Indirect Input – Figure 3 provides a direct comparison to works by Dence et al. and to works by others, and therefore provides a strong corroborative source indicating that use of the relationships proposed by Dence et al. are reasonable for use as direct input.

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C13	Not Applicable	Lennox, D.; Rees, A. (eds.) 1990. *Jane's Air-Launched Weapons.* Alexandria, Virginia: Jane's Information Group. TIC: 255862	Provides the “best source” of information from unclassified materials for weapons capabilities and descriptions.	Not listed in SciSearch®	The Jane’s series of books are widely recognized as an acceptable source of unclassified information on weapons systems for most countries.	Moderate to High – This highly respected series of books contain information collected from a variety of unclassified sources including government documents and vendor information.	Indirect Input – the mass of the largest weapons of various types are taken from the appendix. A conservative assumption is made that the total mass is attributed to high explosives, and an equivalent energy release is calculated.

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C14	Not Applicable	Nelson, R.W. 2001. "Low-Yield Earth-Penetrating Nuclear Weapons." *FAS Public Interest Report, 54,* (1), 1-5. Washington, D.C.: Federation of American Scientists. TIC: 253719. (DIRS 160986)	This paper mentions and briefly discusses existing conventional and potential nuclear earth penetrating weapons.	Article not listed in SciSearch®	This is essentially an editorial article from a public policy institute rather than a scientifically-oriented or technical article.	Low – article provides a brief discussion of various weapons capabilities, but citations are primarily to policy and position papers rather than to technical papers. Weapons capabilities are provided only as attributed quotes.	Indirect Input – The depths stated in the paper may be biased to understating the potential depth of penetration. However, they do provide a minimum or lower bound of possible penetration depths. Containment depths for subsurface explosions are stated. Used to corroborate depth of penetrations calculated based on Backman and Goldsmith and results of experimental test data from Forrestal et al., from Young, and from Patterson.
C15	Not Applicable	Siddiqui, N.A. and Abbas, H. 2002. "Mechanics of Missile Penetration into Geo-Materials." *Structural Engineering and Mechanics, 13,* (6), 639-652. Taejon, Korea: Techno-Press. TIC: 255608. (DIRS 167631)	This paper reexamines the work by Forrestal and refines the model.	No citations in SciSearch®	Peer-reviewed journal	Moderate - The reliability is comparable to that of Forrestal et al.	Indirect Input – This paper reexamines and modifies the approach taken by Forrestal et al.

Table B-3. Sources and Factors Evaluation for Direct Input to Explosions and Crashes (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C16	Not Applicable	Wu, C. 2000. "Powerful Explosive Blasts onto Scene." *Science News Online, 157,* (4), 54. TIC: 255698 (DIRS 167812)	This is a general news article dealing with development of a new explosive compound. This is pertinent to determining the equivalent energy released from a conventional HE warhead.	Article not listed in SciSearch®	This article was taken from an Internet-based weekly science magazine. It has not been peer-reviewed, but the contents of the article have been confirmed by finding a similar citation in a peer-reviewed journal (Angewandte Chemi International).	Low to Moderate – Information is traceable to a somewhat obscure scientific journal, therefore reliability is established. However, the basis for statements regarding relative strength of the high explosive to TNT is not traceable.	Indirect Input – Provides justification for assumption that the explosive yield of HE is no more than twice that of a comparable weight of TNT.

B5.2.3 Discussion

The following discussion has been subdivided by topic, with direct inputs grouped accordingly. The topics of discussion include energy release needed to fracture to depth, kinetic energy release from aircraft, conventional weapons yields, maximum depth of penetration, and fracturing effects from underground nuclear explosions.

B5.2.3.1 Energy Release to Depth of Effect Relationships

The relationship being justified is that:

> The energy release required to create a crater with a diameter sufficient to fracture to 60 m or 200 m (i.e., the depths of interest) is on the order of 10^{12} to 10^{17} Joule.

This relationship is direct input from Item Q4, and is corroborated by the studies summarized in Item C12.

Dence et al. (1977 [DIRS 135253], Figure 12) (Q4) provides a series of curves relating energy release to the surface to crater diameter that is used as direct input. The crater diameters of interest for impact to the repository are 80 m for fracturing to the depth of a key geologic unit (a depth of 60 m), on the order of 300 m for fracturing to repository depth and on the order of 1,000 m for exhumation to repository depth (a depth of 200 m) as explained in Appendix D of this analysis report. For these depths, the curve from Dence et al. (1977 [DIRS 135253]) (Q4) indicates that energy releases at the surface on the order of 10^{12} to 10^{17} Joules or greater could potentially cause damage to the repository.

The relationships presented in Dence et al. (1977 [DIRS 135253]) (Q4) are corroborated by a similar figure presented in Hughes (1998 [DIRS 162562], Figure 3) (C12). Hughes shows the Dence et al. curve in relation to similar curves developed by five other investigators. For the range of diameters of interest, the plot from Dence et al. is shown to be the least conservative (i.e., more energy required for a given diameter), with other investigators showing that a crater with a given diameter could be produced with less energy. The lowest most curve shown by Hughes requires approximately an order of magnitude less energy than that required by Dence et al. For a 1 km diameter crater, Dence et al. requires approximately 10^{23} ergs, while the lowermost curve requires 10^{22} ergs (equating to 10^{17} and 10^{16} Joules respectively). At a diameter of 100 m, the required energies are 10^{20} ergs and 10^{19} ergs (10^{13} and 10^{12} Joules respectively).

Use of the curve from Dence et al. (1977 [DIRS 135253], Figure 12) (Q4) with a stated range of 10^{12} to 10^{17} Joules is corroborated by Hughes (1998 [DIRS 162562], Figure 3) (C12). However, because the values from Dence et al. are the least conservative, a limitation on the use of the data is discussed in Section B5.2.4.1.

B5.2.3.2 Energy Released by Aircraft Impact

The bounding condition being justified is that:

> Kinetic energy for jet aircraft is approximately 2 tons TNT equivalent or less.

This value was taken as direct input from Item Q8 and is corroborated, based on three different aircrafts, using information from Item C9.

Stix and Yam (2001 [DIRS 160994]) (Q8) provide, in a sidebar column, the results of calculations for energy released from a jet airliner crash (1 to 2 tons TNT equivalent), excluding the release from onboard fuel. In Stix and Yam (2001 [DIRS 160994]) (Q8), the stated mass of a Boeing 767, larger than the aircraft listed below and fully loaded, is listed as 412,000 pounds (186,880 kg), and the stated kinetic energy for a velocity of 530 mph (237 m/s) is given as the equivalent of 1 ton TNT.

With regard to aircraft crashes and the associated energy release, an equivalent calculation for three types of aircraft used in analyzing the aircraft crash hazard for nuclear power plants is given for corroboration. In the corroborating source, Abbas et al. (1996 [DIRS 167627], Figures 9, 10, 11; and p 25) (C9) provide the information on mass distribution and velocity for various size aircraft. These can be used to determine the kinetic energy available upon impact.

Table B-4. Corroborative Information for Determining Kinetic Energy of Various Aircraft

Aircraft Type	Velocity (m/s)	Total Length (m)	Linear Mass Density (kg/m) (approximate length and associated density)	Mass (kg)	Kinetic Energy (at stated velocity) $K_e = 1/2mv^2$ $(kg\text{-}m^2)/s^2$ or Joules	TNT Equivalent (tons) (1 ton TNT = 4.2×10^9 Joules)
Boeing 707-320	102.8	40	0-15 m – 2000 kg/m 15-25 m – 10,000 kg/m 25-40 m – 2000 kg/m	30,000 100,000 30,000 160,000	8.5×10^8	0.2
FB-111	102.8	22	0-11 m – 2000 kg/m 11-15 m-9000 kg/m 15-22 m-3000 kg/m	22,000 36,000 21,000 79,000	4.2×10^8	0.1
F4 Phantom	215.8	16	0-5 m 10,000 kg/m 5-7 m 25,000 kg/m 7-10m – 40,000 kg/m 10-16 m – 20,000 kg/m	5,000 5,000 12,000 8,000 30,000	7.0×10^8	0.17

If the stated velocity for the Boeing 707 and for the FB-111 is scaled upward to 236 m/s, then a factor of 2.3 is applied to the velocity. Given that the kinetic energy is a function of the square of the velocity, an increase of 2.3 times would increase the kinetic energy by 5.3 times, and the corresponding release in TNT equivalent would increase by that same factor. This would equate to a release of approximately 1 ton from the Boeing 707-320, and less for the other aircraft shown.

Thus, the energy release given by Stix and Yam is corroborated using equivalent information from Abbas et al. (1996 [DIRS 167627]) (C9), and the direct input is shown to be at the upper range of likely releases from aircraft impacts.

B5.2.3.3 Energy Released by Targeted Weapons

The direct inputs discussed in this section are used to determine whether the energy releases by targeted weapons are capable of affecting the repository at depth, based on the curve from Dence et al. (1977 [DIRS 135253], Figure 12) (Q4) described in Section B5.2.3.2 of this appendix. The condition being justified is that:

> The energy yield of conventional weapons is on the order of 2 tons.

This is taken as direct input from Item Q5, and is corroborated by information presented in Q8, C13, and C16.

The direct input is based on Ferguson (2002 [DIRS 160988]) (Q5), who states an explosive capability of 2 tons for the GBU-28. Based on corroborative sources, this direct input appears to be a reasonable representation of the upper end of yields from conventional weapons.

Corroboration is based on information taken from *Jane's Air-Launched Weapons* (Lennox and Rees 1990 [DIRS 167804]) (C13). This is the "standard" unclassified resource for weapons systems information. The appendices provide total mass and dimensions for missiles and bombs from all major countries, as well as the mass of warheads and mass of the munition in terms of high explosives, without specifying the type of high explosive. To convert to equivalence in TNT, a factor of 2 is assumed. This is based primarily on Wu (2000 [DIRS 167812]) (C16). Wu reports on the synthesization of a new explosive compound (octanitrocubane) that is stated to be "twice as powerful as trinitrotoluene (TNT) and it's thought to be 20 to 25 percent more effective than HMX (octagen), which is the state-of-the-art military explosive right now." The statement is attributed to a source at the Nation Institute of Standards and Technology. Accordingly, a factor of 2 is assumed to convert from mass of high explosive to equivalence of TNT.

Further corroboration is provided by Stix and Yam (2001 [DIRS 160994], p. 15) (Q8), who indicate that the energy release for a U.S. cruise missile (with a conventional warhead) is 0.5 ton TNT equivalent. With regard to the reported TNT equivalent of 0.5 tons for a Tomahawk cruise missile with conventional warhead, Lennox and Rees report that the U.S. AGM-131 SRAM conventional warhead contains 250 kg of high explosive. Using the factor of 2-multiplier, this suggests that the yield cited by Stix and Yam above is correct.

Additional corroborative information from Lennox and Rees (1990 [DIRS 167804]) (C13) indicates that the largest conventional warheads for air-to-surface missiles are listed as 1,000 kg HE, and are associated with the former USSR AS-4 and AS-6 air-to-surface missiles. This would be equivalent to 2,000 kg (or about 2 tons) TNT. With regard to bombs (such as the GBU-28), Lennox and Rees indicate that the total weight of Iraq's NASR-9000 is 9,000 kg. If all this mass were attributed to HE, then the TNT equivalent would be upwards of 9 tons of TNT.

However, for most of the bombs listed by Lennox and Rees, the total weight is typically a few hundred to a thousand kg, suggesting that TNT equivalents of about 1 ton are more "typical."

Accordingly, a suggested value of 2 ton TNT equivalent for conventional ordnance is corroborated and considered suitable for use in FEP screening considerations.

B5.2.3.4 Maximum Depth of Penetration

Given that the repository is located no less than 200 m below the ground surface, the maximum depth of penetration of a projectile in dry rock is of particular interest. The condition being justified is that:

> The maximum penetration depth of earth penetrating weapons is approximately 30 m.

This stems from direct inputs either based on, or taken, from Items Q3, Q6, Q7, Q9 (which are all mutually corroborating) and are further corroborated either directly by, or using information from, Q5, C11, C13, C14, and C15.

Direct input is taken from Backman and Goldsmith (1978 [DIRS 167628], pp. 32 through 38) (Q3) in the form of a table stating penetration depths in terms of projectile diameters, and in the form of the Poncelet equations and associated resistance constants for hard soil. Direct input is also taken from Forrestal et al. (1981 [DIRS 167630]) (Q6), Patterson (1974 [DIRS 167805]) (Q7), and from Young (1976 [DIRS 167806]) (Q9), which present results of experimental data in a variety of geomaterials.

Backman and Goldsmith (1978 [DIRS 167628], p. 32) (Q3) indicates that for a round-ended steel projectile with a length to diameter ratio of 8, striking normally at 150 m/s, sand will be penetrated to a depth of 350 diameters, and high strength concrete (5000 psi compressive strength) will be penetrated to a depth of only 25 diameters. Given that samples of the volcanic tuff, with only a few exceptions, exhibit compressive strengths of well in excess of 50 MPa (or in excess of 7500 psi), as shown in Appendix C of this analysis report, a value associated with 5000 psi concrete can be chosen as a conservative surrogate. However, to calculate a maximum penetration depth, a projectile diameter is needed. A maximum diameter of 1 meter is assumed based on information from the corroborating source, Lennox and Rees (1990 [DIRS 167804]) (diameter for the NASR 9000, C13). Accordingly, the maximum penetration depth will be on the order of 25 meters in the volcanic tuffs present at the site.

Backman and Goldsmith (1978 [DIRS 167628], Eq. 6-2 and p. 38) (Q3) also cite to the Poncelet equation, which indicates that the depth of penetration (P) is dependent on two resistance constants a_{10} and a_8. The equation is given as:

$$P = \frac{m}{2a_{10}} \ln\left[1 + \frac{a_{10} v_o^{\ 2}}{a_8}\right] \qquad \text{(Eq. B-8)}$$

For this equation, P is the penetration depth in cm, m is the mass in kg, and v_o is the impact velocity in m/sec. The resistance coefficients for hard soil are given as $a_8 = 15.7$ and $a_{10} = 24.7$.

Assuming a mass of 9,000 kg (again based on the maximum mass reported in Lennox and Rees (1990 [DIRS 167804]) (total mass for the NASR 9000, C13), and assuming a mid-range velocity of 411 m/sec, yields a penetration depth of 22.8 m (2,275 cm).

These results based on the relationships and equations in Backman and Goldsmith and the experimental data from the following direct input sources are mutually corroborating. Experimental data from Young (1976 [DIRS 167806], Table II) (Q9) indicate a maximum penetration depth of 220 feet (67 meters) into hard playa lake soils composed of sand, silt, and clay. The compressive strengths of these materials ranged from approximately 300 psf to 45,000 psf (13 to 312 psi). These tests were made with a 6-inch (0.15 m) diameter projectile. A significant increase in penetration depths in sandy soils versus rock is expected, as Backman and Goldsmith (1978 [DIRS 167628], p. 32) (Q3) indicate total penetration depth for sand is 350 times the diameter, compared to 25 diameters for concrete-equivalent compressive strengths. Thus for a 0.15 m diameter projectile, a penetration depth of 53 m could be expected in sand. These results (i.e., 67 m from experimental data and 53 m by equation) are mutually corroborating with Patterson (1974 [DIRS 167805]) (Q7) by taking into account the difference in target materials.

Patterson reports a penetration depths ranging from 9.08 meters of 20.7 m into a glacial lakebed, a harder geomaterial than that targeted by Young (1976 [DIRS 167806]). The Patterson tests were conducted using a penetrator of mass of 181.4 kg and diameter of 0.152 m. Initial velocities ranged from 93 m/s to 150.9 m/s. Backman and Goldsmith provide an intermediate value of 36 diameters for 2500 psi strength material. Applying the factors of 36 and 350 diameters (to bound the potential depths of penetration) provides anticipated depth of penetration from 5.4 m to 52.5 m. Using Equation B-8 (the Poncelet equation from Backman and Goldsmith), the estimated depths of penetration would be 0.3 m to 38.5 m. In either case, the experimental results from Patterson are bracketed by the calculated depths based on Backman and Goldsmith, and taking into account the difference in geo-materials, substantiates the results from Young (1976 [DIRS 167806]). One further mutual corroboration can be made to the results of Forrestal et al. (1981 [DIRS 167630], p. 28) (Q6).

Forrestal et al. report that penetration depth in an unsaturated, welded tuff achieved a penetration depth of only 2.6 m. This is significant in that the materials at Yucca Mountain are a series of unwelded and welded tuffs. This penetration depth was achieved using a penetrator of mass of 182 kg and diameter of 0.165 m and initial velocity of 411 m/s. The measured depth of penetration was 2.6 m. Using these values, and substituting into the equations presented by Blackman and Goldsmith, provides estimated depths of penetration of 4.1 m using a penetration factor of 25 diameters. However, the unconfined compressive strength of welded tuff materials is on the order of 100 MPa or greater (14,500 psi) (see Appendix C of this analysis report for rock property information). This is about three times the compressive strength used to determine the factor of 25 diameters. Thus, an overestimate of penetration depth should be anticipated. Application of Equation B-8 suggests an anticipated depth of penetration of about 0.5 m. Thus, the experimental data (2.6 m) is bounded by the range (0.5 m to 4.1 m) in the calculated data, and they are considered corroborative. The results of Forrestal et al. are independently corroborated with the indirect input taken from the additional work of Siddiqui and Abbas (2002 [DIRS 167631]) (Item C15 above), who refined the theoretical estimated penetration depth to be 2.9 m.

Given that the calculated depths and experimental depths have been shown to be corroborative, and given values for maximum penetration depths of 25 m (calculated for an assumed maximum diameter), 60.7 m (observed for hard playa soils), 20.7 m (observed for glacial lake bed), and 2.6 m (observed for an unsaturated welded tuff), then the averaged value for depth of penetration is 29 m. Thus, the statement that "The maximum penetration depth of earth penetrating weapons is approximately 30 m," is defensible and reasonable. This is particularly so, given that the penetration into a welded volcanic tuff was a factor of 10 less than that value of being used as bounding condition, and is probably more representative of site conditions than the other direct inputs.

The direct inputs, and the calculated average, are corroborated from two additional sources used as indirect inputs (Items C11 and C14). Gronlund and Wright (2002 [DIRS 160989]) (C11) indicate that the U.S. arsenal includes two air dropped weapons that are capable of penetrating six meters of concrete or 30 meters of earth. Additionally, Nelson (2001 [DIRS 160986]) (C14) suggests a maximum penetration depth to be on the order of 100 feet (33 meters) based on long rod penetration, and projects that the maximum penetration depth can be no more than 10 times the length of the penetrator. These indirect inputs corroborate the direct inputs discussed above.

B5.2.3.5 Fracturing Effects of Underground Nuclear Explosions

The FEP description for explosions and crashes specifically mentions the potential for nuclear war and underground testing. Although, as discussed for the FEP, there is basis for a regulatory exclusion, direct inputs also indicate that these events would be of low consequence. The condition being justified is:

> The energy release from underground nuclear detonations results in fracturing to distances on the order of 100 meters or less.

This is based on direct input taken from Item Q4, and is corroborated by Items C10 and C11.

Dence et al. (1977 [DIRS 135253], p. 262) (Q4) provide the direct input by reference to the 64-kt Pile Driver test producing stresses at about 100 meters (328 feet) that were slightly less than those needed to propagate fractures in granodiorite. This is corroborated by two indirect input sources. Glasstone and Dolan (1977 [DIRS 160992], Section 2.104) (C10) describe the results of the RAINIER underground nuclear test. The authors indicate that the deep (240 meters, 790 feet) underground detonation of the 1.7-kt event fractured the surrounding materials out to a radius of only 54 meters (180 feet)—which is less than one drift spacing. In describing the penetration depth needed to contain an underground detonation, Gronlund and Wright (2002 [DIRS 160989]) (C11) indicate a depth of 60 meters would contain a one-kiloton explosion, and 300 meters would contain a 100-kiloton explosion. Thus, for detonation less than 100-kiloton, the stated condition is corroborated, as is the direct input taken from Dence et al.

B5.2.4 Data Status and Limitations

For quantitative data, the criteria regarding standard deviations and establishment of conservative bounding values have been satisfied. The above literature review and corroboration of the direct input provides a suitable level of confidence that the data are suitable for their intended use, which is for FEP screening. The status of the direct input evaluated above should be considered as qualified for use within this technical product. However, some limitations apply.

B5.2.4.1 Energy Release to Depth of Effect Relationships

Use of the curve from Dence et al. (1977 [DIRS 135253], Figure 12) (Q4) with a stated range of 10^{12} to 10^{17} Joules is corroborated by Hughes (1998 [DIRS 162562], Figure 3) (C12). However, the lower threshold for FEP screening should be based on 10^{12} Joules to ensure that the lower range of energy levels documented in corroborating sources cited by Hughes has been adequately addressed.

B5.2.4.2 Energy Released by Aircraft Impact

The energy release for a large jet aircraft given by Stix and Yam (2001 [DIRS 160994]) (Q8) has been corroborated and shown to be at the upper range of likely releases from aircraft impacts. However, it should be noted that the calculated energy release pertains only to kinetic energy, and does not consider other factors such as explosion of on-board fuel, detonation of on-board ordnance, or other factors.

B5.2.4.3 Energy Released by Targeted Weapons

Ferguson (2002 [DIRS 160988]) (Q5) states an explosive capability of 2 tons for the GBU-28. This value has been corroborated and is believed to be representative of possible energy releases from conventional weapons systems. However, the maximum potential release, though speculative, should be mentioned to ensure that conservative bounding values have been taken into account and used to address the range in uncertainty.

B5.2.4.4 Maximum Depth of Penetration

Based on these mutually corroborating and independently corroborating sources, a maximum depth of penetration of 30 m into volcanic tuffs should be used. The penetration factor of 25 diameters reported by Backman and Goldsmith (1978 [DIRS 167628], p. 32) (Q3); the reported value of 67 m from Young (1976 [DIRS 167806], Table II) (Q9); the maximum value of 20.7 m from Patterson (1974 [DIRS 167805]); and the value of 2.6 m from Forrestal et al. (1981 [DIRS 167630], p. 28) (Q6) are mutually corroborating and are judged appropriate for use in FEP screening analysis. However, the value of 67 m represents conditions that are unlikely to be encountered at Yucca Mountain. Tests on material similar to that at Yucca Mountain yielded the value of only 2.6 m. Consequently, a conservative, but reasonable, bounding value for the maximum penetration depth at the site would be approximately 30 m, based on the cited source information and corroborating information used as indirect input.

B5.2.4.5 Fracturing Effects of Underground Nuclear Explosions

For detonation less than 100-kiloton, the stated condition is corroborated. Use of the 100-m fracturing extent should quote Dence et al. (1977 [DIRS 135253], p. 262) (Q3) directly to avoid uncertainty regarding a bound on the yield of the detonation.

B5.3 SUITABILITY DEMONSTRATION FOR DIRECT INPUTS FOR FEP 1.2.05.00.0A METAMORPHISM

The conditions being justified are stated in the form of boundary conditions required for the onset of regional metamorphism.

The minimum conditions needed for onset of metamorphism are:

T> 150-200ºC
P = 0.5-1 kbar
Depth = 4-5 km

The range in geothermal gradients is 10 to 25º and the pressure gradient is approximately 0.6 kbar/km.

The following statements are based on information taken from Item Q10, and are shown to be conservative bounding conditions by corroboration with Items C17, C18, and C19.

For the FEPs analysis, all that is needed is to show that existing burial rates and geothermal gradients are insufficient to result in significant temperature and pressure increases. Therefore, the qualitative criteria for general agreement will be applied. The criteria specifically indicate that this standard may be used when corroborating boundary conditions that define the conditions necessary for the initiation of an FEP (e.g., temperature and pressure conditions associated with metamorphism).

B5.3.1 Literature Search

A review of available "at-hand" geology textbooks was conducted to verify conditions necessary for metamorphism to occur. The intent of the search was to verify that the conditions being used as direct input could be corroborated with other sources. In reviewing sources to be used for evaluating diagenetic effects, a third corroborating source was identified and has been evaluated.

B5.3.2 Evaluation of Factors

For each of the sources to be used in the justification (whether as direct input or indirect input and used for corroboration of the direct input), pertinent factors are evaluated in tabular form in Table B-5.

Table B-5. Sources and Factors Evaluation for Direct Inputs to Metamorphism

Items	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q10	C17, C18, C19	Ehlers, E.G. and Blatt, H. 1982. *Petrology, Igneous, Sedimentary, and Metamorphic.* New York, New York: W.H. Freeman and Company. TIC: 255657. (DIRS 167802)	This is a standard petrology textbook and contains applicable discussions and text.	Not Applicable	Textbook	All that is needed here is a statement of temperature and pressure ranges that represent the onset of metamorphism.	Direct Input - The minimum conditions needed for onset of metamorphism are: T> 150-200ºC P = 0.5-1 kbar Depth = 4-5 km p. 566 The range in geothermal gradients is 10 to 25ºC and the pressure gradient is approximately 0.6 kbar/km pp. 684-685 and p. 169, Figure 3.
C17	Not Applicable	Hyndman, D.W. 1972. *Petrology of Igneous and Metamorphic Rocks.* International Series in the Earth and Planetary Sciences. New York, New York: McGraw-Hill. TIC: 248141. (DIRS 150295)	This is a standard geology textbook and contains applicable discussions and text.	Not Applicable	Textbook	All that is needed here is a statement of temperature and pressure ranges that represent the onset of metamorphism.	Indirect Input – This text provides corroborative information for metamorphic conditions From p, 270 "Temperatures of about 300 to 400 degrees C to 700 to 800 degrees C. Geothermal gradients average about 15 to 25 degrees C/km for margins, compared to about 10 degrees C/km for stable shield area." From p. 272, Pressures are uncertain but for most areas are estimated to range from about 2,000 or 3,000 bars (or atmospheres). The normal load pressure at depth, resulting from the weight of overlying rocks, is about 285 bars/km.

Table B-5. Sources and Factors Evaluation for Direct Inputs to Metamorphism (Continued)

Items	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C18	Not Applicable	Press, F. and Siever, R. 1978. *Earth.* 2nd Edition. Chapters 11 and 16. San Francisco, California: W. H. Freeman and Company. TIC: 255856. (DIRS 167965)	This is a standard geology textbook and contains applicable discussions and text.	Not Applicable	Textbook	All that is needed here is a statement of temperature and pressure ranges that represent the onset of metamorphism.	Indirect Input – This text provides corroborative information for metamorphic conditions. From p. 298, “As a sediment is buried, it becomes subjected to increasingly high temperatures – on the average of 1ºC for each 30 meters (100 feet) of depth – and high pressures – on the average about 1 atmosphere for each 4.4 meters. The boundary between diagenesis and metamorphism is somewhat arbitrary, usually drawn at a temperature of about 300ºC.
C19	Not Applicable	Retallack, G. J. 1991. "Untangling the Effects of Burial Alteration and Ancient Soil Formation." *Annual Review of Earth and Planetary Sciences.* Weatherhill, G. Vol. 19, 183-206. Palo Alto, California: Annual Reviews Inc. TIC: 255912. (DIRS 167870)	This paper focuses on defining and describing differences and effects associated with burial alteration and soil formation.	Book not found in SciSearch ®	This paper was extracted from a book series.	Moderate – The paper is focused on distinguishing between burial alteration affects and characteristic of ancient soils. The paper provides a survey of applicable studies by others, and a lengthy citation list is provided.	Indirect Input – The paper focuses on information for related to diagenesis effects. However, it also defines the onset of metamorphism. p. 200 “in excess of 200ºC and depths greater than 7 km.”

B5.3.3 Discussion

The direct input for this FEP is taken from Ehlers and Blatt (1982 [DIRS 167802]) (Q10), largely because the values they present suggest the least temperature, pressure and depth of burial needed for the onset of regional metamorphism (i.e., conservative bounding conditions for onset). Using it as the basis of the FEPs, screening is, therefore, conservative. It is corroborated by two other texts: Hyndman (1972 [DIRS 150295], p. 270 and 272) (C17) and Press and Siever (1978 [DIRS 167965], pp. 303) (C18), and from a third book source, Retallack (1991 [DIRS 167870], p. 200) (C19).

Table B-6. Comparison of Various Stated Conditions for Metamorphism

Source	Temperature Gradient	Pressure Gradient	Onset Temperature	Onset Pressure	Onset Depth
Ehlers and Blatt 1982 TIC: 255657 (DIRS 167802) (Q10)	Approximately 1000ºC per 100 km or 10ºC/km (p. 169, Figure 6-3)	Approximately 1 Mbar per 1500 km or equivalent of 0.6 kbar/km (p. 169, Figure 6-3)	150 – 200ºC (p. 566)	Pressures on the order of 0.5-1 kbar (p. 566)	Depth within the crust of about 4-5 km (p. 566)
Hyndman 1972 TIC: 248141 (DIRS 150295) (C17)	About 10ºC/km for stable shield area, and average about 15 to 25ºC/km for a "geosynclinal" environment (p. 270)	About 285 bars/km, or 0.28 kbar/km (p. 272)	300 to 400ºC (p. 270)	About 2,000 or 3,000 bars (or atm); equivalent to 2 to 3 kbars (p. 272)	Not Given
Press and Siever 1978 TIC: 255856 (DIRS 167965) (C18)	Average of 1ºC for each 30 meters (100 feet) of depth or about 33ºC/km (p. 303)	About 1 atmosphere for each 4.4 meters, or about 0.3 kbars/km (p. 303)	About 300ºC (p. 303)	Not Given	Not Given
Retallack 1991 TIC: 255912 (DIRS 167870) (C19)	Not Given	Not Given	In excess of 200ºC (p. 200)	Not Given	Greater than 7 km (p. 200)

Ehlers and Blatt (1982 [DIRS 167802], p. 566) (Q10) indicate 0.5 to 1 kbar is necessary for the onset of metamorphism, which is clearly conservative compared to Hyndman (1972 [DIRS 150295], p. 272) (C17), which indicates that 2 to 3 kbars of pressure are required. The onset temperature, 150 – 200ºC given by Ehlers and Blatt (1982 [DIRS 167802], p. 566) (Q10), is also clearly conservative and as much as one-half of that cited by the corroborating sources. Given the respective pressure gradients, Ehlers and Blatt (1982 [DIRS 167802], p. 566) (Q10) would suggest metamorphic onset at depths as little as 1 to 2 km, but also clearly indicate a burial depth of 4 to 5 km is needed. In any case, these conditions are clearly conservative compared to the temperature and pressures, and to the depth of 10 km, based on Hyndman's information. They are also clearly conservative compared to the 9 km depth based on the average thermal gradient, and they are conservative with respect to the onset temperatures presented by Press and Siever (1978 [DIRS 167965], p. 303) (C18). They are also more restrictive than the conditions indicated by Retallack (1991 [DIRS 167870], p. 200) (C19) of greater than 200ºC and burial greater than 7 km.

B5.3.4 Data Status and Limitations

For qualitative data, the criterion of general agreement has been satisfied. The above literature review and corroboration of the direct input provides an acceptable level of confidence that the data are suitable for their intended use, which is for FEP screening. The status of the direct input for metamorphism from Ehlers and Blatt (1982 [DIRS 167802], p. 566) (Q10) evaluated above should be considered as qualified for use within this technical product. Because they represent the lowest temperature and pressure required for the onset of metamorphism, no further limitation on their use is required.

B5.4 SUITABILITY DEMONSTRATION FOR DIRECT INPUTS FOR FEP 1.2.08.00.0A DIAGENESIS

Diagenesis is an ongoing process of chemical and physical changes to sediments undergoing compaction, cementation, and burial. The conditions being evaluated and the associated direct input are as follows:

The time required for complete diagenesis to occur is less than 10,000 years: This is taken from Items Q11 and Q12.

SiO_2 cementation is not dependent of climatic conditions, but cementation does exhibit distinctive trends that correspond with the ages of the surficial deposits: This is taken from Item Q15.

Accumulation rates are attributable to several climatic scenarios, but climate change was insufficient to significantly decrease the rate of accumulations: This is taken from Item Q15.

$CaCO_3$ may translocate to greater depths given greater precipitation, and cementation is a reversible effect: This is taken from Item Q15.

Compaction does not become an important factor until the onset of deep burial: This is taken from Item Q11.

The net effect of shallow diagenesis is to stabilize the surface environment and decrease the net infiltration rate: This is taken from Item Q14.

Cementation by $CaCO_3$ is not a significant process in rhyolitic tuff due to the lack of carbonate source material: This is taken from Items Q11, Q13, and Q15.

Cements other than carbonate may develop: This is taken from Items Q11, Q13, and Q15.

Accumulation rates for Yucca Mountain favor SiO_2 over $CaCO_3$, which is accessory cement: This is taken from Items Q13 and Q15.

The data being evaluated include Items Q11 through Q15 in Table B-1. The data is in the form of conceptual statements and is generally qualitative in nature. Therefore, the qualitative criteria for general agreement will be applied.

B5.4.1 Literature Search

A literature search was performed using SciSearch® and the GeoRef® databases and was focused on recent papers and updates directly relevant and applicable to the analysis. The intent of the search was to identify potential citations that addressed factors that significantly affected rates of diagenesis in arid environments and that quantified the effects of diagenesis in the near subsurface (less than 1 km). The keyword and subject based searches utilized various "AND" combinations for the keywords "diagenesis," "caliche," "silcrete," "duricrust," "duripans," "effects," "factors," and "infiltration" in various combinations. The SciSearch® database (limited to publication dates for 1900 to 2004), for the search term "diagenesis" alone returned 2,940 returns. Addition of the search term "shallow" restricted the search to 380 returns, and further restriction with "effects" generated one return; this was found to not be of particular interest. Use of the combined terms "diagenesis" and "effects" yielded 423 returns. These 423 returns were evaluated based on titles and available abstracts, and only two citations appeared applicable. Use of the individual search terms "silcrete," "duricrust," and "duripans" returned 26, 12, and 2 records, respectively. Only one of these citations was judged applicable.

Using the GeoRef® database, the search on "diagenesis" returned 37,855 records. Restricting the search by adding the term "effects" limited the search to 1900 returns. Further restriction by adding the term "infiltration" yielded only five records. These were reviewed by title and abstract, and none were found applicable. Other searches using various search terms such as "calcrete," "arid," "cementation," "duirpan," and "polygenesis" yield a few more useable citations. Searches on the term "silcrete" yield 352 returns, and addition of the word "effects" restricted the search and yielded only nine returns. A similar search for "duricrust" and "effects" yield 11 returns. These 11 records were reviewed by title and available abstract, and none were found to be applicable. The bibliographies of citations were then reviewed to identify other sources that might be of interest. The combined result of the searches and the preliminary review based on titles and abstracts is reflected in the lists of citations provided in Table B-7.

Citations that were not selected for evaluation were discarded because they dealt with deep diagenetic processes, were focused on description of the characteristics and properties of formations not of particular interest to Yucca Mountain (such as marine deposits or large scale sedimentary and costal basin), or did not appear to characterize the net change in properties since initial disposition or describe factors that affected the rate and extent of the diagenetic process. Additionally, most of the papers available focused on the interrelationship between the formation properties and the potential impact on petroleum or natural gas exploration or production.

B5.4.2 Evaluation of Factors

For each of the sources to be used in the evaluation (whether as direct input or reference only and corroboration of the direct input), pertinent factors are evaluated in tabular form in Table B-7.

Table B-7. Sources and Factors Evaluation for Direct Inputs to Diagenesis

Item	Corroborating Item	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q11	Q12, Q15, C20, C21, C23, C25, C28, C29, C30, C31	Krystinik, L.F. 1990. "Early Diagenesis in Continental Eolian Deposits." Chapter 8 of *Modern and Ancient Eolian Deposits: Petroleum Exploration and Production.* Fryberger, S.G.; Krystinik, L.F.; and Schenk, C.J., eds. Denver, Colorado: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section. TIC: 247781. (DIRS 135295)	This information is taken from a chapter describing early diagenesis in continental eolian deposits and is directly applicable to diagenesis in arid environments.	Book not found in SciSearch®	Special book publication	Moderate – The text provides adequate citations to support the summary discussion of diagenetic processes, and provides summary tables and figures as needed.	Direct Input –The time required for complete diagenesis to occur is less than 10,000 years (p. 8-1) that lithification in desert environments can occur within 5,000 years, and Compaction does not become an important factor until the onset of deep burial: (pp. 8-2 and 8-3) that after initial settling compaction is not a significant diagenetic process until significant burial depth is achieved. Cementation by $CaCO_3$ is not a significant process in rhyolitic tuff due to the lack of carbonate source material: Cements other than carbonate may develop. It also indicates (p. 8-4) that iron, aluminum, and silica may be the primary cements, rather than carbonate.

Table B-7. Sources and Factors Evaluation for Direct Inputs to Diagenesis (Continued)

Item	Corroborating Item	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q12	Q11, C20, C25, C23, C31	Lattman, L.H. and Simonberg, E.M. 1971. "Case-Hardening of Carbonate Alluvium and Colluvium, Spring Mountains, Nevada." *Journal of Sedimentary Petrology, 41,* (1), 274-281. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists. TIC: 223189. (DIRS 129306)	This paper describes field observations on carbonate alluvium and colluvium near Las Vegas, Nevada. Because of the field study location and the nature of the observations, the results are applicable, but likely overstate the case for igneous source materials.	Paper not found in SciSearch®	Peer-reviewed journal	Moderate – This paper addresses field observations rather than laboratory analysis. Field procedures are not discussed, and the number of supporting citations is limited.	Direct Input – The time required for complete diagenesis to occur is less than 10,000 years. The paper indicates (p. 277) that case hardening can occur within a few tens of years.
Q13	Q15	Lattman, L.H. 1973. "Calcium Carbonate Cementation of Alluvial Fans in Southern Nevada." *Geological Society of America Bulletin, 84,* (9), 3013-3028. Boulder, Colorado: Geological Society of America. TIC: 235904. (DIRS 129305)	This paper addresses cementation effects in alluvium and colluvium in southeastern Nevada. The author discusses these processes for basic and igneous material in the absence of a carbonate source, which is a directly applicable situation.	Paper not found in SciSearch®	Technical journal	Low to Moderate – This paper addresses field observations rather than laboratory analysis. Field procedures are not discussed, but a bibliography of cited sources is provided.	Direct Input – Cementation by $CaCO_3$ is not a significant process in rhyolitic tuff due to the lack of carbonate source material (p. 3015) states that calcification is not a significant process for rhyolitic tuffs unless a source for carbonates is present.
Q14	Q15, C20, C27	Reeves, C.C. 1976. *Caliche: Origin, Classification, Morphology and Uses.* Lubbock, Texas: Estacado Books. TIC: 245928. (DIRS 104303)	This book was the only text found devoted to the formation of caliche and other duripans.	Book not found in SciSearch®	Book	High- This book is a survey and comparison of pertinent studies on calcrete, silcrete, and other duripans.	Direct Input – The net effect of shallow diagenesis is to stabilize the surface environment and decrease the net infiltration rates. The book states (p. 110) that the net effect is to decrease infiltration.

Table B-7. Sources and Factors Evaluation for Direct Inputs to Diagenesis (Continued)

Item	Corroborating Item	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q15	Q11, Q14, Q13, C22, C24, C26, C28, C30	Taylor, E.M. 1986. *Impact of Time and Climate on Quaternary Soils in the Yucca Mountain Area of the Nevada Test Site.* Master's thesis. Boulder, Colorado: University of Colorado. TIC: 218287. (DIRS 102864)	This is a Master's thesis focusing on correlation of soils characteristics to paleoclimate effects.	Citation not found in SciSearch®	Thesis – not subject to peer-review, but subject to academic defense.	Moderate to High - Because this is a Master's thesis, the degree of documentation is high, although the quality of the data has not been evaluated within the thesis itself.	Direct Input – SiO_2 cementation is not dependent on climatic conditions, but cementation does exhibit distinctive trends that correspond with the ages of the surficial deposits (p. 86). Accumulation rates are attributable to several climatic scenarios, but climate change was insufficient to significantly decrease the rate of accumulations: (p. 89). $CaCO_3$ may translocate to greater depths given greater precipitation, and cementation is a reversible effect (p.82). Cementation by $CaCO_3$ is not a significant process in rhyolitic tuff due to the lack of carbonate source material. Cements other than carbonate may develop. Accumulation rates for Yucca Mountain favor SiO_2 over Ca CO_3, which is an accessory cement (p. 33). The relationships of $CaCO_3$ and opaline $Si0_2$ for Yucca Mountain soils to climate change are provided (Chapter 5). Additionally, (Figure 9 and pp. 31-33) the relative importance of $Si0_2$ over $CaCO_3$ is discussed.

Table B-7. Sources and Factors Evaluation for Direct Inputs to Diagenesis (Continued)

Item	Corroborating Item	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C20	Not Applicable	Arakel, A.V. 1996. "Quaternary Vadose Calcretes Revisited." *AGSO Journal of Australian Geology and Geophysics, 16,* (3), 223-229. Canberra, Australia: Australian Government Public Service TIC: 255481 (DIRS 167623)	This paper describes the formation and distribution of calcretes in arid vadose zone of western Australia and is, therefore, potentially applicable. However, the focus is on establishing various soil profiles with respect to paleoenvironmental reconstruction and mineral exploration activities.	Paper not listed in SciSearch®	Peer-reviewed journal, but with restricted focus to Australian geology.	Low to Moderate – This paper appears to be a survey of other studies done in the region and is focused on overarching trends in the information, rather than on detailed descriptions of factors and effects.	Indirect Input – This paper provides corroboration for the conceptualization of initial plugging of porosity and permeability (p. 223), and for the "rapid" maturation of cemented soil profiles within a relatively short time (p. 226).
C21	Not Applicable	Baldwin, B. and Butler, C. O. 1985. "Compaction Curve." *American Association of Petroleum Geologists Bulletin, 69,* (4), 622-626. Tulsa, Oklahoma: American Association of Petroleum Geologists. TIC: 255917. (DIRS 167871)	This paper provides compaction curves for sandstones and shales, and shows changes in solidity with burial depth.	161 citations in SciSearch®	Technical journal	Moderate to High – This paper presents a brief review of earlier papers describing compaction curves and provides adequate citations. The paper compares the proposed curves to results of the other studies and discusses the implications of the results and the limitations of other types of curves.	Indirect Input – This paper reproduces the Sclater-Christie sandstone curve (Figure 3), which shows the solidity (i.e., the complement of porosity) is nearly constant above about 100 m, and it approaches but never reaches 100 percent.

Table B-7. Sources and Factors Evaluation for Direct Inputs to Diagenesis (Continued)

Item	Corroborating Item	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C22	Not Applicable	Chadwick, O.A.; Nettleton, W.D.; and Staidl, G.J. 1995. "Soil Polygenesis as a Function of Quaternary Climate Change, Northern Great Basin, USA." *Geoderma, 68,* (1-2), 1-26. New York, New York: Elsevier. TIC: 255603. (DIRS 167626)	This paper describes a soil profile transect in the northern Great Basin, and shows the relationship between climate changes and pedogenic processes.	Seven citations on SciSearch®	Peer-reviewed journal.	Moderate to High – This paper provides an extensive set of tables that summarize various analysis done on soils collected along the transect.	Indirect Input – This paper provides corroboration that climate change drives soil characteristics related to the presence and depth distribution of opaline silica and calcium carbonate. It also indicates that desert loess accumulation is episodic, accumulating more rapidly during interpluvial periods, and the resulting soil profiles have greater surface area, which tends to increase water retention and mineral weathering and decrease the depth of leaching for a given precipitation regime.
C23	Not Applicable	Eghbal, M.K. and Southard, R.J. 1993. "Stratigraphy and Genesis of Durorthids and Haplargids on Dissected Alluvial Fans, Western Mojave Desert, California." *Geoderma, 59,* (1-4), 151-174. Amsterdam, The Netherlands: Elsevier. TIC: 255601. (DIRS 167624)	This paper addresses geomorphology and soils in a desert environment of southwestern California that is similar in many ways to the Yucca Mountain Region. The paper reports results of a trench study through an alluvial fan sequence and associated soils and draws conclusions regarding the distribution of associated duripans.	Five citations in SciSearch®	Peer-reviewed journal	Moderate to High – Detailed soil profile descriptions are provided along with a summary of laboratory methods used for the analyses. The basis for conclusions is clearly stated.	Indirect Input – This paper provides a corroborative value for rate of $CaCO_3$ accumulation needed to form a duripan compared to estimated accumulation rates (pp. 170-171) and attributes the excess accumulation to bioturbation.

Table B-7. Sources and Factors Evaluation for Direct Inputs to Diagenesis (Continued)

Item	Corroborating Item	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C24	Not Applicable	Eghbal, M.K. and Southard, R.J. 1993. "Micromorphological Evidence of Polygenesis of Three Aridisols, Western Mohave Desert, California." *Soil Science Society of America Journal, 57,* (4), 1041-1050. Madison, Wisconsin: Soil Science Society of America. TIC: 255602. (DIRS 167625)	This paper addresses geomorphology and soils in a desert environment of southwestern California that is similar in many ways to the Yucca Mountain Region. The paper thoroughly describes results of a trench study through an alluvial fan sequence and associated soils and draws conclusions regarding the distribution of associated duripans.	Seven citations in SciSearch®	Peer-reviewed journal	Moderate to High – Detailed soil profile descriptions are provided along with a summary of laboratory methods used for the analyses. The basis for conclusions is clearly stated	Indirect Input – One conclusion of this paper is that development of carbonate-free-argillic horizons probably occurred during pluvial periods, whereas calcification occurred during drier periods, and silicification appears to have been contemporaneous with both clay illuviation and calcification and, thus, may be related to pedochemical conditions rather than climate (p. 1049).
C25	Not Applicable	Humphrey, J.D.; Ransom, K.L.; and Matthews, R.K. 1986. "Early Meteoric Diagenetic Control of Upper Smackover Production, Oaks Field, Louisiana." *The American Association of Petroleum Geologists Bulletin, 70,* (1), 70-85. Tulsa, Oklahoma: American Association of Petroleum Geologists. TIC: 246098. (DIRS 118461)	This paper discusses the effects of early meteoric diagenesis on a grainstone formation. The paper discusses rates of early meteoric diagenesis, and indicates that intervals that had been stabilized early were less susceptible to solution compaction that those intervals retaining significant proportions of unstable mineralogy.	20 citations in SciSearch®	Technical journal	Moderate – Results of studies and some supporting information is provided, but analytical procedures are not provided or discussed.	Indirect Input – provides a brief discussion (p. 77-78) of the rate of meteoric diagenesis in carbonate systems in the vadose zone. Shallow vadose diagenesis can reach completion within 10,000 years, while it may take an order of magnitude longer for the deep vadose zone.

Table B-7. Sources and Factors Evaluation for Direct Inputs to Diagenesis (Continued)

Item	Corroborating Item	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C26	Not Applicable	Lattman, L. H. 1972. "Relation of Caliche (Calcrete) Horizons to Alluvial Fan Processes in Southern Nevada." *Abstracts with Programs-Geological Society of America, 4, (7), 574.* Boulder, Colorado: Geological Society of America. TIC: 255828. (DIRS 167813)	This abstract addresses the formation of extensive caliche layers in respect to changes in climate conditions.	Abstract not found in SciSearch®	This information is provided only in abstract form and was presumably not subject to peer-review	Low – Only the abstract is presented. Basis for conclusion is presumably on field observations, but no documentation is provided.	Indirect Input – This abstract corroborates other better-documented sources that link diagenetic processes to climatic conditions.
C27	Not Applicable	Lattman, L. H. 1983. "Effect of Caliche on Desert Processes." Chapter 4 *Origin and Evolution of Deserts.* Wells, S. G.; Haragan, D. R. (eds.). 1^{st} Edition. 101-109. Albuquerque, New Mexico: University of New Mexico Press. TIC: 255700. (DIRS 167815)	This book addresses desert process, and the author of Chapter 4 specifically addresses caliche formation in desert environments.	Book not found in SciSearch®	Book published by the Committee on Desert and Arid Research of the Southwestern and Rocky Mountain Division of the American Associate for the Advancement of Science.	Low to Moderate – This chapter summarizes results of studies and a bibliography of cited sources is included. However, no analytical information is provided.	Indirect Input – This text corroborates statements by others that the rate of caliche formation depends on climate, parent material, supply of calcium carbonate and topography. It also corroborates statements that formation of caliche inhibits infiltration and tends to stabilize the surface (p. 107-108).

Table B-7. Sources and Factors Evaluation for Direct Inputs to Diagenesis (Continued)

Item	Corroborating Item	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C28	Not Applicable	Machette, M. N. 1982. "Morphology, Age, and Rate of Accumulation of Pedogenic $CaCO_3$ in Some Calcareous Soils and Pedogenic Calcrete of Southwestern United States." *GSA Abstracts with Programs, 14,* (4). Boulder, Colorado: Geological Society of America pp 182-183. TIC: 209942. (DIRS 167814)	This abstract addresses the accumulation rate of $CaCO_3$ at various locations in Utah and New Mexico.	Abstract not found in SciSearch®	This information is provided only in abstract form and was presumably not subject to peer-review	Low – Only the abstract is presented. Basis for conclusion is presumably on field observations and laboratory analysis of soil samples, but no documentation is provided.	Indirect Input – This abstract corroborates accumulation rates cited in better-documented journal papers.
C29	Not Applicable	Palmer, S.N. and Barton, M.E. 1987. "Porosity Reduction, Microfabric and Resultant Lithification in UK Uncemented Sands." *Geological Society Special Publication, 36,* 29-40. Oxford, United Kingdom: Blackwell Scientific Publications. TIC: 246095. (DIRS 118483)	This paper addresses the extent of diagenetic change in Jurassic to Recent matrix-free, uncemented sands in the UK that are thought to have experienced only a relatively small depth (<1 km) of burial. However, materials are either beach material or from stable, shelf areas and are shallow water deposits.	Paper not found in SciSearch®	This was extracted from a Special Publication	Moderate to High – The characteristics of the studied materials are well documented. The methods used are mentioned, but not further discussed.	Indirect Input – The results of this paper are used to corroborate the minimal effects of compaction at shallow burial depths (pp. 32 and 39).

Table B-7. Sources and Factors Evaluation for Direct Inputs to Diagenesis (Continued)

Item	Corroborating Item	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C30	Not Applicable	Salem, A.M.K.; Abdel-Wahab, A.; and McBride, E.F. 1998. "Diagenesis of Shallowly Buried Cratonic Sandstones, Southwest Sinai, Egypt." *Sedimentary Geology, 119,* (3-4), 311-335. New York, New York: Elsevier. TIC: 255708. (DIRS 167869)	This paper is focused on description of sandstones deposited on the Arabian shield in fluvial and shallow-marine environments. However, the burial depth is suspected to be no more than 1.5 to 2.5 km, so represent shallow burial effects.	Two citations in SciSearch®	Peer-reviewed journal	Moderate to High – The paper is focused on description of the geologic materials. Procedures are briefly described, and analysis results are provided.	Indirect Input – The paper provides examples of the occurrence of ferricrete and silcretes that represent incipient silcrete cement rather than normal burial quartz cement, and reduction in porosity by compaction was about 19 percent (pp. 319-331).
C31	Not Applicable	Yaalon, D.H. 1967. "Factors Affecting the Lithification of Eolianite and Interpretation of Its Environmental Significance in the Coastal Plain of Israel." *Journal of Sedimentary Petrology, 37,* (4), 1189-1199. Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists. TIC: 255600. (DIRS 167622)	This paper addresses the early diagenesis of eolian deposits in a coastal plain setting in southern Israel.	Citation not found in SciSearch®	Peer-reviewed journal	Moderate – Sampling and analytical procedures are discussed and results are provided.	Indirect Input – This paper provides corroboration for the rate of lithification (p. 1189) and indicates the percent of $CaCO_3$ needed to initiate lithification in coastal sands (p. 1194).

B5.4.3 Discussion

Corroboration of direct input is discussed under four general topics: the time required for diagenesis, the relationships between diagenesis and climate, the role of compaction, and the role of cementation.

B5.4.3.1 Time Required for Diagenesis

The conditions being justified and the associated direct input are as follows:

> The time required for complete diagenesis to occur is less than 10,000 years: This is taken from Items Q11 and Q12. Corroboration is given in Items C20, C23, C25, C28, and C31.

Direct inputs related to the time required for complete diagenesis come from Krystinik (1990 [DIRS 135295], p. 8-1) (Q11) and from Lattman and Simonberg (1971 [DIRS 129306], p. 277) (Q12), Krystinik states that cementing minerals can precipitate in quantities sufficient to lithify sand to friable sandstone in less than 5,000 years. Lattman and Simonberg cite several examples of roadcuts and gully banks that are case-hardened in the timeframe of a few tens of years.

Corroborating sources include Arakel (1996 [DIRS 167623], p. 226) (C20), which indicates that rapid maturation of cemented soils profiles can occur within a relatively short time – within the context of the paper, a relatively short time is inferred to be within the time scale of 10,000 years, though a quantitative statement is not made. Humphreys et al. (1986 [DIRS 118461], pp. 76-78) (C25) provides citations for carbonate systems that indicate that diagenesis in shallow vadose zones subject to meteoric processes may reach completion within a few thousand years, but deeper vadose zone diagenesis may be much more prolonged. Machette (1982 [DIRS 167814]) (C28) and the paper by Eghbal and Southard (1993 [DIRS 167624], p. 170-171) (C23) provide $CaCO_3$ accumulation rates that range from 0.03 g/cm^2 to as great as 0.26 g/cm^2 per 1000 years. Yaalon (1967 [DIRS 167662], p.1189) (C31) indicates that as little as 8 percent $CaCO_3$ is sufficient to initiate lithification. If one assumes a soil density of 1.9 gm/cm^3, then only 0.15 gm of $CaCO_3$ is needed to initiate lithification. Depending on the accumulation rate, this could occur on the timescale of less than 1,000 years (assuming an accumulation rate of 0.26 g/cm^2 per 1,000 years) to on the order of 5,000 years (assuming an accumulation rate of 0.03 gm/cm^2). Thus, the direct inputs are corroborated by other sources.

Diagenetic Effect Relationship to Climate

The conditions being evaluated and the associated direct input are as follows:

> SiO_2 cementation is not dependent on climatic conditions, but cementation does exhibit distinctive trends that correspond with the ages of the surficial deposits. This is taken from Item Q15. This is corroborated in Items C22, C24, and C26.
>
> Accumulation rates are attributable to several climatic scenarios, but climate change was insufficient to significantly decrease the rate of accumulations. This is taken from Item Q15. This is corroborated in Items C23 and C28.

$CaCO_3$ may translocate to greater depths given greater precipitation, and cementation is a reversible effect. This is taken from Item Q15 and corroborated by Items C22 and C26.

Because the time frame of interest is 10,000 years, the potential for effects of climate change on shallow diagenesis must be considered. As direct input, Taylor (1986 [DIRS 102864], Chapter 5) (Q15) indicates silts that formed in alluvium and eolian fines of Holocene to early Pleistocene or late Pliocene age near Yucca Mountain are characterized by distinctive trends in the accumulation of secondary clay, $CaCO_3$, and opaline SiO_2 that correspond with the ages of the surficial deposits. However, there is no macro- or micromorphological evidence that suggests that silica cementation occurred under climatic conditions cooler and wetter than those of present climate. In contrast, Taylor also states that accumulation rates of these materials during the Holocene can be attributed to several possible climatic scenarios associated with the Holocene-Pleistocene climate change, but suggest that precipitation has not been a limiting factor, and that climatic change was not sufficient to significantly decrease rate of accumulation. Taylor also suggests that the climatic change was the result of decreases in temperature rather than precipitation. Modeling results discussed by Taylor suggest that increased precipitation in the future may translocate $CaCO_3$ accumulations to greater depths, where precipitation is greater. Taylor also suggests that the cementation process, particularly for $CaCO_{3,}$ is reversible, and that the material can be redissolved and moved deeper into the soil profile.

The dependence of the accumulation depth of $CaCO_{3,}$ and the dependence of other diagenetic effects related to chemical changes is corroborated by several sources. Eghbal and Southard (1993 [DIRS 167625], p. 1049) (C24) suggest that, in the Mojave Desert, development of carbonate-free argillic horizons probably occurred during pluvial periods, whereas calcification occurred during drier periods. Silicification appears to have been contemporaneous with both clay illuviation and calcification and, thus, may be related to pedochemical conditions rather than to climate. This corroborates the results by Taylor (1986 [DIRS 102864], Chapter 5) discussed above, and for a similar arid setting. Eghbal and Southard further unequivocally state that soils in arid regions are often polygenetically related to climatic variations. This trend for calcification is also corroborated in the abstract by Lattman (1972 [DIRS 167813]) (C26) in the statement that "It is suggested that extensive calcrete layers in southern Nevada formed during and immediately following the onset of pluvial periods which were times of fan aggradation. They were generally destroyed during the interpluvial, which were times of fan stability or degradation." This statement also tends to suggest that calcification effects may be reversible, whereas silicification may be ongoing regardless of the climate state. Further corroboration is gained from Chadwick et al. (1995 [DIRS 167626]) (C22), which documents changes in soil profiles along a transect that reflect cooler and wetter conditions due to elevation changes. However, these serve as a surrogate for change in climate conditions. In particular, they observed that climatic extremes drive pedogenic processes that leave polygenetic imprints on soils of Pleistocene age. In particular, soils that are now dominated by opaline silica, carbonate, and smectite, contain evidence of earlier, more acidic, chemical environments conducive to dissolution of primary carbonate and formation of kaolinite. During interglacial times (i.e., drier and warmer), Chadwick et al. attribute the changes to more eolian activity and less effective moisture combining to decrease the depth of leaching, increase base cations, and modify the soil chemical environment in relict paleosols.

This trend toward increased calcification during pluvial times is corroborated in the accumulation rates noted in the abstract by Machette (1982 [DIRS 167814]) (C28), who indicates that soils <25,000 years old have accumulation rates 2-3 times higher that older soils. This observation is attributed to "less effective precipitation and vegetation cover in Holocene time," which is due in large part to a drier climate state. The increased accumulation rates of $CaCO_3$ are also noted by Eghbal and Southard (1993 [DIRS 167624], p.170-171) (C23).

Reversibility of cements is mutually corroborative with Krystinik (1990 [DIRS 135295], p. 8-4) (Q11), who clearly indicates that cementations processes are reversible. Indirect inputs also corroborate this aspect of cementation. Chadwick et al. (1995 [DIRS 167626]) (C22) note that climatic drying at the end of the Pleistocene decreased leaching depth by about 150 cm, and corroborates the changes modeled by Taylor (1986 [DIRS 102864]). This trend for calcification during pluvial periods and decalcification during interpluvial periods is also corroborated in the abstract by Lattman (1972 [DIRS 167813]) (C26) mentioned above, and points to the reversibility of the calcification process at any given location.

Compaction During Shallow Diagenesis

The conditions being justified and the associated direct input are as follows:

> Compaction does not become an important factor until the onset of deep burial: This is taken from Item Q11. It is corroborated by Items C21, C29, and C30.

The two primary mechanisms for early and shallow diagenetic changes are related to compactions and cementation. Krystinik (1990 [DIRS 135295], pp. 8-3 and 8-4) (Q11) indicates that early diagenesis "begins at or near the depositional interface and entails weathering, compaction, cementation and numerous allied physical, chemical and biochemical processes, at temperature below 50 degrees C." As direct input, Krystinik notes that "wind-laid sand can be deposited with up to 25-40 percent porosity and that early compaction reduces porosity to 20-30 percent, depending upon sorting." Krystinik further states that "Beyond increasing capillarity, compaction does not generally become an important factor in diagenesis until the onset of grain deformation and pressure solution during deeper burial diagenesis." By minimizing compaction, then, the primary means of diagenesis becomes cementation processes.

By way of corroborating the role of compaction in early diagenesis, Palmer and Barton (1987 [DIRS 118483], pp. 32 and 39) (C29) compare similar, uncemented sands of increasing ages and burial depth with porosities. In the first 169 meters of burial, the porosity of the sand decreases from 47.2 to 35.6 percent, but from 169 m to 780 meters, the compaction only decreased the porosity an additional 2 percent, for a total decrease of 13.6 percent. This corroborates Krystinik's assertion of an initial reduction of no more than few percent, followed by minimal effects. The lack of compaction during initial burial is also corroborated by the Sclater-Christie compaction curve given in Baldwin and Butler (1985 [DIRS 167871], Figure 3) (C21). The curve shows that change in porosity during the first 300 m of burial is insignificant, but becomes increasingly more important at greater depths, with changes of up to 50 percent porosity relative to the initial porosities occurring at depths approaching 10 km. However, Baldwin and Butler also caution that sandstones show considerable scatter in solidity-depth values and indicate that ranges in values of 25 percent are common. As a "case-in-point," the work by Salem et al. (1998

[DIRS 167869], pp. 319-331) (C30) on cratonic sandstones indicates that sandstones undergoing burial between 1.5 and 2.5 km exhibited only a 19 percent total porosity loss due to compaction. The results of this work match well with the compaction curves of Baldwin and Butler for a 1 to 2 km burial depth, and further corroborates Krystinik's assertion that compaction plays only a minor role during the early stages of shallow burial and diagenesis.

Cementation During Shallow Diagenesis

The conditions being justified, and the associated direct input, are as follows:

- The net effect of shallow diagenesis is to stabilize the surface environment and decrease the net infiltration rate*:* This is taken from Item Q14 and is corroborated in Items C20 and C27.

- Cementation by $CaCO_3$ is not a significant process in rhyolitic tuff due to the lack of carbonate source material*:* This is mutually corroborative for Items Q11, Q13, and Q15.

- Cements other than carbonate may develop: This is mutually corroborative for Items Q11, Q13, Q15, and corroborated by Item C30.

- Accumulation rates for Yucca Mountain favor SiO_2 over $CaCO_3$, which is an accessory cement: This is mutually corroborative with Items Q11, Q13, and Q15.

With regard to the role of cementation in diagenesis and its effects, Reeves (1976 [DIRS 104303], p. 110) (Q14) indicates that the net effects of shallow diagenesis and associated cementation is to decrease the net vertical infiltration rate and sites multiple studies to support that assertion. This net reduction in infiltration is corroborated by Lattman (1983 [DIRS 167815], pp. 107-108) (C27) who states, "The formation of caliche inhibits infiltration into a topographic surface. The degree of this inhibition is a function of density and induration of the caliche. Petrocalcic horizons, laminar layers, and case-hardened layers cause the greatest inhibition." It is also corroborated by Arakel (1996 [DIRS 167623], p. 223) (C20) who refers to progressive plugging of initial porosity/permeability zones. It should be pointed out that while this holds true for the carbonates, Taylor (1986 [DIRS 102864]) (Q15) indicates that in the YMP soils studied, in the absence of effective precipitation or drainage to remove newly dissolved silica, it is precipitated elsewhere within the calcrete horizon, or $CaCO_3$ preferentially precipitates after opaline silica bonds adjacent soil grains. Taylor notes that this process may occur without necessarily plugging intervening pores spaces.

Taylor (1986 [DIRS 102864], Figure 9) (Q15) indicates that the accumulation rate of $CaCO_3$, while occurring, is significantly less than that for SiO_2. This is reflected in statements indicating that carbonate is primarily derived from airborne dust and the opaline SiO_2 from in-place weathering of the parent material and that the cementation by opaline SiO_2 is common in the study area and that opaline SiO_2 accumulation in the soils is favored over that of $CaCO_3$. Taylor also indicates SiO_2 cementation is common in the study area, with $CaCO_3$ as an accessory cement. The direct input from Taylor indicating the predominance of SiO_2 over carbonate in the soil cements is mutually corroborative with direct input by Lattman (1973 [DIRS 129305], p. 3015) (Q13). In studies near Las Vegas, Lattman observed that calcium carbonate cementation is not necessarily a significant cementation process in rhyolitic tuffs due to the lack of carbonate source materials. The above statements by Lattman and Taylor's observations of the predominance of SiO_2 cements mentioned above, is mutually corroborative with statements from Krystinik (1990 [DIRS 135295], p. 8-4) (Q11) that cements other than carbonate may develop, particularly iron, silica, and aluminum. Yaalon (1967 [DIRS 167622], p. 1189) (C31) corroborates this by indicating that one of the controlling factors in diagenesis of eolian sands is the original content of $CaCO_3$. As a corroborative example from indirect input, the presence of cements other than carbonate in arid environments is proposed by Salem et al. (1998 [DIRS 167869], pp. 319-331) (C30). In that particular study, the predominant cements stemming from the generally arid environment were iron and silica.

B5.4.4 Data Status and Limitations

For qualitative data, the criterion of general agreement has been satisfied. The above literature review and corroboration of the direct input provides an acceptable level of confidence that the data are suitable for their intended use, which is for FEP screening. The status of the direct inputs for diagenesis evaluated above should be considered as qualified for use within this technical product. No limitations on use of the qualified data are needed.

B5.5 SUITABILITY DEMONSTRATION OF DIRECT INPUT FOR FEP 1.5.01.01.0A METEORITE IMPACT

The analysis for meteorite impact probability and consequence requires the use of direct input, cited from technical journals and other non-YMP originated sources, to represent the full range of the possible types and size of meteorites potentially striking the repository within a 10,000-year time frame, and the resulting exhumation and fracturing depths and characteristics. This section provides a justification for use of the meteor-related direct input based on its adequacy and appropriateness for its intended use for FEPS screening.

The general type of information and specific topics being addressed follows:

- Meteoroid Flux Entering Earth's Atmosphere
  - Flux data for a range of meteor masses: Taken from Item Q16.
- Compositions and Material Properties of Meteoroids
  - Flux data, by meteor type and related densities: Taken from Item Q17
  - Values for percent of meteor that are of iron composition: Taken from Item Q23.
- Crater Diameter Distributions and Rates
  - Crater rate distribution based on observed earth cratering: Taken from Item Q19 and Q20
  - Cratering rate data for the Canadian shield and application to a hypothetical Canadian repository: Taken from Item Q24.

- Crater Dimensions as a Function of Meteor Type
  - Results of a model (by others) linking a variety of effects to initial meteor radius, including resulting crate diameters and related consequences: Taken from Item Q22.
- Depth and Extent of Crater Features
  - Diameters associated with onset of complex cratering: Taken from Items Q19, Q20, and Q24
  - Crater diameter to depth of effect relationships: Taken from Items Q18, Q21, and Q24.

The data being evaluated include Items Q16 through Q24 in Table B-1. The evaluation criteria for quantitative data are applied. Corroboration will be considered acceptable, if "singular" values (e.g., mean velocity or percent by composition) are shown to be within two standard deviations of the mean value, with the mean and deviations developed by equal weighting of reported mean values from each source. In the case of probability distributions or equations based on probability distributions (e.g., mass flux or cratering rates), corroboration will be considered acceptable if the resulting probability distributions fall within 2 orders of magnitude for any given point in the distribution (e.g., for the probability of crater diameter of a given size).

B5.5.1 Literature Search

A focused literature search was performed to identify past analyses of meteorite impact probabilities for underground facilities (particularly repositories); for current information and studies related to meteorite impact probabilities; for current information and direct input on meteor characteristics; and for information related to crater features and dimensions. The literature search was focused on recent papers and updates, and on information directly relevant and applicable to the analysis. The results of the literature search, using Internet based search engines and the GeoRef® database, and after screening based on titles and abstracts, are given in Table B-8.

B5.5.2 Evaluation of Factors

For each of the sources to be used in the evaluation (whether as direct input as data or as indirect input for corroboration), these factors are evaluated in tabular form in Table B-8.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q16	C32, C33, C35, C36, C37, C40, C42, C44	Ceplecha, Z. 1992. "Influx of Interplanetary Bodies onto Earth." *Astronomy and Astrophysics, 263,* 361-366. New York, New York: Springer-Verlag. TIC: 246784. (DIRS 135242).	This paper represents a compilation of results of studies by others addressing mass flux over a wide range of masses. The paper provides cumulative mass by number of events for meteoroids coming to the earth's atmosphere. Also provides a means to relate mass to impact velocity at the surface if needed.	No prior use for repository design. However, subsequent related papers cite author. Science Citation Index indicates 49 citations.	This paper taken from a respected, peer-reviewed journal (Astronomy and Astrophysics).	Moderate - Citation to the original sources are provided. Quality of derivation of conclusions regarding consequences is moderate but adequate for intended purpose of the paper, and supporting equations are provided. Does not rely solely on single method to determine flux, such as kinetic energy observations, and thus can be corroborated using multiple flux measurements methods.	Direct Input – Flux data for a range of meteor masses. Indirect Input – Provides corroborative-use only information for crater radius comparison.
Q17	For percent by type: Q17 (from an independent data set), C40, C43 For densities: Q17 (from an independent data set), C32, C35, C36, C37, C39, C40, C45	Ceplecha, Z. 1994. "Impacts of Meteoroids Larger than 1m into the Earth's Atmosphere." *Astronomy and Astrophysics, 286,* (3), 967-970. New York, New York: Springer-Verlag. TIC: 246761. (DIRS 135243), Q17	The paper focuses on determining differences in meteor compositions based on differences in atmospheric penetration based on photographed meteors and fireballs. This information is then categorized by type and bulk densities, and types are assigned a percentage basis. Paper is of interest primarily because it provides a distribution of meteors by type for meteoroids with diameters on the order of <1 to 10 m, which is within the range of interest for possible repository damage.	No prior use for repository design. Science Citation Index indicates 17 citations.	This paper was taken from a respected, peer-reviewed journal (Astronomy and Astrophysics).	Moderate – The absence of the presentation of the original information and the process used to "normalize" for classification is lacking. Discussion of methods used to obtain the initial information is not provided. However, paper represents one of the few attempts to categorize small meteoroids by type.	Direct Input – Flux data, by meteor type and related densities.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q18	Q21, Q24	Dence, M.R.; Grieve, R.A.F.; and Robertson, P.B. 1977. "Terrestrial Impact Structures: Principal Characteristics and Energy Considerations." *Impact and Explosion Cratering, Planetary and Terrestrial Implications, Proceedings of the Symposium on Planetary Cratering Mechanics, Flagstaff, Arizona, September 13-17, 1976.* Roddy, D.J.; Pepin, R.O.; and Merrill, R.B., eds. Pages 247-275. New York, New York: Pergamon Press. TIC: 247237. (DIRS 135253).	This is a seminal work in the area of impact cratering and provides a listing and discussion of development of observed crater characteristics. Paper relates energy release and dissipation in the subsurface, which is a principal property of interest.	The effects addressed in this paper have been used in other repository design considerations, and the energy release equations are often cited in other works in the subject area. Science Citation Index indicates 17 citations.	This paper was extracted from an edited compendium of related work. The effects addressed in this paper have been used in other repository design considerations and the cratering rate is generally accepted due to its basis on observed features.	Moderate – The paper provides a summary of characteristics of craters and respective dimensions and compares cratering effects to those of nuclear testing. No information on procedures or quality control is provided.	Direct Input – Crater diameter to depth of effect relationships. Indirect Input – Provides corroborative-use only information for crater radius related to iron meteors.
Q19	Q20, Q24, C32, C35, C4, C42	Grieve, R.F. 1987. "Terrestrial Impact Structures." *Annual Review of Earth and Planetary Sciences, 15,* 245-269. Palo Alto, California: Annual Reviews. TIC: 246788. (DIRS 135254), Q19	This is a seminal work in the area of impact cratering and lists observed craters, crater characteristics, and cratering rates. The paper provides relationships of crater diameter to crater depth and provides a cratering rate estimate for large-diameter craters that are generally used in hazard estimates.	The effects addressed in this paper have been used in other repository design considerations and are heavily cited in other works in the subject area. Science Citation Index indicates 23 citations.	This paper was taken from a peer-reviewed journal. The effects addressed in this paper have been used in other repository design considerations.	Moderate – The documentation is somewhat limited, but is generally accepted as reliable and has been updated on a periodic basis. No information on procedures or quality control is provided.	Direct Input – Crater rate distribution based on observed earth cratering.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q20	Q19, Q24, C32, C35, C40, C42	Grieve, R.; Rupert, J.; and Therriault, A. 1995. "The Record of Terrestrial Impact Cratering." *GSA Today, 5,* (10), 194-196. Boulder, Colorado: Geological Society of America. TIC: 246688. (DIRS 135260)	This is an update to the 1987 paper by the primary author. It provides updated cratering information, refines the constants, and addresses the limits for simple and complex cratering.	The effects addressed in this paper have been used in other repository design considerations and are heavily cited in other works in the subject area. Update to previous paper. Science Citation Index indicates seven citations.	This paper was taken from a technical journal. Acknowledgments are given to peer-reviewers on an earlier version of the document.	Moderate to High – This paper provides a listing of observed cratering impact structures and their diameters and ages, allowing independent confirmation of the developed distribution. A thorough reference list is also provided.	Direct Input – Diameters associated with onset of complex cratering (4 km) (p. 194). Crater rate distribution based on observed earth cratering.
Q21	Q18, Q24	Grieve, R.A.F. 1998. "Extraterrestrial Impacts on Earth: The Evidence and the Consequences." *Meteorites: Flux with Time and Impact Effects.* Grady, M.M.; Hutchinson, R.; McCall, G.J.H.; and Rothery, D.A., eds. Geological Society Special Publication No. 140. Pages 105-131. London, England: Geological Society. TIC: 254143. (DIRS 163385)	This is an update and summary of previous papers and summarizes the results of studies to date, and provides a distinction of the cratering effect data based on craters in sedimentary and crystalline materials.	This paper is focused on updating the “state of knowledge” regarding the number of craters, cratering mechanics, shock metamorphism, and effect of impacts on biological evolution.	This paper was taken from a compendium addressing flux with time and impact effects.	Moderate – This paper is focused on updating the “state of knowledge” and summarizing the corresponding findings, rather than reporting new results of research. An extensive reference list is provided.	Direct Input – Crater diameter to depth of effect relationships.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q22	Q16, Q18, Q23, (these Q items are not mutually corroborative back to Q22), C32, C36, C37, C40	Hills, J.G. and Goda, P.M. 1993. "Fragmentation of Small Asteroids in the Atmosphere." *The Astronomical Journal, 105,* (3), 1114-1144. Woodbury, New York: American Institute of Physics. TIC: 246798. (DIRS 135281).	Paper focuses on evaluating effects of small asteroids impacting the Earth. Paper deals with a multitude of related consequences and serves to relate initial meteor diameters to crater diameters over the range of crater diameters of interest. The paper considers several interrelated physical phenomena to derive resulting crater diameters.	No prior use for repository design. Science Citation Index indicates 81 citations.	This paper was taken from a peer-reviewed journal.	Moderate to High – Los Alamos National Laboratory prepared the work, and the development of the models is well documented and supporting equations are provided. No information is provided on quality control or development procedures. Results are presented for a variety of meteor types and for a wide range of velocities, which allows the paper to be corroborated from other multiple sources.	Direct Input – Crater Dimensions as a function of meteor type. Figures 16 and 17 provide key meteor radius to crater diameter relationship information.
Q23	Q23 (independent data set) C34, C37, C39, C43	Shoemaker, E.M. 1983. "Asteroid and Comet Bombardment of the Earth." *Annual Review of Earth and Planetary Sciences, 11,* 461-494. Palo Alto, California: Annual Reviews. TIC: 246922. (DIRS 135308).	This paper focuses on the roles of asteroids and comet nuclei on the rate of crater formation. Includes a review of astronomic and geologic information and provides citations to support the summaries. This paper is applicable with regard to flux, composition, meteor size–to-crater-diameter relationships, and cratering rate.	No prior use for repository design. Science Citation Index indicates 94 citations-	This paper was taken from a peer-reviewed journal.	Moderate – Sources are fully documented. Assumptions and bases for conclusions are clearly outlined. No information is provided on procedures used or quality control.	Direct Input – Values for percent of meteor that are of iron composition. Indirect Input – Provides corroborative only information for crater radius.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q24	Q18, Q19, Q20, Q21, C32, C35, C40, C42	Wuschke, D.M.; Whitaker, H.H.; Goodwin, B.W.; and Rasmussen, L.R. 1995. *Assessment of the Long-Term Risk of a Meteorite Impact on Hypothetical Canadian Nuclear Fuel Waste Disposal Vault Deep in Plutonic Rock.* AECL-11014. Pinawa, Manitoba, Canada: Atomic Energy of Canada Limited, Whiteshell Laboratories. TIC: 221413. (DIRS 129326).	This paper is directly applicable as it presents a well-documented evaluation equivalent to the evaluation needed for YMP. The paper provides a detailed analysis of the hazard and risk associated with meteorite impact above an underground repository. Assumptions, spatial relationships, mathematical formulations, and uncertainty analysis are all documented within the report.	Paper was prepared by AECL Research to evaluate risk from meteorite impact on a hypothetical underground repository. Science Citation Index indicates no citations.	The paper reports results of a specific technical analysis. No information on prior peer review is available.	High – Citations are provided for all sources and uncertainty analyses are provided. Cites non-peer reviewed work.	Direct Input – Cratering rate data for the Canadian shield and application to a hypothetical Canadian repository.
C32		Bailey, M.E. and Emel'Yanenko, V.V. 1998. "Cometary Capture and the Nature of the Impactors." Meteorites: Flux with Time and Impact Effects. Grady, M.M.; Hutchison, R.; McCall, G.J.H.; and Rothery, D.A.; eds. Geological Society Special Publication No. 140. Pages 11-17. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162564)	Technically Adequate – Paper is focused on addressing uncertainty in the number of particular type comets present and uses existing equations and information from others to develop the argument with regard to cratering rates.	Paper provides information on diameter distributions, associated cratering rates, and provides input on assumed density of asteriods and comets. Low to Moderate. Provides an independent means to establish meteor diameter distribution and cratering rate. Provides densities. Used primarily as	No prior use for repository design considerations. Science Citation Index indicates 1 citation.	Taken from edited and refereed compendium from Geologic Society of London (31 referees, including two who are routinely cited in work of this nature).	Indirect Input – Low to Moderate – None beyond that provided in paper.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C32 (Cont.)				source of corroborative-use-only information for cratering rates.			
C33	Not Applicable	Bland, P.A.; Conway, A.; Smith, T.B.; Berry, F.J.; Swabey, S.E.J.; and Pillinger, C.T. 1998. "Calculating Flux from Meteorite Decay Rates: A Discussion of Problems Encountered in Deciphering a 10^5–10^6 Year Integrated Meteorite Flux at Allan Hills and a New Approach to Pairing." *Meteorites: Flux with Time and Impact Effects.* Grady, M.M.; Hutchison, R.; McCall, G.J.H.; and Rothery, D.A.; eds. Geological Society Special Publication Mo. 140. Pages 43-58. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162563).	This paper is focused on identifying problems and methodologies for pairing of meteorite fragments. It addresses limitations with application of meteorite information to flux and composition determinations.	No prior use for repository design Science Citation Index indicates one citation.	This paper was extracted from an edited and refereed compendium of the London Geologic Society (31 referees, including two who are routinely cited in work of this nature).	Moderate – The paper cites heavily to other related studies and fully documents associated problems, uncertainties, and limitations of its applications. Cites and summarizes previous work of others and thus provides an independent source of information regarding falls to earth.	Indirect Input – Provides summary of multiple related flux studies and provides corroborative-use only information for flux evaluation.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C34	Not Applicable	Bevan, A.W.R.; Bland, P.A.; and Jull, A.J.T. 1998. "Meteorite Flux on the Nullarbor Region, Australia." *Meteorites: Flux with Time and Impact Effects.* Grady, M.M.; Hutchison, R.; McCall, G.J.H., and Rothery, D.A.; eds. Geological Society Special Publication No. 140. Pages 59-73. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162565).	This paper focuses on summarizing meteorite falls in Australia. It is based on collected specimens, and identifies limitations and potential biases of human collections and problems of the sample area are addressed. Addresses mass distribution and frequency of meteorite falls, and breaks out the falls on a percentage-by-type basis.	No prior use for repository design purposes. Science Citation Index indicates one citation.	This paper was extracted from an edited and refereed compendium of Geologic Society of London (31 referees, including two who are routinely cited in work of this nature).	High – information is well characterized; limitations are fully acknowledged; information from related studies are provided for context; and differing interpretations are considered.	Indirect Input – Provides baseline corroborative-use only information for comparison of several meteorite falls with regard to frequency and type. It provides corroborative information for percent of iron meteors.
C35	Not Applicable	Brown, P.; Spalding, R.E.; ReVelle, D.O.; Tagliaferri, E.; and Worden, S.P. 2002. "The Flux of Small Near-Earth Objects Colliding with the Earth." *Nature, 420,* (6913), 294-296. London, England: Macmillan Journals. TIC: 254145. (DIRS 162569).	The study is based on use of state-of-the-art U.S. Department of Defense and U.S. Department of Energy space-based systems in geostationary orbits, and represents eight years of collection efforts and 300 samples representing between 60% and 80% earth coverage. The results represent in essence a "whole earth" detection using state-of-the-art satellite observation. Study is particularly targeted to the meteor diameters of interest.	No prior use for repository design purposes. Paper was published in November 2002, and represents best "direct" measurement of flux into the atmosphere. Paper provides comparison to similar information from related programs. Science Citation Index indicates three citations.	This paper was taken from a highly respected peer reviewed journal (Nature).	High - Paper is well documented and cites many of the authors used for the evaluation. Assumed values are clearly identified. Uncertainty is estimated at less than 30%, which is the least uncertainty documented in studies of this type found during the literature survey. Also clearly states assumptions regarding velocities and assumed densities for meteorites and basis for assumptions.	Indirect Input – This paper represents the most current information of this type available and covers the range of interest with a reasonably large sample set. Used for corroboration of flux and crater rate distribution. Summary equation provided to determine flux rates based on meteoroid diameter and in terms of bolide energy.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C36	Not Applicable	Chapman, C.R. and Morrison, D. 1994. "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard." *Nature, 367,* (6458), 33-40. New York, New York: Nature America. TIC: 246781. (DIRS 135245)	Paper provides a short review of past influx studies and discusses velocities and densities as well as rates and potential resulting hazards. Paper is focused on determining hazard of surface effects from asteroid impact.	No prior use for repository design. Science Citation Index indicates 65 citations.	This paper was taken from a highly respected peer-reviewed journal (Nature).	Moderate – Basis of influx used in analysis of hazard is well documented. Assumed flux and justification is provided and uncertainty in assumed values is provided and stated as between a factor of 2 and 5. Overly conservative values chosen for determining risk. However, the paper is focused on surface effects rather than cratering.	Indirect Input – This paper provides a good overall corroborative summary of influx information, and through Figure 1, links impact interval, diameter, and equivalent yield. It also provides several “singular” events and related probabilities that are corroborative-use-only information.
C37	Not Applicable	Chyba, C.F. 1993. "Explosions of Small Spacewatch Objects in Earth's Atmosphere." *Nature, 363,* (6431), 701-703. London, United Kingdom: Macmillan Journals. TIC: 246762. (DIRS 135248).	Paper provides a short review of past influx studies and discusses velocities, densities, and probabilities of impact. Paper presents results of direct observation of meteors and impact probabilities are discussed.	No prior use for repository design. Cited by later papers and compared to updated information or information obtained by independent means. Science Citation Index indicates 13 citations	This paper was taken from a highly respected peer-reviewed journal (Nature).	Moderate to High – The paper is based on original information obtained from an on-going observation program and compared to results of similar programs. No information on procedures or quality control is provided.	Indirect Input – Paper provides corroborative information on observed velocities and influx of small-diameter objects, which are of particular interest. Provides corroborative information on percent irons and densities, and provides corroborative information for determining resulting crater radius.
C38	Not Applicable	Hartmann, W.K. 1966. *Terrestrial and Lunar Flux of Large Meteorites Through Solar System History.* Publication No. 3. Tempe, Arizona: Arizona State University, Center for Meteorite Studies. TIC: 254144. (DIRS 162567).	The paper deals directly with earth cratering rates for larger scale (>1-km) craters.	Not used for repository design. Science Citation Index indicates no citations. Author was cited for the WIPP meteorite analysis.	No information on peer review process.	Low to Moderate – Paper published by Arizona Statue University’s Center for Meteorite Studies and therefore, considered reliable within context of the time of publishing. However, this paper is dated and, therefore, technical accuracy is limited. It provides a glimpse of	Indirect Input – This paper provides an initial baseline, but due to dated information and limited number of observations should not be given equal weight to papers of a similar nature. This source is not further considered in this evaluation.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C38 (Cont.)						early estimated cratering rates based on initial observations of earth and lunar cratering counts.	
C39	Not Applicable	Hills, J.G. and Goda, P.M. 1998. "Damage from the Impact of Small Asteroids." *Planetary and Space Science, 46,* (2-3), 219-229. Oxford, United Kingdom: Elsevier. TIC: 246675. (DIRS 135291).	Addresses additional variables for considering effects of meteor impacts. This is a follow-on paper that addresses the potential for variation of impact effects due to initial entry angle. It is an expansion of the preceding paper by the same authors.	No prior use for repository design. Science Citation Index indicates three citations.	This paper was taken from a peer - reviewed journal.	Moderate to High – Documentation is similar to that provided in the preceding paper.	Indirect Input – The results of the paper justify use of bounding conditions by establishing a “worst case” condition for angle of entry. It is not further considered in this analysis, but is used to support vertical entry as a bounding consideration.
C40	Not Applicable	Hughes, D.W. 1998. "The Mass Distribution of Crater-Producing Bodies." *Meteorites: Flux with Time and Impact Effects.* Geological Society Special Publication No. 140. Grady, M.M.; Hutchison, R.; McCall, G.J.H.; and Rothery, D.A.; eds. Pages 31-42. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162562).	Paper addresses three factors that define basic relationships of meteor flux to cratering rates. The analysis is applicable to very large diameter meteoroids. The paper uses a subset of highly defensible cratering information to perform an evaluation of various equations and related uncertainties.	No prior use in repository design. Science Citation Index indicates five citations.	This paper was extracted from an edited and refereed compendium of the London Geologic Society of London (31 referees, including two who are routinely cited in work of this nature).	Moderate – Paper provides a good summary of preceding work by others and performs an evaluation of these various sets and range of equations. This paper addresses three interrelated factors, the crater rate equation, the energy diameter equation, and the mass distribution equation. No documentation on procedures or quality control is provided.	Indirect Input – This paper primarily addresses large diameter meteors, which end up being excluded from consideration on a probability basis. However, the paper does provide corroborative–use only information for influx, cratering rate, and meteor properties.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C41	Not Applicable	Marsden, B.G. and Steel, D.I. 1994. "Warning Times and Impact Probabilities for Long-Period Comets." *Hazards Due to Comets and Asteroids.* Gehrels, T., ed. 221-237. Tucson, Arizona: University of Arizona Press. TIC: 246879. (DIRS 129308)	This paper directly addresses probability of intersection with earth and is, therefore, directly applicable. Paper focuses on determining the probability of impact from long period comets under varying sets of assumptions regarding orbital characteristics. The sources used in this analysis are well documented within the paper and the study addresses 411 observed long period comets.	No prior use for repository design. Science Citation Index indicates nine citations.	This paper was extracted from an edited compendium of related papers.	Moderate to High – Paper documents both the theory and practical application used to develop the probabilities of intersection. No documentation on procedures or quality control is provided.	Indirect Input – The paper is useful in defining the range of probabilities of long period comets over a range of assumptions regarding orbital characteristics and supports excluding impact from long period comets based on individual and mean impact probabilities. No further consideration in this evaluation.
C42	Not Applicable	Neukum, G. and Ivanov, B.A. 1994. "Crater Size Distributions and Impact Probabilities on Earth from Lunar, Terrestrial-Planet, and Asteroid Cratering Data." *Hazards Due to Comets and Asteroids.* Gehrels, T., ed. 359-416. Tucson, Arizona: The University of Arizona Press. TIC: 246879. (DIRS 121510).	This paper is directly applicable, and provides an alternative method (i.e., use of lunar cratering and from other planets) to evaluate cratering on Earth. Paper focuses on determining cratering rates for from lunar, terrestrial planet, and asteroid cratering. The sources and discussion of alternate interpretations are fully documented. No original information is developed in this paper.	No prior use for repository design. Science Citation Index indicates 53 citations.	This paper was extracted from an edited compendium of related papers.	Moderate to High – The methodology and assumptions used are fully documented within the paper. No information on quality control or procedures for the selection of craters is provided.	Indirect Input – This paper provides an independent evaluation based on lunar cratering rates that can be used as an upper bound to corroborate flux and cratering rates based on earth observations or derived from flux information.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C43	Not Applicable	Richardson, J. and Bedient, J. 2001. "Frequently Asked Questions (FAQ) About Fireballs and Meteorite Dropping Fireballs." Geneseo, New York: American Meteor Society. Accessed April 22, 2003. TIC: 254120. (DIRS 162571).	This citation provides a range of information regarding general meteor properties and characteristics. The source, while not strictly scientific, serves as a general clearinghouse of information for use by the public.	No prior use for repository design, and no information regarding review process. Science Citation Index indicates no citations.	Not published – downloaded from an Internet site. This citation is to the home page of the American Meteor Society, a nonprofit scientific organization established to encourage and support the research activities of both amateur and professional astronomers	Low to Moderate – The FAQ page states that "...all of the numbers are estimates, and subject to revision as our knowledge level increases. We have attempted to select the most representative values for each." There is no information on the extent of literature search or procedures used to derive the stated values. Citations regarding the stated properties are absent within the text, but a list of supporting references is provided. The stated values appear to have been based on generally reliable sources and agree in general with information from sources evaluated herein	Indirect Input – This cite provides corroborative-use-only information from a reliable Internet cite of a recognized scientific organization. Sufficiently reliable to use as corroborative source for meteor characteristics and addresses the possible range in values.
C44	Not Applicable	Solomon, K.A.; Erdmann, R.C.; and Okrent, D. 1975. "Estimate of the Hazards to a Nuclear Reactor from the Random Impact of Meteorites." *Nuclear Technology, 25,* 68-71. La Grange Park, Illinois: American Nuclear Society. TIC: 241714. (DIRS 103697).	This paper is an early effort at linking meteorite impact damage via kinetic energy to the probability of impact for a nuclear facility. This paper focuses on probability estimates for meteorite impacts for nuclear reactors and takes into account blast effects from "near misses." The paper is primarily focused on probability of a given size, rather than on consequence.	Used in relation to nuclear siting programs, including preclosure external event hazard evaluation for YMP from meteorites. No information on verification is provided. Science Citation Index indicates two citations.	This paper was taken from a journal sponsored by the American Nuclear Society. The type of review process used is unknown.	Low to Moderate – The paper documents the key assumptions used and outlines the mathematics used to determine the probability. However, the basis for developing the damage-to-energy assumption and the basis supporting the mass influx, while cited, is not discussed. The assessment in meteorite hazard dates to 1968, and there has been significant progress since that time. No information is provided on procedures or quality control associated with	Indirect Input – This paper was previously used as the support for eliminating meteorite impact as a preclosure hazard at YMP. It provides the probability of small-body impacts and uses differing sources for flux. Therefore, it provides a corroborative estimate of the probability of impact for a range of various meteorite mass.

Table B-8. Sources and Factors Evaluation for Direct Inputs to Meteorite Impacts (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C44 (Cont.)						the cited sources of information.	
C45	Not Applicable	Stuart, J.S. 2001. "A Near-Earth Asteroid Population Estimate from the LINEAR Survey." *Science, 294,* (5547), 1691-1693. Washington, D.C.: American Association for the Advancement of Science. TIC: 254146. (DIRS 162568).	This paper reports results of a detailed near-space survey (LINEAR). The scope of the survey is described, as are biases and limitations of the study. Paper provides an estimate of flux of small- to medium- size, near-earth objects based on physical observation and represents current results.	No prior use in repository design. Given the currency of the report, use by others is limited. Science Citation Index indicates seven citations.	This paper was extracted from highly respected peer-reviewed journal (Science).	High – This paper provides a detailed description of methodologies and assumptions used in calculating the flux distribution. The sample size used to derive a flux is approximately an order of magnitude larger than used for predecessor programs.	Indirect Input – This paper is of moderate use in that the magnitude observations are not linked to diameter of meteoroids and is not further evaluated. LINEAR is cited by Brown et al. and supports work of Bailey and Emel'Yanenko.
C46	Not Applicable	Zolensky, M. 1998. "The Flux of Meteorites to Antarctica." *Meteorites: Flux with Time and Impact Effects.* Geological Society Special Publication No. 140. Grady, M.M.; Hutchison, R.; McCall, G.J.H., and Rothery, D.A.; eds. Pages 93-104. Bath, England: Geological Society of London. TIC: 254143. (DIRS 162566).	This paper is focused on the summary of meteorite falls in Antarctica. The results are based on collected specimens, and the limitations and potential biases of human collections, and problems of sample area are all addressed. It also addresses mass distribution and frequency of meteorite falls, and breaks out the falls on a percentage-by-type basis.	No prior use for repository design purposes. Science Citation Index indicates one citation.	Paper was extracted from an edited and refereed compendium of the London Geologic Society (31 referees, including two who are routinely cited in work of this nature).	High – The study methods are well characterized and limitations are fully acknowledged. Related studies are discussed for context, and differing interpretations are considered.	Indirect Input – Provides baseline for comparison of several meteorite falls with regard to frequency and type. Not further considered in this evaluation.

B5.5.3 Discussion

The evaluation presented in this section compares direct input used as data to corroborating-use only information (indirect input) also taken from peer-reviewed journal papers or edited and refereed compendiums of relevant work. Comparisons of the information sets are shown by graphical representation, or are provided in tabular format, to allow ready comparison of the cited values from the various sources. Corroboration is considered achieved if a cited "singular" value (e.g., a cited percent by composition or density) is shown to be within one standard deviation of the mean value of the cited sources. In the case of distributions or distributions generated from equations (e.g., mass flux or cratering rates), corroboration is considered acceptable if the resulting distributions fall within one order of magnitude of the median for any given point in the distribution (e.g., ± one standard deviation of the median value for the probability of crater diameter of a given size). For information addressing meteor radius-to-crater radius relationships and crater diameter-to-depth of cratering effects, agreement within a factor of two is considered adequate for intended use.

Consistent with the intended use for FEP screening, latitude in applying these criteria was taken in two instances. The first instance was for direct input representing percent by type and density. No exclusion of information was made for points falling more than one standard deviation from the mean. The exclusion would have affected at most a few of the points in each of the information sets, and retention helps reflect the entire range in reported values. The second instance occurred with regard to the direct input extracted from Hills and Goda (1993 [DIRS 135281]) (Q22) for the meteor radius-to-crater radius relationships. The above-stated criteria did not seem applicable in a strict sense. Rather, examples and ranges or limits identified in the cited literature were plotted as "corroborative-use-only," where feasible, against the curves taken from Hills and Goda (1993 [DIRS 135281]) (Q22). A standard of "reasonable agreement" in trends between the corroborative-use-only information was applied rather than application of a statistical basis because a point-by-point comparison was not feasible due to differing assumptions and basis of calculation. In some instances, the comparison is based on other figures provided in Hills and Goda (1993 [DIRS 135281]) (Q22) that are not part of the direct input being evaluated. The inference is that if individual phenomena and processes (i.e., fragmentation and ablation) agree between the cited sources and Hills and Goda (1993 [DIRS 135281]) (Q22), then this supports the validity of the resultant cratering relationships that depend in part on those phenomena and processes.

Because the data comes from a variety of sources, manipulation of the data was needed to provide direct comparison. Accordingly, supporting spreadsheets showing the calculations are provided.

B5.5.3.1 Meteoroid Flux Entering Earth's Atmosphere

The data being justified in this section addresses:

Flux data for a range of meteor masses.

This direct information is taken from Item Q16, and is corroborated using other multiple sources including Items C32, C33, C35, C36, C37, C40, C42, and C44.

The data from Ceplecha (1992 [DIRS 135242], p. 362 and Figure 1) (Q16) is used as direct input; all other listed sources are used for corroboration only. The basis for selecting Ceplecha as direct input is discussed below. Figure B-1 of this appendix provides a comparison of meteoroid influx information from multiple sources. Flux information presented by Ceplecha (1992 [DIRS 135242], Figure 1) (Q16) and corroborated by Bland et al. (1998 [DIRS 162563], Figure 1) (C33); Brown et al. (2002 [DIRS 162569], Figure 4) (C35); Neukum and Ivanov (1994 [DIRS 121510], Table IV) (C42); and Solomon (1975 [DIRS 103697], Table I) (C44) are of particular interest due to the completeness, range of mass considered, and varying methods of determination. The flux distribution for these sources is noted on Figure B-1 by the symbols with connecting lines. The information in Table B-9 has been grouped by diameter size to allow ease in comparing the relative cumulative number of events.

The work by Ceplecha (1992 [DIRS 135242]) (Q16) is a compilation of the results of works of others and overlaps the corroborative work by Bland et al. (1998 [DIRS 162563]) (C33) by using common sources of information. The two works are based on direct observation of lunar microcraters and space probes, observations of the Spacewatch Telescope program, and by photographs of earth-crossing asteroids. In the case of Ceplecha (1992 [DIRS 135242]) (Q16), however, the full range of flux for all masses is extended by the use of additional information garnered from space probes, radar-tracked meteors, and photographed and television-tracked meteors, all as identified in Ceplecha 1992 ([DIRS 135242], Table 1) (Q16). In the corroborative case of Brown et al. (2002 [DIRS 162569]) (C35), the results are independent from work of others, and the work was derived from observations using geostationary satellites monitored by the U.S. Department of Defense and DOE. The corroborative information from Neukum and Ivanov 1994 ([DIRS 121510], Table IV) (C42) is based on lunar cratering and, using the stated equivalent energy release, is directly comparable to that of Brown et al. (2002 [DIRS 162569]) (C35). In the case of Solomon (1975 [DIRS 103697]) (C44), the corroborative distribution was cited as being based on "historical evidence as well as current information on meteorite crashes" - with "current" being circa 1968. However, the flux matches reasonably well with information circa 2001.

Some mathematical manipulation of the data from the various sources was required to allow direct comparison between direct and indirect data sources. The numerical manipulations needed to convert to equivalent units for comparison along with additional supporting data used to construct Figure B-1 are presented in Table B-10. In the case of Ceplecha (1992 [DIRS 135242]) (Q16) and the corroborative work by Bland et al. (1998 [DIRS 162563]) (C33), points were selected manually from the referenced figures. These papers provide information in terms of number of events by mass. To convert to equivalent diameters, a spherical body of density 3,000 kg/m^3 was assumed, and appropriate unit conversions were performed. The assumed density was based on the conversion made in Brown et al. (2002 [DIRS 162569]) (C35), which used the stated density.

The graph for Brown et al. (2002 [DIRS 162569]) (C35) was generated from Equation 3 of that paper and checked for internal consistency against Figure 4 of the same paper

The corroborative flux from Neukum and Ivanov (1994 [DIRS 121510]) (C42) was extracted directly from their Table IV, with the time between events converted to frequency per year.

For Solomon (1975 [DIRS 103697]) (C44), the corroborative graph was generated by converting the mass intervals to equivalent diameters, and then the number of events of a given size or larger were summed to get the cumulative number of events for a given mass or larger.

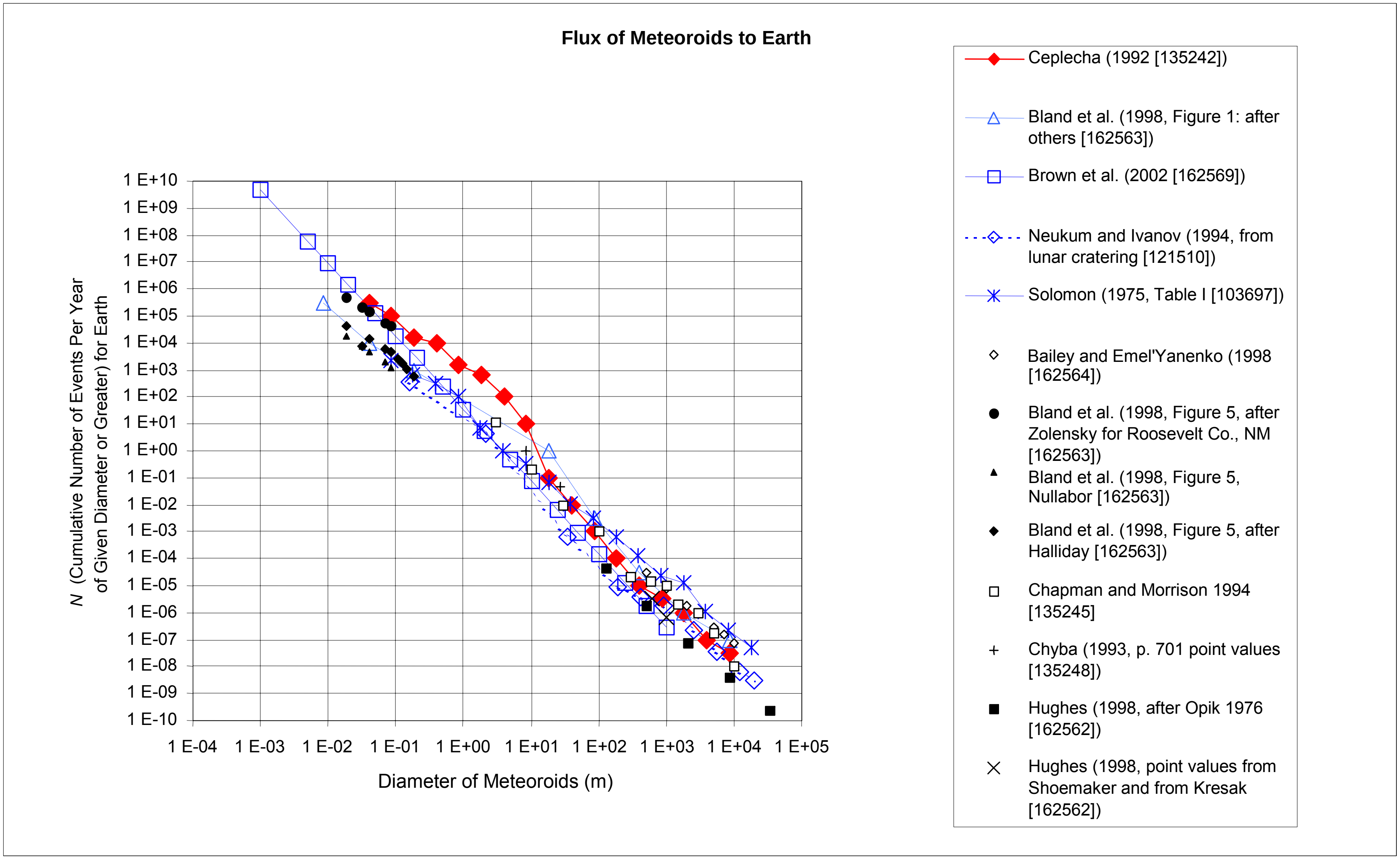
Other corroborative information is also shown on Figure B-1 as symbols without associated lines. This information was taken from peer-reviewed journal papers, but the source of the cited information was not provided, the source of the information was not transparent, or the information covered only a limited range. Other corroborative-use-only information is taken from studies cited by Bland et al. (1998 [DIRS 162563], Figure 5) (C33). Results from Bland et al. overlap with that shown on Figure 1 of the same paper, and provides estimates of flux based on meteorite fall studies from New Mexico and Australia. The author fully discusses the limitations of such estimates due to inherent limitations in sample collection and meteorite pairing. It also covers only a minimal range of small diameters. Additionally, for comparison purposes, the reported flux had to be scaled upwards by two orders of magnitude to represent whole-earth influx.

Chapman and Morrison (1994 [DIRS 135245], Figure 1) (C36) is also a source of corroborative-use only information. In this case, the authors clarify the use of an average total impact flux from a single author (p. 34) and clearly indicate that they have not addressed the influx for objects in the <50-m diameter range, which is within the range of interest for the screening analysis. They cite uncertainty as a factor of 2 for objects >0.5 km, and a factor of 5 for smaller objects capable of doing damage (i.e., inferred to mean surface effects rather than cratering). Furthermore, the method of acquisition is not transparent (though it is stated to have been based on work by Shoemaker et al., which is largely photographic).

Corroborative-use-only information based on Hughes (1998 [DIRS 162562], Table 2) (C40) cites work by others, in particular it cites to previous work after Opik (1976). The nature of acquisition is not discussed. The 1976 publishing date for Opik suggests that the work may be dated regardless of the methodology used for acquisition. Accordingly, the information is treated as corroborative-use only. Hughes (1998 [DIRS 162562], p. 37) (C40) also references two other point values from work by others. These are shown on Figure B-1. They represent only single-point values and are not suitable for evaluation as influx distributions. Additionally, Hughes' focus is on large-scale cratering (i.e., several km), which is not the primary focus of the screening analysis, but does address a portion of the flux distributions.

Work by Bailey and Emel'Yanenko (1998 [DIRS 162564]) (C32) provides an assumed cumulative diameter distribution given in the form of an equation (Equation 3 of the cited paper), without providing justification for its assumption beyond previous work done by Bailey. Additionally, application of the equation is for the total distribution of near-earth asteroids, and does not specifically address the influx of those actually intercepting the earth. However, a mean probability value is given. For corroborative-use only, this mean value was applied to the number of asteroids of a given diameter to provide a number of asteroid events per year. Some support for the assumed equation comes from Stuart (2001 [DIRS 162568]) (C45), wherein the estimate of the total number of Near Earth Asteroids of 1-km diameter or greater is placed at 1227 with an uncertainty range of –90 to +170 from the stated value. This agrees well with Bailey's assumed values of 1,500. Stuart also cites other authors that place the cumulative number as low as 750 ±150.

The direct input for the meteor analysis, and the information from the corroborative papers, are summarized in Table B-9. Numeric manipulations of that information, plus information from the other remaining corroborative papers, are shown in Table B-10. Figure B-1 provides a plot of all the corroborative information and corresponds with information in Table B-10. The evaluation criteria as previous discussed, allows acceptance if, for any given diameter, the reported values fall within one order of magnitude of the median value. As can be seen from Table B-9, and also by inspection of Figure B-1, the distribution from Ceplecha (1992 [DIRS 135242]) (Q16) satisfies those criteria and the total range of values in the cumulative events does not exceed two orders of magnitude.



NOTE: [XXXXXX] in legend denotes DIRS numbers.

Figure B-1. Influx of Meteoroids to Earth

Table B-9. Meteoroid Influx Information

DIRECT INPUT		CORROBORATIVE INFORMATION							
Ceplecha (1992 [DIRS 135242], Figure 1) (Q16)		Bland et al. (1998 [DIRS 162563], Figure 1) (C33)		Brown et al. (2002 [DIRS 162569], Figure 2) (C35)		Neukum and Ivanov (1994 [DIRS 121510], Table IV) (C42)		Solomon (1975 [DIRS 103697], Table 1) (C44)	
D (meters)	Cumulative Number of Events (N) Per Year-Whole Earth	D (meters)	Cumulative Number of Events (N) Per Year-Whole Earth	D (meters)	Cumulative Number of Events (N) Per Year-Whole Earth	D (meters)	Cumulative Number of Events (N) Per Year-Whole Earth	D (meters)	Cumulative Number of Events (N) Per Year-Whole Earth
		4.6E-06	3.2E+17						
		2.1E-05	1.0E+17						
		9.5E-05	1.0E+16						
		4.3E-04	3.2E+13						
				1.0E-03	4.7E+09				
				5.0E-03	6.0E+07				
		9.1E-03	3.2E+05	1.0E-02	9.3E+06				
				2.0E-02	1.4E+06				
4.2E-02	3.2E+05	4.2E-02	1.0E+04	5.0E-02	1.2E+05				
8.9E-02	1.0E+05			1.0E-01	1.9E+04			8.6E-02	3.4E+03
1.9E-01	1.6E+04	1.9E-01	1.0E+03	2.0E-01	2.9E+03	1.60[E]-01	3.7E+02	1.8E-01	1.1E+03
4.1E-01	1.0E+04			5.0E-01	2.4E+02			3.9E-01	4.3E+02
8.7E-01	1.6E+03							8.4E-01	1.1E+02
1.9E+00	6.3E+02			1.0E+00	3.7E+01			1.8E+00	8.7E+00
				2.0E+00	5.7E+00	2.10[E]+00	4.1E+00		
4.0E+00	1.0E+02							3.8E+00	1.4E+00
				5.0E+00	4.8E-01				
8.5E+00	1.0E+01							8.2E+00	4.0E-01-
				1.0E+01	7.4E-02				
1.8E+01	1.0E-01	1.8E+01	1.0E+00					1.8E+01	8.3E-02-
3.9E+01	1.0E-02			2.5E+01	6.2E-03			3.8E+01	1.5E-02-
				5.0E+01	9.6E-04	3.50[E]+01	6.3E-04		
8.3E+01	1.0E-03	8.3E+01	3.2E-03					8.0E+01	3.9E-03-
1.8E+02	1.0E-04			1.0E+02	1.5E-04	1.92[E]+02	9.1E-06	1.7E+02	8.0E-04-
				2.5E+02	1.2E-05				
3.8E+02	1.0E-05	3.8E+02	3.2E-05			4.21[E]+02	3.9E-06	3.7E+02	1.7E-04-
8.1E+02	3.2E-06			5.0E+02	1.9E-06			7.8E+02	3.8E-05-
				1.0E+03	2.9E-07	9.22[E]+02	1.9E-06		
1.7E+03	1.0E-06	1.7E+03	1.0E-06					1.7E+03	1.4E-05-
3.7E+03	1.0E-07					2.60[E]+03	2.2E-07	3.6E+03	1.4E-06-
7.9E+03	3.2E-08	7.9E+03	1.0E-07			5.70[E]+03	3.7E-08	7.7E+03	2.8E-07
						1.25[E]+04	6.6E-09		
						1.98E+04	3.2E-09	1.6E+04	5.2E-08

Table B-10. Spreadsheet Showing Numerical Manipulations of Information from Journal Papers

Direct Input

Ceplecha (1992 [DIRS 135242], Figure 1) (Q17)

Rows:							
A	B	C	D	E	F	G	H
Formulas (Given)	POWER(10, A6)	POWER(10,H6)	(Assumed)	B6/D6	E6*0.75/PI()	F6^(1/3)*2	(Given)
Log Mass (kg)	**Mass (kg)**	**Number of Events Per Year Whole Earth**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3 (m^3)**	**D (meters)**	**Log N**
-1	1.0E-01	3.2E+05	3000	3.3E-05	8.0E-06	4.0E-02	5.5
0	1.0E+00	1.0E+05	3000	3.3E-04	8.0E-05	8.6E-02	5.0
1	1.0E+01	1.6E+04	3000	3.3E-03	8.0E-04	1.9E-01	4.2
2	1.0E+02	1.0E+04	3000	3.3E-02	8.0E-03	4.0E-01	4.0
3	1.0E+03	1.6E+03	3000	3.3E-01	8.0E-02	8.6E-01	3.2
4	1.0E+04	6.3E+02	3000	3.3E+00	8.0E-01	1.9E+00	2.8
5	1.0E+05	1.0E+02	3000	3.3E+01	8.0E+00	4.0E+00	2.0
6	1.0E+06	1.0E+01	3000	3.3E+02	8.0E+01	8.6E+00	1.0
7	1.0E+07	1.0E-01	3000	3.3E+03	8.0E+02	1.9E+01	-1.0
8	1.0E+08	1.0E-02	3000	3.3E+04	8.0E+03	4.0E+01	-2.0
9	1.0E+09	1.0E-03	3000	3.3E+05	8.0E+04	8.6E+01	-3.0
10	1.0E+10	1.0E-04	3000	3.3E+06	8.0E+05	1.9E+02	-4.0
11	1.0E+11	1.0E-05	3000	3.3E+07	8.0E+06	4.0E+02	-5.0
12	1.0E+12	3.2E-06	3000	3.3E+08	8.0E+07	8.6E+02	-5.5
13	1.0E+13	1.0E-06	3000	3.3E+09	8.0E+08	1.9E+03	-6.0
14	1.0E+14	1.0E-07	3000	3.3E+10	8.0E+09	4.0E+03	-7.0
15	1.0E+15	3.2E-08	3000	3.3E+11	8.0E+10	8.6E+03	-7.5

Table B-10. Spreadsheet Showing Numerical Manipulations of Information from Journal Papers (Continued)

Corroborative Information

Bland et al. (1998 [DIRS 162563], Figure 1) (C33)

Rows							
A	B	C	D	E	F	G	H
Formulas (Given)	POWER(10,A35)/ 1000	POWER(10,H35)	3000	B35/D35	E35*0.75/PI()	F35^(1/3)*2	(Given)
Log Mass (g)	**Mass (kg)**	**Number of Events Per Year Whole Earth**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3**	**D (meters)**	**Log N**
-10	1.0E-13	3.2E+17	3000	3.3E-17	8.0E-18	4.0E-06	17.5
-8	1.0E-11	1.0E+17	3000	3.3E-15	8.0E-16	1.9E-05	17.0
-6	1.0E-09	1.0E+16	3000	3.3E-13	8.0E-14	8.6E-05	16.0
-4	1.0E-07	3.2E+13	3000	3.3E-11	8.0E-12	4.0E-04	13.5
0	1.0E-03	3.2E+05	3000	3.3E-07	8.0E-08	8.6E-03	5.5
2	1.0E-01	1.0E+04	3000	3.3E-05	8.0E-06	4.0E-02	4.0
4	1.0E+01	1.0E+03	3000	3.3E-03	8.0E-04	1.9E-01	3.0
10	1.0E+07	1.0E+00	3000	3.3E+03	8.0E+02	1.9E+01	0.0
12	1.0E+09	3.2E-03	3000	3.3E+05	8.0E+04	8.6E+01	-2.5
14	1.0E+11	3.2E-05	3000	3.3E+07	8.0E+06	4.0E+02	-4.5
16	1.0E+13	1.0E-06	3000	3.3E+09	8.0E+08	1.9E+03	-6.0
18	1.0E+15	1.0E-07	3000	3.3E+11	8.0E+10	8.6E+03	-7.0

Table B-10. Spreadsheet Showing Numerical Manipulations of Information from Journal Papers (Continued)

Corroborative Information (Continued)

Brown et al. (2002 [DIRS 162569], Equation 3, Figure 4) (C35)

Cumulative diameter distribution equation							
log N = *c* - *d* log D		*where* *c* = 1.568, and d = 2.70 D = diameter in meters					
Rows:							
A	B	C	D	E			
Formulas: E60/1000	2.7*Log(E60)	1.568-B60	POWER(10,C60)	(Given)			
Diameter			**Events Per Year (N)**	**Diameter (D)**			
(km)	**d log D**	**c-dlogD**	**Whole Earth**	**(meters)**			
0.000001	-8.10	9.7	4.7E+09	1.0E-03			
0.000005	-6.21	7.8	6.0E+07	5.0E-03			
0.00001	-5.40	7.0	9.3E+06	1.0E-02			
0.00002	-4.59	6.2	1.4E+06	2.0E-02			
0.00005	-3.51	5.1	1.2E+05	5.0E-02			
0.0001	-2.70	4.3	1.9E+04	1.0E-01			
0.0002	-1.89	3.5	2.9E+03	2.0E-01			
0.0005	-0.81	2.4	2.4E+02	5.0E-01			
0.001	0.00	1.6	3.7E+01	1.0E+00			
0.002	0.81	0.8	5.7E+00	2.0E+00			
0.005	1.89	-0.3	4.8E-01	5.0E+00			
0.01	2.70	-1.1	7.4E-02	1.0E+01			
0.025	3.77	-2.2	6.2E-03	2.5E+01			
0.05	4.59	-3.0	9.6E-04	5.0E+01			
0.1	5.40	-3.8	1.5E-04	1.0E+02			
0.25	6.47	-4.9	1.2E-05	2.5E+02			
0.5	7.29	-5.7	1.9E-06	5.0E+02			
1	8.1	-6.532	2.9E-07	1.0E+03			

Table B-10. Spreadsheet Showing Numerical Manipulations of Information from Journal Papers (Continued)

Corroborative Information (Continued)

Neukum and Ivanov (1994 [DIRS 121510], Table IV) (C42)

Rows							
A	B	C	D				
Formulas (Given)	1/A88	Given (D)	LOG(B88)				
Time Interval (yr)	**Number of Events Per Year Whole Earth**	**Diameter (D) of Meteor (meters)**	**Log N**				
2.7E-03	3.7E+02	1.6E-01	2.6				
2.4E-01	4.1E+00	2.1E+00	0.6				
1.6E+03	6.3E-04	3.5E+01	-3.2				
1.0E+05	9.1E-06	1.9E+02	-5.0				
2.6E+05	3.9E-06	4.2E+02	-5.4				
5.3E+05	1.9E-06	9.2E+02	-5.7				
4.5E+06	2.2E-07	2.6E+03	-6.7				
2.7E+07	3.7E-08	5.7E+03	-7.4				
1.5E+08	6.6E-09	1.3E+04	-8.2				
3.1E+08	3.2E-09	2.0E+04	-8.5				

Table B-10. Spreadsheet Showing Numerical Manipulations of Information from Journal Papers (Continued)

Corroborative Information (Continued)

Solomon (1975 [DIRS 103697], Table I) (C44)

Rows:								
A	B	C	D	E	F	G	H	I
Formulas (Given)	(A108*2000)*0.454	(Assumed)	B108/C108	D108*0.75/PI()	(Given)	(5.48 x 1015/1.05 x 1014) x F108	SUM(G108:G$127)	E108^(1/3)*2
Weight (tons)	**Mass (kg)**	**Density (kg/m^3)**	**Volume (m^3)**	**R3 (m^3)**	**Number of Events (N) Per Year US**	**Number of Events (N) Per Year Whole Earth**	**Cumulative Number of Events (N) Per Year Whole Earth**	**D (meters)**
1.0E-03	9.1E-01	3000	3.0E-04	7.2E-05	45.0	2.3E+03	3.4E+03	8.3E-02
1.0E-02	9.1E+00	3000	3.0E-03	7.2E-04	12.0	6.3E+02	1.1E+03	1.8E-01
1.0E-01	9.1E+01	3000	3.0E-02	7.2E-03	6.0	3.1E+02	4.3E+02	3.9E-01
1.0E+00	9.1E+02	3000	3.0E-01	7.2E-02	2.0	1.0E+02	1.1E+02	8.3E-01
1.0E+01	9.1E+03	3000	3.0E+00	7.2E-01	0.1	7.3E+00	8.7E+00	1.8E+00
1.0E+02	9.1E+04	3000	3.0E+01	7.2E+00	0.0	1.0E+00	1.4E+00	3.9E+00
1.0E+03	9.1E+05	3000	3.0E+02	7.2E+01	0.0	3.1E-01	4.0E-01	8.3E+00
1.0E+04	9.1E+06	3000	3.0E+03	7.2E+02	0.0	6.8E-02	8.3E-02	1.8E+01
1.0E+05	9.1E+07	3000	3.0E+04	7.2E+03	0.0	1.1E-02	1.5E-02	3.9E+01
1.0E+06	9.1E+08	3000	3.0E+05	7.2E+04	0.0	3.1E-03	3.9E-03	8.3E+01
1.0E+07	9.1E+09	3000	3.0E+06	7.2E+05	0.0	6.3E-04	8.0E-04	1.8E+02
1.0E+08	9.1E+10	3000	3.0E+07	7.2E+06	0.0	1.4E-04	1.7E-04	3.9E+02
1.0E+09	9.1E+11	3000	3.0E+08	7.2E+07	0.0	2.4E-05	3.8E-05	8.3E+02
1.0E+10	9.1E+12	3000	3.0E+09	7.2E+08	0.0	1.3E-05	1.4E-05	1.8E+03
1.0E+11	9.1E+13	3000	3.0E+10	7.2E+09	0.0	1.1E-06	1.4E-06	3.9E+03
1.0E+12	9.1E+14	3000	3.0E+11	7.2E+10	0.0	2.3E-07	2.8E-07	8.3E+03
1.0E+13	9.1E+15	3000	3.0E+12	7.2E+11	0.0	5.2E-08	5.2E-08	1.8E+04

NOTE: Column G uses a scalar ratio of surface of whole earth to the U.S., with values for surface areas taken from Solomon 1974 – therefore internally consistent with the number of events scaled back to whole world.

Table B-10. Spreadsheet Showing Numerical Manipulations of Information from Journal Papers (Continued)

Other Corroborative Information

Bailey and Emel'Yanenko (1998 [DIRS 162564]) (C32)

(for 0.5 < d <10 km)

Cumulative Diameter Distribution of Asteroids
N_A (≥d) = 1500
X {d/1 km}$^{-2}$

NOTE: The value of 1500 is given in the cited paper as a constant for the stated equation.

$N_{impact} = N_A$ x Mean Probability

Rows							
A	B	C	D	E	F	G	H
Formulas (Given)	(Given)	A145^-2	B145*C145	Log(D145)	(Given)	A145*1000	(D145*F145)
Diameter (d) (km)	**-1500**	**d^{-2}**	**Cumulative Number of Asteroids (N_A)**	**log N_A**	**Mean Probability of Asteroid Crossing Per Year Whole Earth**	**$D_{meteoroid}$ (meters)**	**Number of Impact Events (N_{Impact}) Per Year Whole Earth**
0.5	1500	4.00	6000	3.8E+00	5.0E-09	500	3.0E-05
1	1500	1.00	1500	3.2E+00	5.0E-09	1000	7.5E-06
2	1500	0.25	375	2.6E+00	5.0E-09	2000	1.9E-06
5	1500	0.04	60	1.8E+00	5.0E-09	5000	3.0E-07
7	1500	0.02	31	1.5E+00	5.0E-09	7000	1.5E-07
10	1500	0.01	15	1.2E+00	5.0E-09	10000	7.5E-08

Table B-10. Spreadsheet Showing Numerical Manipulations of Information from Journal Papers (Continued)

Other Corroborative Information (Continued)

Bland et al. 1998 ([DIRS 162563], Figure 5) (C33)

* A factor of 512 is applied here in Column H to scale up to whole earth impact. The information in Column B is based on a 106 km^2 area, so the number of events has to be scaled upward to the whole earth surface. The earth's surface is approximately 5.12 x 10^8 km^2, so dividing by a factor of 106 (the area for the cited number of events in this study) leaves a scaling factor of 512.

Rows							
A	B	C	D	E	F	G	*H
Formulas (Given)	(Given)	A161/1000	(Assumed)	C161/D161	E161*0.75/PI()	F161^(1/3)*2	Log(B161*512)
after Halliday							
Mass (g)	**N (for 10^6 km^2)**	**Mass (kg)**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3 (m^3)**	**D (meters)**	**Number of Events (N) Per Year Whole Earth**
10	83	0.01	3000	3.3E-06	8.0E-07	1.9E-02	4.2E+04
50	15	0.05	3000	1.7E-05	4.0E-06	3.2E-02	7.7E+03
100	28	0.1	3000	3.3E-05	8.0E-06	4.0E-02	1.4E+04
500	11	0.5	3000	1.7E-04	4.0E-05	6.8E-02	5.6E+03
1000	9	1	3000	3.3E-04	8.0E-05	8.6E-02	4.6E+03
2000	5	2	3000	6.7E-04	1.6E-04	1.1E-01	2.6E+03
3000	3.5	3	3000	1.0E-03	2.4E-04	1.2E-01	1.8E+03
5000	2.1	5	3000	1.7E-03	4.0E-04	1.5E-01	1.1E+03
10000	1.2	10	3000	3.3E-03	8.0E-04	1.9E-01	6.1E+02
for Nullabor							
Mass (g)	**N (for 10^6 km^2)**	**Mass/kg**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3 (m^3)**	**D (meters)**	**Number of Events (N) Per Year Whole Earth**
10	35	0.01	3000	3.3E-06	8.0E-07	1.9E-02	1.8E+04
50	15	0.05	3000	1.7E-05	4.0E-06	3.2E-02	7.7E+03
100	9.2	0.1	3000	3.3E-05	8.0E-06	4.0E-02	4.7E+03
500	3.7	0.5	3000	1.7E-04	4.0E-05	6.8E-02	1.9E+03
1000	2.5	1	3000	3.3E-04	8.0E-05	8.6E-02	1.3E+03
after Zolensky (Roosevelt County)							
Mass (g)	**N (for 10^6 km^2)**	**Mass/kg**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3 (m^3)**	**D (meters)**	**Number of Events (N) Per Year Whole Earth**
10	930	0.01	3000	3.3E-06	8.0E-07	1.9E-02	4.8E+05
50	400	0.05	3000	1.7E-05	4.0E-06	3.2E-02	2.0E+05
100	270	0.1	3000	3.3E-05	8.0E-06	4.0E-02	1.4E+05
500	110	0.5	3000	1.7E-04	4.0E-05	6.8E-02	5.6E+04
1000	80	1	3000	3.3E-04	8.0E-05	8.6E-02	4.1E+04

Table B-10. Spreadsheet Showing Numerical Manipulations of Information from Journal Papers (Continued)

Other Corroborative Information (Continued)

Chapman and Morrison (1994 [DIRS 135245], Figure 1) (C36)

Rows							
A	B	C	D				
Formulas (Given)	1/A197	(Given)	LOG(B197)				
Time Interval (years)	**Number of Events (N) Per Year Whole Earth**	**D (meters)**	**Log N**				
0.08	1.2E+01	3	1.1				
5	2.0E-01	10	-0.7				
100	1.0E-02	30	-2.0				
1000	1.0E-03	100	-3.0				
5.0E+04	2.0E-05	300	-4.7				
7.0E+04	1.4E-05	600	-4.8				
1.0E+05	1.0E-05	1000	-5.0				
5.0E+05	2.0E-06	1500	-5.7				
1.0E+06	1.0E-06	3000	-6.0				
6.0E+06	1.7E-07	5000	-6.8				
1.0E+08	1.0E-08	10000	-8.0				
Chyba 1993 (p. 701) (DIRS 135248), C37							
Rows:							
A	B	C	D	E	F	G	H
Formulas: (Given)	(Given)	1/B219	(Assumed)	A219/D219	E219*0.75/PI()	F219^(1/3)*2	Log(C219)
Mass (kg)	**Interval (yrs)**	**Number of Events (N) Per Year Whole Earth**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3 (m^3)**	**D (meters)**	**Log N**
3.2E+07	21	0.05	3000	1.1E+04	2.5E+03	2.7E+01	-1.3
1.0E+06	1	1	3000	3.3E+02	8.0E+01	8.6E+00	0.0

Table B-10. Spreadsheet Showing Numerical Manipulations of Information from Journal Papers (Continued)

Other Corroborative Information (Continued)

Hughes 1998 (DIRS 162562), C40

after Kresak 1978 and after Shoemaker 1979

Rows:							
A	B	C	D	E	F	G	H
Formulas: –	(Given)	(Given)	(Given)	(Assumed)	C233/D233	F233*0.75/PI()	(B233*1000) (for Kresak) F234^(1/3)*2 (for Shoemaker)
Source)	**Diameter (km)**	**Number of Events (N) Per Year Whole Earth**	**Mass (kg)**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3 (m^3)**	**D (meters)**
Kresak 1978	**1**	**6.67E-07**	–	–	–	–	**1000**
Shoemaker 1979	–	**3.50E-06**	3.80E+11	3000	1.3E+08	3.0E+07	623
after Opik 1976 (sum of frequencies in Table 2)							
Rows:							
A	B	C	D				
Formulas:							
	(Given)	(Given)	B245*1000	LOG (A245)			
	Number of Events (N) Per Year Whole Earth	**Diameter (km)**	**D (meters)**	**log N**			
	4.6E-05	0.13	130	-4.3E+00			
	1.7E-06	0.52	520	-5.8E+00			
	7.4E-08	2.1	2100	-7.1E+00			
	3.8E-09	8.5	8500	-8.4E+00			
	2.3E-10	34	34000	-9.6E+00			
	5.6E-11	68	68000	-1.0E+01			

B5.5.3.2 Composition and Material Properties of Meteoroids Entering the Earth's Atmosphere

The following section addresses the flux in terms of percent by compositions and examines the range in possible density values. In this discussion, meteors are identified as stony, carbonaceous, cometary, asteroidal, chondrite, non-chondrite, carbonaceous chondrites, and ordinary chondrites. For this analysis comets classified as asteroidal include both stony and carbonaceous. Chondrite refers to a meteoric stone characterized by the presence of chondrules that are rounded granules of cosmic origin often found embedded in meteoric stones and sometimes free in marine sediments. Carbonaceous chondrites and ordinary chondrites are also considered asteroidal.

The direct input justified includes:

Flux data, by meteor type and related densities:

The percent-by-type data is taken primarily from Item Q17 for diameters less than about 10 m, but an assumed value, based on the corroborative information, is used for the larger sizes. Corroborative information is taken from a table of independent information in Item Q17, and Items C40 and C43. The density values for two of the categories (cometary and stony) are taken from Item Q17, and the density for irons is taken from Item Q22. Corroborative information comes from separate citations with Item Q17, and other sources including Items C32, C35, C36, C37, C39, C40, and C45.

Values for percent of meteor that are of iron composition:

A value of five percent iron is taken from Item Q23, and corroborative information includes separate citations with Item Q23, and corroborative Items C34, C37, C39, and C43.

Percent-by-Type

The literature provides an intermixing of information on influx, on composition of observed fireballs, on percent composition of various meteorite finds, and on cratering rates by type of meteor. In only a few instances are distributions given based on meteoroid mass or size. The following summary tables attempt to sort and identify the percent-by-type based on information and descriptions provided in the cited sources. Because it constitutes only a few percentage of the total flux to earth, most authors do not address the percentage of iron and iron-stony material. For this analysis, however, it represents a significant potential for impact damage (due to lack of fragmentation in the atmosphere) and is addressed separately from the following discussion for cometary, carbonaceous, and stony materials. For direct input, the distribution proposed by Ceplecha (1994 [DIRS 135243], Figure 2) (Q17) is used, along with an assumed equal distribution of asteroidal and cometary material for the large size ranges. These data are presented in Table 4 of the cited document and are provided in Table B-11. This information differs slightly from that taken Figure 2 of the same citation due to differences in mass and sizes used to choose points for the distribution.

Table B-11. Distribution of Meteoroid Types

	Diameter of Incident Body (meters)						
Type of Incident Body	**0.1**	**0.2**	**0.5**	**1**	**2**	**5**	**10**
Type I (Stony) - %	15	17	15	10	6	3	1
Type II (Carbonaceous) - %	31	41	46	48	47	42	30
Type III (Cometary) - %	54	42	39	42	47	55	69

Source: Ceplecha 1994 (DIRS 135243), Table 4 (Q17).

A value of five percent iron meteorites (based on Shoemaker 1983 [DIRS 135308], p. 480) (Q23) is used for the entire range of sizes.

Corroboration of Percent of Comets, Carbonaceous, and Stony Materials

With regard to the influx into the atmosphere, three corroborative sources of information present pertinent information. Hughes (1998 [DIRS 162562], Table 2) after Opik (1976) provides the cumulative frequency per year for asteroids and comets based on diameter of the incident body. Hughes does not clarify whether this is tied to cratering rates or represents influx to the atmosphere, but based on the nature of Opik's work, it is presumed here to represent influx. The information from Table 2 of Hughes (1998 [DIRS 162562]) (C40) is provided in the first three rows of Table B-12. From that information, determining the percentage of cometary matter is a straightforward calculation for the given size ranges.

Table B-12. Cumulative Annual Frequency of Asteroid and Comet Impacts on Earth

	Diameter of Incident Body (m)					
	130	**520**	**2,100**	**8,500**	**34,000**	**68,000**
Asteroid (impacts per year)	2.8 E-05	7.1 E-07	2.1 E-08	9.2 E-10	6.9 E-11	2.2 E-11
Comet (impacts per year)	1.8 E-05	9.8 E-07	5.3 E-08	2.9 E-09	1.6 E-10	3.7 E-11
Asteroid to Comet Ratio	1.58	0.72	0.39	0.32	0.43	0.57
Total Impacts (per year)	4.6E-05	1.7E-06	7.4E-08	3.8E-09	2.3E-10	5.6E-11
Percent Cometary	39.1%	57.6%	71.6%	76.3%	69.6%	66.1%

Source: Hughes 1998 (DIRS 162562), Table 2 (C40).

The table clearly reflects that bodies of increasing diameter (regardless of type) enter the atmosphere with decreasing frequency. For FEP screening, the threshold of occurrence is set at an annual equivalence of 10^{-8}, so incident bodies of 8,500 m or greater diameter are not of interest (on a whole-earth basis), and the percent of cometary influx of interest is in the range of 39 to 76 percent.

Hughes (1998 [DIRS 162562]) (C40) also cites works of others with regard to percent of cratering based on meteor type. In most cases, the division between stony and carbonaceous asteroids is not given, so it is assumed that they are equally distributed between the two groups. In addition, for cometary material, the division between short-period and long-period comets is ignored, and the total percentage is given in Table B-13. All of the reported values from Hughes (1998 [DIRS 162562]) (C40) are reflected in statistical summary provided in Table B-13.

For smaller bodies, Ceplecha (1994 [DIRS 135243], Table 4) (Q17) provides a detailed breakdown by diameter for the size range of 0.1 to 10 m based on fireball observations and photographed meteors. The breakdown provided by Ceplecha is on fireball-types as described in Appendix D of this document, and Ceplecha assumes that Type I represents stony materials, Type II represents carbonaceous materials, and Type III represents cometary materials. Type I materials are likely asteroidal in origin, Type II are probably transitional, and Type III are generally assumed to be cometary (Richardson and Bedient 2001 [DIRS 162571], FAQ #15) (C43). The last column of Ceplecha's Table 4 provides and division by type, which is from an independent data set, compared to what is shown in Table B-11.

In FAQ #16, Richardson and Bedient (2001 [DIRS 162571]) (C43) do not provide citations for the given information on compositions, and do not provide distributions by size. However, they do indicate that most of the current information on meteoroids comes from photographic fireball studies with magnitude > –4 (whereas, the magnitudes reported by Ceplecha (1994 [DIRS 135243], Table 2) (Q17) are general magnitude ≤ –18.

For the meteoroid population as a whole, the fainter the meteoroid population, the more likely it is cometary in origin. Richardson and Bedient (2001 [DIRS 162571]) (C43) provide the following:

Cometary meteoroids:	95%
Chondritic meteoroids:	5%
Non-chondritic meteoroids:	<1%

However based on the population of observed meteors with magnitude > –4, Richardson and Bedient (2001 [DIRS 162571]) (C43) provide the following:

Type III – Cometary Meteoroids:	38%
Type IIIa – low density comets:	9%
Type IIIb – high density comets:	29%
Type II – Carbonaceous Chondrites:	33%
Type I – Ordinary Chondrites:	29%
Non-chondritic meteoroids:	<1%

The lack of quantification of the respective percentages and the lack of explanation of the basis for the anecdotal statements precludes their considerations in the statistical basis or listing as corroborative data.

A calculation of the mean and standard deviation of the percent-by-type distribution is shown in Table B-13. The information listed in Table B-13, which falls beyond one deviation from the mean value, except as noted, has been italicized. However, these point values represent the possible range in reported values despite their apparent unreasonableness. For analysis purposes, utilizing a "preferred value" or any combination of percent compositions that honors the means and standard deviations is considered appropriate.

The following information will be used for direct input. Down to an initial meteor mass of approximately 10^8 kg (radius of 14 m for iron, 19 m for stony, and 28 m for carbonaceous meteors), the total flux is presumed to be comprised of 5 percent iron material regardless of initial meteor radius, and the remainder is divided equally between stony and carbonaceous material regardless of initial meteor radius. For initial meteor masses below 10^7 and down to 10^{-1} kg (minimum radius of 0.014 m for iron, 0.019 m for stony, and 0.028 m for carbonaceous meteors), the total flux is presumed to be comprised of 5 percent iron materials regardless of initial meteor radius, and 2 to 18 percent stony material depending on initial meteor radius; and the remainder (93 to 77 percent) is attributed as carbonaceous/cometary material. These values fall within the mean value plus one standard deviation determined from the available literature, and are primarily based on Ceplecha (1994 [DIRS 135243], Figure 2 and Table 4) (Q17) for the masses from 10^8 to 10^{-1} kg. The corroboration for an assumed 5 percent iron is presented below.

Corroboration of Percent of Iron Meteoroids

Because the iron and stony-iron meteorites are the least likely to be affected by atmospheric effects, and because of their increased density, the potential effects of iron meteors are considered separately by most authors from the of effects of asteroidal and cometary bodies. A listing of percentage of iron meteors in the meteoroid flux is provided below. Because of the durability of iron meteorites, both during meteor fall and through time in desert environments, meteorite falls are included in the following table as they likely represent an upper bound on the percent of iron meteors. The "falls" information differs from "find" information in that biases in collection are considered. Richardson and Bedient (2001 [DIRS 162571]) (C43) give the "find" percentage as 54 percent—clearly representing a collection and identification bias for iron and iron-stony meteorites. Information including "finds," therefore, has been omitted.

The direct input in Table B-14 is used to calculate the mean value and standard deviation for iron meteoroids. Italicized values in Table B-14 indicate that the reported values fall outside of the calculated standard deviation. However, these point values should be retained for corroboration purposes because they represent the possible range in reported values, despite their apparent unreasonableness. For analysis purposes, utilizing a "preferred value" or any combination of percent compositions that honors the mean and standard deviations is considered appropriate.

Table B-13. Summary Table for Percent by Type of Meteoroid

Stony	Carbonaceous	Cometary	Source
DIRECT INPUT			
16	31	53	Ceplecha (1994 [DIRS 135243], Figure 2) (mass = 1 x 10^{-1} kg)
16	34	50	Ceplecha (1994 [DIRS 135243], Figure 2) (mass = 1 kg)
18	42	40	Ceplecha (1994 [DIRS 135243], Figure 2) (mass = 1 x 10^{1} kg)
14	47	39	Ceplecha (1994 [DIRS 135243], Figure 2) (mass = 1 x 10^{2} kg)
10	48	42	Ceplecha (1994 [DIRS 135243], Figure 2) (mass = 1 x 10^{3} kg)
8	46	46	Ceplecha (1994 [DIRS 135243], Figure 2) (mass = 1 x 10^{4} kg)
6	42	52	Ceplecha (1994 [DIRS 135243], Figure 2) (mass = 1 x 10^{5} kg)
4	30	66	Ceplecha (1994 [DIRS 135243], Figure 2) (mass = 1 x 10^{6} kg)
2	30	68	Ceplecha (1994 [DIRS 135243], Figure 2) (mass = 1 x 10^{7} kg)
47	26.5	26.5	Assumed for all masses > 1 x 10^{7} kg
CORROBORATIVE INFORMATION			
Data Segmented as Stony, Carbonaceous, and Cometary			
Stony	**Carbonaceous**	**Cometary**	
14.0	29.0	57.0	Average for following values
13.1	27.2	32.9	Standard Deviation for following values
8	54	38	Ceplecha (1994 [DIRS 135243], Table 4 last column, for 1 to 10 m)
5	0	*95*	Richardson and Bedient (2001 [DIRS 162571], for population as a whole)
29	33	38	Richardson and Bedient (2001 [DIRS 162571], observed meteors with magnitude > –4)
CORROBORATIVE INFORMATION			
Data Segmented as Asteroidal and Cometary			
Asteroidal		**Cometary**	
50.7		49.3	Average for following values
22.0		22.0	Standard Deviation for following values
60.9		39.1	Hughes (1998 [DIRS 162562], after Opik 1976)
42.4		57.6	Hughes (1998 [DIRS 162562], after Opik 1976)
28.4		*71.6*	Hughes (1998 [DIRS 162562], after Opik 1976)
23.7		*76.3*	Hughes (1998 [DIRS 162562], after Opik 1976)
30.4		69.6	Hughes (1998 (DIRS 162562], after Opik 1976)
33.9		66.1	Hughes (1998 [DIRS 162562], after Opik 1976)
67		33	Hughes (1998 [DIRS 162562], after Schultz 1988)
70		30	Hughes (1998 [DIRS 162562], after Wetherhill 1989)
60		40	Hughes (1998 [DIRS 162562], after Shoemaker et al. 1994)
90		*10*	Hughes (1998 [DIRS 162562], after Bailey 1991)
47.2		51.1	Average for lumped corroborative values*
23.6		23.6	Standard Deviation for lumped corroborative values*

* Italicized values indicate that the reported value falls outside of the calculated standard deviation.

NOTE: Asteroidal percentages should be roughly equivalent to stony plus carbonaceous percentages. Not all literature distinguishes by particular composition, so the values are shown as grouped in the source literature, and statistics are grouped accordingly. The final listed average and standard deviation assume that stony + carbonaceous percentage = asteroidal percentage, and lumps all as either asteroidal or cometary percentages.

Table B-14. Summary Table for Percent of Iron Meteoroids

Percent Iron	Percent Stony Iron	Total Percent	Source
DIRECT INPUT			
5.0	- -	5.0	Shoemaker (1983 [DIRS 135308], p. 480 assumed value of observed objects)
CORROBORATIVE INFORMATION			
Average Values and Standard Deviation			
4.2	1.2	4.9	Average Value for All Corroborative Information
3.5	0.9	4.0	Average Value (excluding outliers from Bevan and from Chyba)
4.3	0.9	5.0	Standard Deviation for all Corroborative Information
Individual Indirect Inputs			
4.8	1.1	5.9	Bevan et al. (1998 [DIRS 162565], Table 4 Modern Falls)
15.1	*2.7*	*17.8*	Bevan et al. (1998 [DIRS 162565], Table 4 Australia)
1.3	0.5	1.8	Bevan et al. (1998 [DIRS 162565], Table 4 Antarctica)
1.5	0.4	1.9	Bevan et al. (1998 [DIRS 162565], Table 4 Nullarbor)
1.9	0.7	2.5	Bevan et al. (1998 [DIRS 162565], Table 4 Sahara)
3.5	- -	3.5	Hills and Goda (1998 [DIRS 135291], p. 225 and Figure 7)
8	- -	8	Chyba (1993 [DIRS 135248], p. 703 – meteorite falls)
6	- -	6	Chyba (1993 [DIRS 135248], p. 703 – main belt asteroids)
0	- -	*0*	Chyba (1993 [DIRS 135248], p. 703 – lunar source for Spacewatch objects)
6	2	8	Richardson and Bedient (2001 [DIRS 162571], FAQ #15 – observed falls/fresh finds)
1.5	- -	1.5	Shoemaker (1983 [DIRS 135308], p. 480 assumed lower value)
3.0	- -	3.0	Shoemaker (1983 [DIRS 135308], p. 480 assumed lower value)

NOTE: Italicized values indicate that the reported value falls outside of the calculated standard deviation for all corroborative information.

Meteoroid Densities

For the meteorite impact calculations, the densities used as direct input include 8 g/cm^3 for metallic materials, which is consistent with Hills and Goda (1993 [DIRS 135281], Figure 1) (Q22). This agrees with the average density for iron meteorites, and is within one standard deviation of the average value for iron plus stony irons, as shown in Table B-15. The density used as direct input for hard stone materials is 3.7 g/cm^3 as taken from Ceplecha (1994 [DIRS 135243], Table 1) (Q17) and is within one standard deviation of the average density for stony irons plus stony material plus carbonaceous material, as shown in Table B-15. The density for soft stone materials (carbonaceous and cometary materials) is 1.1 g/cm^3 and is taken from Ceplecha (1992 [DIRS 135242], Table 3, average bulk density) (Q16). This agrees with the group average for carbonaceous plus cometary material shown in Table B-15. The use of these values is consistent with the use of the meteorite influx and percent-by-type information from Ceplecha (1992 [DIRS 135242]) (Q16) and 1994 (DIRS 135243) (Q17), respectively.

Corroborative information comes from Chapman and Morrison (1994 [DIRS 135245], p. 34) (C36), who give the possible range in densities as "the total range in bulk density is about a factor of 10 (~8 g cm^{-3} for iron, down to $\leq$ 1 g cm^{-3} for cometary ices)." Other corroborative peer-reviewed papers provide or assume differing values. Corroborating data from these sources are summarized in Table B-15, and the mean values and standard deviations are calculated.

Italicized values in Table B-15 indicate that the reported value falls outside of the calculated standard deviation for both the individual type of meteor and for the groupings by meteor type. However, these point values should be retained as corroborative information because they represent the possible range in reported values, despite their apparent unreasonableness. For analysis purposes, utilizing a "preferred value" or any combination of percent compositions that honors the mean and standard deviations is considered appropriate. Table B-15 shows that the values selected for direct input satisfies that requirement. The use of these values is consistent with the use of the meteorite influx and percent-by-type information from Ceplecha (1992 [DIRS 135242]) and Ceplecha (1994 [DIRS 135243]), respectively.

B5.5.3.3 Crater Diameter Distributions and Rates

This section justifies data being used to determine cratering distributions based on observed cratering information. The direct inputs include the following:

- Crater rate distribution based on observed earth cratering: This information is taken from Items Q19 and Q20, which are mutually corroborative with Item Q24.

- Cratering rate data for the Canadian shield and application to a hypothetical Canadian repository: This information is taken from Item Q24, which is mutually corroborative with Items Q19 and Q20.

These distributions are corroborated by distributions given in Items C42, C32, C35, and C40.

Grieve (1987 [DIRS 135254]) (Q19) and Wuschke et al. (1995 [DIRS 129326]) (Q24) are used as direct input for the analysis. This is because the work by Grieve is widely cited for these types of studies, and the work by Wuschke et al. has previously been applied to a potential nuclear waste repository site.

One of the corroborative sources, Neukum and Ivanov (1994 [DIRS 121510], Table IV) (C42), is unique in that it estimates cratering rates for an atmosphereless earth based on lunar cratering data. They also present information on crater diameters, equivalent energy releases, and the time between events. Because it is for an atmosphereless earth, the distribution is very useful for corroboration and use as an upper bound, so it has been treated in more detail and is corroborated to Brown et al. (2002 [DIRS 162569]) (C35) to further establish its corroborative use as an upper bound.

Table B-15. Summary Table for Density of Meteors

Cited Values for Density (g/cm^3)			Cited Sources
Irons + Stony Irons	**Stony-Irons + Stony + Carbonaceous**	**Carbonaceous + Cometary**	
DIRECT INPUT			
8			Hills and Goda (1993 [DIRS 135281], Figure 1 – assumed values)
	3.7		Ceplecha (1994 [DIRS 135243], Table 1)
		1.1	Ceplecha (1994 [DIRS 135243], Table 3)
CORROBORATIVE INFORMATION			
7.0	3.4	1.1	Grouped Average Value
1.4	1.4	0.8	Standard Deviation of Group
8 – 5	7 – 2	2.6 – 0.2	Range of Values

Irons (Siderites)	**Stony-Irons (Siderolites)**	**Stony (Aerolites, Ordinary Chondrites, Achondrites, Enstaties, Type I Fireballs)**	**Carbonaceous (Carbonaceous Chondrites, Type II Fireballs)**	**Cometary (Type III Fireballs)**	
8.0	6.0	3.5	2.2	0.7	Average Value By Specific Type
0.1	1.4	0.4	0.3	0.4	Standard Deviation
- -	- -	- -	2.0	0.6	C32, Bailey and Emel'Yanenko (1998 [DIRS 162564], p. 14, for long period comet or Halley-type object and for near-Earth asteroid)
- -	- -	3.4	2.6	- -	Brown et al. (2002 [DIRS 162569], p. 294, reported as 3,400 and 2,600 kg/m^3)
- -	- -	- -	2.0	0.75	Ceplecha (1994 [DIRS 135243], Table 1, 0.75 for Types IIIA, IIIAi, IIIA (C3))
- -	- -		- -	0.27	Ceplecha (1994 [DIRS 135243], Table 1, 0.27 for Type IIIB)
8	- -	- -	- -	1	Chapman and Morrison (1994 [DIRS 135245], p. 34)
		3.5	2.2	1	Chyba (1993 [DIRS 135248], p. 703-704)
- -	- -	3	- -	0.5	Hills and Goda (1993 [DIRS 135281], Figure 1 – assumed values)
- -	-	3.65	- -	1.3	Hughes (1998 [DIRS 162562], p.34 and 40: Asteroids presumed to be of stony material and cited as 3650 kg m^{-3})
- -	- -	- -	- -	*0.2*	Hughes (1998 [DIRS 162562], p. 40)
7.9		3.7	2		Richardson and Bedient (2001 [DIRS 162571], FAQ #16, densities reported in units of g/cc)
- -	7	4	- -	0.8	Richardson and Bedient (2001 [DIRS 162571], FAQ #16, densities reported in units of g/cc – upper value for given ranges)
- -	5	3	- -	0.3	Richardson and Bedient (2001 [DIRS 162571], FAQ #16, densities reported in units of g/cc – lower values for given ranges)

Grieve (1987)

An applicable cumulative cratering rate can be derived from Grieve (1987 [DIRS 135254]) (Q19), which is commonly used for this type of analysis. Based on observed earth crater diameters, Grieve (1987 [DIRS 135254]) (Q19) indicates that the number of impact craters larger than a crater diameter *D*, produced per year per square km is inversely proportional to the apparent crater diameter to the 1.8 power (Grieve 1987 [DIRS 135254], p. 248, p. 257, and Figure 8) (Q19) and is given as:

$$\mathrm{F}(D) \propto D^{-1.8} \qquad \text{(Eq. B-9)}$$

where F(*D*) is equal to the number of craters larger than a given diameter, produced per year per km^2, as a function of diameter, *D*.

Converting the proportionality into equation form gives:

$$\mathrm{F}(D) = \mathrm{K}\, D^{-1.8} + \mathrm{B} \qquad \text{(Eq. B-10)}$$

Values for K and B can be derived form available observed cratering diameters. The constant B is zero since F(D) must approach zero as the crater diameter (D) becomes infinite. Grieve et al. (1995 [DIRS 135260], p. 196) fixes F(*D*) for *D* = 20 km at $(5.5 \pm 2.7)\times10^{-15}/km^2/yr$.

So from Eq. B-10:

$$\mathrm{F}(20) = \mathrm{K}(20)^{-1.8} = (5.5 \pm 2.7)\times10^{-15}/\mathrm{km}^2/\mathrm{yr}, \qquad \text{(Eq. B-10a)}$$

which allows a value of $(1.2 \pm 0.6)\times10^{-12}$ to be assigned to K, and setting the equation for events per year per km^2 in the form of

$$\mathrm{F}(D) = 1.2 \times 10^{-12} \times D^{-1.8} \qquad \text{(Eq. B-10b)}$$

The given proportionality ($D^{-1.8}$) applies for earth crater diameters greater than 10 km, per analysis by Neukum and Ivanov (1994 [DIRS 121510], p. 404) (C42). The deviation from the proportionality below diameters of 10 km is shown for the distribution as plotted in Figure 8 of Grieve (1987 [DIRS 135254], p. 257) (Q19) and varies noticeably from the higher frequency of smaller diameter craters observed on lunar and other planetary surfaces (Neukum and Ivanov 1994 [DIRS 121510], Figure 24) (C42). The slope change represents a decreased number of small crater observations and is explained by Grieve as atmospheric effects on small meteors, increased obscuration of smaller diameter craters by weathering and burial, and the implicit difficulty in identifying small diameter craters.

For the purposes of the plot in Figure B-2, and calculations shown in Table B-15, the distribution was extended to the 10-m diameter, and for purposes of the analysis of probability, as discussed in later sections of this appendix, has been extended to 1-m diameter. This introduces an increased uncertainty (unquantified) in the cratering rate for small diameter (i.e., less than 10 km) craters. However, it does compensate for the obscuration of small diameter craters, and is presumed to be conservative. The basis for the presumed conservatism is that the large diameter craters, from which the proportionality is extrapolated, result from fragmentation of larger meteors, with the larger fragments less subject to atmospheric effects and dissipation than small meteors due to the initially greater mass, resulting in more and larger fragments impacting the earth surface.

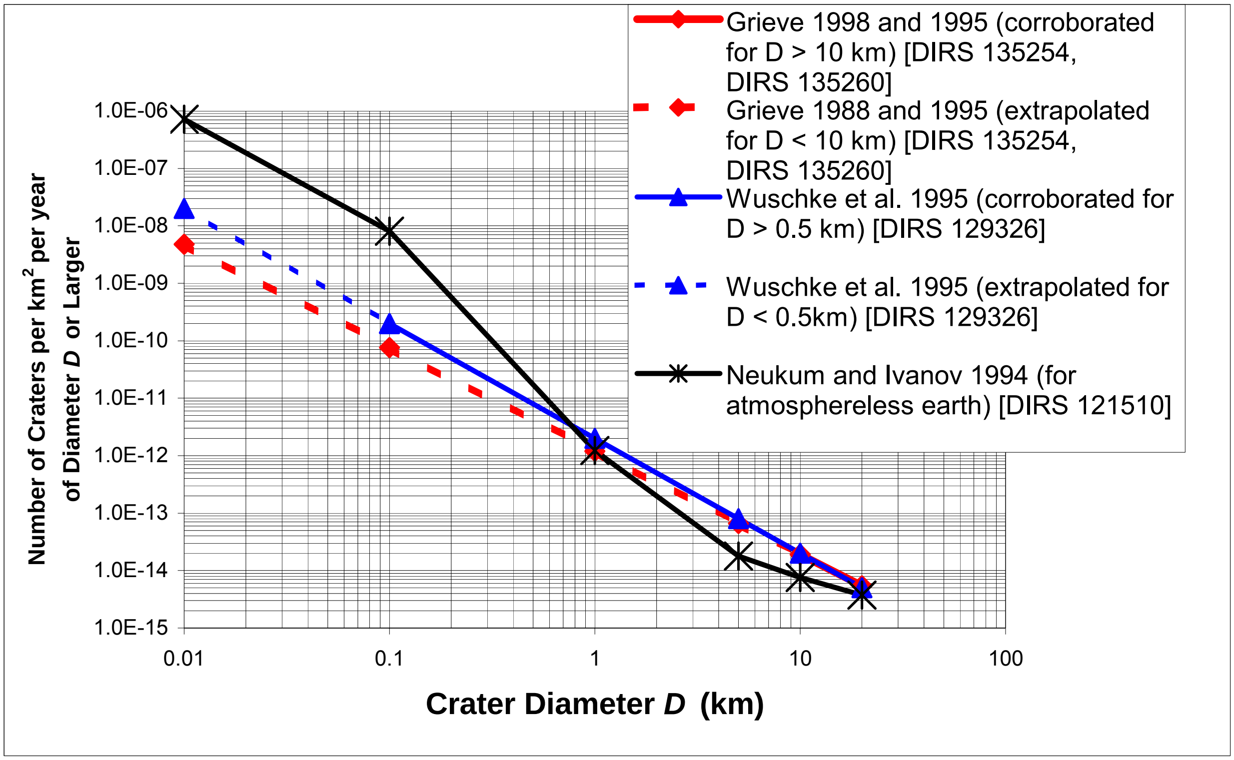


Figure B-2. Cratering Rate Distribution

Table B-16a. Cratering Rate Distribution for Direct Input

Grieve 1987 (DIRS 135254), Q19 and Grieve et al. 1995 (DIRS 135260), Q20		Wuschke et al. 1995 (DIRS 129326), Equation 3, C32	
Crater Diameter (km)	**Annual Frequency/km^2**	**Crater Diameter (km)**	**Annual Frequency/km^2**
0.01	4.8E-09	0.01	2.0E-08
0.1	7.6E-11	0.1	2.0E-10
1	1.2E-12	1	2.0E-12
5	6.6E-14	5	8.0E-14
10	1.9E-14	10	2.0E-14
20	5.5E-15	20	5.0E-15

Table B-16b. Cratering Rate Distributions Used for Corroborative-Use-Only

Hughes 1998 (DIRS 162562), C40		Neukum and Ivanov 1994 (DIRS 121510), Table IV, C42	
Crater Diameter (km)	**Annual Frequency/km^2**	**Crater Diameter (km)**	**Annual Frequency/km^2**
0.01	2.2E-08	0.01	7.1E-07
0.1	2.2E-10	0.1	8.1E-09
1	2.1E-12	1	1.2E-12
5	8.4E-14	5	1.8E-14
10	2.1E-14	10	7.6E-15
20	5.2E-15	20	3.7E-15

Bailey and Emel'Yanenko 1998 (DIRS 162564), C32					
(Assuming all cometary)		**(Assuming all asteroid)**		**(Observed cratering)**	
Diameter (km)	**Annual Frequency/km^2**	**Diameter (km)**	**Annual Frequency/km^2**	**Diameter (km)**	**Annual Frequency/km^2**
0.1	1.4E-10	0.1	4.8E-10	0.1	2.4E-10
1	2.1E-12	1	3.1E-12	1	2.4E-12
5	1.1E-13	5	9.4E-14	5	9.4E-14
10	3.0E-14	10	2.1E-14	10	2.4E-14
20	8.4E-15	20	4.6E-15	20	5.9E-15

Wuschke et al. (1995)

For Wuschke et al. (1995 [DIRS 129326], p. 44) (Q24), the distribution is derived from subsets of the observed Earth cratering distribution used by Grieve (1987 [DIRS 135254]) (Q19). The equation is given as:

$$\Phi = 2.0\times10^{-12}\times D^{-2}\times A\ a^{-1} \qquad \text{(Eq. B-11)}$$

where Φ is the frequency of cratering events of diameter D (km) or larger represented on an annual basis (a) that occur in target area A (km^2). Putting $\Phi = F(D)$ and setting A = 1 km^2 sets this equation in a form similar to that for Grieve.

$$F(D) = 2.0\times10^{-12}(D)^{-2} \qquad \text{(Eq. B-11a)}$$

This denotes a slightly steeper slope compared to Grieve (2.0×10^{-12} compared to Grieves $1.2 \pm 0.6 \times10^{-12}$). Wuschke's approach slightly decreases the annual frequency for a 20-km diameter crater (5.0×10^{-15} per km^2 compared to the values from Grieve of 5.5×10^{-15} km^2). This difference is reflected in the plot in Figure B-2.

Neukum and Ivanov (1994)

This distribution was previously discussed in this appendix, and the meteor diameter distribution was shown to be adequate and appropriate for use as corroborative information for meteoroid flux. Neukum and Ivanov's distribution (1994 [DIRS 121510]) (C42) is based on the lunar cratering rate, with the lunar crater diameter distribution adjusted for earth conditions by assuming an "atmosphereless" earth (i.e., not adjusted for ablation or atmospheric effects, but effects of gravity on crater diameters are considered). The corroborative information from Neukum and Ivanov (1994 [DIRS 121510]) (C42) is given in Table B-17.

Table B-17. Cratering Rate Distribution for "Atmosphereless" Earth

Neukum and Ivanov (1994 [DIRS 121510], Table IV, C42)		
Crater Diameter (km)	**Energy Release (MT)**	**Time Interval (year) for Whole Earth**
0.01	2.65E-07	2.75E-03
0.1	5.26E-04	2.42E-01
1.0	2.58E+00	1.60E+03
5	4.21E+02	1.10E+05
10	4.43E+03	2.58E+05
20	4.66E+04	5.25E+05

To show adequacy and appropriateness, the corroborative work of Brown et al. (2002 [DIRS 162569]) is used for comparison. The work by Brown et al. (2002 [DIRS 162569]) (C35) is based on direct observation of bolide events (a bolide is a meteor that show signs of explosion or fragmentation), and the study uses observed energy releases in Earth's atmosphere to determine flux. The work is described in more detail in this appendix and was previously evaluated based on meteor diameter equivalents. By showing corroboration between the energy releases directly observed by Brown et al. (2002 [DIRS 162569]) (C35) and the theoretical equivalents determined by Neukum and Ivanov (1994 [DIRS 121510]) (C42), the equivalent cratering rate provided in the Neukum and Ivanov (1994 [DIRS 121510]) (C42) can be evaluated. In effect, this has already been achieved in that Neukum and Ivanov (1994 [DIRS 121510]) (C42) relate the meteor diameter to crater diameters, and Brown et al. (2002 [DIRS 162569]) (C35) and Neukum and Ivanov (1994 [DIRS 121510]) (C42) were both shown to be adequate and appropriate for use as direct input for meteoroid flux. Regardless, the comparison of Brown et al. (2002 [DIRS 162569], Figure 4) (C35) to Neukum and Ivanov (1994 [DIRS 121510], Table IV) (C42) is shown on Figure B-3, with the Neukum and Ivanov (1994 [DIRS 121510]) (C42) information converted from megaton (mt) to kiloton (kt) by multiplying by a factor of 10^3. The cratering rate distribution based on Neukum and Ivanov (1994 [DIRS 121510], Table IV) (C42) represents and upper bound to the cratering rate distribution for smaller diameter craters, and is shown on Figure B-2 for comparison to other cratering rate distributions that are used as technical and corroborative information for the analysis.

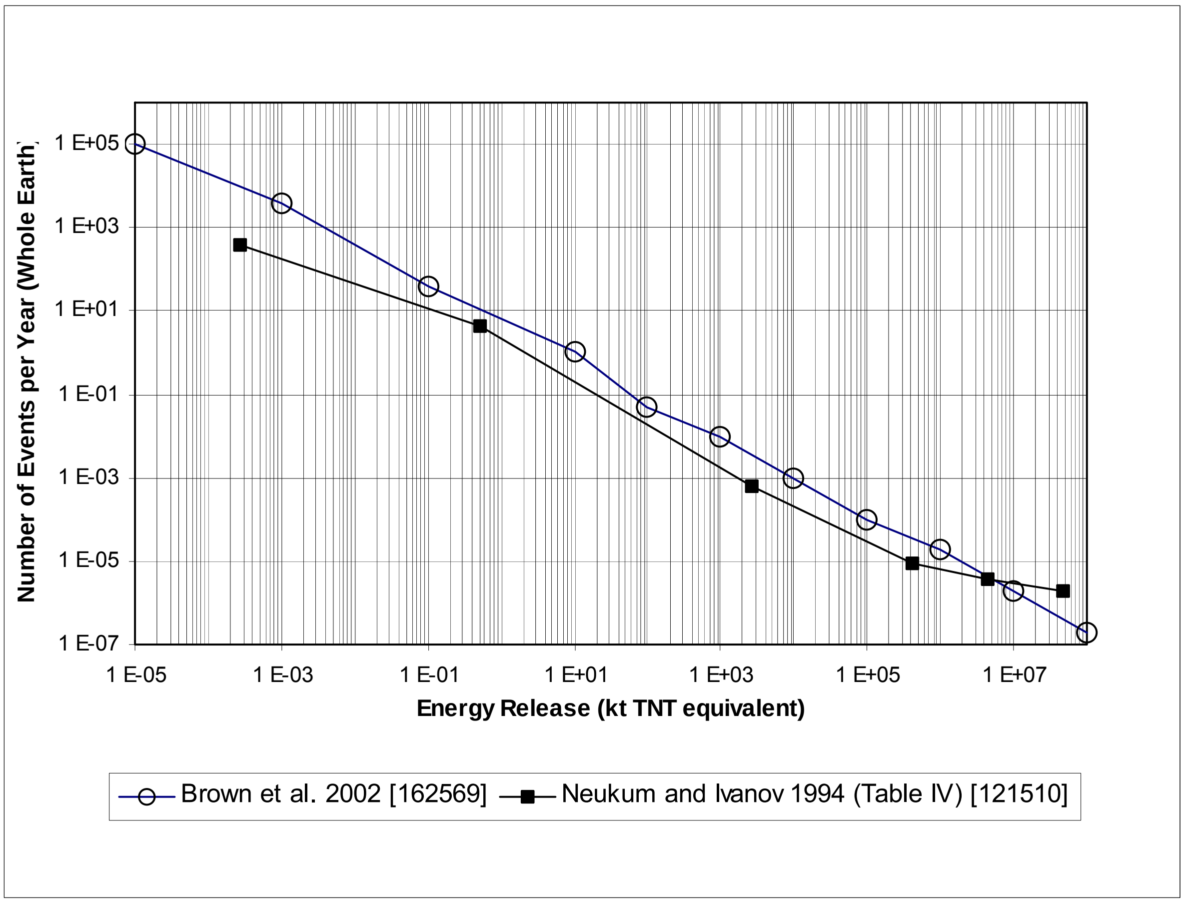


Figure B-3. Frequency of Meteor Energy Release in Earth's Atmosphere

Given the previous comparison in this appendix and that on Figure B-3, the plot of Neukum and Ivanov (1994 [DIRS 121510], Table IV) (C42) falls within about one-half order of magnitude of the plot for Brown et al. (2002 [DIRS 162569]) (C35), the corroborative information in Table B-17 is appropriate for its intended use. The use of this information, however, must recognize that it is for an "atmosphereless" earth and any calculations or use must be adjusted accordingly.

Additional Corroborative Information

The additional distribution equations represented on Figure B-2 and in Table B-16 includes distributions provided by equations in C32, Bailey and Emel'Yanenko (1998 [DIRS 162564], Equations 4 and 10, and p. 15) and by Hughes (1998 [DIRS 162562], Equation 2, p. 4) (C40).

The equations from C32, Bailey and Emel'Yanenko (1998 [DIRS 162564]) for assumed cometary and asteroidal flux are based on kinetic energy of the meteor, material properties of the impacted surface, and associated scaling laws. Bailey and Emel'Yanenko (1998 [DIRS 162564]) is focused on large-scale diameter craters, and likely applies to crater diameters of 20 km or greater, although this is not specifically stated.

The equation, assuming all impacts are cometary, is given (Bailey and Emel'Yanenko 1998 [DIRS 162564], Eq. 10) (C32) in the form of:

$$N_c\,(\geq D) \approx 4.3\times10^{-6}\,(D/20\text{ km})^{-1.84}\,a^{-1} \qquad \text{(Eq. B-12)}$$

where N_c is the number of cometary-cratering events of Diameter D or larger that occur per year and assumes that all influx is cometary in nature. Putting $N_c\,(\geq D) = F(D)$, stating it on an annual basis, and dividing by the area of the earth's surface (5.1 x 10^8 km^2) sets this equation in a form similar to that for Grieve for annual frequency per km^2:

$$F(D) = 2.1\times10^{-12}\,(D)^{-1.84} \qquad \text{(Eq. B-12a)}$$

The equation assuming all impacts are asteroidal is given by Bailey and Emel'Yanenko (1998 [DIRS 162564], Eq. 4) (C32) in the form of:

$$N_c\,(\geq D) \approx 2.34\times10^{-6}\,(D/20\text{ km})^{-2.18}\,a^{-1} \qquad \text{(Eq. B-13)}$$

where N_c is the number of asteroidal-cratering events of Diameter D or larger that occur per year and assumes that all influx is asteroidal in nature. Putting $N_c\,(\geq D) = F(D)$, stating it on an annual basis, and dividing by the area of the earth's surface (5.1 x 10^8 km^2) sets this equation in a form similar to that for Grieve for annual frequency per km^2:

$$F(D) = 3.2\times10^{-12}\,(D)^{-2.18} \qquad \text{(Eq. B-13a)}$$

The *observed* cratering rate is given (Bailey and Emel'Yanenko 1998 [DIRS 162564], p. 15) as

$$N = 3\times10^{-6}\,D_{20}^{-2}\,a^{-1} \qquad \text{(Eq. B-14)}$$

where N is the number of cratering events of Diameter D or larger that occur per year for the whole earth. Putting N = $F(D)$, stating D_{20} as (D/20 km), restating it on an annual basis, and dividing by the area of the earth's surface (5.1 x 10^8 km^2) sets this equation in a form similar to that for Grieve for annual frequency per km^2.

$$F(D) = 2.4\times10^{-12}\,(D)^{-2.18} \qquad \text{(Eq. B-14a)}$$

Hughes (1998 [DIRS 162562], Equation 2) (C40) is stated as strictly applying only to the range of diameters of 19 < D < 45 km, but allows that this could reasonably be stretched to 1 < D < 500 km. It is derived from subsets of the cratering distribution used by Grieve (1987 [DIRS 135254]) (Q19). The equation is given as:

$$\log\Phi c = -11.67 - (2.01) \log D \qquad \text{(Eq. B-15)}$$

where Φc is the number of cratering events of diameter D (km) or larger that occur per year per km^2. Putting Φc = F(D) and simplifying the form to match that for the Grieve equation (Eq. 9a, this appendix) sets the equation to the form of:

$$F(D) = 2.1 \times 10^{-12} (D)^{-2.0} \qquad \text{(Eq. B-15a)}$$

This information has been plotted to Figure B-2 and shown in Table B-16. Plots for these equations from the corroborative papers essentially are identical to that of Wuschke et al. (1995 [DIRS 129326]) (Q24), as shown in Figure B-2.

The "adequate and appropriate" direct input is listed in Table B-16. The plots of the corroborating distributions generally span about one order of magnitude or less. It is slightly greater for crater diameters of 0.1 km than for larger crater diameters. The plot of the Neukum and Ivanov (1994 [DIRS 121510]) (C42) represents an absolute upper bound of event frequency (i.e., an "atmosphereless" earth which neglects effects of ablation and fragmentation). The Grieve distribution likely overestimates the number of small diameter craters due to extrapolation of a curve fitted to a 10-km crater diameter, for which atmospheric phenomena and obscuration of the crater are less significant than for smaller crater diameters. The number of observed small-diameter craters is substantially less than that projected by the plotted distributions. The crater diameter distribution extrapolated from the observations by Grieve, however, at least includes the effects of ablation and fragmentation as reflected for large-diameter craters. The slightly higher event frequency distribution derived from Wuschke et al. (1995 [DIRS 129326]) (Q24) may represent a more realistic distribution of actual size, and it has been applied for a hypothetical Canadian repository. Regardless, the range in the number of events per year for any given diameter generally falls within one order of magnitude and, therefore, the event frequency distributions derived from Grieve and from Wuschke et al. are adequate and appropriate for use as direct input.

B5.5.3.4 Crater Dimensions as a Function of Meteor Type

This section addresses data being used to develop a cratering rate distribution based on meteoroid flux. A direct input for that calculation is based on the results of non-YMP modeling done by others. The direct inputs include the following:

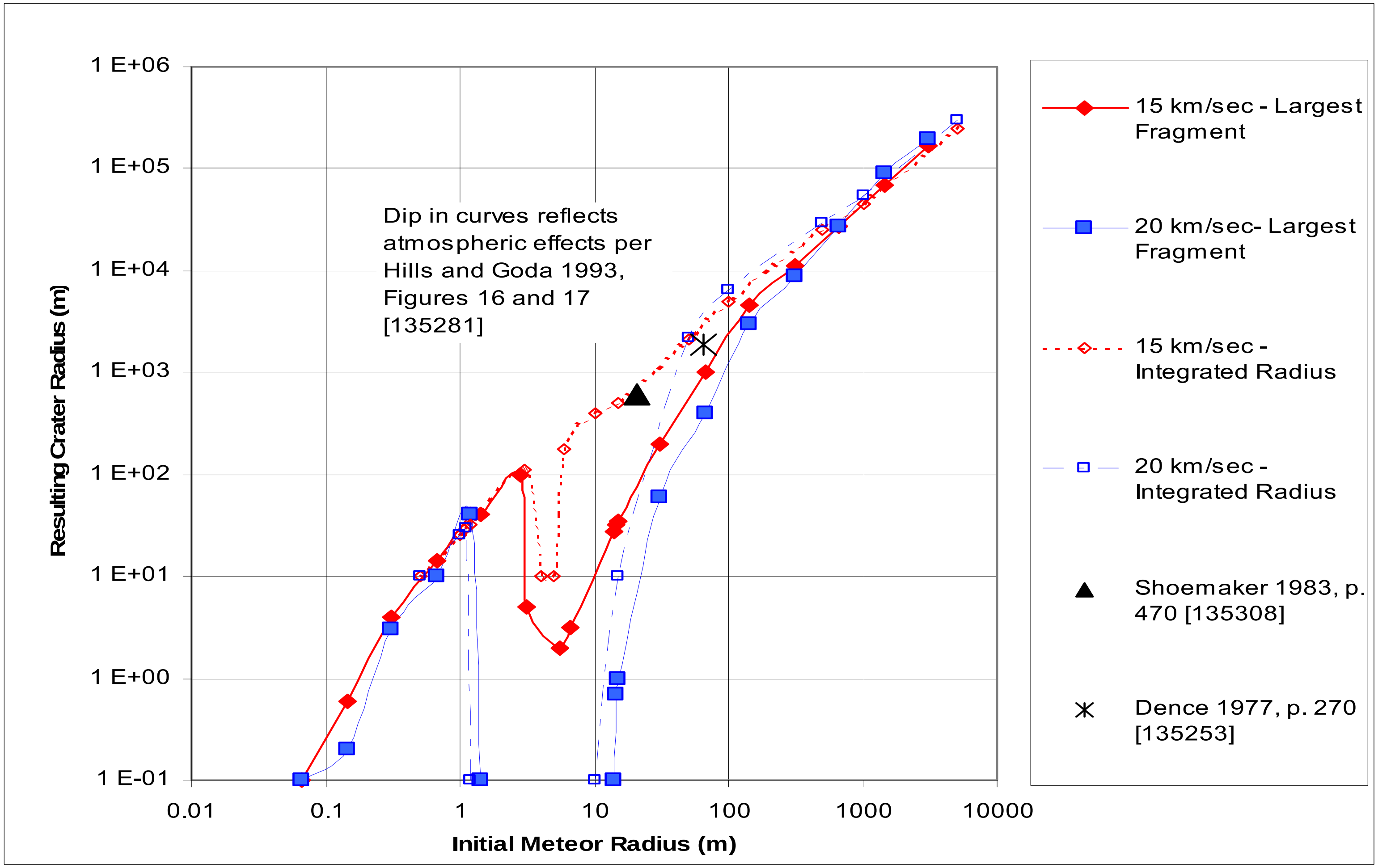
> Results of a model (by others) linking a variety of effects to initial meteor radius, including resulting crate diameters and related consequences.

This information is taken from Item Q22, but is corroborated from a large number of sources including Items Q16, Q18, Q23, C32, C36, C37, and C40.

The direct input that relates initial meteoroid diameter to crater diameter are extracted from Hills and Goda (1993 [DIRS 135281], Figures 16 and 17). These figures represent the results of modeling documented in the peer-reviewed paper, and include a variety of atmospheric effects, including fragmentation of the meteors, changing velocity of dispersed fragments, radius of the debris cloud, energy dissipation in the atmosphere through velocity reduction and ablation and velocity. These relationships are shown on Figures B-4a, B-4b, and B-4c.

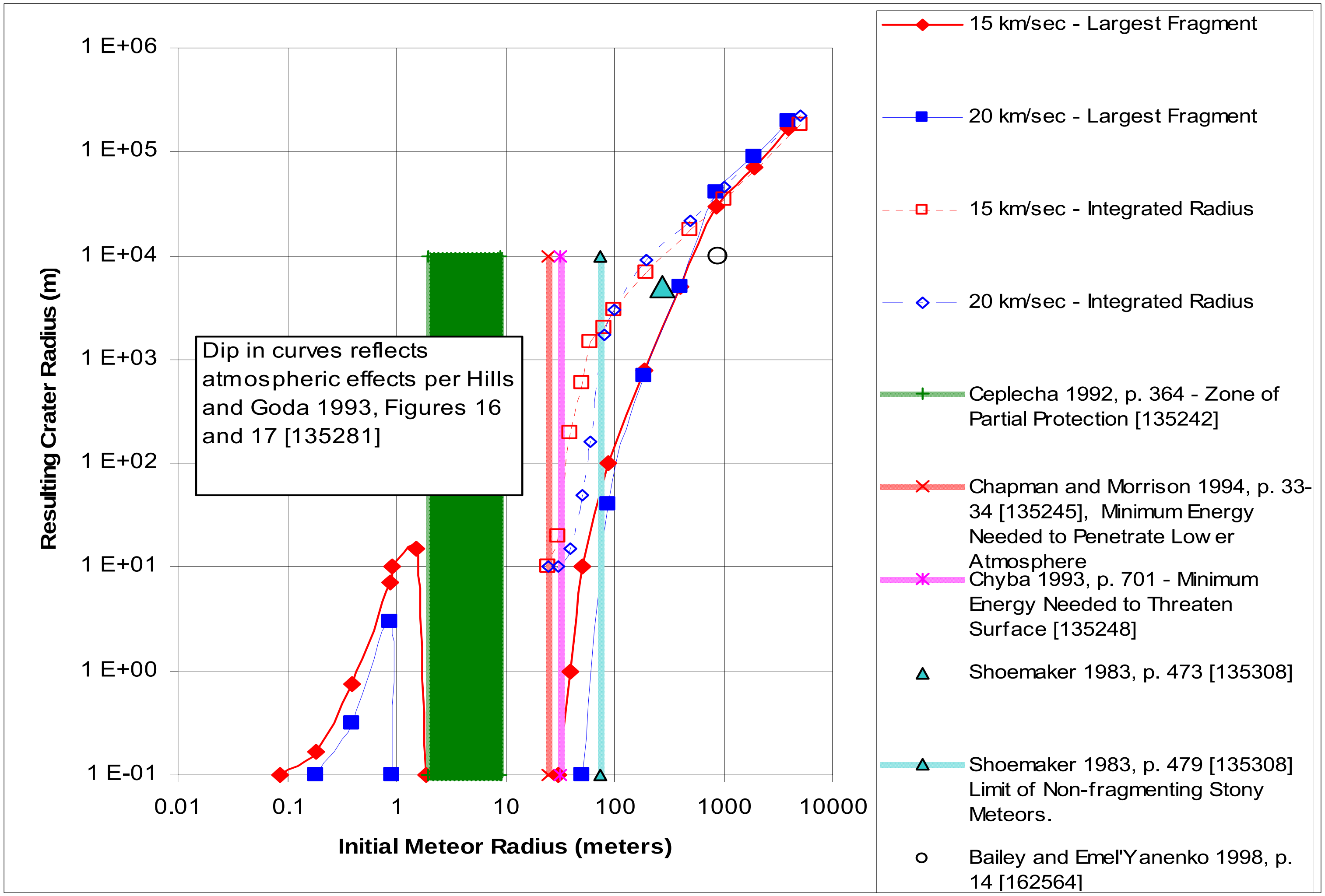
Table B-18 presents the direct input taken from Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) for velocity curves of 15 km/s and 20 km/s for the various meteor types. It should be noted that relationships listed in Table B-18 for diameters in excess of 1,000 meters for iron, and in excess of about 300 m for hard stone and soft stone, were in fact extracted from Figure 16 of Hills and Goda (1993 [DIRS 135281], Figures 16 and 17). This is reflected on Figures B-4a, B-4b, and B-4c by the overlap of the curves.

Also shown on the figures is corroborative-use-only information from other peer-reviewed or refereed papers that relate meteor radius to resulting crater radius. The relationships taken from Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) are being compared to corroborative-use-only information and statements by others regarding meteor-diameter to crater-diameter relationships, minimum sizes and conditions needed to penetrate the atmosphere, fragmentation heights, and other calculations regarding atmospheric effects. These comparisons are shown on the figures, where feasible, and are shown as wide bars for limits or boxes representing a range of stated effects. In some cases, the corroborative-use-only information is compared to other figures within Hills and Goda (1993 [DIRS 135281]) (Q22) that address specific phenomena or processes other than crater diameter. The inference is that if individual components of the work by Hills and Goda (1993 [DIRS 135281]) (Q22) can be shown to agree reasonably with works of others (e.g., decrease in velocity, range of explosive effects), then by inference, this further supports the defensibility of the relationship of initial meteor radius to crater radius given by Hills and Goda (1993 [DIRS 135281]) (Q22). Table B-19 provides a summary of the comparison to the corroborative-use-only information.



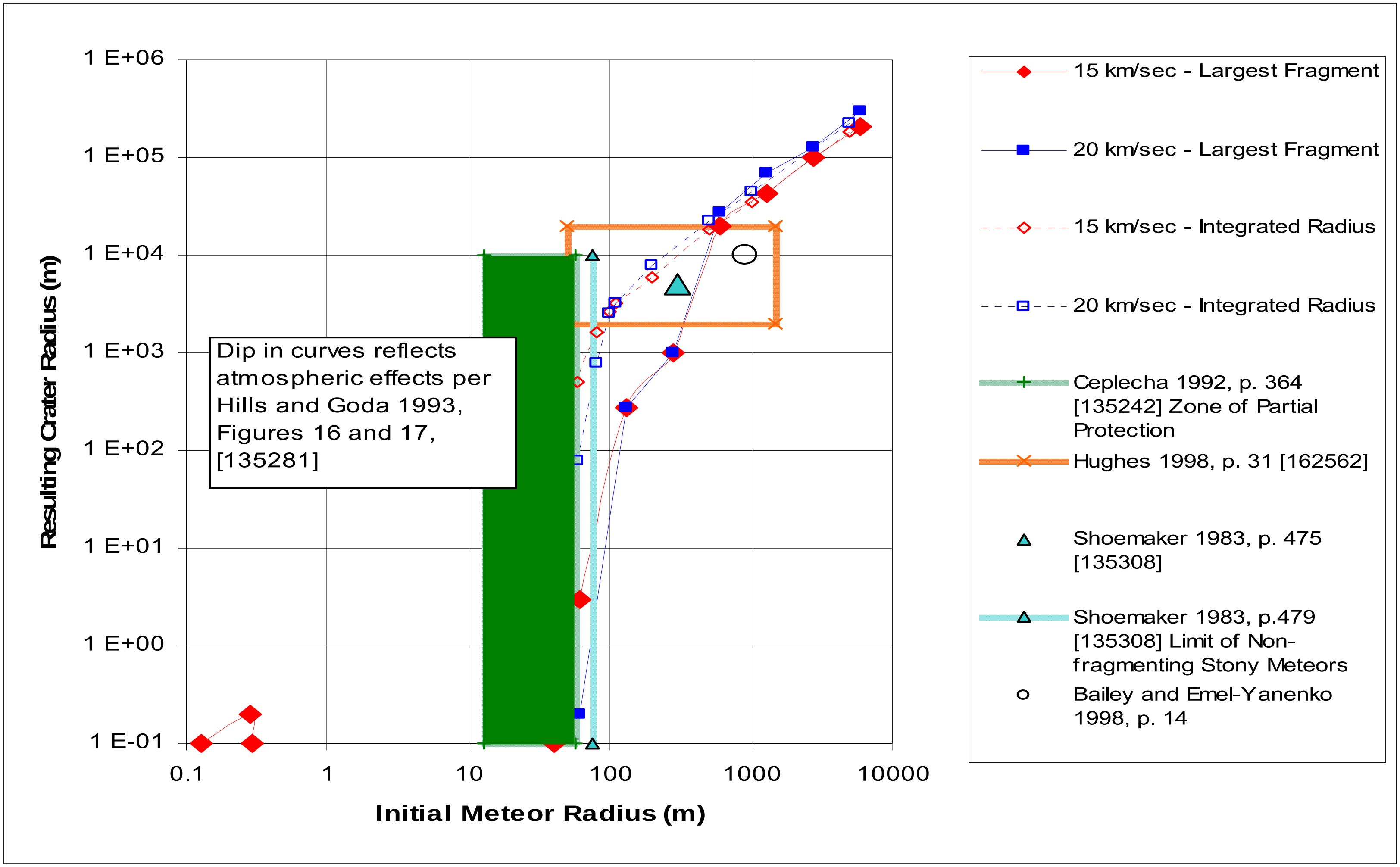
NOTE: This figure represents a cross-plot of crater radius data provided in Table B-12 of this analysis report with corroborative information provided in Table B-13 of this appendix. The data from Table B-12 for iron meteors are shown as solid or dashed line symbols. Stand-alone symbols represent corroborative information from Table B-13.

Figure B-4a. Resulting Crater Radius for Iron Meteors



NOTE: This figure represents a cross-plot of crater radius data provided in Table B-12 of this analysis report with corroborative information provided in Table B-13 of this analysis report. The data from Table B-12 for hard stone meteors are shown as solid or dashed lined symbols. Stand-alone symbols, boxed areas, and "shaded" lines represent corroborative information from Table B-13.

Figure B-4b. Resulting Crater Radius for Hard Stone Meteors



NOTE: This figure represents a cross-plot of crater radius data provided in Table B-12 of this analysis report with corroborative information provided in Table B-13 of this analysis report. The data from Table B-12 for soft stone meteors are shown as solid or dashed “lined” symbols. Stand-alone symbols, boxed areas, and “shaded” lines represent corroborative information from Table B-13. Break in largest fragment curve due to differences in curves for Figures 16 and 17 in Hills and Goda 1993 for radii greater than 100 m.

Figure B-4c. Resulting Crater Radius for Soft Stone Meteors

Table B-18. Initial Meteor Radius to Resulting Crater Radius for Use as Direct Input

Iron Meteors			Hard Stone Meteor			Soft Stone Meteor		
	R_{crater} from Largest Fragment (m)			R_{crater} from Largest Fragment (m)			R_{crater} from Largest Fragment (m)	
R_{meteor} (m)	15 km/s	20 km/s	R_{meteor} (m)	15 km/s	20 km/s	R_{meteor} (m)	15 km/s	20 km/s
3100	170,000	200,000	4000	170,000	200,000	6000	210,000	300,000
1400	70,000	90,000	1960	70,000	90,000	2800	100,000	130,000
670	27,000	27,000	870	30,000	40,000	1300	43,000	70,000
310	11,000	9,000	400	5,000	5,000	600	20,000	28,000
140	4,500	3,000	190	800	700	280	1,000	1,000
67	1,000	400	86	100	40	130	280	280
31	200	60	50	10	0.1	60	3	0.2
15	35	1	40	1	- -	40	0.1	- -
14.5	32	0.7	30	0.1	- -	28	- -	- -
14	28	0.1	19	- -	- -	13	- -	- -
6.7	3	- -	8.7	- -	- -	6	- -	- -
5.5	2	- -	4	- -	- -	2.8	- -	- -
3.1	5	- -	1.9	0.1	- -	1.3	- -	- -
2.8	100	- -	1.5	15	- -	0.60	- -	- -
1.4	40	0.1	0.90	10	0.1	0.30	0.1	- -
1.2	40	40	0.87	7	3	0.28	0.2	- -
0.67	14	10	0.40	0.8	0.3	0.13	0.1	- -
0.31	4	3	0.19	0.2	0.1	- -	- -	- -
0.14	0.6	0.2	0.09	0.1	- -	- -	- -	- -
0.07	0.1	0.1	- -	- -	- -	- -	- -	- -

	R_{crater} for Integrated Equivalent (m)			R_{crater} for Integrated Equivalent (m)			R_{crater} for Integrated Equivalent (m)	
R_{meteor} (m)	15 km/s	20 km/s	R_{meteor} (m)	15 km/s	20 km/s	R_{meteor} (m)	15 km/s	20 km/s
5,000	250,000	300,000	5,000	180,000	220,000	5,000	180,000	220,000
1,000	45,000	55,000	1,000	35,000	45,000	1,000	35,000	45,000
500	25,000	30,000	500	18,000	22,000	500	18,000	22,000
100	5,000	6,500	200	7,000	9,000	200	6,000	8,000
50	2,100	2,200	100	3,000	3,000	100	2,600	2,500
15	500	10	80	2,000	1,700	80	1,600	800
10	400	0.1	60	1,500	160	60	500	80
6.0	180	- -	50	600	50	40	30	15
5.0	10	- -	40	200	15	30	15	10
4.0	10	- -	30	20	10	25	10	- -0.1
3.0	110	- -	25	10	10	- -	- -	- -
1.2	32	0.1	- -	- -	- -	- -	- -	- -
1.1	30	30	- -	- -	- -	- -	- -	- -
1.0	25	25	- -	- -	- -	- -	- -	- -
0.50	10	10	- -	- -	- -	- -	- -	- -

NOTE: - - Indicates that either there is no resulting crater due to fragmentation effects or the result radius is less than the scale used by Hills and Goda. For Figure 17 the minimum radius plotted is 0.1 m and for Figure 16 is 0.01 km (10 m). Taken from Hills and Goda (1993 [DIRS 135281], Figure 16 and 17) (Q22).

Table B-19. Comparison of Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) (Q22) to Corroborative-Use-Only Information

Citation	Statement	Restatement for Comparison	Results from Hills and Goda 1993		Corroboration Statement
Hughes (1998 [DIRS 162562], p. 31) (C40)	Considering the typical impact velocities of asteroids and comets with Earth and the energy diameter equation mentioned above, the impacting objects have diameters that are between 1/15 and 1/30 the diameter of the craters they produce, so 4-40 km craters are produced by 0.1-3 km meteors.	Composition of asteroid/cometary probably is equivalent to soft stone. Meteor diameters of 0.1-3 km relate to meteor radius of 50 to 1500 m. Crater diameters of 4-40 km relate to radii of 2000 to 20,000 meters.	Hills and Goda (1993 [DIRS 135281], Figure 16) (Q22). The integrated crater radius for a 50-m meteor is 1 to 2 km. The integrated crater radius for a 1500-m meteor is on the order of 50 km.	Hills and Goda (1993 [DIRS 135281], Figure 17) (Q22). The radius of the largest fragment from a 50-m meteor yields a crater radius on the order of a few meters, and initial meter radius of greater than a few hundred meters is not provided.	Hughes (1998 [DIRS 162562]) (C40) is based on an energy-derived relationship that holds for large diameter meteors, but does not consider fragmentation effects. The integrated radius of Hills and Goda is similar to the “box” of the relationships suggested by Hughes. See Figure B-4c.
Hughes (1998 [DIRS 162562], p. 37) (C40)	When it comes to cratering potential, it is worth noting that an impacting short-period comet has a mean relative velocity of 38.5 km/s, in comparison with a mean velocity of 20.8 km/s for an impacting asteroid. Crudely, the diameter of the resulting crater increases as the square root of the impact velocity. So a 1 km comet will produce a crater that is about 1.36 times bigger than that produced by a 1 km asteroid.	The ratio of crater radius resulting from an asteroid (hard stone) with a radius of 0.5 km (500 m) at a velocity of 20.8 km/s, to the crater radius from a cometary body with the same radius but a velocity of 38.5 km/s, is about 1.36. Hughes does not consider fragmentation effects.	At a velocity of 20.8 km/s, a hard stone meteor with radius of 500 m yields a crater radius of about 20 km. A same-sized cometary meteor at a rate of 40 km/s yields a maximum crater radius of about 12 km, although the curve is essentially vertical at that point suggesting complete fragmentation and disintegration of the meteor. The ratio of the crater radii is 20/12 = 1.66, whereas the square root of the velocity ratio (40/20.8) is about 1.38.	Meteor radii for stony materials are covered only up to 200 m, and no curve is shown for cometary material.	The ratio suggested by Hughes holds in Hills and Goda for the integrated radius if fragmentation potential is ignored. This is not plotted on the figures. The results from Hills and Goda has a radius ration of about 1.66 similar to the 1.38 ratio proposed by Hughes.

Table B-19. Comparison of Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) (Q22) to Corroborative-Use-Only Information (Continued)

Citation	Statement	Restatement for Comparison	Results from Hills and Goda 1993	Corroboration Statement
Shoemaker (1983 [DIRS 135308]) TIC: 246922 p. 470	If the rms impact velocity of 20 km/s obtained from Earth-crossing asteroids is adopted for the projectile that formed Meteor Crater, a spherical asteroid of meteoritic iron about 42 m in diameter has the kinetic energy required to form the initial 1.16-km-diameter crater.	This equates to a 21-m initial meteor radius and a crater radius of about 600m for a velocity of 20 km/s.	Figure 16 indicates that an initial iron meteor of 21 m yields an integrated crater of about 500 m for a velocity of 20 km/s, and approximately 1000 m for 15 km/s.	See Figure B-4a. The value from Shoemaker plots along the 15-km/s velocity curve for the integrated crater radius.
p. 473	Applying Equation (2) to estimate the energy required to form a 10-km-diameter impact crater, we get 1.04 x 10^4 megatons TNT; an asteroid with this kinetic energy and a density of 2.38 g/cm^3 traveling at 20 km/s has a diameter of 0.57 km.	Equates to a 5,000-m crater radius and an initial meteor radius of 280 m for a density of 2.38 g/cm^3. .	This example plots between the resulting crater radius of the largest fragment and the integrated crater radius, on Figures 17 and 16 of Hills and Goda (1993 [DIRS 135281]) (Q22).	See Figure B-4b. This point value plots between the largest fragment curve and the integrated crater radius curves. It is in agreement with Hills and Goda (1993 [DIRS 135281]) (Q22).
p. 475	From Equation (2), using an estimated effective density of 1.7 g/cm^3, the diameter of an average C-type asteroid that will produce a 10-km crater is 0.61 km.	Equates to a 5000-m crater radius and an initial meteor radius of 305 m for a density of 1.7 g/cm^3.	This example also plots between the resulting crater radius of the largest fragment and the integrated crater radius, on Figures 17 and 16 of Hills and Goda (1993 [DIRS 135281]) (Q22).	See Figure B-4c. This point value plots between the largest fragment curve and below the integrated crater radius curves. It is in agreement with Hills and Goda (1993 [DIRS 135281]) (Q22).
p. 479	Because of the low strength, nearly all stony bodies less than 150 m diameter are sheared apart by aerodynamic stress in the lower atmosphere.	This corresponds to a limit on meteor radius of 75 m.	This threshold corresponds with the decrease in the integrated crater radius, which signifies significantly increased fragmentation.	This limit is shown on Figures B-4b and B-4c as a vertical line, it corresponds with a steepening of the integrated radius curves, and the largest fragment curve. It is consistent with the results of Hills and Goda (1993 [DIRS 135281]) (Q22).

Table B-19. Comparison of Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) (Q22) to Corroborative-Use-Only Information (Continued)

Citation	Statement	Restatement for Comparison	Results from Hills and Goda 1993	Corroboration Statement
Dence et al. (1977 [DIRS 135253], p. 270) (Q18)	The energy calculated for Brent would be delivered by an iron meteorite with a velocity of 15 km/s and diameter of 130 m.	The diameter of the Brent crater is noted by Dence in Table 1 as 3.8 km or a radius of 1900 m from an impacting meteorite radius of 65 m at impact. We will neglect the effects of ablation on the initial meteor radius.	The point value plots between the curve sets for the largest fragment and the integrated crater radius.	See Figure B-4a. This point value supports the results of Hills and Goda (1993 [DIRS 135281]) (Q22). The results from Hills and Goda bracket this example.
Bailey and Emel'Yanenko (1998 [DIRS 162564], p. 14) (C32) TIC: 254143	… which shows that a long-period comet or Halley-type object has a diameter d = 1.8 km in order to produce a 20 km crater.	This roughly corresponds to an initial soft stone radius of 900 m and a crater radius of 10,000 m.	The point value was plotted for the both hard stone and soft stone rather than cometary material, and the Hills and Goda plot should plot as a larger crater due to the increase in density of stony meteors compared to cometary meteors.	See Figures B-4b and B-4c. The corroborative-use-only point values plot below the curves from Hills and Goda (1993 [DIRS 135281]) (Q22) as expected due to the difference in assumed densities.
Ceplecha (1994 [DIRS 135243], Figure 3) (Q17)	This figure shows the resulting impact velocity for diameter (plotted as log d) for various initial entry velocities for a stony composition.	Initial and resulting impact velocities are: For 5 m radius: <u>Initial Impact</u> 15 km/s → 1 km/s 20 km/s → 4 km/s 25 km/s → 6 km/s 30 km/s → 6 km/s For 50 m radius: <u>Initial Impact</u> 15 km/s →14 km/s 20 km/s →18 km/s 25 km/s →23 km/s 30 km/s →28 km/s	Comparison here is made to Hills and Goda (1993 [DIRS 135281], Figure 10) (Q22), which is directly comparable. For 5-m radius: The impact velocity for all initial velocities is shown as 0 km/s. For 50-m radius: <u>Initial Impact</u> 15 km/s → 5 km/s 20 km/s → 8 km/s	The results of Hills and Goda (1993 [DIRS 135281]) (Q22) include all energy dissipation, not just ablation effects considered by Ceplecha and consequently showing a more marked decrease in velocity.

Table B-19. Comparison of Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) (Q22) to Corroborative-Use-Only Information (Continued)

Citation	Statement	Restatement for Comparison	Results from Hills and Goda 1993	Corroboration Statement
Ceplecha (1992 [DIRS 135242], p. 364) (Q16) TIC: 246784	Figure 4 (*same as Figure 3 from Ceplecha 1994, but expressed as log m rather than log d*) also shows that protection by the Earth's atmosphere against explosive impacts of stony bodies is effective only below 10^5 kg. For masses of 10^6 kg, the protection is partial, i.e., against high velocity bodies. Stony bodies more massive than 10^7 kg impact the surface explosively for all initial velocities. For carbonaceous bodies the situation is similar except that the border is shifted two orders higher to larger masses with a steeper velocity gradient. Thus the protection against carbonaceous bodies is much more effective. Cometary bodies with masses under 3×10^{11} kg (initial velocity of 28 km/s) do not impact the Earth surface explosively. While bodies with mass of 10^{12} kg and greater do, although their terminal mass at impact is 4×10^{10} kg and greater.	Equivalent diameters are calculated assuming stony density of 3000 kg/m^3, carbonaceous density of 1100 kg/m^3, cometary density of 500 kg/m^3, and assuming spherical shape. Accordingly the equivalent meteor radii for explosive impact protection, partial protection, and no protection, respectively, are as follows: For stony material 10^5 kg ≈ 2 m 10^6 kg ≈ 4 m 10^7 kg ≈ 9 m For carbonaceous materials: 10^7 kg ≈ 13 m 10^8 kg ≈ 28 m 10^9 kg ≈ 60 m For cometary material: 3×10^{11} kg ≈ 520 m 10^{12} kg ≈ 780 m 4×10^{10} kg ≈ 270 m For cometary material: 10^{12} kg ≈ 780 m 4×10^{10} kg ≈ 270 m This suggests an ablation ratio of about 96 percent of the initial meteor mass.	Given that Ceplecha bases his statement on velocity relationships and has linked that to ablation effects, corresponding velocity and ablation figures from Hills and Goda 1993 (DIRS 135281) (Q22) should also be used, which are Figures 10 and 6 respectively. For stony material, impact velocity drops to 4 km/s or less (the threshold used by Ceplecha 1992 [DIRS 135242]) for all initial entry velocities if the meteor radius is less than 20 m, with some explosive impact damage from fragments possible if the radius is in the range of 1 to 3 m. Ablation has a significant effect for meteor radii less than 40 m and is largely ineffective for meteor radii greater than about 100 m. For soft stone (an assumed surrogate for "carbonaceous"), velocity drops to zero for all meteor radii less than about 30 m, and no protection from explosive impacts is provided if the meteor radius is greater than about 60 m. Ablation has a significant effect for meteor radii less than about 70 m, and is largely ineffective for meteor radii greater than about 150 m. For cometary material, with initial velocities of 30 km/s, velocity drops to less than the explosive threshold at a meteor radius of about 300 m. For a given velocity of 30 km/s and an initial radius of 780 m, Hills and Goda (1993 [DIRS 135281]) (Q22) predict an ablation fraction of about 0.2 or 20 percent (1993 [DIRS 135281], Figure 6) (Q22). A 90-percent ablation occurs for cometary bodies of no larger than 300- to 400-m radius per Hills and Goda (1993 [DIRS 135281], Figure 6) (Q22) for the stated velocity, and for a radii of 700 m at velocities in excess of 50 km/s.	As previously mentioned, the velocity curves for Hills and Goda (1993 [DIRS 135281]) (Q22) include a greater reduction due to effects other than just ablation. Consequently, it is to be expected that the upper range will be greater than that given by Ceplecha, but should be on the same order of magnitude, which is the case. The limits proposed by Ceplecha are plotted on Figures B-4b and B-4c as a "box," which falls in the "shielding effect" portion of the Hills and Goda curves. Hills and Goda (1993 [DIRS 135281]) (Q22) indicate significantly less ablation than Ceplecha (1992 [DIRS 135242]) – the basis for the difference is not discernible from Ceplecha (1992 [DIRS 135242]). This may be in agreement if Ceplecha has misstated the velocity or based ablation on the final size.

Table B-19. Comparison of Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) (Q22) to Corroborative-Use-Only Information (Continued)

Citation	Statement	Restatement for Comparison	Results from Hills and Goda 1993	Corroboration Statement
Chapman and Morrison (1994 [DIRS 135245], p. 33 and p. 34) (C36)	Most projectiles <50 m in diameter, with energies <10 megatons dissipate the energy harmlessly in the upper atmosphere. The height of fragmentation depends primarily on the meteoroid's physical strength; only the strongest iron meteoroids reach the ground in one piece. For non-iron meteoroids, the minimum energy required to penetrate to the lower atmosphere is 10 MT or 50 m diameter for stony object hitting at 20 km/s.	This corresponds to radii of <25 m and at a velocity of 20 km/s.	Hills and Goda (1993 [DIRS 135281], Figures 6 and 10) (Q22). For hard stone, impact velocity drops to 4 m/s or less (the threshold used by Ceplecha (1992 [DIRS 135242]) for all initial entry velocities if the meteor radius is less than 20 m, with some damage from fragments possible if the meteor radius is in the range of 1 to 3 m. Per Hills and Goda, ablation has a significant effect for meteor radii less than 40 m and is largely ineffective for meteor radii greater than about 100 m. Additionally, Figure 4 of Hills and Goda (1993 [DIRS 135281]) (Q22) provides the height of half energy dissipation. This figure indicates half energy dissipation occurs in the atmosphere at heights greater than 5 km, for hard stone with initial radii less than 20 m, and for soft stone with initial radii less than 50 m. Figure 5 indicates that although all meteors of hard stone greater than about 1 m radius will break, significant dispersion of the fragments does not occur if the initial meteor radius is greater than about 25 m for the given velocity of 20 km/s.	The statements by Chapman and Morrison (1994 [DIRS 135245]) support the findings by Hills and Goda (1993 [DIRS 135281]) (Q22). This has been plotted on Figure B-4b as a vertical line representing the stated limit, and corresponds with the break in the Hills and Goda curve.
Chyba (1993 [DIRS 135248], p. 701) (C37) TIC: 246762	Figure 1 shows that the Spacewatch objects with energies below 10 MT (at 13.3 km/s a stony asteroid approximately 32 m in radius) do not threaten the surface.	Directly comparable for radius, and velocity is less than 15 km/sec.	The same values discussed for Chapman and Morrison (1994 [DIRS 135245]) apply here as well. The 11.2 km/s and 15 km/s velocity curves from Hills and Goda were considered surrogate velocities. Figure 4 indicates that for a radius of 32 m or greater, half dissipation occurs at heights greater than 4 km for the 11.2 km/s curve. Chyba is addressing atmospheric release and is not addressing potential for cratering impacts.	The statement by Chyba supports the findings by Hills and Goda (1993 [DIRS 135281]) (Q22). This corresponds with the break in the Hills and Goda curve.

B5.5.3.5 Depth and Extent of Cratering Features

The meteorite impact analysis must consider the spatial relationship of crater diameter and related phenomena such as exhumation and fracturing depth. Direct input pertaining to the spatial relationships of crater diameter to the extent of exhumation and depth of fracturing has been taken from existing published literature. Because these may be the best or only information available, and have been developed by others for analyzing similar problems, it is technically justified to use the values for formulation of the analysis.

> Diameters associated with onset of complex cratering. This information is taken from Items Q19, Q20, and Q24. These sources are mutually corroborating.
>
> Crater diameter to depth of effect relationships. This information is taken from Items Q18, Q21, and Q24. These sources are mutually corroborating.

Simple and Complex Cratering

The amount of kinetic energy acting in combination with the impacted rock properties determines the features, shape, size, and depth of any crater and any related cratering effects such as fracturing. The potential consequences are divided at the first level on the two basic types of observed cratering. Complex cratering involves the uplift and significant vertical displacement of a central portion of the crater. Complex cratering can be initiated with crater diameters greater than 2 km in sedimentary rocks; however, terrestrial simple craters may also exhibit crater diameters up to 4 km, which is the threshold for simple-to-complex cratering in crystalline rocks (Grieve 1987 [DIRS 135254], p. 249 [Q19], Grieve et al. 1995 [DIRS 135260], p. 194 [Q20], and Wuschke et al. 1995 [DIRS 129326], p. 3 [Q24]). Complex cratering is typically associated with larger-scale (greater than 2- to 4-km-diameter) craters and several mechanisms are involved in their formation. The threshold for FEP screening based on probability is stated as an annualized equivalence of 1×10^{-8} events per year for the repository area. Based on the cratering rate distributions presented earlier in this appendix, a 2-km crater diameter event occurs 10^{-12} times or less per year. Consequently, complex cratering features do not occur with sufficient frequency to be of concern for FEP screening and only simple cratering effects need be further evaluated.

Depth and Extent of Exhumation

The direct input for depth and extent of simple cratering exhumation come from three sources: Dence et al. (1977 [DIRS 135253]) (Q18), Wuschke et al. (1995 [DIRS 129326]) (Q24), and Grieve (1998 [DIRS 163385]).

Wuschke et al. subdivide the total exhumed depth into two zones. The first zone is based on exhumation and ejection of materials from the crater. Wuschke et al. assign a depth value of 10 percent (0.10) of the crater diameter for simple craters (Wuschke et al. 1995 [DIRS 129326], p. 3) (Q24). The second zone of exhumation extends below the first. It is defined by shattering and redistribution of material within the crater itself. Wuschke et al. (1995 [DIRS 129326], p. 3) (Q24) suggest that the second zone extends to a depth of about 14 percent (0.14) of the crater diameter for simple craters. Wuschke et al. (1995 [DIRS 129326], p. 3) (Q24) indicate that the depth of shock, compression, and displacement without redistribution is approximately

42 percent of the crater diameter, but does not specifically identify this as part of the "true crater depth."

The true crater depth is equivalent to an exhumation depth. Grieve (1998 [DIRS 163385], p. 113) (Q21) expresses the true crater depth-to-crater diameter relationship for simple craters as an equation:

$$d_t = 0.28\, D^{\,0.98} \qquad \text{(Eq. B-16)}$$

where d_t= true crater depth and D = the crater diameter, with d_t and D in km. This suggests that the ratio of the true depth (d_t) to crater diameter (D) decreases as the crater diameter increases. This equation yields calculated true depth-to-crater diameter ratios of 0.32 to 0.27 for a range of crater diameters of 0.001 km to 2 km, with a 2-km diameter representing the potential for onset of complex cratering. Grieve (1998 [DIRS 163385]) (Q21) also suggests on Figure 8 that the "depths of structures in sedimentary targets are shallower than for equivalent size structures in crystalline targets" and attributes this to target rock effects as it pertains to variable rock strength in cratering mechanics.

Combined, the relationships presented by Wuschke et al. and by Grieve suggest exhumation ratios ranging from 0.10 to as much as 0.33 of the crater diameter. These ratios are mutually corroborative with information from Dence et al. (1977 [DIRS 135253], pp. 247 and 270) (Q18). Dence et al. refer to the Brent crater, a simple crater with a crater diameter of approximately 3.8 km, and suggest a meteorite of 130-m-diameter impacting the surface (i.e., the impacting diameter, not initial entry diameter) caused the crater. Dence et al. state that the peak pressure begins to drop at a depth of about 1.3 $D_{meteorite}$ and the excavation continues to a depth of about 4.1 $D_{meteorite}$, or a depth of about 533 m deep, which is 14 percent of the crater diameter. Dence et al. also indicate that there is further cavity expansion due to displacement of bedrock below the excavated cavity to give a total depth of 8 $D_{meteorite}$, or a depth of 1,040 m, which is 27 percent of the crater diameter. Based on this description, it appears that at least part of the second zone (i.e., extending to 14 percent of the crater diameter) described by Wuschke et al. (1995 [DIRS 129326]) (Q24) corresponds with the depth of the transient cavity described by Dence et al. In a summary statement, Dence et al. (1977 [DIRS 135253], p. 250) (Q18) state "the depth to the bottom of the lining (true depth) is typically one-third to one-quarter the diameter of the crater."

A range of crater diameter-to-exhumation depth ratios of 0.10 to 0.32 is, therefore, adequate and appropriate for use as direct input. A depth of 200 m is used to evaluate the potential for damage at the repository depth. This gives a lower bound to the crater diameter of interest for exhumation of the repository of about 625 m (i.e., 200 m / 0.32). A key geologic unit is at 60 m depth. This gives an upper bound of concern of about 188m (i.e., 60 m / 0.32).

Depth and Extent of Fracturing

The ratio of crater diameter-to-fracture depth inferred from Grieve (1998 [DIRS 163385]) (Q21), and the ratio stated in Wuschke et al. (1995 [DIRS 129326]) (Q24), are used as direct input and are further evaluated in this section. These data are mutually corroborative with information taken from Dence et al. (1977 [DIRS 135253]) (Q18).

As discussed in the previous section, Grieve places the depth of exhumation or true crater depth (d_t) at no less than 0.27 *D* based on available field observations from some 14 sites, and possibly ranging as high as 0.32 *D,* where for both cases *D* is the crater diameter in km. This true depth represents the depth of exhumation and the onset of fracturing below the crater.

Wuschke et al. (1995 [DIRS 129326], p. 3) (Q24) indicate that the depth of shock, compression, and displacement without redistribution is approximately 42 percent of the crater diameter, but does not specifically identify this as part of the "true crater depth." Wuschke et al. (1995 [DIRS 129326]) (Q24) further states that an ancillary zone of fractured but stationary rock extends to a depth of 76 percent in plutonic rock for simple craters.

Mutually corroborative information is derived from relationships provided in Dence et al. (1977 [DIRS 135253]) (Q18). Based on Dence et al. (1977 [DIRS 135253]) (Q18), the lower limit of fracturing values is based on the Hugoniot Elastic Limit of 4.5 gigapascals (GPa) for granodiorite (Melosh 1989 [DIRS 146025], p. 35), which is a very low-porosity rock. From the Pile Driver nuclear test, it appears that fracturing was initiated when the shock wave pressure was reduced to 4.5 GPa. Fracturing ceased at depths corresponding to pressures of about 2 GPa, where the rock responds elastically (i.e., without permanent deformation or fracturing) (Dence et al. 1977 [DIRS 135253], p.261) (Q18).

In the attenuation models, Dence et al. (1977 [DIRS 135253], p. 261) (Q18) relate pressure to the radius of the affected region by:

$$P = a\,R^{-k}. \qquad \text{(Eq. B-17)}$$

The ratio of the pressures at 4.5 GPa and 2 GPa is, therefore, also the ratio of the powers of the respective radii, that is:

$$P_{4.5\ GPa}/P_{2\ GPa} = [R_{2\ GPa}/R_{4.5\ GPa}]^k\ , \qquad \text{(Eq. B-18)}$$

or,

$$R_{2\ GPa} = R_{4.5\ GPa}\,(P_{4.5\ GPa}/P_{2\ GPa})^{1/k}. \qquad \text{(Eq. B-18a)}$$

The radius ($R_{4.5\ GPa}$) for the onset of fracturing corresponds to the true crater depth (or exhumation depth) and, as described in Section B3.2.5.1, is stated by Dence et al. (1977 [DIRS 135253], p. 250) (Q18) as one-third to one-half the crater diameter (*D*). Presuming ratios of 0.33 and 0.25 and substituting terms into Eq. 10a, then the radius ($R_{2\ GPa}$) of fracturing expressed as a function of crater diameter (*D*) may range from:

$$R_{2\ GPa} = 0.33D\,(4.5\,/\,2)^{1/k}. \qquad \text{(Eq. B-18b)}$$

$$R_{2\ GPa} = 0.25D\,(4.5\,/\,2)^{1/k}. \qquad \text{(Eq. B-18c)}$$

The k values (2, 3, and 4.5) for the models are based on fits to the Brent crater and the Piledriver nuclear test (Dence et al. 1977 [DIRS 135253], p. 261) (Q18). Insertion of the values for k provides a range in the relationship of fracture depth to crater diameter (D) of R = 0.5 *D* (for k=2 and a ratio of 0.33 or ⅓) to R = 0.3 *D* (for k=4.5 and a ratio of 0.25).

As previously mentioned, Wuschke et al. (1995 [DIRS 129326], p. 3) (Q24) indicates that the depth of shock, compression, and displacement without redistribution is approximately 42 percent of the crater diameter, and an ancillary zone of fractured but stationary rock extends to a depth of 76 percent in plutonic rock for simple craters.

Accordingly, the fracture depth could be a value of 0.3 *D* based on Equation B-18c and assuming k=4.5. This corresponds well to the depth of exhumation (0.27 to 0.3 *D*) suggested by Grieve (1998 [DIRS 163385]) (Q21) and based on simple crater observation. A value of 0.5 *D* based on Equation B-18c and assuming k=2 may be a more reasonable estimate of the depth of penetration by fractures. This also encompasses the zone of displacement (depth of 0.42 *D*) as identified by Wuschke et al. (1995 [DIRS 129326]) (Q24). The value of 0.5 *D* is derived from possible models for the Brent crater, and as inferred from Grieve (1998 [DIRS 163385]) (Q21), depths in sedimentary rocks tend to be shallower. At Yucca Mountain, however, the rock above and around the repository is layered welded and non-welded tuff, deposited in tilted strata. These tuffs are porous, but largely unsaturated. Therefore, the exhumation and fracturing depths in the tuffs are likely to be between that of sedimentary rock and granodiorite, and likely to be shallower at Yucca Mountain than in the granodiorite or plutonic rock used as the basis for this analysis for a given cratering event. However, a factor of 0.76 from Wuschke et al. (1995 [DIRS 129326], p. 3) (Q24) is specifically identified as the zone of fracturing. No support for this depth is given beyond a reference, which appears in a proceedings paper. However, a value of 0.76 represents the largest ratio of fracturing depth to crater diameter proposed in the reviewed literature and is therefore used as a basis for FEP screening.

The minimum depth of interest is 60 m, which is the top of a key hydrogeologic unit. Using the above relationships, then the minimum crater diameter of interest is on the order of 79 m (i.e., 60 m / 0.76). As described in Section B5.2, a depth of 200 m is used to evaluate the potential for fracturing to the repository depth. This gives an upper bound to the crater diameter of interest for fracturing of 263 m (i.e., 200 m / 0.76).

B5.5.4 Data Status and Limitations

The above literature review and corroboration of the direct input provides an acceptable level of confidence that the data are suitable for their intended use, which is for FEP screening. For quantitative data, the criterion of general agreement has been satisfied. The direct inputs are considered acceptable because "singular" values (e.g., percent by composition) are shown to be within two standard deviations of the mean value, with the mean and deviations developed by equal weighting of reported mean values from each source. In the case of probability distributions or equations based on probability distributions (e.g., mass flux or cratering rates), direct inputs are acceptable because the resulting probability distributions fall within two orders of magnitude for any given point in the distribution (e.g., for the probability of crater diameter of a given size).

In the case of determining crater diameter-to-depth of effect ratios, in lieu of corroboration, a bounding or conservative value (with respect to inclusion of the FEP) approach has been recommended, and the resulting values are considered as qualified under this exercise. The status of the direct inputs for diagenesis evaluated above should be considered as qualified for use within this technical product.

The datasets that are considered as qualified for use within this technical product, and any limitations, are as follows:

B5.5.4.1 Meteoroid Influx Entering Earth's Atmosphere

For the meteoroid flux, the mass influx derived by Ceplecha (1992 [DIRS 135242], p. 362 and Figure 1) (Q16) is used. The comparison showed that distribution of meteor diameter (derived from the mass influx distribution) from Ceplecha (1992 [DIRS 135242]) (Q16) is generally conservative in that it represents the largest number of events within the primary range of interest (79 m to 625 m) for fracturing and exhumation. Therefore, no limitations are placed on this data.

B5.5.4.2 Composition and Material Properties of Meteoroids Entering the Earth's Atmosphere

The following section addresses the flux in terms of percent by compositions and examines the range in possible density values. The qualified direct input includes:

Percent-by-Type

Down to an initial meteor mass of approximately 10^8 kg (radius of 14 m for iron, 19 m for stony, and 28 m for carbonaceous meteors), the total flux is presumed to be comprised of five percent iron material regardless of initial meteor radius, and the remainder is divided equally between stony and carbonaceous material regardless of initial meteor radius. For initial meteor masses below 10^8 and down to 10^{-1} kg (minimum radius of 0.014 m for iron, 0.019 m for stony, and 0.028 m for carbonaceous meteors), the total flux is presumed to be comprised of five percent iron materials regardless of initial meteor radius, and 2 to 18 percent stony material depending on initial meteor radius; and the remainder (93 to 77 percent) is attributed as carbonaceous/cometary material.

Meteoroid Densities

For the meteorite impact calculations, the densities used for meteoroids are 8 g/cm^3 for metallic materials, 3.7 g/cm^3 for stony materials, and 1.1 g/cm^3 for carbonaceous/cometary materials. These values fall within the mean value plus one standard deviation determined from the available literature and are used by Ceplecha (1994 [DIRS 135243], p. 967, Tables 1 and 3) (Q17).

B5.5.4.3 Crater Diameter Distributions and Rates

The distribution derived from Grieve et al. (1995 [DIRS 135260]) (Q20), and the distribution from Wuschke et al. (1995 [DIRS 129326]) (Q24) represent a "realistic case" and are qualified for use. However, the extrapolation of the distribution from Grieve (1998 [DIRS 163385]) (Q21) for very small crater diameters likely overestimates the number of small-diameter craters, due to extrapolation of a curve fitted to a 10-km crater diameter down to crater diameters on the meter scale. The number of observed small diameter craters as noted by Grieve is substantially less than that projected by the extrapolated distribution, and would in fact be the true lower bound. The number of observed small diameter craters is skewed because it does not account for atmospheric effects on small meteors, increased obscuration of smaller diameter craters by weathering and burial, and the implicit difficulty in identifying small diameter craters. The crater diameter distribution observed by Grieve and based on large crater diameters, however, at least includes the effects of ablation and fragmentation as reflected for large diameter craters. The data derived from Wuschke et al. (1995 [DIRS 129326]) (Q24) may represent a more realistic distribution of actual size and have been applied to a hypothetical Canadian repository. The plot of the corroborative Neukum and Ivanov (1994 [DIRS 121510]) information represents a true upper bound (i.e., an "atmosphereless" earth which neglects effects of ablation and fragmentation). Because it is unrealistic due to an "atmosphereless" earth, it is discussed for corroborative purposes only, but it also provides a true upper bound. However, it should not be used to represent cratering on earth because it is not representative of surface conditions.

B5.5.4.4 Crater Dimensions as a Function of Meteor Type

The direct input used in this analysis that relate initial meteoroid diameter to crater diameter are extracted from Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) (Q22) and are given in Table B-18.

B5.5.4.5 Depth and Extent of Cratering Features

A range of crater diameter-to-exhumation depth ratios of 0.10 to 0.32 is used in the analysis, and is based on direct input provided in Wuschke et al. (1995 [DIRS 129326]) (Q24) and Grieve (1998 [DIRS 163385]) (Q21). A minimum value for crater diameter-to-fracture depth ratios of 0.32 is realistic based on Grieve (1998 [DIRS 163385]) (Q21). Because the intended use is for FEP screening and analysis, the conservative value of increased fracturing depth to 0.76 of the crater diameter, as indicated by Wuschke et al. (1995 [DIRS 129326]) (Q24), is examined to ensure that the range of uncertainty in relationships is covered. The use of this value based on effects in plutonic rock is somewhat contrary to the observation made by Grieve (1998 [DIRS 163385], p. 113) (Q21) that depths in sedimentary rocks tend to be shallower than in plutonic rock. However, the use of these values is consistent with use of cratering rate and crater diameter distributions from these same sources.

B5.6 SUITABILITY DEMONSTRATION FOR DIRECT INPUTS FOR FEP 1.5.01.02.0A EXTRATERRESTRIAL EVENTS (SECTION 6.2.4.6)

This section addresses direct inputs used to determining the potential consequence of extraterrestrial events such as a solar flares, supernovae, and gamma bursters. The direct inputs being justified are as follows:

- Frequency of supernova event (1 event per 100 years), magnitude (10^{50} ergs), and potential consequences of the event (nitrogen enrichments, ozone depletion, global cooling) due to a supernova event. This information is taken from Item Q25.

- Relationship exists between the decadal Sun cycle, and overall solar activity and the Earth's surface temperature, and possible link from changes in IR and visible and IR radiation to changes in earth's temperatures and climate. This information is taken from Items Q26.

- Types of engineered systems potentially affected by space weather. This information is taken from Item Q27.

The data being evaluated include Items Q23 through 26 in Table B-1. The data is in the form of conceptual statements and is generally qualitative in nature. Therefore, the qualitative criteria for general agreement will be applied. Multiple sources are available to corroborate the data.

B5.6.1 Literature Search

A literature search was performed using SciSearch® and the GeoRef® databases and was focused on recent papers and updates directly relevant and applicable to the analysis. The intent of the search was to identify citations that identified possible effects to earth-based natural and engineered systems from such extraterrestrial events, and if possible, quantify the effect. The keyword and subject based searches utilized various “AND” combinations for the keywords “space weather,” “extraterrestrial,” “supernova,” “effects,” and “earth.” For the keyword “space weather,” the SciSearch® database (limited to publication dates for 1900 to 2004) returned 95 records. Upon examination of titles and abstracts, all of these records were found to be specific instances of space weather events, or to describe disturbances to specific engineered systems that were not relevant to postclosure repository performance and that were documented in other more generic papers that are referenced in the following evaluation. The term “extraterrestrial” yielded 160 returns and addition of the term “effects” limited the results to 72 records. The combined search terms “supernova,” “effects,” and “earth” yielded nine returns, one of which was judged potentially relevant. A review of titles and available abstracts yielded the applicable citations that are listed in Table B-20. Similar searches of the GeoRef® databases (based on all records including 2004) returned 58 records. Based on the titles and available abstracts, none of these citations appeared relevant.

B5.6.2 Evaluation of Factors

For each of the sources to be used in the evaluation (whether as direct input or reference only and corroboration of the direct input), pertinent factors are evaluated in tabular form in Table B-20.

Table B-20. Sources and Factors Evaluation for Direct Inputs to Extraterrestrial Events

Items	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q25	C47, C50, C51, C55	Brakenridge, G.R. 1981. "Terrestrial Paleoenvironmental Effects of a Late Quaternary-Age Supernova." *Icarus, 46,* (1), 81-93. New York, New York: Academic Press. TIC: 255707. (DIRS 167873), Q25	This paper discusses the frequency of gamma and X radiation incident upon the earth and discusses potential climate forcing mechanisms. The paper also proposes evidence that such events are recorded in paleosoil horizons.	Not found in SciSearch®	Technical journal	Moderate – The paper quantifies the influx of radiation upon the earth from an extraterrestrial event and provides an indication of the frequency of such events. It also discusses potential climate forcing mechanisms and provides a brief description of studies identifying potential soil layers that recorded such an event.	Direct Input – Frequency of a supernova event (1 event per 100 years), magnitude (10^{50} ergs), and potential consequences of the event (nitrogen enrichments, ozone depletion, global cooling) Figure 1 and pp. 85-86.
Q26	C49, C52, C53, and C54	Lean, J. 1997. "The Sun's Variable Radiation and its Relevance for Earth." *Annual Review of Astronomy and Astrophysics, 35,* 33-67. Palo Alto, California: Annual Reviews. TIC: 255614. (DIRS 167639)	This paper provides a summary of the current understanding of the Sun's radiance variability and cycles and its linking to Earth's global environment.	40 citations in SciSearch®	Paper from book series	Moderate to High – Although a survey of related studies, the author provides numerous citations and provides graphs and plots to substantiate the discussion and conclusions.	Direct Input – Relationship exists between the decadal Sun cycle, and overall solar activity and the Earth's surface temperature, and possible link from changes in IR and visible and IR radiation to changes in earth's temperatures and climate. Indirect Input – The paper also briefly discusses the effects of space weather on spacecraft and communication systems and is therefore corroborative with other papers dealing more specifically with those issues.

Table B-20. Sources and Factors Evaluation for Direct Inputs to Extraterrestrial Events (Continued)

Items	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q27	Q25 (but not mutually corroborative), C48	Maynard, N.C. 1995. "Space Weather Prediction." *Reviews of Geophysics (Supplement), 33,* (Part 1), 547-557. Washington, D.C.: American Geophysical Union. TIC: 253729. (DIRS 160888), Q27	This paper addresses a wide range of space weather related topics. Of particular applicability is the discussion of engineered systems potentially affected by space weather, including several ground-based systems.	Nine citations in SciSearch®	Technical journal	Moderate – The cited portion of this paper provides a concise overview of documented disturbances in engineered systems and associated costs.	Direct Input – List of engineered systems potentially affected by space weather.
C47	Not Applicable	Arnold, N.F. 2003. "Space Plasma Influences on the Earth's Atmosphere." *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 361,* 127-132. London, England: Royal Society of London. TIC: 255613. (DIRS 167638), C47	This paper is targeted to providing a conceptual satellite-based investigation. However, the paper's summary of various affects is adequate for corroborative support only.	Not found in SciSearch®	Technical Journal	Low – Only a limited reference is provided. The paper is largely qualitative and citations are provided to support development of a "strawman" satellite mission specification.	Indirect Input – discussion of cosmic-ray influences, relativistic electrons, and auroral particles and magnetic fields influences on the atmosphere are briefly summarized.

Table B-20. Sources and Factors Evaluation for Direct Inputs to Extraterrestrial Events (Continued)

Items	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C48	Not Applicable	Cole, D.G. 2003. "Space Weather: Its Effects and Predictability." *Space Science Reviews, 107,* (1-2), 295-302. Dordrecht, The Netherlands: Kluwer Academic. TIC: 255616. (DIRS 167641), C48	This paper is useful for corroborating other papers dealing with space weather effects as it cites to a separate set of references than those providing a fuller treatment of the subject.	No citations in SciSearch®	Technical journal	Low – This paper is a cursory treatment of potential space weather effects. No mathematical treatment is provided, and no analytical results or measurements or provided. A short reference list is provided.	Indirect Input – This paper addresses the potential linkages between space weather solar activity, the earth’s magnetosphere and ionosphere, and how space weather affects those natural systems and engineered systems operating in those environments.
C49	Not Applicable	Hagan, M.E. 1995. "Thermospheric Connections." *Reviews of Geophysics (Supplement), 33,* (Part 1), 729-735. Washington, D.C.: American Geophysical Union. TIC: 253731. (DIRS 160890)	This is a good concise summary of the potential connections between space and earth environs.	One citation in SciSearch®	Technical journal	Moderate – This paper is a survey of “work to date” and a summation of collaborative efforts of various researchers. The discussion provides adequate citations to support assertions and conclusion. No mathematical treatment or analytical results are discussed in any detail.	Indirect Input –This paper provides a thorough survey of work addressing connections between the extraterrestrial environment and earth's atmosphere, magnetosphere, and ionosphere.
C50	Not Applicable	Karam, P. A. 2002. "Gamma and Neutrino Radiation Dose from Gamma Ray Bursts and Nearby Supernovae." *Health Physics, 82,* (4), 491-499. Baltimore, Maryland: Lippincott, Williams, and Wilkins. TIC: 255918. (DIRS 167872), C50	This paper provides specific dose information and is used to corroborate other papers addressing supernova effects.	One citation in SciSearch®	Peer-reviewed journal	Moderate to High – This paper provides a calculation of dose stemming from extraterrestrial events. Base equations and assumed values are given. The discussions and conclusions are adequately documented and supporting citations are provided.	Indirect Input – This paper provides a discussion of the frequency of supernovae and gamma ray bursts and quantifies the expected dose in the surface and subsurface.

Table B-20. Sources and Factors Evaluation for Direct Inputs to Extraterrestrial Events (Continued)

Items	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C51	Not Applicable	Novotna, D. and Vitek, V. 1991. "The Atmospheric Mean Energetic Level and External Forcing." *Studia Geophysica et Geodaetica, 35,* (1), 33-38. Prague, Czechoslovakia: Geophycial Institute of the Czechoslovak Academy of Sciences. TIC: 255610. (DIRS 167634), C51	This paper provides corroborative support for external forcing on earth's atmosphere. However, it only provides a link to potential climate affects and not to subsurface affects.	Not found in SciSearch®	Peer-reviewed journal	High – The paper documents the mathematics leading to the conclusions of interrelationships to external forcing.	Indirect Input – This paper develops a mathematical argument relating external forcing to changes in the earth's atmospheres vorticity. It specifically lists potential forcing mechanisms including galactic cosmic rays, solar cosmic rays, and equivalent particles from other sources. It identifies galactic cosmic rays as the best candidate for forcing and suggests it may also influence cirrus cloud formation.
C52	Not Applicable	Reid, G.C. 1995. "The Sun-Climate Question: Is There a Real Connection?" *Review of Geophysics (Supplement), 33,* (Part 1), 535-538. Washington, D.C.: American Geophysical Union. TIC: 253730. (DIRS 160889), C52	This is a good concise summary of the potential connections between space and earth environs.	Five citations in SciSearch®	Technical journal	Moderate – This paper is a survey of "work to date" and a summation of collaborative efforts of various researchers. The discussion provides adequate citations to support assertions and conclusion. No mathematical treatment or analytical results are discussed in any detail.	Indirect Input – This paper provides a thorough survey of work addressing connections between the sun and earth's climatic systems.

Table B-20. Sources and Factors Evaluation for Direct Inputs to Extraterrestrial Events (Continued)

Items	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C53	Not Applicable	Rozelot, J.P. 2001. "Possible Links Between the Solar Radius Variations and the Earth's Climate Evolution Over the Past Four Centuries." *Journal of Atmospheric and Solar-Terrestrial Physics, 63,* (4), 375-386. New York, New York: Pergamon. TIC: 255615. (DIRS 167640), C53	This paper provides corroboration of linkage of solar activity to earth's climate.	Not found in SciSearch®	Peer-reviewed journal	Moderate – The paper provides an adequate statistical correlation of data to support its conclusions regarding connection between earth's climate and solar irradiance and solar radius.	Indirect Input – This paper investigates the effect of solar radius variance on Earth's climate over the past four centuries.
C54	Not Applicable	Pechala, F. 1985. "The Effect of Extraterrestrial Interactions on Change of Tropospheric Circulation in the Polar Regions of the Earth." *Studia Geophysica et Geodaetica, 29,* (4), 405-412. Prague, Czechoslovakia: Geophycial Institute of the Czechoslovak Academy of Sciences. TIC: 255609. (DIRS 167633)	This paper provides corroborative support for external forcing on earth's atmosphere. However, it only provides a link to potential climate affects and not to subsurface effects.	Not found in SciSearch®	Peer-reviewed journal	Moderate – The paper documents the mathematics leading to the conclusions of interrelationships to external triggering.	Indirect Input – This paper is presented as a proof of extraterrestrial interactions functioning as triggering mechanisms in the process of redistribution of energy accumulated in the earth's systems.

Table B-20. Sources and Factors Evaluation for Direct Inputs to Extraterrestrial Events (Continued)

Items	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C55	Not Applicable	Ruderman, M. A. 1974. "Possible Consequences of Nearby Supernova Explosions for Atmospheric Ozone and Terrestrial Life." *Science, 184,* 1079-1081. TIC: 255914. (DIRS 167875)	Discussions in this paper are used to corroborate discussions by Brakenridge	Not found in SciSearch®	Peer-reviewed journal	Moderate – The discussion is supported by citations, and the assumptions and reasoning are clearly stated. No analytical results or numerical models are discussed.	Indirect Input – This paper provides a brief discussion of the potential for an extraterrestrial event to remove earth's ozone cover and the potential consequences on terrestrial life.

B5.6.3 Discussion

The evaluation of results has been subdivided by topic. Direct Inputs include Items Q25, and Q26. Corroborative sources include Items C47 through C55.

B5.6.3.1 Effects of Nonsolar Extraterrestrial Events (Supernovae, Gamma Ray Bursts, Cosmic Rays)

The direct inputs being justified include the frequency, magnitude, and consequences associated with a supernova event.

> Frequency of a supernova event (1 event per 100 years), magnitude (10^{50} ergs), and potential consequences of the event (nitrogen enrichments, ozone depletion, global cooling).

This information is taken from Item Q25, and is corroborated by Items C47, C50, C51, and C55.

Brakenridge (1981 [DIRS 167873], Figure 1, p.83, and p. 85 and 86) (Q25) is being used as direct input. The paper discusses the potential effects of Late Quaternary-Age supernova on the terrestrial paleoenvironment. The paper indicates that over 120 radio-emitting galactic supernova remnants have been cataloged. Figure 1 of the paper provides a plot of the peak flux and the timing of the initiating supernova event. At least 24 significant (i.e., greater than 500 erg/cm^2) peaks were observed for events occurring within the 15,000 years before present. Using a value of 120 events in the past 15,000 years suggests a rate of approximately one event per 100 years. The most significant of these peak fluxes was for the Vela supernova, which was calculated to have a peak flux of about 40,000 ergs/cm^2. The paper indicates (p. 83) that supernova events release on the scale of 10^{49} to 10^{50} ergs of gamma radiation. The paper asserts (pp. 85-86) that such an event has the potential to cause ozone depletion in earth's atmosphere for a period of two to six years and created nitrogen-rich environments at the earth's surface. Observable effects are suggested to include kerogen rich sediments at 11 sites worldwide. The effects are also stated to include short-term terrestrial global cooling (i.e., on the scale of 1,000 years). The paper also asserts that such events could precipitate increased ultraviolet-light penetration by ozone layer depletion. The increased intensity could be as much as 2 to 10 times the present level. Aside for the potential impact on C_{14} dating, no other effects are discussed.

Ruderman (1976 [DIRS 167875]) (C55) corroborates that ozone depletion in the atmosphere could occur and that nitrogen-enriched surface conditions could result. Ruderman also cites to work of others and corroborates that supernova explosions result in release of 10^{48} to 10^{50} ergs. Ruderman briefly mentions that increased UV influx could have altered life through mutations or suppression. The paper mentions that there is no compelling fossil evidence for past biological cataclysms related to supernova events.

Arnold (2003 [DIRS 167638], p. 127) (C47) also corroborates the assertions of Brakenridge. Arnold notes that considerable attention has been focused on "the possibility that climate change may be attributable to variations in galactic cosmic-ray fluxes that are modulated by the heliospheric magnetic field." Arnold further discusses the interaction between cosmic rays and role of ionization trails in cloud formation. This suggests a possible climate modifying effect. Similarly, Novotna and Vitek (1991 [DIRS 167634], p. 35) (C51) also discuss external forcing mechanisms and specifically mention, galactic cosmic rays, solar cosmic rays, and equivalent particle from other sources, with galactic cosmic rays being the best candidate for both short-term and long-range forcing. They also mention its role in cirrus cloud formation.

Further corroboration comes from Karam (2002 [DIRS 167872]) (C50), who calculates the potential gamma and neutrino radiation dose resulting from supernovae and gamma ray bursts at and beneath the earth's surface. Sea-level doses are calculated to have been about 1 Gray (Gy) every five million years and about 0.2 Gy every million years. Karam indicates that radiation levels, while not lethal may have been genetically significant. The paper corroborates Brakenridge further by indicating that supernovae release between 10^{42} Joules (10^{49} ergs) of gamma radiation supernovae are noted as occurring at a frequency of about 1 to 2 per century. Gamma ray bursts are noted to release the equivalent of about 10^{53} ergs and occur once every million to ten million years (Karam (2002 [DIRS 167872], p. 491-492) (C50). Karam further indicates that due to the relatively short outburst time, no more than one half of the earth would be exposed to radiation and the actual exposure will vary according to the location of the burst in the sky. By comparison, supernovae will irradiate the entire planet, although no single location would be subject to more than one-half of the integrated radiation because of the shielding provided by the earth. Karam (2002 [DIRS 167872], Table 1) (C50) indicates that at distances of for gamma ray bursts, the resulting dose at sea level would be on the order of 420 to 0.17 Gy from gamma ray bursts, and from 42 to 0.017 for supernovae, at distances of 1 and 50 kiloparsecs, respectively. More importantly, the paper clearly indicates that there is a 10^{-8} reduction in "typical dose" within the top 20 mm of rock, suggesting that dose (i.e., energy) at the repository depth from such events would be negligible (Karam 2002 [DIRS 167872], Table 1) (C50).

B5.6.3.2 Solar-Related Effects

This section specifically addresses the impact of solar events. The information being justified is conceptual in nature.

> Relationships exist between the decadal Sun cycle, and overall solar activity and the Earth's surface temperature, and possible link from changes in IR and visible and IR radiation to changes in earth's temperatures and climate.

This information is taken from Items Q26 and is corroborated by Items C49, C52, C53, and C54.

The conclusions from Lean (1997 [DIRS 167639]) (Q26) are in the form of a conceptual summary statement; "Numerous associations are evident between solar variability and terrestrial parameters that range from the earth's surface to hundreds of kilometers above it, on the time scales from days to centuries." In particular, Lean points out the decadal cycles in the Sun's activity are evident in temperatures at the earth's surface and through the atmosphere. Lean also indicates that there is also an apparent association of surface temperature with overall solar activity, but it is unclear weather the sun's variable radiation is responsible. According to Lean, least certain is the extent to which tenths percent changes in visible and IR radiation modify global surface temperature and climate. Lean also mentions that there is a current inability to adequately quantify all climate and ozone forcings, which adds ambiguities to assessments of the global change.

There are multiple corroborating sources to support Lean's conclusions. Rozelot (2001 [DIRS 167640]) (C53) indicates that regression analysis shows that, at least over the last four centuries, warmer and cooler periods on Earth are inversely correlated to changes in the Sun's diameter. Pechala (1985 [DIRS 167633]) (C54) indicates that extraterrestrial interaction function as triggering mechanisms in the process of redistribution much large amounts of energy in the polar regions. The paper is primarily focused on energy releases from the sun and uses the examples of solar recurrences of differential rotation and changes in solar radiation, and the correlated response of earth's atmosphere. Pechala also suggests that "corpuscular radiation of galactic origin" may also play an important part in modulation of transformation of energy through the atmosphere, particularly in the polar regions. Pechala also alludes to the complicated processes and interactions involved. A summary of thermospheric connections is presented in Hagan (1995 [DIRS 160890]) (C49). Hagan specifically mentions that zonal winds were found to increase with increased solar activity in the low latitudes; that natural variations in photoabsorption of solar radiations excite global-scale atmospheric solar tides whose periods are harmonics of a solar day and are commonly observed in the thermosphere. The papers by Hagan (1995 [DIRS 160890]) (C49) and by Reid (1995 [DIRS 160889]) (C52) also summarize recent studies linking the interaction of the earth's magnetic field, the interplanetary magnetic fields, and the result on thermospheric heating and circulation.

B5.6.3.3 Space Weather Effects

This section addresses engineered systems that are potentially affected by extraterrestrial events. The direct input being justified is:

> List of engineered systems potentially affected by space weather.

This information is taken from Item Q27, and is corroborated by Items Q26 and C48.

Maynard (1995 [DIRS 160888]) (Q27) provides direct input in the form of an extensive list of engineered systems that are potentially or have been observed to be affected by space weather. The list includes spacecraft operations, satellite operations, GPS-locating operations (which are satellite based), space object tracking, over-the-horizon radar operations, high frequency communications, telecommunications such as transatlantic fiber optic communications, geomagnetically induced currents in power transmission lines and transformers, applied-DC currents for pipeline corrosion mitigation, and semi-conductor manufacturing (likely related to power line fluctuations).

The list of affected systems is corroborated from two sources. Lean (1997 [DIRS 167639]) (Q26) was qualified above for statements regarding solar interaction. Additionally, the paper also provides a discussion of systems potentially affected by solar activities. Lean cites others who group the systems into communication, navigation, surveillance, and commerce. The discussion in Lean is focused on spacecraft and communications. The discussion of spacecraft focuses on the effects of solar drag and difficulties in locating spacecraft and associated debris, and the discussion on communications is focused on systems utilizing the ionosphere for signal transmission. Navigation systems (LORAN and OMEGA) are specifically mentioned, as are possible interferences with satellite-based positioning systems including Global Positioning Systems, Very Long Baseline Interferometery, and Satellite Laser Ranging. Corroboration is also taken from Cole (2003 [DIRS 167641]) (C48). Cole mentions that space weather can affect the planning of space projects and impairment of satellite systems. Cole also mentions the potential impact to spacecraft through vehicle damage, deterioration of solar cells, semiconductor damage, and electric charging of spacecraft. Other disturbed systems listed by Cole include radio communication, and satellite and navigation. Ground level effects are listed as disturbances in terrestrial power systems and long pipe lines – specifically power lines, railway lines, steel pipelines, or telecommunication cables of long length.

B5.6.4 Data Status and Limitations

For qualitative data, the criterion of general agreement has been satisfied. The above literature review and corroboration of the direct input provides an acceptable level of confidence that the data are suitable for their intended use, which is for FEP screening. The status of the direct inputs for extraterrestrial events evaluated above should be considered as qualified for use within this technical product. No limitations are needed for the intended use.

B5.7 SUITABILITY DEMONSTRATION FOR DIRECT INPUTS FOR FEP 1.5.03.01.0A CHANGES IN THE EARTH'S MAGNETIC FIELD

This section addresses direct inputs addressing the potential consequences of changes in the earth's magnetic field. There is abundant literature and modeling results regarding the fluctuation and changes in the field and possible causes, but little if any information on the potential effects on natural or engineered systems. The direct inputs listed below are taken from the only source found during the literature search.

- The periodicity of pole reversals is on the scale of a few hundred thousand years to once every million years.
- There has been a decrease in the earth's magnetic intensity in the last few thousand years, and some evidence that a reversal may occur sometime during the next few to several thousand years.
- There is no identifiable fossil evidence (such as mutation or extinctions) stemming from magnetic field changes.

The data being justified includes Item Q28 in Table B-1. The direct input being qualified is in the form of conceptual statements and is generally qualitative in nature. Therefore, the qualitative criteria for general agreement will be applied. Only a few sources are available to corroborate the data regarding frequency. No sources were found to directly corroborate the discussion of potential affects on natural systems, nor were sources were found that contradict the information provided.

B5.7.1 Literature Search

A literature search was performed using SciSearch® and the GeoRef® databases and was focused on recent papers and updates directly relevant and applicable to the analysis. The intent of the search was to identify potential citations that addressed the frequency and potential effects of changes in earth's magnetic field. The keyword and subject based searches utilized an

"AND" combination for the keywords "geomagnetic" and "reversal." The SciSearch® database (limited to publication dates for 1900 to 2004) returned 321 records. A search using the term "pole reversal" yielded 61 citations. Of those, a review of available title and abstracts resulted in locating only one applicable citation. No applicable citations were found in the GeoRef® database. Most of the articles listed dealt with observation of variances in the magnetic field for particular geologic formation, discussed modeling of the earth's magnetic field, or were addressing correlation of various observed geologic formations based on age, field intensity, or other nongermane issues.

B5.7.2 Evaluation of Factors

For each of the sources to be used in the evaluation (whether as direct input or reference only and corroboration of the direct input), these factors are evaluated in tabular form in Table B-21.

Table B-21. Sources and Factors Evaluation for Direct Inputs Used for Changes in the Earth's Magnetic Field

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q28	C56, C57, C58	Odenwald, S. 2003. "Earth - Magnetic Field" Poetry Space Science Education: Ask the Space Scientist http://image.gsfc.nasa.gov/poetry/ask/askmag.html. Washington, D.C.: National Aeronautics and Space Administration. Accessed February 25, 2003. TIC: 253712. (DIRS 160892)	Information is taken from a response found on a public information FAQ page that addresses various questions regarding the earth's magnetic field.	Not Applicable – This is a general information source and not ameneable for rigorous research activities. Not found in SciSearch®.	Internet FAQ page sponsored and supported by NASA.	Low – The information is the "best available" result from Internet search and the only information found which directly addresses the issue of potential effects. Because it is a NASA-sponsored site and because it is the "best available" information, the citation is used as direct input.	Direct Input – The periodicity of pole reversals is on the scale of a few hundred thousand years to once every million years. There has been a decrease in the earth's magnetic intensity in the last few thousand years, and some evidence that a reversal may occur sometime during the next few to several thousand years. There is identifiable fossil evidence (such as mutation or extinctions) stemming from magnetic field changes.

Table B-21. Sources and Factors Evaluation for Direct Inputs Used for Changes in the Earth's Magnetic Field (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C56	Not Applicable	Biggin, A.J. and Thomas, D.N. 2003. "Analysis of Long-Term Variations in the Geomagnetic Polodial Field Intensity and Evaluation of Their Relationship with Global Geodynamics." *Geophysical Journal International, 152,* (2), 392-415. Oxford, England: Blackwell Publishing. TIC: 255680. (DIRS 167876)	This paper provides a detailed and rigorous statistical analysis to determine whether intensity and pole reversals are correlatable.	Three citations found in SciSearch®	Peer-reviewed journal	High – The paper thoroughly documents the statistical analysis procedures and results are fully documented and transparent.	Indirect Input – This paper indicates that the record is too sparse to definitively conclude anticorrelation, but the analysis does suggest an anticorrelation. It also provides some discussion linking geomagnetic phenomena to global-scale geodynamics.
C57	Not Applicable	Hoffman, K.A. 1995. "How are Geomagnetic Reversals Related to Field Intensity?" Eos, Volume 76, July 18, 1995, p. 289 Washington, D.C.: American Geophysical Union. Accessed April 23, 2003. TIC: 253732. http://www.agu.org/sci-soc/hoffman.html (DIRS 160891)	This short paper addresses the potential relationships between magnetic field reversals and intensity and goes to addressing the probability of a magnetic pole reversal event within the next 10,000 years.	Not found in SciSearch®	Technical journal	Low – Aside from the two graphs presented, no quantitative or analytical information is provided. Reference is made to various studies, but no reference to the studies is given. However, the author does have other works of similar nature in the technical literature.	Indirect Input – The paper only provides a brief overview of the potential relationship between intensity and reversals.

Table B-21. Sources and Factors Evaluation for Direct Inputs Used for Changes in the Earth's Magnetic Field (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C58*	Not Applicable	Pechala, F. 1985. "The Effect of Extraterrestrial Interactions on Change of Tropospheric Circulation in the Polar Regions of the Earth." *Studia Geophysica et Geodaetica, 29,* (4), 405-412. Prague, Czechoslovakia: Geophysical Institute of the Czechoslovak Academy of Sciences. TIC: 255609. (DIRS 167633), C54	This paper is presented as a proof of extraterrestrial interactions functioning as triggering mechanisms in the process of redistribution of energy accumulated in the earth's systems.	Not found in SciSearch®	Peer-reviewed journal	Moderate – The paper documents the mathematics leading to the conclusions of interrelationships to external triggering.	Indirect Input – This paper provides corroborative support for external forcing on earth's atmosphere. However, it only provides a link to potential climate affects and not to subsurface affects.

*C58 is also denoted as Item C54 in Table B-20.

B5.7.3 Discussion

The direct input from Odenwald (2003 [DIRS 160892]) (Q28) was taken from a National Aeronautics and Space Administration-sponsored site and is therefore considered reliable. It is the only source found that addresses the potential effect of magnetic reversal on earth's natural systems. The direct input from that Internet site indicates that the frequency of magnetic pole reversals is on the timescale of a few hundred thousand and that 60 such reversals have occurred in the last 20 million years. Odenwald also indicates that polar wander occurs and that field intensity waxes and wanes and may range between zero and 1 gauss. This frequency and variations in intensity is corroborated by Biggin and Thomas (2003 [DIRS 167876], Figure 11) (C56), which shows that the number of reversals over 10 Myr periods (for the last 160 million years before present) varies from 0 to 50. This same figure also shows the variance in the mean dipole moment. The scale of frequency and variation in intensity is also indirectly corroborated by the discussion in Hoffman (1995 [DIRS 160891]) (C57), which states that a statistical model exists which shows following a reversal there exists a 5,000 year-long dead-time during which there is zero probability of another occurrence. Then the probability of reversal steadily increases with time, but only for some 45,000 years.

Odenwald indicates that there are no identifiable fossil effects (i.e., mutations or extinctions) associated with the previous reversals. However, no corroborating information regarding the possible effects of a pole reversal or intensity fluctuations was found in the literature. The only related citations that were found address the interrelationship of earth's magnetic field with influxing cosmic and solar rays and the potential cause of earth's magnetic field changes being global–scale tectonic processes. Pechala (1985 [DIRS 167633]) (C58) indicates that the least controversial findings with regard to tropospheric circulation are with regard to the interrelations between the changes in magnetic pole position and intensity of the magnetic field, and changes of atmospheric circulation. Pechala indicates that some authors use the relationship as a basis for explaining past changes in earth's climate. Biggin and Thomas (2003 [DIRS 167876]) (C56) propose a model that conceptualizes that global-scale tectonic processes such as slab subduction and related mantel processes and the cause for changes and variations in the earth's magnetic field, rather than the reverse condition of changes in the earth's magnetic field initiating such changes.

B5.7.4 Data Status and Limitations

For qualitative data, the criterion of general agreement has been satisfied. No contradictory information indicating significant change to regional or smaller scale geologic or hydrologic systems due to variations in the earth's magnetic field, with the possible exception of a climate change relationship. The above literature review and corroboration of the direct input provides an acceptable level of confidence that the data are suitable for their intended use, which is for FEP screening. No limitations are needed for the intended use. The status of the direct inputs for Earth's magnetic fields evaluated above should be considered as qualified for use within this technical product.

B5.8 SUITABILITY DEMONSTRATION FOR DIRECT INPUTS FOR FEP 1.5.03.02.0A EARTH TIDES

This section addresses the direct input used to determine the magnitude of earth tides effects. The direct input being justified is as follows:

> Earth tides causes fluctuations in water levels at Yucca Mountain that are on the order of a few centimeters.

The data being evaluated includes Item Q29 in Table B-1. The data is in the form observed fluctuations in water levels stemming from the subject FEP and are approximately 2 cm. This is corroborated in Items C59 and C60.

The objective is to justify input representing the magnitude of the effect (i.e., upper bound of possible conditions) against a theoretical threshold of significance (i.e., distance between the existing water level and the repository). An "order of magnitude" understanding of the affect is sufficient. Therefore, the qualitative criteria of general agreement will be applied.

B5.8.1 Literature Search

A literature search was performed using SciSearch® and the GeoRef® databases and was focused on recent papers and updates directly relevant and applicable to the analysis. The intent of the search was to identify potential citations that addressed the measurable affects of earth tides, and not just the conceptualization and mechanisms of such tides that most of the available citations address. The keyword and subject based-searches utilized the search term "earth tides." The SciSearch® database (limited to publication dates for 1980 to 2004) returned 55 records, and only one applicable citation was found. Additionally, previous references used for TSPA-SR FEPs discussion were reviewed.

B5.8.2 Evaluation of Factors

For each of the sources to be used in the evaluation (whether as direct input or reference only and corroboration of the direct input), these factors are evaluated in tabular form in Table B-1.

Table B-22. Sources and Factors Evaluation for Direct Inputs Used for Earth Tides

Items	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
Q29	C59, C60	Bredehoeft, J.D. 1997. "Fault Permeability Near Yucca Mountain." *Water Resources Research, 33,* (11), 2459-2463. Washington, D.C.: American Geophysical Union. TIC: 236570. (DIRS 100007)	This paper is focused on the effects of fault permeability at Yucca Mountain. However, earth tides and other water level fluctuations are specifically analyzed and the magnitude of the fluctuations are stated. This is not a project-controlled document.	Not Available	Peer-reviewed journal	Moderate – The water level fluctuation data is not presented, but a supporting reference for the quantification is given.	Direct Input – The data used is from a site-specific well. The fluctuation in Well U-25 pl is cited as being 2.05 cm.
C59	Not Applicable	Kies, A.; Majerus, J.; and de Lantremange, N.D. 1999. "Underground Radon Gas Concentrations Related to Earth Tides." *Il Nuovo Cimento della Società Italiana di Fisica, 22C,* (3-4), 287-293. Bologna, Italy: Editrice Compositori. TIC: 253721. (DIRS 160882)	This paper reviews observations on the influence of earth tides or radon gas release in an underground mine in Luxembourg. The mine is located in a gypsum deposit located 80 m below ground surface.	Not Available	Technical journal	Moderate to High – The experimental methods and treatment of collected data are discussed, and supporting citations are given.	Indirect Input – The paper is of interest but is not directly applicable because it does not address water level fluctuation and the geologic formation is significantly different.

Table B-22. Sources and Factors Evaluation for Direct Inputs Used for Earth Tides (Continued)

Item	Corroborating Items	Source	1. Demonstrates Properties of Interest	2. Prior Use by Others	3. Type of Publication and Review	4. Extent and Reliability of Documentation	5. Proposed Input Status
C60	Not Applicable	Fenelon, J.M. 2000. *Quality Assurance and Analysis of Water Levels in Wells on Pahute Mesa and Vicinity, Nevada Test Site, Nye County, Nevada.* Water-Resources Investigations Report 00-4014. Carson City, Nevada: U.S. Geological Survey. ACC: MOL.20030904.0304. (DIRS 160881)	This paper reviews water level information from the Nevada Test Site and identifies the fluctuation of water levels due to earth tides.	Not available	USGS Report	High – This paper is focused on quality assurance and the documentation is extensive for that reason.	Indirect Input – The information is relevant, but site-specific information is available. Information from the Nevada Test Site indicates fluctuations of a few cm due to earth tides.

B5.8.3 Discussion

Direct input is taken from Bredehoeft (1997 [DIRS 100007]) (Q29). The earth tide fluctuation for Well UE-25 pl at Yucca Mountain is cited from non-YMP references as 2.05 cm. This low magnitude of water level fluctuation is confirmed by Fenelon (2000 [DIRS 160881]) wherein earth tide fluctuations at the Nevada Test Site are on the order of several hundredths of a foot (i.e., on the order of a few centimeters). Additional corroboration is given by Kies et al. (1999 [DIRS 160882]) (C59), which indicates that strain variations induced by earth tides are very small (less than on the order of 10^{-8}), which would translate to minimal fluctuations in water levels.

B5.8.4 Data Status and Limitations

The above literature review and corroboration of the direct input provides a suitable level of confidence that the data are suitable for their intended use, which is for FEP screening. The direct input considered as qualified for use within this technical product is intended for use only in FEP screening.

B6. DATA GENERATED BY THE EVALUATION

No data was generated by this suitability demonstration effort. Calculations were performed as shown herein to allow corroboration of direct input to indirect inputs. However, the results of the calculations are not being qualified and are not to be used directly as data or serve as the sole basis for FEP screening decisions.

B7. THE EVALUATION RESULTS

The third section for each FEP dataset (Section B5.x.3) provides a comparison of the data being justified to the corroborative information. Any manipulations or calculations needed for the comparison are provided in that section of the discussion. In some case, this may be further subdivided by specific data topic.

B8. CONCLUSION FOR/AGAINST CHANGING THE DIRECT INPUT STATUS

This is addressed in Section B5.x.4 for each FEP-specific dataset. The fourth section of the discussion for each FEP dataset provides a statement of recommendation and a discussion of any specific limitations that apply. This is addressed for each FEP-specific data set under the heading "Data Status and Limitation."

The direct inputs listed and discussed above have been reviewed against the stated review criteria. In some cases, limitations have been applied. However, all the data evaluated satisfied the respective criteria and the status should be considered as qualified for use within this technical product.

B9. LIMITS OR CAVEATS

The intended use of the data justified herein is for use in FEP screening. For all data discussed in Section B5, the data provide a desired level of confidence that is suitable for the intended use. The data are considered qualified for use only within this technical product. These data should not be used or referenced by others as direct input without qualification external to this technical product. The fourth section of the discussion for each FEP dataset is Section B5 specifies any additional limitations that are applicable. This is addressed for each FEP-specific data set under the heading “Data Status and Limitation.”

B10. IDENTIFICATION OF ANY SUPPORTING INFORMATION

Supporting information (i.e., corroborating information) is identified in Section B5.x.2 of each FEP-specific data set. The table includes an appropriate reference identifier for each citation, such as an accession number, DIRS number, or TIC catalog number.

APPENDIX C

SUPPORTING DOCUMENTATION FOR DETERMINING TIMING OF A HUMAN-INTRUSION WITHOUT RECOGNITION BY THE INTRUDER

C1. INTRODUCTION

This appendix is related to FEP screening for human intrusion-related FEPs, as discussed in Section 6.2.3 and its subsections of the main body of this analysis report. The analysis provided in this appendix indicates that an unrecognized intrusion will not occur prior to 10,000 year following closure of the repository, and leads to the FEP decisions to exclude the human intrusion related FEPs from consideration in the TSPA-LA. This appendix is pertinent to evaluation of the following FEPs:

FEP 1.4.04.00.0A Drilling activities (human intrusion)	Section 6.2.3.6
FEP 1.4.04.01.0A Effects of drilling intrusion	Section 6.2.3.7

The human intrusion FEP 1.4.11.00.0A Explosions and crashes (human activities) is more closely aligned with cratering/energy release equations associated with meteorite impacts. This FEP is addressed in Section 6.6.2.3.9 and Appendices B and D.

Section C2 of this appendix addresses the purpose. Section C3 reviews the pertinent literature on factors that influence drilling conditions. Section C4 discusses regulatory and technical background information pertinent to the analysis. Section C5 brings forward pertinent points from Section C4 and places them in the context of the potential for waste package penetration by drilling. Discussions in Section C5 include an outline of drill bit and drilling operation principles and a discussion of bit operating conditions and changes in conditions that would signify that a significant change in subsurface conditions had occurred. These concepts are then related to a conceptual model of resulting conditions if the drip shield and waste package were encountered and the significant role that comparative material properties have in determining those conditions. Section C6 summarizes and supports the exclusion of the human-related FEPs, as referenced in Section 6.2.3 and subsections of the main body of this analysis report.

C2. PURPOSE

The purpose of this appendix is to document the analysis of whether a driller, using techniques and practices currently employed in exploratory drilling for groundwater in the region surrounding Yucca Mountain, would or would not recognize that a waste package had been penetrated, and to document whether such a condition could occur at or before 10,000 years, or at more than 10,000 years after disposal.

Such an analysis and determination require definition and discussion of conditions that would cause recognition of such an event. Given that there is no regulatory definition or description of such conditions, the recognition would be based on drill performance characteristics observable at the surface. Such measures could be qualitative (e.g., smoothness of operation, excessive vibration or “chatter”) or could be quantitative (e.g., drill penetration rates rotation speed, readily observable or measurable change in drilling fluid circulation, or changes in machinery hydraulic pressures required to maintain an existing drilling condition).

C3. BACKGROUND INFORMATION

C3.1 RESOURCE POTENTIAL

The U.S. Nuclear Regulatory Commission (NRC), in the discussion regarding the timing and frequency of human intrusion (66 FR 55732 [DIRS 156671], p. 55761), states that "some evaluations of resource potential suggest that Yucca Mountain and the area around it does not represent an active candidate for either systematic or random exploratory drilling at this time." A list of citations for those studies is available in the regulation. Furthermore, the elevation of the mountain, with the resultant greater depth to water compared to shallower groundwater wells that would be drilled to the south of the mountain, decreases the likelihood of groundwater exploration through the repository footprint. Regardless, the regulations specify evaluation of the timing of a human intrusion event and consideration of a stylized human intrusion based on a groundwater exploration assumption (10 CFR 63.322 [DIRS 156605]).

C3.2 REGULATORY BACKGROUND

At 10 CFR 63.321 (DIRS 156605), the NRC specifies the criteria under which human intrusion must be evaluated:

> DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers.

Furthermore, per 10 CFR 63.321(a) (DIRS 156605), the DOE must:

> Provide the analyses and its technical bases used to determine the time of occurrence of human intrusion (see §63.322) without recognition by the drillers.

In addition, if complete waste package penetration is projected to occur at or before 10,000 years after disposal, then per 10 CFR 63.321(b)(1) (DIRS 156605), the DOE is to provide a demonstration that:

> …there is a reasonable expectation that the reasonably maximally exposed individual receives no more than an annual dose of 0.15 mSv (15 mrem) as a result of a human intrusion, at or before 10,000 years after disposal.

And, per 10 CFR 63.321(b)(2) (DIRS 156605), if the exposure of the RMEI occurs more than 10,000 years after disposal or if the intrusion is not projected to occur before 10,000 years after disposal, the results of the analysis and the bases of the analysis are to be provided in the environmental impact statement for Yucca Mountain as an indicator of long-term disposal system performance.

C3.3 PERFORMANCE ASSESSMENT BACKGROUND

C3.3.1 Results of Human Intrusion in Total System Performance Analysis–Site Recommendation

The assumptions used in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000 [DIRS 153246], Section 4.4) for a stylized human intrusion into the repository are summarized in Table 4.4-1 of the TSPA-SR. The stylized human intrusion into the repository was assumed to occur 100 years following permanent closure. The TSPA-SR (Figure 4.4-11) shows 300 simulated annual dose histories along with some statistical measures of the annual dose distribution. The peak mean human intrusion annual dose during the first 10,000 years after repository closure for the TSPA-SR model is approximately 0.008 mrem/yr, occurring at approximately 1,000 years. No annual dose for any of the 300 realizations exceeds 0.5 mrem/yr over the first 10,000 years. TSPA-SR Figure 4.4-12 shows a comparison of the mean human intrusion annual dose curve from an intrusion at 10,000 years with the mean annual dose curve from the base case intrusion at 100 years. For the intrusion at 10,000 years, the peak mean annual dose over 100,000 years is less than that for the base case intrusion at 100 years. At 100,000 years, the mean annual dose is nearly identical to the mean annual dose from the base case and is approximately 0.004 mrem/yr (CRWMS M&O 2000 [DIRS 153246], Section 4.4).

C3.3.2 Results of Human Intrusion in the Final Environmental Impact Statement

Two human intrusion scenarios were simulated and discussed in *TSPA Report for Final Environmental Impact Statement and Suitability Evaluation* (Williams 2001 [DIRS 157307], Section 6.4), a sensitivity analysis assuming one intrusion at 100 years after repository closure and a sensitivity analysis assuming intrusion at 30,000 years, the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers. The results of the simulations for a human intrusion at 100 years after closure show a peak mean dose of 0.0048 mrem/yr over the period of regulatory compliance. The results of the 30,000-year simulation analyses are included in *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada* (DOE 2002 [DIRS 155970]). The result for an intrusion occurring at 30,000 years indicates a mean annual peak dose of 0.002 millirem, occurring a short time after 100,000 years after repository closure. Again, because the DOE determined that an unrecognized human intrusion could not occur at or before 10,000 years, the dose limits for the human intrusion do not apply in this suitability evaluation.

Although some uncertainty exists about the timing of when penetrating a waste package would not be detected, the results above, based upon an assumption of penetration at 100 years, show that the resulting dose is orders of magnitude less than the applicable radiation protection standard. Therefore, even if penetration were much earlier than expected, the resulting doses are of little consequence for the suitability evaluation.

In summary, the TSPA-SR (CRWMS M&O 2000 [DIRS 153246]) considered a stylized event occurring at both 100 and 30,000 years. The human intrusion stylized analysis occurring at 30,000 years is provided in the FEIS (DOE 2002 [DIRS 155970], Section 5.7.1). Both of these evaluations showed that the dose following a stylized human intrusion remained below the regulatory limits, based on the TSPA-SR modeling results.

Furthermore, the results of the previous TSPA-SR drip shield and waste package studies indicate long lifetimes for these components (CRWMS M&O 2000 [DIRS 153246], Section 3.4), with the first drip shield failures occurring after about 20,000 years. The first failures of the waste package outer material, Alloy 22 (UNS N06022), by general corrosion occurred after approximately 30,000 years. The TSPA-SR results corroborate the drip shield and waste package barrier capability for consideration in TSPA-LA, which are based on the updated information for repository conditions and physical properties of the drip shield and waste packages and are described in the following section.

C3.3.3 Total System Performance Analysis for License Application Waste Package Degradation Analysis Results

Degradation of the engineered barrier components with time is discussed in BSC (2004 [DIRS 169996], Sections 6.5 and 7.2), which indicates that:

- Because of the low corrosion rate of titanium alloy used for the drip shields, the initial breaches of the drip shields are not expected to occur until well after 10,000 years; more specifically, the modeling indicates approximately 40,000 years, with the median estimate of the mean time to initial breaching of drip shields at approximately 300,000 years.

- Because the corrosion rates of Alloy 22 (UNS N06022) used for the waste packages are low, it is not expected that any waste packages would be breached by general corrosion during the first 10,000 years; models indicate that the time to initial breaching of the waste packages due to general corrosion is on the order of 100,000 years.

Because the drip shields remain intact for a post-10,000-year period, concerns regarding penetration based on localized corrosion of the waste packages are also excluded during the initial 10,000-year period.

The results of the waste package degradation analyses cited from BSC (2004 [DIRS 169996], Sections 6.5 and 7.2) result from the use of representative thermal hydrologic history files produced to allow model runs to be exercised in the cited waste package degradation (WAPDEG) report (BSC 2004 [DIRS 169996]). The actual drip shield and waste package degradation profiles used in the TSPA-LA model will make use of the actual thermal hydrologic history files appropriate for the repository, which introduces some uncertainty in the exact calculated timing of the first failure of the drip shield and waste package. Because representative histories were used, however, significant differences in the degradation profile generated for TSPA-LA are not expected, and the initial model results are corroborated by the TSPA-SR results discussed in Section C3.3.2 of this appendix.

While general corrosion occurs gradually over time up to the time of failure, the oxidation process is a surface phenomenon, and the underlying metal retains its integrity and resistance to drilling. For the drip shield, Drawing 800-IED-WIS0-00401-000-00D in *D&E / PA/C IED*

Interlocking Drip Shield and Emplacement Pallet (BSC 2004 [DIRS 169220]) indicates that the total corrosion of the drip shield material in 10,000 years is approximately 1.6 to 2 mm. From Table 5 of Drawing 800-IED-WIS0-00401-000-00D (BSC 2004 [DIRS 169220]), the drip shield plates have an original thickness of 15 mm. General corrosion is insufficient to significantly compromise strength properties of the drip shield since the corroded depth is only 11 percent to 13 percent of the original thickness. Although TSPA-SR results show some failures at early time, these failures are the result of manufacturing defects that increase susceptibility to stress corrosion cracking (BSC 2004 [DIRS 169996], Section 6.3.8), and are not associated with degradation of the overall structural integrity of the waste package, and the resistance to drilling is maintained.

Barring volcanic events or seismic events of large magnitude, until a breach of the drip shield occurs, the structural integrity of the waste package itself is maintained and provides an additional barrier to borehole drill penetration.

C3.3.4 Seismic Consequences Abstraction Analysis Results

Igneous and seismic-related damage mechanisms are not included in the time to failure stated in Section C3.3.3 of this appendix, because the WAPDEG results cited are based on nominal scenario assumptions.

Igneous disruptive events capable of causing significant damage are unlikely (i.e., igneous intrusion of the repository footprint has an annual probability of exceedance of less than 10^{-5} but greater than 10^{-8}). Therefore, further consideration of an igneous event in consort with a human intrusion stylized analysis is excluded from consideration. The exclusion is consistent with requirements of 10 CFR 63.322 (g) (DIRS 156605), which exclude consideration of unlikely events in consort with a human intrusion event.

The analyses for seismic damage to the drip shield and waste package are documented in *Seismic Consequence Abstraction* (BSC 2004 [DIRS 169183]). The analyses indicate seismic events that may occur have the potential to lead to relatively minor drip shield damage due to seismic ground motion or due to induced rockfall, via imposed residual stresses in the drip shield. For the seismic analysis, the threshold for considering the potential for damage is reached if the residual stress from mechanical damage exceeds the residual stress threshold for the barrier. The presence of residual stress induced by seismic events and/or related rockfall may result in local barrier degradation from accelerated stress corrosion cracking. However, the morphology of the resulting crack network and the potential for mineral precipitation within the cracks will prevent advective flow through the drip shield and into a potentially breached waste package.

While this criterion is appropriate for consideration to flow and transport aspects, it does not necessarily reflect changes to the effective material properties and may not constitute “failure” with respect to recognition of a change in conditions while drilling. Even with an imposed residual stress and even with minor amounts of corrosion and cracking, a rotating drill bit that encounters a metallic object will behave significantly different than when encountering naturally-occurring geologic materials, provided the drill bit encounters a patch of relatively intact material that is roughly the same diameter of the drill bit. This is because the failure mode and drill bit interaction is significantly different for rock and metals, as discussed below.

Consequently, for human intrusion without recognition of waste package penetration, additional conditions would need to have occurred. These would include, but not necessarily be limited to, (1) a significant degradation of material strength due to excessive cracking, fracturing, or corrosion or (2) physical separation of the drip shields.

In contrast, the seismic damage analysis results (BSC 2004 [DIRS 169183], Section 6.5) for the drip shield indicate that:

- For ground motions roughly equated to a 5 x 10^{-4} per year annualized probability, no area of the drip shield exceeds the residual stress threshold of 50 percent of the yield strength of Titanium Grade 7 for degradation by stress corrosion cracking.

- For ground motions roughly equated to a 10^{-6} per year annualized probability, the mean fraction damage area with the potential for stress corrosion cracking is 0.70 percent and the maximum fraction damage area is only 2.13 percent. There is no indication of separation of drip shields in the calculations for the 10^{-6} per year ground motion level.

- For ground motions roughly equated to a 10^{-7} per year annualized probability, the analysis for an unfilled drift indicates separation of adjacent drip shields does not occur because the weight of the rubble from the drift collapse prevents the drip shields from separating.

As explained in BSC (2004 [DIR 167780], Section 6.3.2), the residual stress threshold for failure of the drip shield by stress corrosion cracking was fixed by a lower bound of 50 percent of the yield strength of the drip shield plate material. With regard to the waste package, the residual stress threshold for the abstraction has been set at 80 to 90 percent of the yield strength of the waste package outer material. For the ground motion level equivalent to a 10^{-6} per year annualized probability, the mean value of damage fraction is 0.31 percent and a maximum value of 0.71 percent. A corroborating analysis based on the ground motion level equivalent to 10^{-5} annualized probability indicates that at that ground motion level, the resulting damage area for waste packages is about 0.04 percent (BSC 2004 [DIRS 167780], Section 6.5.2).

Consequently, with regard to the human intrusion stylized analysis in consort with a seismic event, it is concluded that seismic events occurring with an annual frequency of greater than 10^{-5} are of insufficient magnitude to significantly alter material properties of the drip shield or impose damage to the waste packages. Furthermore, at 10^{-5} per year annualized probability, although the drip shield may be increasingly vulnerable, no separation has occurred, and the material properties of the waste package remain intact. Increased damage effects could potentially occur with less frequently occurring events, but the regulations at 10 CFR 63.322(g) and 10 CFR 63.342 (DIRS 156605) specifically exclude consideration of unlikely events in consort with the human intrusion stylized analysis (i.e., unlikely events are those events with less than a 10^{-5} per year annual frequency of occurrence).

C4. POTENTIAL FOR WASTE PACKAGE PENETRATION BY DRILLING

The following discussion presents several lines of evidence relevant to estimating the time when a human intrusion could occur, based upon the earliest time that current technology and practices used for groundwater exploration could lead to waste package penetration without a recognition by a driller.

There are a number of operational parameters that would indicate to a driller that down-hole conditions had changed, merit additional investigation, and possibly justify a bit run (the removal of the bit from the hole for review and grading). These include loss of circulation, decreased penetration rate, increased drill string and bit instability, and increased drill string torque caused by differing material properties.

C4.1 INITIAL BIT SELECTION AND DRILLING PRINCIPLES

Per the regulatory requirement discussed in Sections C3.1 and C3.2 of this appendix, the bases for the following discussions are focused on typical practices used in drilling water wells in southwestern United States. Generally speaking, the drill string assembly consists of the drill bit, a drill collar, the drill pipe, and in some instances, the use of stabilizers.

As described in Driscoll (1986 [DIRS 116801], pp. 278 to 286) and Bourgoyne et al. (1986 [DIRS 155233], Section 5.1), roller bits are typically used in drilling water wells due to their low cost and wide range of operational flexibility. Polycrystalline diamond cutter and diamond cutter drag bits typically are not used in water well drilling because of the high costs of these drill bits. Direct circulation hammer drills are sometimes used to drill brittle competent rock such as welded volcanic tuff, but they typically are inefficient in unconsolidated alluvium or incompetent rock formations. This limitation reduces the use of these drills in typical water well drilling. The discussions provided herein would be generally applicable to roller or hammer bits.

The initial selection of bit type is typically based on what is known about the formation characteristics. The terms usually used by drilling engineers to describe the formation characteristics are drillability and abrasiveness. The drillability of the formation is a measure of how easy the rock formation is to drill. It is inversely related to the compressive strength of the rock, although other factors are also important. The abrasiveness of the formation is a measure of how rapidly the cutting surface of a bit will wear when drilling the formation. Although there are some exceptions, the abrasiveness tends to increase as the drillability decreases (Bourgoyne et al. 1986 [DIRS 155233], Chapter 5).

The International Association of Drilling Contractors (IADC 1992 [DIRS 155232]) has developed a classification chart for selection of roller bits. Using this classification chart, roller bits with characteristics of 7-1 or 7-2 (hard semi-abrasive and abrasive formations) would be selected for drilling through the welded geologic units at Yucca Mountain, based on geomechanical properties. Roller bits are designed to take advantage of brittle failure of the rock matrix to crush, break, and remove the rock in an efficient manner. The volume of rock that is newly fractured by a tooth depends on the geometry, rock properties, and tooth penetration depth below the rock surface. The force applied to the tooth is supplied by the drill string torque and the weight on the bit. The force applied to a particular situation determines the tooth penetration depth. The bit tooth penetrates into the rock until the resistant force offered back by the rock equals the force applied to the tooth. As a load is applied to a bit tooth, the pressure beneath the tooth increases until it exceeds the crushing strength of the rock and a wedge of finely powered rock is formed beneath the tooth.

As the force of the tooth increases, the material in the wedge compresses and exerts high lateral forces on the solid rock surrounding the wedge until the shear stress exceeds the shear strength of the solid rock and the rock fractures. The rock may also exhibit ductility such that a greater tooth penetration is required to cause sufficient strain for chipping to occur (Warren 1987 [DIRS 155234]). The tooth will penetrate until the shear stress on the tooth is balanced by the shear strength of the rock.

These forces generate fractures that propagate along a maximum shear surface. As the force of the tooth increases above the threshold value, subsequent fracturing occurs in the region above the initial fracture, forming a zone of broken rock. The bit tooth moves forward until it reaches the margins of the wedge and/or fracture zone, and the process repeats (Bourgoyne et al. 1986 [DIRS 155233], Chapter 5). The crushed and broken material is then removed from the boring using circulated drilling fluids (air, water, or admixtures thereof) that also provide cooling and cleaning for the drill bit.

The drill collar is a heavy-walled length of drill pipe with a diameter less than the borehole diameter. If too much force is applied at the top of the drill stem, the drill pipe will bow and tend to cause the bit to cut off-center and, thereby, cause deviations in the borehole alignment. To compensate, drill collars are used to add weight to the lower part of the drill string assembly. This concentration of weight and the increased rigidity of the collars helps to keep the lower part of the drill assembly in alignment and provide weight to the bit to maintain appropriate penetration rate (Driscoll 1986 [DIRS 116801], p. 281). Drill collars may also be fitted with stabilizer devices that contact the borehole walls. The drill collars and stabilizers are used to maintain alignment of the drill string within the borehole and reduce vibration or “wobble” of the bit and the drill pipe that transfers the torque from the surface to the drill bit.

C4.2 BIT OPERATING CONDITIONS AND CHANGE-IN-CONDITIONS

Bit operating conditions (i.e., drilling fluid properties and circulation rates, drill string stability, bit weight, and rotary speed) affect the rate of penetration and the vibrations felt on the drill rig. These factors would be affected by the drilling assembly’s entry into the emplacement drift, and the bit operating conditions would be significantly affected by the rounded geometry of the emplacement drift, drip shield, and waste package.

The loss of drilling fluid circulation and the sudden drop in weight on the bit when the drill bit breaks through the top of the emplacement drift would provide initial indications that conditions had changed significantly. The loss of circulation would occur because of the flow of drilling fluids from the borehole and into the emplacement drift which, at 5.5 m diameter and on the scale of a kilometer in length, represents an essentially instantaneous increase in volume compared to the borehole volume. At that point, the driller would either try to continue drilling without compensating for the fluid loss in the hope of passing through the “loss” zone, would try various additives in the drilling fluid to try to “seal” the formation (Driscoll 1986 [DIRS 116801], p. 360) or would have to pull the drill assembly and either change drilling methods or run casing to seal off the cavity. In the event of continued drilling, the encountering of the drip shield or waste package would prevent progress, and the lack of cooling from circulated fluids would eventually destroy the drilling bit and result in the drilling assembly being pulled from the hole (or otherwise cause the driller to consider alternative courses of action). Given the volume difference between the borehole and the emplacement drift, it is implausible that any amount of additive would resolve the lost circulation problem, again leading the driller to some alternative course of action. Alternative courses of action, such as spot cementing through the loss zone or setting casing through the cavity, would involve pulling the drilling assembly from the borehole. In either scenario, the driller would then encounter continued volumetric problems or would encounter problems in trying to set casing due to the presence of the drip shield or waste package within the emplacement drift. If successful in such attempts, alternative scenarios involve progressing the boring without penetration of the drip shield (i.e., along the side of gap between the drip shield and drift wall) or have the potential for contacting the drip shield.

In addition to loss of circulation, the space between the crown or sides of the emplacement drift (5.5 m) and the drip shield would cause the operating conditions to become unstable and would evidence themselves as a sudden increase in rotation speed as the weight on the drill bit was "unloaded," sudden drop in the drill assembly (i.e., essentially free fall until the drip shield or invert of the drift was encountered), and or a significant increase in the amount of vibration at the surface. Any of these conditions would cause the destabilization of the drill bit (i.e., tend to allow the bit to change direction from the original concentric alignment) and would trigger a response by the driller to address the change in conditions. This is particularly true as drilling conditions would noticeably change (due to the difference in rock and alloy material properties) if the drilling assembly came in contact with the drip shield material as discussed in Section C4.4 of this appendix.

These various scenarios and alternatives assume that the drift has not collapsed. However, the lithophysal and fractured nature of some the Topopah Spring Tuff rock units could provide similar indications, or a rubble accumulation at a collapse point could limit the degree of lost circulation, and the various alternatives discussed above might allow the borehole to progress. Rubble material in a collapsed drift could reduce the degree of the effects on drilling but would likely not eliminate them. The drift stability through time has been examined in *Drift Degradation Analysis* (BSC 2004 [DIRS 166107]). The analysis indicates that during the regulatory period of 10,000 years, the ground support will completely lose its integrity, and drift degradation will occur due to strength decay of the rock mass within the lithophysal zone (BSC 2003 [DIRS 166107], p. 188). However, the collapse results in the bulking of, or increase in volume of the rock, as the rock mass disintegrates into a number of pieces, resulting in increased porosity and overall volume. The resulting bulk properties of the fill are different from that of the intact rock mass. Loss of drilling fluid circulation would still occur but perhaps could be accommodated by the driller. Additionally, the rubble pile of rocks would tend to move or shift under small loads, and the uneven loading on the drill bit would increase the lateral deviation forces (Bourgoyne et al. 1986 [DIRS 155233], Chapter 5). As such, even if the drifts collapse, the character of the rubble would be insufficient to stabilize the drill string. Severe wobbling bit action would result as the bit is rotated if the drill collars or stabilizers above the bit are not held in a concentric position in the borehole.

C4.3 PENETRATION OF THE DRIP SHIELD AND WASTE PACKAGE

To have any possibility of penetrating the drip shield or waste package, the drilling assembly would have to contact the surfaces in an essentially perpendicular orientation. In general, deviation in alignment may be caused by the character of the subsurface material. This is because lateral deviation forces increase with relatively small changes in the contact angle between the bit and the drilled material (Bourgoyne et al. 1986 [DIRS 155233], Chapter 5). Deviations may also be caused by too much or too little weight on the drill bit and differences in the pull-down force applied to the drill pipe during rotary drilling. Additionally, the varying hardness of different materials being penetrated deflects the bit from a consistent alignment.

Given that the top of the drip shield is curved and that most groundwater exploration holes are drilled in a near-vertical orientation (i.e., angle and directional drilling are possible but are not typically used for groundwater exploration purposes due to increased difficulty and cost), the drill bit would have to make contact at the relatively small areas that make up the apex of the drip shield or waste package, where the surfaces are essentially perpendicular to the drill bit orientation. Only the apex of the drip shield or waste package provides a perpendicular surface for which drip shield and waste package geometry would not increase the lateral deviation forces.

If the drilling assembly contacts any location other than the relatively small areas that make up the apex of the drip shield or waste package, then the relatively small drill bit diameter and high rotational speeds and the increased strength of material used for the drip shield and waste package compared to the geologic materials (see Section C4.4 of this appendix) would result in large lateral deviation forces and uneven loading on the bit. In turn, this would lead to drilling assembly instability and the bit would essentially bounce and slide on the top or side of the engineered barriers and potentially cause the drill bit to slip off of the drip shield or waste package apex. Consequently, no penetration of the waste package would occur. Furthermore, any non-slip contact with the drip shield or the waste package would be accompanied by a noticeable increase in drill string torque and reduced rate of penetration as the bit teeth contacted the metallic alloy. At the surface, the driller would recognize these conditions as a lack of drill bit penetration and excessive vibration. High levels of vibration and correspondingly low rates of penetration, such as these observed with poorly designed bits when crossing hard and abrasive formations would prompt the driller to adjust the rotary speed and weight on bit that eliminates shock. In some cases, this could include removing the drilling assembly from the borehole to inspect the bit condition (Putot et al. 2000 [DIRS 167791], p. 118), which would increase the chance for recognition of excessive bit wear and possible recognition that a metallic object had been encountered.

C4.4 COMPARATIVE MATERIAL STRENGTHS

Assuming that the drilling assembly does not slide off the apex of the drip shield, then a significant change in downhole conditions would also be recognized because the failure mechanisms of brittle rock (such as that present at the repository host horizon) and ductile alloys (such as the drip shield and waste packages) differ significantly. These changes in failure mechanisms are so significant that specialized downhole techniques and tools are used to drill through metal. Milling produces a different failure mechanism than brittle failure that roller bits and hammer bits typically produce. Bits designed for drilling rock would not be efficient for drilling through metal and would likely be seriously damaged, and the milling techniques needed to bore metals (Avallone 1987 [DIRS 103508], pp. 13-63 to 13-64) are not used in rock drilling, unless required for "fishing" operations or other specialized applications (e.g., Driscoll 1986 [DIRS 116801], Figure 10.10 and Figure 10.54, pp. 316 to 319).

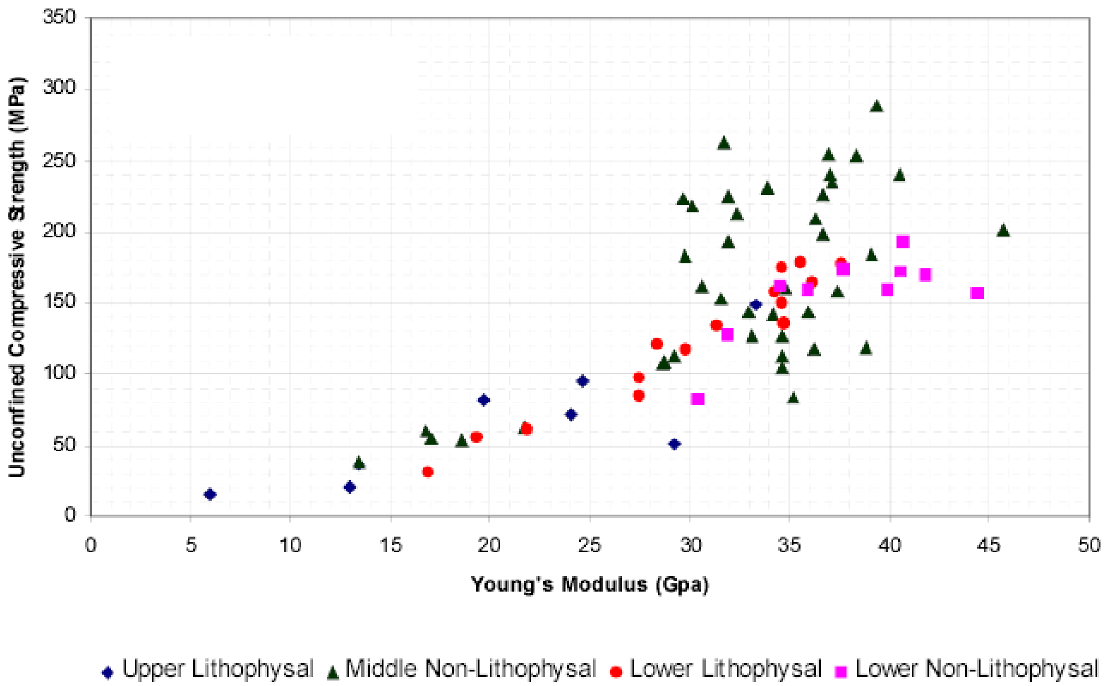
Brittle materials are characterized by the fact that rupture occurs without any noticeable prior change in the rate of elongation. Thus, for brittle materials under tension, there is no difference between the ultimate strength and the breaking strength. Also, under tension, the strain at the time of rupture is much smaller for brittle than for ductile materials (Beer and Johnston 1981 [DIRS 166708], p. 36). In general, brittle materials are weaker in tension than in shear (Beer and Johnston 1981 [DIRS 166708], p. 101), and brittle materials are significantly stronger in compression than in tension (e.g., the tensile strength of concrete is about 10 to 20 percent of its compressive strength; also see Table C-1 of this appendix for a comparison of rock strength in compression and tension). For brittle materials, strength is typically reported as compressive strength rather than tensile strength, while ductile material strengths are typically determined in tension.

The ductility of a material, such as the alloys used for the drip shields and waste packages, is usually measured as the percent reduction in area (or the elongation that occurs during a tensile test. Ductile materials, with a minimum elongation in tensile testing, will not fail in service through brittle fracture (Boyer and Gall 1984 [DIRS 155318]), which is the failure mode exhibited by the repository host horizon materials. Also, for ductile metals, the compression strength is generally assumed equal to the tensile strength (Beer and Johnson 1981 [DIRS 166708], p. 584). Generally speaking, values obtained for the yield strength and ultimate strength of a given material are only about half as large in shear as they are in tension, and the shear modulus is generally less than one-half, but more than one third, of the modulus of elasticity of that material (Beer and Johnston 1981 [DIRS 166708], pp. 68-69).

Therefore, if the differences between milling and rotary drilling tools are ignored and rotary bits could be used to penetrate the engineered barriers, a measure for comparing strength properties between brittle and ductile materials is needed. One such parameter is a comparison of the modulus of elasticity of these differing materials. Because of the lack of elongation, the stress-strain diagram for brittle materials is generally linear, and the modulus of elasticity provides a convenient method for comparing material properties between brittle and ductile materials. This also suggests that comparison of tensile strength of brittle materials to yield strength of ductile materials may also be appropriate. Comparison of the compressive strength of rock materials and tensile strength of alloy is also appropriate. Furthermore, the reported shear modulus could be compared (if available) or a value of twice to three times the shear modulus could be compared to the modulus of elasticity.

Various rock properties for materials at Yucca Mountain are shown in Figure C-1 and Table C-1, including uniaxial compressive strength and the modulus of elasticity (Young's modulus), tensile strength, and ultimate strength. Based on the design drawings and data tracking numbers (DTNs) cited, the yield strength, tensile strength, and modulus of elasticity for the drip shield and waste package materials are shown in Table C-2.

Studies that have been conducted to correlate operational parameters to rate of penetration of the drill bit indicate that the rate of penetration may range from inversely proportional to the square of the strength of the material being drilled to inversely proportional to strength of the material, all other factors being equal (Bourgoyne et al. 1986 [DIRS 155233], Equation 5-19; Kahraman 2000 [DIRS 167761], Equations 8, 12, and 14). Putot et al. (2000 [DIRS 167791], p. 123) suggests, at least for balling tendencies in shales and for a given weight on bit, drilling performance collapses upon a doubling of the rotary speed. As shown in Appendix B, Section B5.1.3, penetration rate is directly proportional to rotary speed. Assuming that a change in the penetration rate by a factor of 1.5 or greater (increase) or 0.66 or less (decrease) (i.e., some condition occurring before "performance collapse") would be sufficient to be noticed by a driller, a change in compressive strength of materials by a factor of 1.5 (or possibly less if one assumes the inverse square relationship presented by Bourgoyne et al. 1986 [DIRS 155233]) would cause a significant change in drilling conditions that would be recognized by the driller.



Source: BSC 2003 (DIRS 166660), Figure 8-45.

Figure C-1. Unconfined Compressive Strength vs. Young's Modulus 50.8 mm Specimens, Saturated, Room Temperature, L:D = 2:1

Table C-1. Uniaxial Compressive Strength and Young's Moduli by Rock Unit

Rock Unit	Uniaxial Compressive Strength Mean (MPa)	Tensile Strength Mean; Range (MPa)	Ultimate Strength Mean; Range (MPa)	Shear Modulus (GPa)	Elasticity (Young's Modulus) Mean; Range (GPa)
Topopah Springs Tuff – upper lithophysal zone (Tptpul)	39.0	- -	19.3; 9.4 – 37.0	- -	11.1; 5.0 – 20.5
Topopah Springs Tuff – lower lithophysal zone (Tptpll)	110.6	8.3; 3.2 – 14.3	23.8; 13.3-32.2	0.80 to 8.21	6.9; 5.0 – 9.2
Topopah Springs Tuff – middle nonlithophysal zone (Tptpmn)	188.0	10.9; 4.3 – 16.8	212.8; 16.08 – 360.0	- -	33.6; 16.6 – 47.3
Topopah Springs Tuff – lower nonlithophysal zone (Tptpln)	136.1	7.9; 4.8 – 13.7	- -	- -	

Sources: Mean Uniaxial Compressive Strength Data based on data provided in DTN: MO0311RCKPRPCS.003 (DIRS 166073) and Table E-14.

Tensile Strength taken from BSC 2004 (DIRS 166107), Table E-7.

Ultimate Strength taken from BSC 2004 (DIRS 166107), Table E-8.

Shear Modulus estimated for rock mass qualities 1 through 5 and taken from BSC 2004 (DIRS 166107), Table E-10.

Mean for Elastic Modulus (Young's Modulus) based on data from BSC 2004 (DIRS 166107), Tables E-6 and E-9.

The tables the follow indicate that the mean compressive strength of the rock material ranges from 39.0 MPa to 154.0 MPa. At room temperature, the tensile strength of the drip shield materials ranges from 345 MPa to 895 MPa. Thus, the factor of compressive strengths ranges from about 2.2 (345/154) to as great as 22.9 (895/39.0). The tensile strength of the waste package material at room temperature ranges from 550 MPa to 802 MPa. This represents factors of 3.6 (550/154) to as great as 205 (802/39.0). If one conservatively assumes the yield strength of the engineered barrier materials is comparable to rock compressive strength, the factors decrease. For the drip shield material at room temperature, the factor ranges from 1.8 (275/154) to 11.5 (450/39.0). For the waste package material at room temperature, the factors range from 1.6 (240/159 to great as 10.3 (403/39.0). However, given that all waste packages include Alloy 22 (UNS N06022) material as outer barrier, the lower end of the range is bounded at a factor of 2.3 (358/154). Therefore, at room temperature, a minimum factor of two, and potentially much greater is present for at least one of the engineered barriers. If one assumes an inverse proportionality of rock strength to rate of penetration, the penetration rates would decrease by a minimum factor of 0.62 and, therefore, be recognizable, as previously discussed in Section C4.4.

Table C-2. Material Properties for Drip Shield and Waste Package Fabrication

Engineered Barrier Material	Use	Yield Strength at 0.2% Offset (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
Titanium Grade 7[a] and Grade 16 (at room temperature)	Drip Shield	275 to 450	345	106.87
Titanium Grade 7[a] and Grade 16 (at 400°F/204°C)	Drip Shield	138-152	207-228	- -
Titanium Grade 24	Drip Shield	- -	895[b]	113.8[c]
Alloy 22 (UNS N06022) (at room temperature)	Waste Package	358-403	765-802	206
Alloy 22 (UNS N06022) (at 400°F/204°C)	Waste Package	262-303	662-701	196
Type 316 N Grade Stainless Steel (minimum properties)[e]	Waste Package	240	550	196

[a] DTN: MO0003RIB00073.000 (DIRS 152926) for Titanium Grades 7 and 16.
[b] Tensile Strength for Titanium Grade 24, ASME 1998 (DIRS 145103), Section II, Table 1.
[c] Modulus of Elasticity for Titanium Grade 24, ASM International 1990 (DIRS 141615), p. 621.
The source of values for Titanium Grades 7, 16, and 24 are given on Drawing 800-IED-WIS0-00401-000-00D in *D&E / PA/C IED Interlocking Drip Shield and Emplacement Pallet* (BSC 2004 [DIRS 169220]).
[d] DTN: MO0003RIB00071.000 (DIRS 148850) for Alloy 22 (UNS N06022).
[e] DTN: MO0003RIB00076.000 (DIRS 153044) for Type 316N.
The source of values for Alloy 22 and for Type 316N Grade is given on Drawing 800-IED-WIS0-00201-000-00E in *D&E / PA/C IED Typical Waste Package Components Assembly* (BSC 2004 [DIRS 169480]).

At elevated temperatures, such as those during the thermal period (e.g., 200°C), the strength properties of the drip shield material are reduced. The factor reduces in range from 1.3 (207/154) to as great as 5.8 (228/39.0), based on compressive strength. However, the properties of the Alloy 22 (UNS N06022) outer barrier are not as significantly reduced. The factor for compressive strengths for the elevated temperature ranges from 4.3 (662/154) to 17.9 (701/39.0), and for yield strength is 1.7 (262/154) to 7.8 (303/39.0). Thus, a factor of at least 1.5 is maintained and changes in the rate of penetration would be noticeable, even at the elevated temperature.

Furthermore, the mean tensile strength and mean ultimate strength of the rock units are reported to range from 11.6 MPa to 23.8 MPa (or approximately 8 to 22 percent of the corresponding mean compressive strength). These rock tensile strengths are, at a minimum, a factor of 14 less than those of the engineered barrier materials at room temperature. Even conservatively assuming an equivalence of the yield strength of a ductile material to tensile or ultimate strength of brittle material generates a difference of a factor of greater than 10. Similarly, the mean modulus of elasticity for the rock materials is on the order of 6.9 to 33 GPa. Correspondingly, the reported shear modulus for the repository host horizon ranges from 0.42 to 8.21 GPa (or no greater than 1/4 of the maximum reported modulus of elasticity). By contrast, for the ductile alloys, the modulus of elasticity ranges from 107 to 206 GPa, representing a minimum factor of 3.2 different from the rock properties. These factors would be reduced at elevated temperatures.

The discussion provided above would be applicable even if the drip shield or one of the materials used in the waste package were degraded to the point where structural integrity were lost or (in the case of the drip shield) the interlock mechanism were bent and penetrated by the drilling assembly.

C5. CONCLUSION

The information presented in this appendix addresses the issue of when a human intrusion could occur based upon the earliest time that current technology and practices could lead to waste package penetration without the driller noticing waste package penetration. Conclusions based on information presented in this appendix suggest that a human intrusion event, if it were to occur during the time frame of regulatory compliance, would not happen without recognition.

Selection of a bit for drilling involves knowledge of the characteristics of the rock. As indicated in Tables C-1 and C-2, there are significant differences between the tensile strengths and other material properties of the geologic units at Yucca Mountain and the materials for the drip shield and waste package. Because the materials used in the drip shield and waste packages have high tensile strengths, yield strengths, and increased modulus of elasticity compared to the host rock properties, the tooth of a roller bit cannot penetrate enough to cause sufficient strain for chipping to occur. Rather, if contact with the drip shield occurs, the rotation of the bit would result in a tearing or shearing action with associated and recognizable high torque values. Consequently, the ductility of the metals makes them nearly impenetrable by techniques used in drilling rock. Boring in metals typically utilizes a milling technique. The downhole milling tools needed to penetrate the drip shield and waste package are not typically used in groundwater exploration, and use of such tools would be a clear indicator of recognition of penetration of some type of metallic, anthropogenic structure. Furthermore, general corrosion failure of the drip shields is not expected to occur prior to 35,000 years, and the maximum corrosion depth in 10,000 years is predicted to be less than one-half the total thickness of the drip shield plates. Consequently, penetration of the drip shield or waste package without recognition by the driller prior to general corrosion failure of the engineered barriers is not feasible prior to the end of the 10,000-year regulatory period. Before this time, the presence of metallics will be recognizable to the driller, generally through loss of rate of penetration or significantly increased torque on the drill assembly.

Because the evaluation for TSPA-SR indicated that the earliest time that current technology and practices could lead to waste package penetration without the driller noticing waste package penetration was after 10,000 years, the evaluation of the human intrusion stylized analysis was previously placed in the FEIS (DOE 2002 [DIRS 155970], Section 5.7.1) as required at 10 CFR 63.321(b)(1) (DIRS 156605). The analysis and materials properties data for TSPA-LA do not lead to any significantly different conclusions regarding the timing of human intrusion.

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APPENDIX D

SCIENTIFIC ANALYSES DISCUSSION AND SUPPORTING DOCUMENTATION FOR METEORITE IMPACT AND CRATERING PROBABILITY AND CONSEQUENCE

D1. INTRODUCTION

This appendix supports the feature, event, and process (FEP) screening for meteorite impact, as summarized in Section 6.2.4.5 of the main body of this analysis report. It provides a detailed calculation and discussion regarding meteorite impact and provides the technical basis for exclusion based on probability for meteorite crater diameters larger than the threshold diameter associated with a frequency of one per 10,000 per 10,000 years. It also provides the technical basis for exclusion based on consequences for meteorite crater diameters smaller than the threshold diameter.

AP-SIII.9Q, *Scientific Analyses*, Attachment 3, allows for the use of appendices to the main body of the analysis report. To wit "Supporting documentation, such as computer output, that are lengthy or cannot be conveniently included with the main text of the documentation may be included as appendices." This appendix is not intended to be used as stand-alone documentation separate from the main document. The application of the probability and consequence information described here in is intended for FEP screening purposes. Specifically, it is directly applicable to consideration of meteorite impacts, and indirectly may be applicable to other surface energy-release phenomena such as crashes and/or explosions and detonations. The FEP screening process is described in Section 6.1 of the main body of the analysis report and is not repeated in this appendix.

Because of the length of the analysis, this appendix has been organized into sections. Section D2 addresses the overall scientific approach and methods used in the analysis. Section D3 provides the calculation of the probability of intersection with the repository footprint based on meteoroid flux data and the repository-specific dimensions. A discussion of related uncertainties is also provided. Section D4 discusses the FEP implications of the results.

D2. SCIENTIFIC APPROACH AND TECHNICAL METHODS

The analysis of meteorite-impact probability and consequence is needed to perform FEP screening. The initial question is "What is the probability of meteorite impact at the repository?" The answer to the question is that the probability of impact of a meteorite of *any size* without regard to resulting consequence, at or near the repository, *in 10,000 years,* is approximately one. The initial question is incomplete, however, in that not all meteorites impact with energy sufficient to cause damage at the surface, to crater the surface, or otherwise affect the subsurface. Additionally, it is recognized that impacts *near* the repository, if of sufficient energy to cause damage, also need to be considered. Consequently, the question is refined to address the minimum size meteorite (or more precisely, the minimum resulting crater diameter) sufficient to affect repository performance, and the associated probability. The question is restated as "What is the probability or consequence of damage to or impairment of repository performance stemming from meteorite impact in 10,000 years?"

The probability of an impact crater of a given size occurring directly over or adjacent to the repository is dependent on the total flux of meteorites to the earth surface and on the repository footprint area (or target area). The size of the crater of interest is determined by the depth from ground surface to the top of the repository and/or any intervening geologic layers of particular interest due to their physical or hydrologic properties, and the spatial relationship of crater diameter to exhumation depth and fracture depth. Accordingly, this analysis report appendix specifically examines the target area to be considered and the probability of crater diameters sufficient to exhume waste, to fracture overlying rock units down to the repository depth, and to fracture to a depth less than the repository depth but sufficient to impair performance.

Most authors express the target area as either the whole earth's surface (5.1×10^8 km^2) or some fraction thereof, such as only the landmass as in the case of meteorite fall studies, or probability per km^2. In either case, to use the stated values in the literature, a first approximation of the target area can be used to scale probabilities. This approach is taken for Sections D3.1 and D3.2. Section D3.1 provides a "first order" approximation based on the probability of intersection from individual and known objects. This section only addresses individual objects and not the full range of potential meteorite sizes. It is, therefore corroborative, in nature and utilizes only indirect input. The results are not used as the basis of the FEP screening decision, but strengthen the results that are presented in Sections D3.2 and D3.3. Section D3.2 provides a "first order" approximation based on distributions developed from observed lunar and earth cratering data. Section D3.2 also develops a cratering rate distribution based on meteoroid flux, meteoroid properties, and crater relationship information. This first order approximation of probability based on footprint area slightly under-represents the probability of impact because it fails to consider the potential for "near-miss" impacts in which the center of a crater occurs outside the repository footprint, but a portion of the crater diameter extends within the boundary. At most, the target area would be expanded by adding one-half of the crater diameter (for the crater diameter that occurs at an annualized frequency of 10^{-8}) to all four sides of the repository footprint (presuming a roughly rectangular footprint). Consequently, a more accurate representation of probability is achieved by expressing the area as a function of the two rectangle dimensions plus the crater diameter, coupling this to a known distribution, such as meteorite influx or cratering rate, and integrating the function over the range of possible values. Section D3.3 uses this approach and uses the distributions discussed in Section D3.2 and applies them to repository-relate target areas, including the TSPA-LA emplacement area footprint and to the geologic outcrop area of the Paintbrush unit. This results in a more detailed analysis that considers the repository footprint area and other key target areas (i.e., geologic unit outcrop). Corroborative analysis based on the TSPA-LA siting area and the TSPA-SR footprint is also provided for comparison. Each of the approaches used in Sections D3.1, D3.2, and D3.3 have inherent uncertainties, which are discussed in Section D3.4.

The implications and conclusion from this analysis to be used in FEP screening of meteorite impact is discussed in Section D4 of this appendix.

D3. METEORITE IMPACT ANALYSIS AND DISCUSSIONS

This section provides an analysis of meteorite impact probability. The results of this analysis provide the technical basis used for screening the FEP, as described in Section 6.2.4.5 of the main body of the document.

Direct inputs used in this section are addressed in Section 4 of the main body of this document as required by procedure AP-SIII.9Q. Data qualification for non-YMP sources used for direct inputs is provided in Section B5.5 of Appendix B of this document, which also provides the list of indirect inputs, as required by procedure AP-SIII.9Q.

For the calculations provided in Section D3 of this appendix, metric units are used throughout, with distances and depths being expressed in either meters or kilometers. Densities are expressed as either kg/m^3 or g/cm^3. Energy release is expressed as either equivalent tonnage of TNT (i.e., as either kiloton or megaton) or as Joules. The conversion from number of events, whole earth to number events per km^2 is simply division by the surface area of the earth (5.1×10^8 km^2).

Assumptions used in this analysis are identified under Assumption 5.4 of the main body of this document and are referenced within the following discussion as needed. Formulations, equations, algorithms, and numerical methods used are discussed when used, with equations being sequentially numbered throughout this appendix. Justification for use of the equations and relationships used is provided in Section B5.5 of Appendix B of this document. Multiple approaches and alternative methods were used in developing this analysis, and are described within this section. No modeling was performed for this analysis. The calculations were performed using simple spreadsheets, examples of which are provided as separate tables.

For clarity, the following terms are used in the discussions. *Meteoroid* refers generically to a non-anthropogenic space object prior to entry to earth's atmosphere, *meteor* refers to the object once it enters earth's atmosphere and prior to impact, and *meteorite* refers to the object (or fragments of the object) impacting on (or in the case of aerial explosion, occurring near) the earth's surface. The terms *bolide* and *fireball* are also used. A *bolide* is defined as a meteor that shows signs of explosion or fragmentation, and a *fireball* is defined as a bright meteor with luminosity that equals or exceeds that of the brightest planets (generally magnitude of –3 or brighter).

D3.1 PROBABILITY OF IMPACT BASED ON INDIVIDUAL OBJECTS

Various authors have calculated the probability of entry of known individual interplanetary bodies into the earth's atmosphere. These probabilities are for any entry into the earth's atmosphere. However, our interest is in the cumulative probability of impact of all objects, not just for individual objects, so the following information is considered as corroborative-use only.

Chyba (1993 [DIRS 135248], Table 1a) addresses 12 objects with diameters of less than 50 m that have been observed to date. Excluding object 1991-VG (a suspected possible human artifact), the mean calculated probability of impact on the earth's atmosphere for the known bodies is 29 per gigayear, suggesting rates on the order of 3×10^{-8} per year, or on the order of 3×10^{-4} in 10,000 years (Chyba 1993 [DIRS 135248], p. 701) for the whole earth surface, and it is stated to be a factor of approximately seven greater than for other earth-crossing asteroids. Since impact is a spatially random process (Grieve 1987 [DIRS 135254], p. 257), dividing this value by the surface area of the earth (5.1×10^8 km^2), and multiplying by the maximum area of the repository footprint (18 km^2), yields a probability of impact above the repository on the order of 1.1×10^{-15} per year, or approximately 10^{-11} in 10,000 years.

Marsden and Steel (1994 [DIRS 129308], p. 235, Figure 4) provide the calculated atmospheric-entry probabilities, defined as crossing within 0.1 to 1 astronomical unit (AU) (1 =AU = 149,598,000 km) of earth's orbit, for all observed long period comets (i.e., orbit duration of greater than 200 years). The greatest calculated probability is 2.6×10^{-7} per orbit and the estimated mean impact probability is 2×10^{-9} to 3×10^{-9} per orbit. Dividing by the minimum orbital period of 200 years (by definition of a long-period comet) yields a maximum probability of approximately 1.3×10^{-9} per year, or on the order of 10^{-5} in 10,000 years for the whole earth. If one neglects atmospheric shielding effects, the probability of impact above the repository can be estimated by dividing the probability by 5.1×10^{8} km^2, the approximate surface area of the earth, and multiplying by the maximum repository footprint. This yields a maximum probability of approximately 4.5×10^{-17} per year or about 4.5×10^{-13} in 10,000 years.

The probability of the impact of any individual, known object is, therefore, at least seven orders of magnitude less than the regulatory threshold of an annualized equivalence of about 10^{-8} or, more specifically, 10^{-4} in 10,000 years.

D3.2 PROBABILITY OF IMPACT BASED ON OBSERVED CRATERING DISTRIBUTIONS

The FEP screening considers the cratering rate distributions derived from Grieve et al. (1995 [DIRS 135260]) that is based on world-wide cratering information (Section D3.2.1). It also considers the distribution from Wuschke et al. (1995 [DIRS 129326]), which is based on cratering of the Canadian shield, and serves as a “realistic case” (Section D3.2.2). In addition, the analysis examines the distribution proposed by Neukum and Ivanov (1994 [DIRS 121510]), which is based on lunar cratering data (Section D3.2.3). Because this distribution was developed assuming an “atmosphereless earth,” it serves as an upper bound for earth cratering. However, this distribution is only used for corroboration purposes, as it is unrealistic to expect that the atmosphere has no effect on the cratering distribution.

Existing distributions in the literature are stated, generally, to apply to crater diameters on the scale of kilometers, rather than within the primary range of interest for this analysis (79 to 625 m as discussed in Section D3.3.2). Accordingly, this analysis also develops an independent distribution based on meteor influx and couples that with work by Hills and Goda (1993 [DIRS 135281]) to derive a cratering distribution applicable to the smaller diameter range. This flux-derived distribution is developed based on meteoroid flux, meteoroid properties, and on meteoroid radius to crater diameter relationships (Section D3.2.4).

The respective distributions based on observed earth and lunar cratering are shown in the following figure, Figure D-1 (and justified for use per Figure B-2 of Appendix B), and are described in the following subsections.

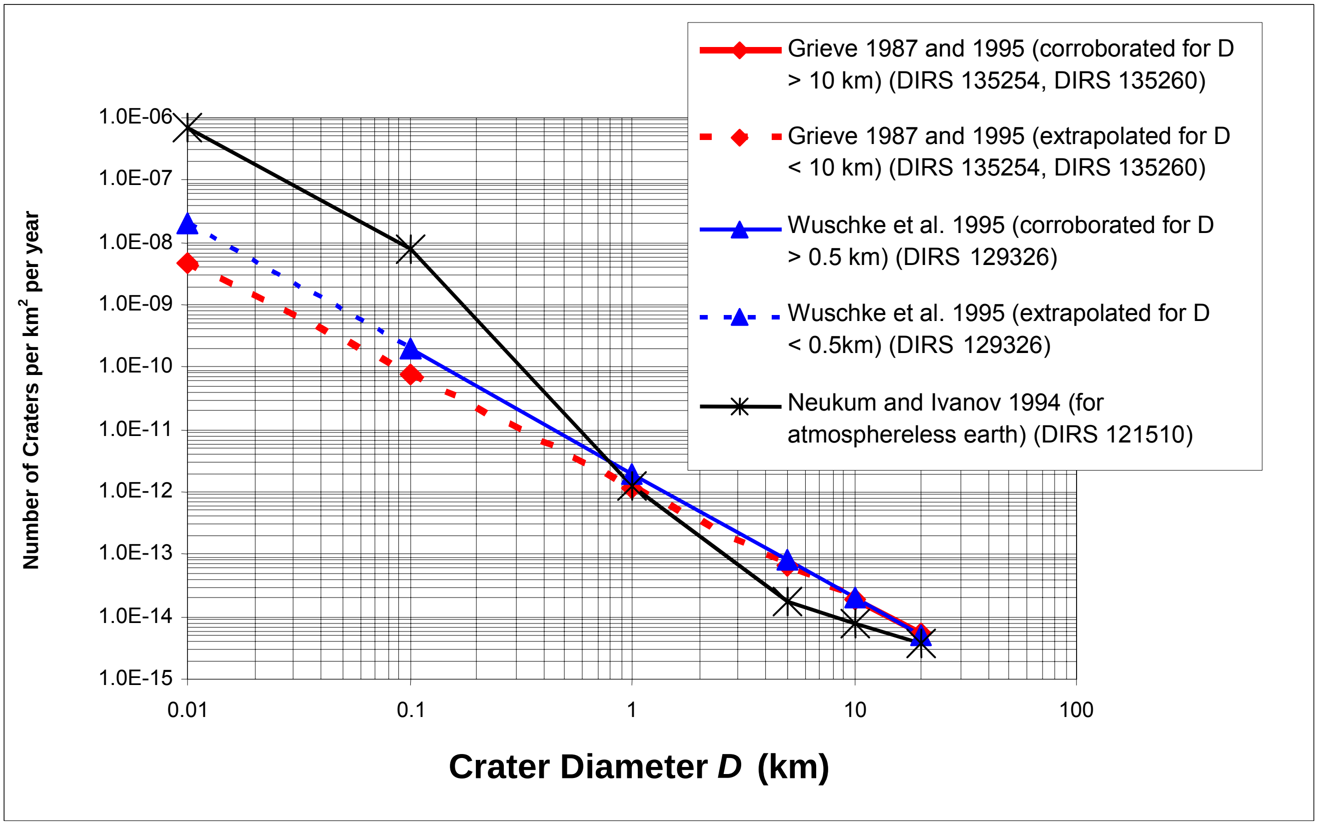


Figure D-1. Cratering Rate Distribution from Three Sources

D3.2.1 Grieve (1987)

An applicable cumulative cratering rate (and one commonly used for these types of analyses) can be derived from Grieve (1987 [DIRS 135254]), Grieve et al. (1995 [DIRS 135260]), and Grieve (1998 [DIRS 163385]). The number of impact craters larger than a crater diameter D, produced per year per square km is proportional to the apparent crater diameter to the –1.8 power (Grieve 1987 [DIRS 135254], p. 257 and Figure 8).

Using the Fundamental Theorem of Calculus, and the definition of F(D) provided in Equation B-9 of Appendix B of this analysis report, a distribution function for the frequency of impact for craters of a given diameter D can be found.

By definition:

$$F(D) = \int_0^\infty f(x)dx = K\,D^{-1.8} \qquad \text{(Eq. D-1)}$$

Therefore:

$$f(D) = 1.8\,K\,D^{-2.8} \qquad \text{(Eq. D-2)}$$

Equations D-1 and D-2 will be used later in this appendix to determine the frequency of impact cratering in the repository area. As shown in Section B5.5.3.3 of Appendix B (Equation B-10b), the value of K is fixed at 1.2×10^{-12}, based on the frequency of earth craters with diameter of 20 km or greater. That equation is restated here as:

$$F(D) = 1.2 \text{ x } 10^{-12} \text{ x } D^{-1.8} \qquad \text{(Eq. D-3)}$$

where F(*D*) is equal to the number of craters larger than a given diameter, produced per year per km^2, as a function of diameter, *D*. A plot for this equation is provided in Figure D-1.

Using a repository emplacement area of no greater than 11.9 km^2 (see Section D3.3.1) then the cratering diameter of interest is that associated with an annualized probability of $8.4\times10^{-10}/km^2$ (i.e., 8.4 x $10^{-10}/km^2$ multiplied by an area of 11.9 km^2 roughly equates to an annualized probability of 1 x10^{-8}, which is the regulatory threshold for consideration). Based on Figures D-2a, D-2b, and D-3, this equates to a crater diameter of no more than 30 m. It should be noted that the Grieve distribution is routinely cited as being applicable only for crater diameters of greater than 20 km, although Neukum and Ivanov (1994 [DIRS 121510]) support use of the distribution down to diameters of as low as 10 km. Given the distribution of crater diameters by Grieve (1998 [DIRS 163385]), it is conservative (in relation to observed craters) to extend the distribution to lesser diameters. This is because the extrapolation overstates the number of craters that would occur compared to the actual number observed to date. However, the number of observed small diameter craters is obscured by the ability to recognize such features and the destruction through time due to natural and anthropogenic processes, so the degree of true conservatism cannot be quantified.

Using the exhumation and fracturing depth relationships described in Section D3.3.2, a crater diameter of 30 m could result in an exhumation depth on the order of 3 to 10 m, which is insufficient to exhume waste at the depth of the proposed repository (i.e., greater than 200 m below ground surface (BSC 2003 [DIRS 165572], Section 7.1.8). With regard to fracturing, the depth of fracturing could be as little as 10 m to as great as 23 m. These depths are insufficient to reach the repository depth or to significantly alter infiltration through the Paintbrush nonwelded unit.

D3.2.2 Wuschke et al. (1995)

A particular example of the use of Grieve distribution and the consideration of exhumation and fracturing depths is presented in Wuschke et al. (1995 [DIRS 129326]). The analyses presented therein was for a hypothetical depository deep in plutonic rock of the Canadian shield, located at least 500 m below ground surface with a total area of 4 km^2. The curve from Wuschke et al., if comparable to the information used by Hughes (1998 [DIRS 162562], p. 34), may only be valid down to diameters of 1 km. For Wuschke et al. (1995 [DIRS 129326], p. 44), the distribution is derived from subsets of the observed earth cratering distribution used by Grieve (1987 [DIRS 135254]). The equation (Equation B-11a in Appendix B of this document) is given as:

$$F(D) = 2.0\times10^{-12}(D)^{-2} \qquad \text{(Eq. D-4)}$$

This denotes a slightly steeper slope compared to Grieve (2.0×10^{-12} compared to Grieves $1.2 \pm 0.6 \times10^{-12}$). Wuschke's approach slightly decreases the annual frequency for a 20-km diameter crater (5.0×10^{-15} per km^2 compared to the values from Grieve of 5.5×10^{-15} km^2). This difference is reflected in the plot in Figure D-1.

The findings of this study are presented in Table 1 of Wuschke et al. (1995 [DIRS 129326], p. 26) and provide the annual probability and cumulative probability for 10,000 years for meteorite impact events. The results indicate that the annualized probability of impact for the Canadian repository design sufficient to cause damage by exhumation and fracturing is approximately 7.6×10^{-12} to 6.5×10^{-11} per year, respectively. This is associated with crater diameters of 7.6 to 0.66 km for exhumation and fracturing, respectively. Given the parameters used for the hypothetical Canadian repository (area of 4 km^2 and depth of 500 m), the reported probabilities should be less than the probability of impact for the Yucca Mountain repository (depths greater than 200 m below the surface and total area not to exceed 11.9 km^2 [BSC 2003 (DIRS 165572), Section 7.1.8 and Figure 1, respectively]) for the same effects of exhumation and fracturing. For exhumation of the Yucca Mountain repository, the least frequent and maximum crater diameter that could cause such an event is a crater diameter of 2 km (i.e., 200 m/0.10) and the most frequent would be a crater diameter of 625 m (200 m/0.32). Based on Figure D-3, and using a siting area of 11.9 km^2, such events occur with annual frequencies on the order of 6×10^{-12} to 6×10^{-11}, or about an order of magnitude more frequently than for the hypothetical Canadian design. For fracturing to repository depth, the crater diameter of interest is 263 m (i.e., 200 m/0.76). This occurs, based on Figure D-3, with an annual frequency of 3.6×10^{-10}, and again this is more frequent than predicted for the Canadian repository as expected.

Using the probability threshold for the Yucca Mountain repository, the crater diameter associated with a 8.4×10^{-10} probability (i.e., 8.4×10^{-10}/yr-km^2 x 11.9 km^2 = 1×10^{-8}/yr) for the distribution from Wuschke et al. (1995 [DIRS 129326]) is no more than 60 m, and slightly greater than that from for Grieve distribution, as shown in Figure D-3. This results in a maximum exhumation depth of about 20 m and a maximum fracturing depth of about 46 m. These depths are insufficient to reach to the proposed Yucca Mountain repository depth or to significantly alter infiltration through the Paintbrush nonwelded unit.

D3.2.3 Neukum and Ivanov (1994)

The plot of the Neukum and Ivanov (1994 [DIRS 121510]) information represents a true upper bound (i.e., an “atmosphereless” earth which neglects effects of ablation and fragmentation). Because it is unrealistic due to an “atmosphereless” earth, it is discussed for corroborative purposes only, but it also provides a true upper bound.

Neukum and Ivanov (1994 [DIRS 121510], Table IV) provides a tabulation of impact accumulation rates and mean time intervals between impacts for earth, based on lunar craters and adjusted for gravity differences. This table includes the mean interval between events with energies equal to or greater than that required to form a crater of a given diameter. The cumulative cratering rate (or frequency) of such events can be derived from the calculated mean intervals by using the inverse of the mean interval. The frequency per-square-km of the earth’s surface can be derived by dividing the frequency by the area of earth’s surface. This curve represents an extreme upper bound for the cratering rate on earth in the range of crater diameters of interest as it accounts for gravity differences between the lunar and earth surfaces and includes data for small-diameter craters. It does not take into account atmospheric shielding effects, which are known to exist and are significant in reducing crater frequency and size. The data used in plotting Figure D-1 is found in Section B5.5, Table B-17 of Appendix B.

Given that the footprint area is no greater than 11.9 km^2 as previously mentioned, then the cratering diameter of interest is that associated with an annualized probability of $8.4 \times 10^{-10}/km^2$ (i.e., $8.4 \times 10^{-10}/km^2$ multiplied by an area of 11.9 km^2 roughly equates to an annualized probability of 1×10^{-8}, which is the regulatory threshold for consideration). Based on Figure D-1, this equates to a crater diameter of slightly less than 200 m. Using the exhumation depth relationship mentioned above, such a crater diameter could result in exhumation depths greater than 20 m and less than 64 m, which are insufficient to exhume waste at the depth of the proposed repository (i.e., greater than 200 m below ground surface (BSC 2003 [DIRS 165572], Section 7.1.8) or to exhume significant portions of the Paintbrush hydrogeologic unit. With regard to fracturing, the depth could be as little as 70 m to as great as 150 m. These depths are insufficient to reach to the proposed repository depth, although the values may represent depths that are sufficient to fracture to the Paintbrush nonwelded unit in the eastern portions of the siting area. Depending on the choice of factors (0.3 or 0.76), the fracturing may or may not be penetrate throughout the Paintbrush nonwelded unit in the emplacement area. However, it must be kept in mind that the stated values represent the "worst-case" model proposed in the literature for exhumation and fracturing, coupled with the "upper bound" for crater diameter distribution. They are not realistic in that they are based on an "atmosphereless" earth.

D3.2.4 Probability of Impact Based on Meteoroid Influx and Meteoroid Characteristics

The direct application of the Neukum and Ivanov cratering distribution is limited because it does not consider atmospheric shielding. The Grieve distribution and the Wuschke distribution are limited because they are applicable for large-diameter craters, but uncertain for small diameter craters. Consequently, to determine probabilities of meteorite-impact cratering damage, a cratering diameter distribution curve is developed based on cumulative meteoroid influx information developed during the 1980s and 1990s. The flux distribution is applied against information on percent by type and density of meteors to determine a flux by meteor size and type. The resulting meteor diameters are then coupled with direct input relating initial meteor radius to resulting crater size, and an effective cratering distribution is determined that accounts for atmospheric shield effects such as ablation and fragmentation.

D3.2.4.1 Mass Flux of Meteoroids

Ceplecha (1992 [DIRS 135242]) has compiled flux information from a variety of authors for masses ranging from 10^{-21} to 10^{15} kg (46 orders of magnitude). This compilation is provided in graphical form (Ceplecha 1992 [DIRS 135242], Figure 1) as the log of the mass (*m*) to the log of the cumulative number (*N*) of interplanetary bodies of a mass equal to or greater than *m* coming to the earth's atmosphere every year. The present analysis of probability, however, is only concerned with the range of bodies capable of creating craters in the earth's surface. Selected values from the cited figure over the potential range of interest are provided in Table D-1, which describes the flux of material coming to the entire earth's atmosphere. This information is provided on Figure B-1 of Appendix B of this analysis report. This direct input is justified for use in Section B5.5.3.2 and Table B-10 of Appendix B.

Table D-1. Mass Flux Used as Direct Input

Log Mass (kg)	Mass (kg)	Number of Events Per Year Whole Earth
-1	1.0E-01	3.2E+05
0	1.0E+00	1.0E+05
1	1.0E+01	1.6E+04
2	1.0E+02	1.0E+04
3	1.0E+03	1.6E+03
4	1.0E+04	6.3E+02
5	1.0E+05	1.0E+02
6	1.0E+06	1.0E+01
7	1.0E+07	1.0E-01
8	1.0E+08	1.0E-02
9	1.0E+09	1.0E-03
10	1.0E+10	1.0E-04
11	1.0E+11	1.0E-05
12	1.0E+12	3.2E-06
13	1.0E+13	1.0E-06
14	1.0E+14	1.0E-07
15	1.0E+15	3.2E-08

Source: Ceplecha 1992 (DIRS 135242), Figure 1.

The mass distribution from Ceplecha (1992 [DIRS 135242], p. 362 and Figure 1) was chosen for use in this analysis because it provides a conservative estimate compared to influx determined from lunar cratering data or from direct observation of energy releases in earth's atmosphere by geostationary satellites. The degree of conservatism is approximately one-half to one order of magnitude in terms of the number of events occurring for a meteor of a given diameter. For consistency and traceability, the use of a single distribution was preferred to construction of a fully conservative data set constructed by hand-picking the maximum values from the literature for any given meteor diameter. This distribution does not however, address the nature of the material, its velocity, atmospheric shielding effects, the frequency and size of material actually impacting the earth's surface, or the resulting impact crater size.

D3.2.4.2 Influx of Meteoroids Based on Percent by Type

As defined by Chapman and Morrison (1994 [DIRS 135245], p. 34) and by Shoemaker (1983 [DIRS 135308], p. 464), meteor composition is described as metallic (iron to iron-nickel, and relatively rare), stony (mixtures of iron and stony material, chondritic–type S asteroids), or cometary (low-density silicates, organics and volatiles–type C asteroids). The term carbonaceous is also used for those bodies that lie between stony and cometary bodies. The differences in composition also reflect differences in the structural make-up and strength of the meteors.

Down to an initial meteor mass of approximately 10^8 kg (radius of 14 m for iron, 19 m for stony, and 28 m for carbonaceous meteors), the total flux is comprised of 5 percent iron material regardless of initial meteor radius, and the remainder is divided equally between stony and carbonaceous material regardless of initial meteor radius. For initial meteor masses below 10^8 and down to 10^{-1} kg (minimum radius of 0.014 m for iron, 0.019 m for stony, and 0.028 m for carbonaceous meteors), the total flux is comprised of 5 percent iron materials, regardless of initial meteor radius; 2 to 18 percent stony material depending on initial meteor radius; and the remainder (93 to 77 percent) is attributed as carbonaceous/cometary material. The bases for these values, and the qualification of this data, are discussed in Section B5.5.3.2 and Tables B-13 and B-14 of Appendix B. The values are applied to the mass influx to derive at a number of events by type. The result distribution considering percent-by-type is provided in Table D-2.

D3.2.4.3 Density and Initial Radii of Meteoroids

For the meteorite impact calculations, the densities used for meteoroids are 8 g/cm^3 for metallic materials, 3.7 g/cm^3 for stony materials, and 1.1 g/cm^3 for carbonaceous/cometary materials. The bases for these values are discussed, and the data justified for use, in Section B5.5.3.2 and Table B-15 of Appendix B. The use of these values is consistent with the use of the meteorite influx and percent-by-type information from Ceplecha (1992 [DIRS 135242]) and Ceplecha (1994 [DIRS 135243]), respectively.

The total range in bulk densities can vary from 8 g/cm^3 to less than 1 g/cm^3 for the metallic and cometary materials respectively (Chapman and Morrison 1994 [DIRS 135245], p. 34). The basis for these density values used in the analysis is discussed in Section B5.5.3.2 and Table B-15 of Appendix B. For the meteorite impact calculations, the densities used for meteoroids are 8 g/cm^3 for metallic materials, 3.7 g/cm^3 for stony materials, and 1.1 g/cm^3 for soft stone/carbonaceous/ cometary materials.

By using the flux values from Ceplecha (1992 [DIRS 135242]), described above and presented in Table D-2, and assuming spherical meteoroids with the density values listed above, the corresponding radius by meteoroid composition can be calculated. As used to determine the radius listed in Table D-3, the mass (m) of a sphere is:

$$m = (4/3\ \pi\ R^3)(\rho) \qquad \text{(Eq. D-5)}$$

where:

m = mass (kg)
ρ = density (kg/m^3), which is 10^3 times g/cm^3
R = radius (m)

and correspondingly:

$$R = [(m\ /\ (4/3\ \pi\ \rho)]^{1/3} \qquad \text{(Eq. D-5a)}$$

Table D-2. Annualized Mass Influx and Percent by Type Allocation

Log *m* (kg)	Mass (kg)	Log N_{total}, Annualized Number of Events *(N)*, whole earth	N_{total} Annualized Number of Events per km^2	Percent Iron	N_{iron} Annualized Number of Iron Events per km^2	Percent Hard Stone	N_{stone} Annualized Number of Hard Stone Events per km^2	Percent Soft Stones and Comets	N_{comet}, Annualized Number of Soft Stone and Comet Events per km^2
-1	1.0E-01	5.5	6.2E-04	0.05	3.1E-05	0.16	9.9E-05	0.79	4.9E-04
0	1.0E+00	5	2.0E-04	0.05	9.8E-06	0.16	3.1E-05	0.79	1.5E-04
1	1.0E+01	4.2	3.1E-05	0.05	1.6E-06	0.18	5.6E-06	0.77	2.4E-05
2	1.0E+02	4	2.0E-05	0.05	9.8E-07	0.14	2.7E-06	0.81	1.6E-05
3	1.0E+03	3.2	3.1E-06	0.05	1.6E-07	0.10	3.1E-07	0.85	2.6E-06
4	1.0E+04	2.8	1.2E-06	0.05	6.2E-08	0.08	9.9E-08	0.87	1.1E-06
5	1.0E+05	2	2.0E-07	0.05	9.8E-09	0.06	1.2E-08	0.89	1.7E-07
6	1.0E+06	1	2.0E-08	0.05	9.8E-10	0.04	7.8E-10	0.91	1.8E-08
7	1.0E+07	-1	2.0E-10	0.05	9.8E-12	0.02	3.9E-12	0.93	1.8E-10
8	1.0E+08	-2	2.0E-11	0.05	9.8E-13	0.47	9.2E-12	0.48	9.4E-12
9	1.0E+09	-3	2.0E-12	0.05	9.8E-14	0.47	9.2E-13	0.48	9.4E-13
10	1.0E+10	-4	2.0E-13	0.05	9.8E-15	0.47	9.2E-14	0.48	9.4E-14
11	1.0E+11	-5	2.0E-14	0.05	9.8E-16	0.47	9.2E-15	0.48	9.4E-15
12	1.0E+12	-5.5	6.2E-15	0.05	3.1E-16	0.47	2.9E-15	0.48	3.0E-15
13	1.0E+13	-6	2.0E-15	0.05	9.8E-17	0.47	9.2E-16	0.48	9.4E-16
14	1.0E+14	-7	2.0E-16	0.05	9.8E-18	0.47	9.2E-17	0.48	9.4E-17
15	1.0E+15	-7.5	6.2E-17	0.05	3.1E-18	0.47	2.9E-17	0.48	3.0E-17

NOTES: Based on Ceplecha (1992 [DIRS 135242] and 1994 [DIRS 135243]).

Mass and associated number of events based on the direct input from Ceplecha 1992 (DIRS 135242) as discussed in Section B5.5.3.1 and Table B-10 of Appendix B of this analysis report. Percent by type based on direct inputs given in Tables B-13 and B-14 of Appendix B of this analysis report.

Table D-3 is primarily interested in accounting for differences in size and type, due to later use in the analysis for determining resulting crater diameters, so differing densities are used. By using the flux values from Ceplecha (1992 [DIRS 135242]), described above and presented in Table D-2, and assuming spherical meteoroids with the density values listed above, the corresponding radius by meteoroid composition is calculated.

Table D-3. Annualized Number of Events by Meteor Type and Radius

Iron Meteors					
Annualized Number of Events N_{iron} per km^2	**Mass *m* (kg)**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3**	**Initial Meteor Radius (m)**
3.1E-05	1.00E-01	8000	1.3E-05	3.0E-06	1.4E-02
9.8E-06	1.00E+00	8000	1.3E-04	3.0E-05	3.1E-02
1.6E-06	1.00E+01	8000	1.3E-03	3.0E-04	6.7E-02
9.8E-07	1.00E+02	8000	1.3E-02	3.0E-03	1.4E-01
1.6E-07	1.00E+03	8000	1.3E-01	3.0E-02	3.1E-01
6.2E-08	1.00E+04	8000	1.3E+00	3.0E-01	6.7E-01
9.8E-09	1.00E+05	8000	1.3E+01	3.0E+00	1.4E+00
9.8E-10	1.00E+06	8000	1.3E+02	3.0E+01	3.1E+00
9.8E-12	1.00E+07	8000	1.3E+03	3.0E+02	6.7E+00
9.8E-13	1.00E+08	8000	1.3E+04	3.0E+03	1.4E+01
9.8E-14	1.00E+09	8000	1.3E+05	3.0E+04	3.1E+01
9.8E-15	1.00E+10	8000	1.3E+06	3.0E+05	6.7E+01
9.8E-16	1.00E+11	8000	1.3E+07	3.0E+06	1.4E+02
3.1E-16	1.00E+12	8000	1.3E+08	3.0E+07	3.1E+02
9.8E-17	1.00E+13	8000	1.3E+09	3.0E+08	6.7E+02
9.8E-18	1.00E+14	8000	1.3E+10	3.0E+09	1.4E+03
3.1E-18	1.00E+15	8000	1.3E+11	3.0E+10	3.1E+03
Hard Stone Meteors					
Annualized Number of Events N_{stone} per km^2	**Mass *m* (kg)**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3**	**Initial Meteor Radius (m)**
9.9E-05	1.00E-01	3700	2.7E-05	6.5E-06	1.9E-02
3.1E-05	1.00E+00	3700	2.7E-04	6.5E-05	4.0E-02
5.6E-06	1.00E+01	3700	2.7E-03	6.5E-04	8.6E-02
2.7E-06	1.00E+02	3700	2.7E-02	6.5E-03	1.9E-01
3.1E-07	1.00E+03	3700	2.7E-01	6.5E-02	4.0E-01
9.9E-08	1.00E+04	3700	2.7E+00	6.5E-01	8.6E-01
1.2E-08	1.00E+05	3700	2.7E+01	6.5E+00	1.9E+00
7.8E-10	1.00E+06	3700	2.7E+02	6.5E+01	4.0E+00
3.9E-12	1.00E+07	3700	2.7E+03	6.5E+02	8.6E+00
9.2E-12	1.00E+08	3700	2.7E+04	6.5E+03	1.9E+01
9.2E-13	1.00E+09	3700	2.7E+05	6.5E+04	4.0E+01
9.2E-14	1.00E+10	3700	2.7E+06	6.5E+05	8.6E+01

Table D-3. Annualized Number of Events by Meteor Type and Radius (Continued)

Annualized Number of Events N_{stone} per km^2	Mass *m* (kg)	Density (kg/m^3)	Volume (m^3)	R^3	Initial Meteor Radius (m)
Hard Stone Meteors (Continued)					
9.2E-15	1.00E+11	3700	2.7E+07	6.5E+06	1.9E+02
2.9E-15	1.00E+12	3700	2.7E+08	6.5E+07	4.0E+02
9.2E-16	1.00E+13	3700	2.7E+09	6.5E+08	8.6E+02
9.2E-17	1.00E+14	3700	2.7E+10	6.5E+09	1.9E+03
2.9E-17	1.00E+15	3700	2.7E+11	6.5E+10	4.0E+03
Soft Stone Meteors					
Annualized Number of Events N_{comet} per km^2	**Mass *m* (kg)**	**Density (kg/m^3)**	**Volume (m^3)**	**R^3**	**Initial Meteor Radius (m)**
4.9E-04	1.00E-01	1100	9.1E-05	2.2E-05	2.8E-02
1.5E-04	1.00E+00	1100	9.1E-04	2.2E-04	6.0E-02
2.4E-05	1.00E+01	1100	9.1E-03	2.2E-03	1.3E-01
1.6E-05	1.00E+02	1100	9.1E-02	2.2E-02	2.8E-01
2.6E-06	1.00E+03	1100	9.1E-01	2.2E-01	6.0E-01
1.1E-06	1.00E+04	1100	9.1E+00	2.2E+00	1.3E+00
1.7E-07	1.00E+05	1100	9.1E+01	2.2E+01	2.8E+00
1.8E-08	1.00E+06	1100	9.1E+02	2.2E+02	6.0E+00
1.8E-10	1.00E+07	1100	9.1E+03	2.2E+03	1.3E+01
9.4E-12	1.00E+08	1100	9.1E+04	2.2E+04	2.8E+01
9.4E-13	1.00E+09	1100	9.1E+05	2.2E+05	6.0E+01
9.4E-14	1.00E+10	1100	9.1E+06	2.2E+06	1.3E+02
9.4E-15	1.00E+11	1100	9.1E+07	2.2E+07	2.8E+02
3.0E-15	1.00E+12	1100	9.1E+08	2.2E+08	6.0E+02
9.4E-16	1.00E+13	1100	9.1E+09	2.2E+09	1.3E+03
9.4E-17	1.00E+14	1100	9.1E+10	2.2E+10	2.8E+03
3.0E-17	1.00E+15	1100	9.1E+11	2.2E+11	6.0E+03

NOTES: Number of events and mass taken from Table D-2 of this appendix.

Densities taken from direct input in Table B-15 of Appendix B of this analysis report and converted from g/cm^3 to kg/m^3.

D3.2.4.4 Atmospheric Shielding Effects

Upon entering the earth's atmosphere, a meteor is subject to multiple destructive processes including ablation and fragmentation caused by heating and differential stresses. These processes tend to dissipate energy into the atmosphere. The magnitude of the atmospheric dissipation of energy is a function of the radius and composition of the body, the initial entry velocity, and the angle of the entry. Hills and Goda (1998 [DIRS 135291], p. 228) provide a series of figures that show the fraction of energy dissipated into the atmosphere for various radii of meteors. The dissipation of energy is such a significant effect that, for a certain range of radii and initial velocities, the energy dissipation is total and no surface impact occurs.

The relationship used in this analysis between initial meteoroid diameter and crater diameter is extracted from Hills and Goda (1993 [DIRS 135281], Figures 16 and 17). These figures represent the results of modeling that is documented in the peer-reviewed paper, and include atmospheric effects such as fragmentation of the meteors, changing velocity of dispersed fragments, radius of the debris cloud, and energy dissipation in the atmosphere through velocity reduction and ablation. These data are justified for use in Section B5.5.3.4 of Appendix B.

The range of values bracketing this atmospheric shielding window varies depending on the composition of the meteor. Hills and Goda (1993 [DIRS 135281], p. 1142) indicate that the threshold for impact to the surface corresponds to a critical radius of 100 m for a stony asteroid, and 500 m for a comet. For iron meteoroids with initial velocities of 20 km/s, the critical radius is 20 m to 30 m; however, for initial velocities of 11.2 - 15 km/s the critical radius is lowered to about 2 m. Hills and Goda (1993 [DIRS 135281], p. 1140) indicate that meteors with initial radii of 1 to 5 m can form craters with radii of approximately 50 m to 100 m, if the initial velocity is below 15 km/s.

This analysis considers cratering rates for assumed initial velocities of 15 and 20 km/s for all meteors regardless of composition or size. These values are at the lower end of the range of velocities specified by various authors. Given that lower initial values generally yield larger impact craters (Hills and Goda 1993 [DIRS 135281], Figure 17), the assumption of velocities of 15 and 20 will tend to slightly overestimate the probability of craters of a given size. Available velocity information is discussed in Table 5-1 of the main body of the report. However, as discussed for Assumption 5.4 of the main body of the document, velocities less than 15 km/sec would result in larger crater diameters. There is no indication in the literature of the frequency of occurrence of these very low velocity events, so lower velocities are not further considered because they would not be consistent with available corroborating information.

Also, as discussed for Assumption 5.4, this analysis considers all objects to enter the atmosphere at zenith angle zero, and could potentially yield surface impacts. This is a conservative selection, since objects entering at nonzero zenith angles have more kinetic energy absorbed (Hills and Goda 1998 [DIRS 135291]) as discussed in Assumption 5.4 of the main body of the document. There are no data available relating flux and angle of entry. Furthermore, it is assumed per Assumption 5.4 that the zone of fracturing is cylindrical with depth, rather than parabolic. That is, the extent of the zone of fracturing is at the same depth at the edges of the crater as it is at the center.

The modeling work by Hills and Goda (1993 [DIRS 135281], Figure 17) relates initial meteor radius and initial velocity to the radius of the impact crater produced by the largest fragment (or the residual meteorite). Table B-18 of Appendix B of this analysis report provides the justification for using the relationship between meteor composition, initial meteor radius, initial velocity, and resulting crater radius. It was derived from the curves in Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) by selecting the velocity curve and initial meteor radius, and reading the corresponding point for the resulting crater radius. Those data were combined with the data presented in Table D-3, to get a distribution for number of events by mass and type, which is shown in Table D-4, and plotted. Combined plots of these data for 15 km/s and 20 km/s are provided as Figures D-2a and D-2b. For events that would result in no crater, a minimum value of 0.1 m was assigned to aid in plotting and calculation.

Table D-4. Annualized Number of Events by Type and Crater Radius

Number of Events per km^2	Mass *m* (kg)	Initial Meteor Radius (m)	Crater Radius (m) for 15 km/s	Crater Radius (m) for 20 km/s
Iron Meteor				
3.1E-05	1.00E-01	1.4 E-02	0.10	0.10
9.8E-06	1.00E+00	3.1E-02	0.10	0.10
1.6E-06	1.00E+01	6.7E-02	0.10	0.10
9.8E-07	1.00E+02	1.4E-01	0.60	0.20
1.6E-07	1.00E+03	3.1E-01	4.0	3.0
6.2E-08	1.00E+04	6.7E-01	14	10
9.8E-09	1.00E+05	1.4E+00	40	0.10
9.8E-10	1.00E+06	3.1E+00	5.0	0.10
9.8E-12	1.00E+07	6.7E+00	3.2	0.10
9.8E-13	1.00E+08	1.4E+01	32	0.70
9.8E-14	1.00E+09	3.1E+01	200	60
9.8E-15	1.00E+10	6.7E+01	1,000	400
9.8E-16	1.00E+11	1.4E+02	4,500	3,000
3.1E-16	1.00E+12	3.1E+02	11,000	9,000
9.8E-17	1.00E+13	6.7E+02	27,000	27,000
9.8E-18	1.00E+14	1.4E+03	70,000	90,000
3.1E-18	1.00E+15	3.1E+03	170,000	200,000
Hard Stone Meteors				
9.9E-05	1.00E-01	1.9E-02	0.10	0.10
3.1E-05	1.00E+00	4.0E-02	0.10	0.10
5.6E-06	1.00E+01	8.6E-02	0.10	0.10
2.7E-06	1.00E+02	1.9E-01	0.17	0.10
3.1E-07	1.00E+03	4.0E-01	0.75	0.32
9.9E-08	1.00E+04	8.6E-01	7.0	3.0
1.2E-08	1.00E+05	1.9E+00	0.10	0.10
7.8E-10	1.00E+06	4.0E+00	0.10	0.10
3.9E-12	1.00E+07	8.6E+00	0.10	0.10
9.2E-12	1.00E+08	1.9E+01	0.10	0.10
9.2E-13	1.00E+09	4.0E+01	1.0	0.10
9.2E-14	1.00E+10	8.6E+01	100	40
9.2E-15	1.00E+11	1.9E+02	800	700
2.9E-15	1.00E+12	4.0E+02	5,000	5,000
9.2E-16	1.00E+13	8.6E+02	30,000	40,000
9.2E-17	1.00E+14	1.9E+03	70,000	90,000
2.9E-17	1.00E+15	4.0E+03	170,000	200,000

Table D-4. Annualized Number of Events by Type and Crater Radius (Continued)

Number of Events per km^2	Mass *m* (kg)	Initial Meteor Radius (m)	Crater Radius (m) for 15 km/s	Crater Radius (m) for 20 km/s
Soft Stone Meteors				
4.9E-04	1.00E-01	2.8E-02	0.10	0.10
1.5E-04	1.00E+00	6.0E-02	0.10	0.10
2.4E-05	1.00E+01	1.3E-01	0.10	0.10
1.6E-05	1.00E+02	2.8E-01	0.20	0.10
2.6E-06	1.00E+03	6.0E-01	0.10	0.10
1.1E-06	1.00E+04	1.3E+00	0.10	0.10
1.7E-07	1.00E+05	2.8E+00	0.10	0.10
1.8E-08	1.00E+06	6.0E+00	0.10	0.10
1.8E-10	1.00E+07	1.3E+01	0.10	0.10
9.4E-12	1.00E+08	2.8E+01	0.10	0.10
9.4E-13	1.00E+09	6.0E+01	3.0	0.20
9.4E-14	1.00E+10	1.3E+02	280	280
9.4E-15	1.00E+11	2.8E+02	1,000	1,000
3.0E-15	1.00E+12	6.0E+02	20,000	28,000
9.4E-16	1.00E+13	1.3E+03	43,000	70,000
9.4E-17	1.00E+14	2.8E+03	100,000	130,000
3.0E-17	1.00E+15	6.0E+03	210,000	300,000

NOTES: After Hills and Goda (1993 [DIRS 135281], Figures 16 and 17).

Number of events and mass taken from Table D-2 of this appendix.

Initial meteor radius taken from Table D-3.

Crater radius derived directly from Hills and Goda (1993 [DIRS 135281], Figures 16 and 17); the source for the meteor radius-to-crater diameter relationship (Table B-18 of Appendix B) was justified for use as direct input based on Table B-19 of Appendix B of this analysis report.

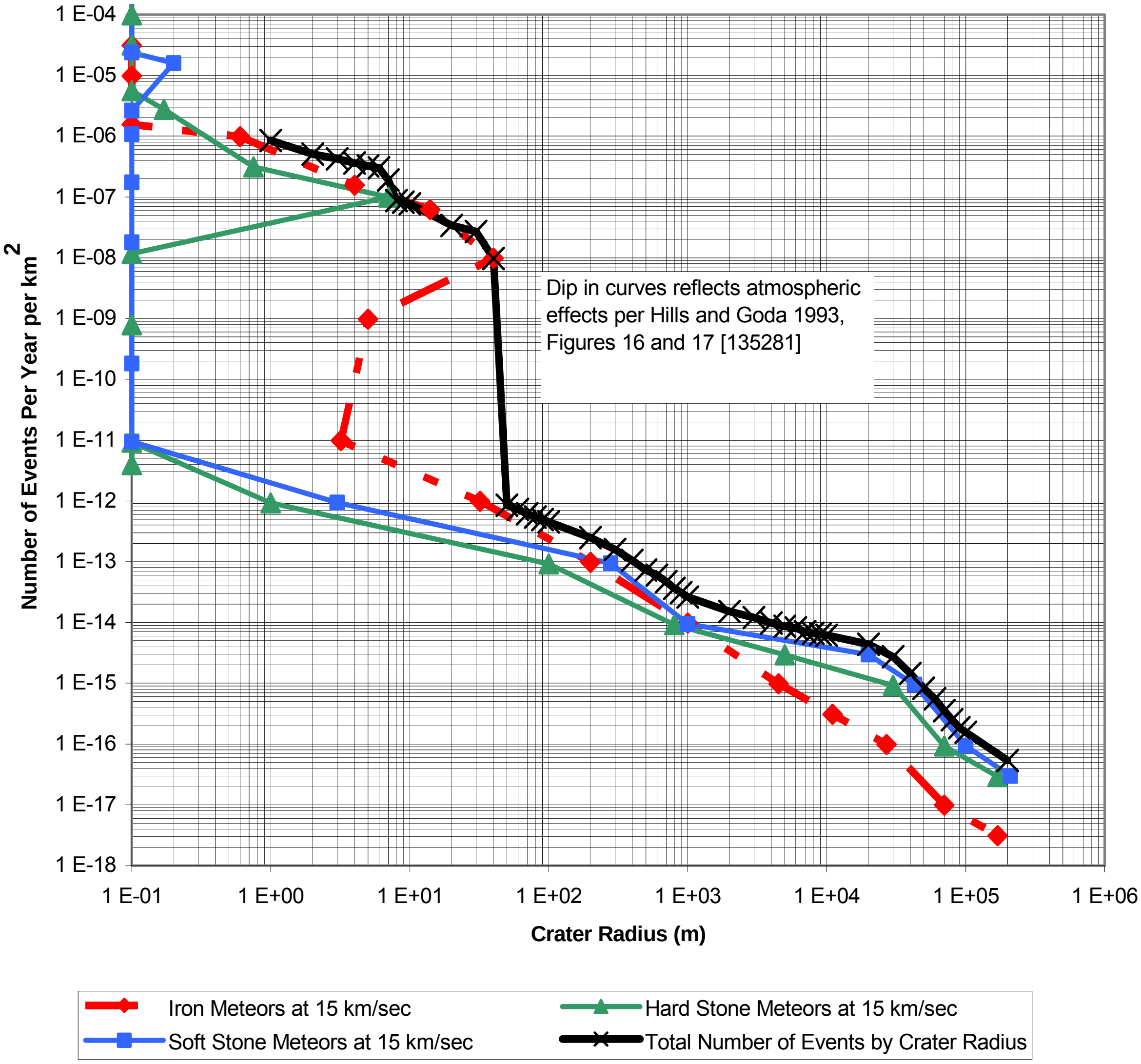


Figure D-2a. Total Number of Events by Type and Crater Radius (15 km/s)

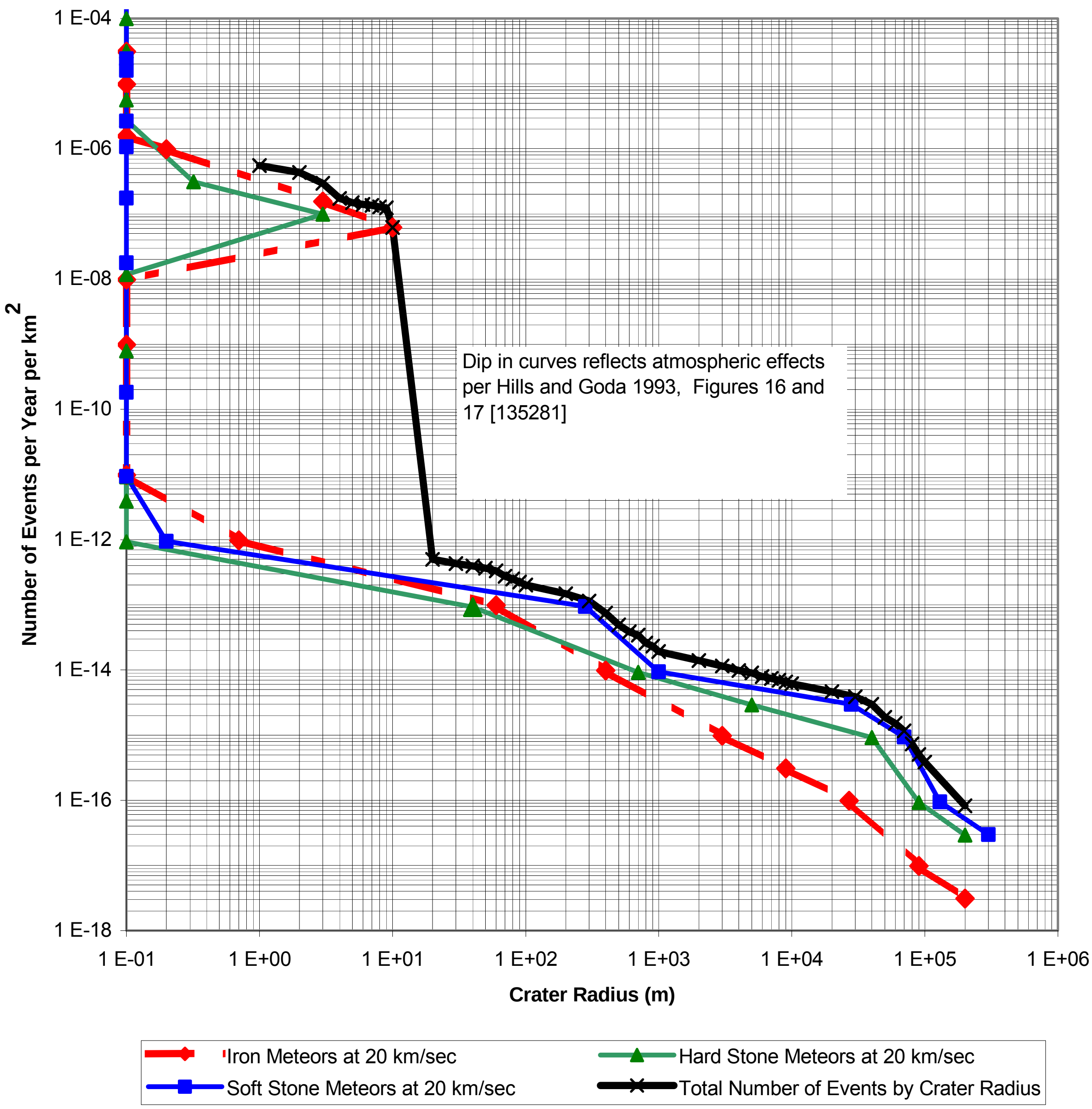


Figure D-2b. Total Number of Events by Type and Crater Radius (20 km/s)

The difficulty with relating the impact events by mass and type (Table D-4) to a singular probability for a given crater diameter is that for a given initial velocity, meteors of equal initial radius but differing compositions result in different crater diameters. In addition, meteors with different initial radii but the same composition can result in equal crater diameters. A method was needed to determine the number of impact events resulting in crater diameter "D" by composition and to sum the number of possible events resulting in crater diameter "D" regardless of meteor composition or radius of the initial meteor. A graphical method was chosen to sum the number of cratering events of diameter "D" or larger.

Once the curves for each of the three types of meteors were plotted, the cumulative number of cratering events was read for each composition for a range of crater radius from 0.1 m to 200 km. The total number of events for each crater radius size was manually summed (Table D-5). The total number of events by crater radius is shown on the Figures D-2a and D-2b.

D3.2.4.5 Resulting Cratering Distribution

The cratering distribution curves for 15 km/s and 20 km/s from Figures D-2a and D-2b based on the modeling results from Hills and Goda (1993 [DIRS 135281], Figures 16 and 17) are shown on Figure D-3. Figure D-3 allows comparison to the distribution curves derived from Grieve (1987 [DIRS 135254]); Wuschke et al. (1995 [DIRS 129326]); and for corroboration with Neukum and Ivanov (1994 [DIRS 121510]); all from Figure D-1. The cumulative curves from Figure D-2a and D-2b have been plotted as crater diameter (km), rather than crater radius (m), to allow comparison to the earlier figure. The translation from meteor radius to crater diameter, along with the total number of events for each crater diameter, are shown in Table D-5. There is good agreement in the curves for crater diameters greater than 10 km, which is the stated limit for Grieve distribution, and for the portion of the curves less than 0.02 km for V=15 km/sec, and for the portion of the curve less than 0.1 km for V=15 k/sec. However, the range of crater diameter of primary interest is roughly from 0.08 km to 0.6 km (79 m to 625 m) based both on the probability threshold and potential for effects on the repository. The distributions show the greatest divergence in this range.

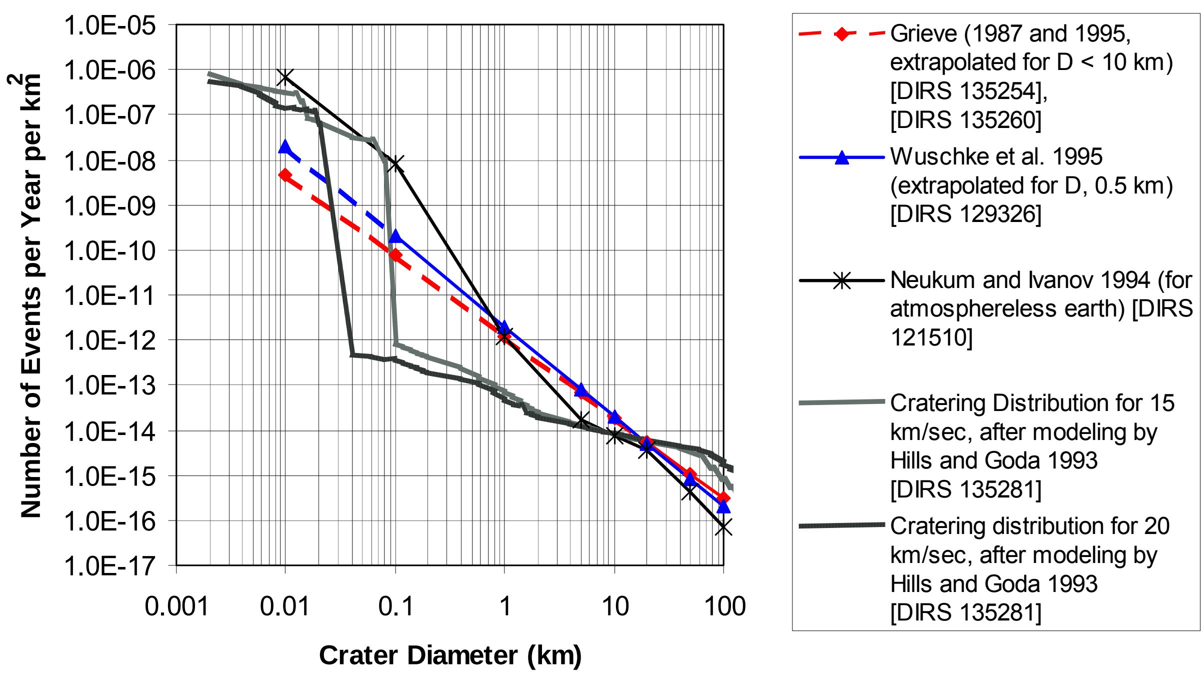
Table D-5. Annualized Total Number of Events by Crater Radius and Diameter

Crater Radius (m)	Crater Diameter *D* (km)	Annualized Frequency (F) for V = 15 km/s	Annualized Frequency (F) for V = 20 km/s
1	0.002	8.5E-07	5.6E-07
2	0.004	5.1E-07	4.3E-07
3	0.006	4.3E-07	2.9E-07
4	0.008	3.6E-07	1.7E-07
5	0.010	3.2E-07	1.5E-07
6	0.012	3.0E-07	1.4E-07
7	0.014	1.9E-07	1.4E-07
8	0.016	8.7E-08	1.3E-07
9	0.018	8.2E-08	1.2E-07
10	0.020	7.7E-08	6.2E-08
20	0.040	3.4E-08	5.0E-13
30	0.060	2.7E-08	4.3E-13
40	0.080	9.8E-09	3.9E-13
50	0.10	8.5E-13	3.7E-13
60	0.12	7.3E-13	3.3E-13
70	0.14	6.1E-13	2.8E-13
80	0.16	5.4E-13	2.5E-13
90	0.18	4.9E-13	2.2E-13
100	0.20	4.5E-13	2.0E-13
200	0.40	2.5E-13	1.5E-13
300	0.60	1.6E-13	1.1E-13
400	0.80	1.1E-13	7.5E-14
500	1.0	7.3E-14	4.9E-14
600	1.2	6.0E-14	3.9E-14
700	1.4	4.7E-14	3.4E-14
800	1.6	3.6E-14	2.6E-14
900	1.8	3.1E-14	2.3E-14
1,000	2.0	2.6E-14	1.9E-14
2,000	4.0	1.5E-14	1.4E-14
3,000	6.0	1.2E-14	1.1E-14
4,000	8.0	9.8E-15	9.8E-15
5,000	10	8.7E-15	9.0E-15
6,000	12	8.1E-15	7.9E-15
7,000	14	7.0E-15	7.5E-15
8,000	16	6.6E-15	6.9E-15
9,000	18	6.4E-15	6.5E-15
10,000	20	6.1E-15	6.1E-15
20,000	40	4.4E-15	4.6E-15
30,000	60	2.7E-15	3.9E-15
40,000	80	1.4E-15	3.0E-15

Table D-5. Annualized Total Number of Events by Crater Radius and Diameter (Continued)

Crater Radius (m)	Crater Diameter *D* (km)	Annualized Frequency (F) for V = 15 km/s	Annualized Frequency (F) for V = 20 km/s
50,000	100	8.3E-16	1.9E-15
60,000	120	5.5E-16	1.5E-15
70,000	140	3.5E-16	1.2E-15
80,000	160	2.5E-16	7.3E-16
90,000	180	1.9E-16	5.0E-16
100,000	200	1.6E-16	3.9E-16
200,000	400	5.3E-17	8.2E-17

NOTE: These are the supporting values used to plot Figure D-3. The two right hand columns represent the total number of cratering events per year per km^2 for initial velocities of 15 km/s and 20 km/s respectively and were derived by summing the number of events from each meteor type for a given crater radius.



NOTE: This figure compares the results of the mass flux distributions given in Table D-5 to plots based on lunar cratering data (for an atmosphereless earth) and observed earth cratering data as previously provided in Figure D-1.

Figure D-3. Comparison of Cratering Distribution Based on Meteoroid Flux to Cratering Distributions of Others

D3.3 PROBABILITY OF A CRATER DIAMETER OF INTEREST OCCURRING WITHIN THE REPOSITORY FOOTPRINT

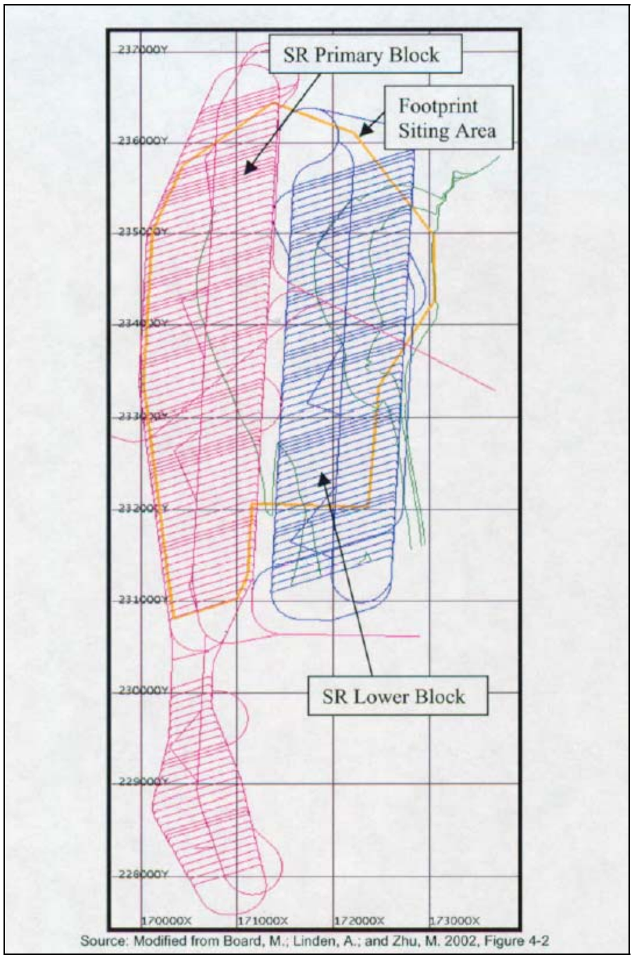
Figure D-3 represents the range of possible frequencies of impacts resulting in a given or larger crater diameter per km^2. All frequency curves fall below the Neukum and Ivanov curve. This is to be expected since the curve derived from Neukum and Ivanov (1994 [DIRS 121510], Table IV) is based on the lunar cratering rate and neglects any atmospheric shielding effects. The relationship of the Neukum and Ivanov curve to the other curves show that the Neukum and Ivanov curve is an upper bound within the range of interest. As discussed below, the bounding nature is used to divide the mass flux curves and to define the related coefficients and integration limits for those curves. The Neukum and Ivanov curve is not further used in the probability calculations, since it would unrealistically overestimate the frequency of occurrence.

D3.3.1 Footprint

To apply the distributions described above to the TSPA-LA repository, it is necessary to define the target area and the depths of interest, adjust the target area for "near misses," and integrate the distributions over the range of possible crater diameters.

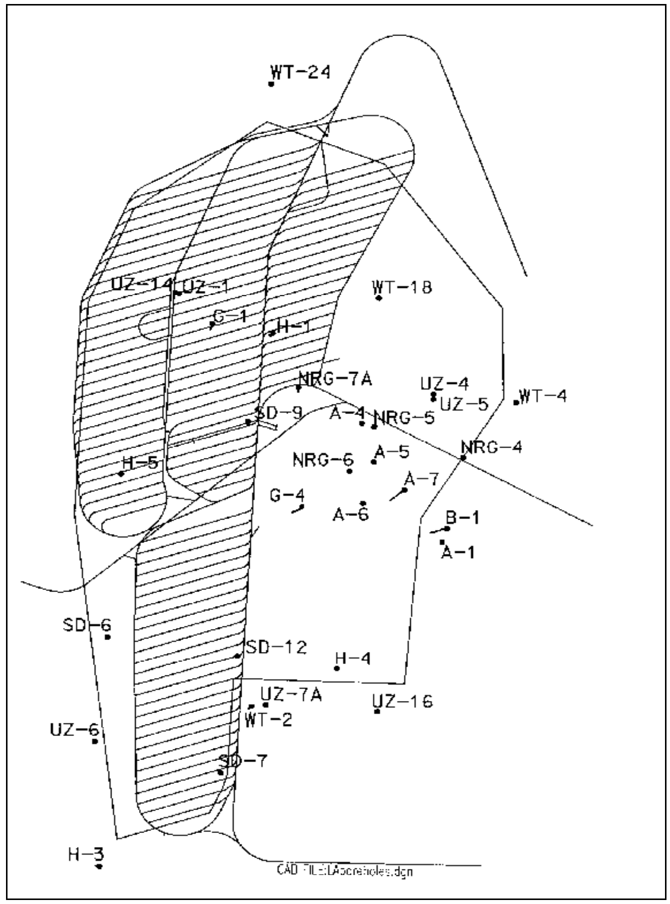
D3.3.2 TSPA-LA Repository Footprint and Other Target Areas

Potential target areas to be used for FEP screening, include the TSPA-LA emplacement area footprint and the outcrop of the Paintbrush geologic unit. For corroboration and sensitivity analysis the TSPA-SR footprint and the TSPA-LA siting area are also of potential interest. These various repository and siting area footprints are given on Figure D-4a. Figure D-4b show the outlines of the TSPA-LA siting area, the drift layout for the TSPA-LA, and nearby boring locations. Corroborative probability analyses are performed for the TSPA-SR footprint and for the TSPA-LA siting area.



Source: 800-P0C-MGR0-00100-00E (DIRS 165572), Figure 1.

Figure D-4a. TSPA-SR Repository Footprint and TSPA-LA Siting Area



Source: 800-P0C-MGR0-00100-00E (DIRS 165572), Figure II-4.

Figure D-4b. TSPA-LA Siting Area

D3.3.2.1 TSPA-LA Repository Footprint

The analysis for TSPA-LA uses the footprint for the emplacement area for direct input. As represented in Drawing 800-IED-WIS0-00101-000-00A from *D&E / PA/C IED Subsurface Facilities* (BSC 2004 [DIRS 164519]), the maximum extent of the drifts is shown in Table D-6.

Table D-6. Drift End Coordinates

Drift Number and Basis	Drift End Coordinate (meters)
(3-1W) northernmost drift end	N236237
(2-27) southernmost drift end	N230944
(3-2E) easternmost drift end	E172231
(4-20) westernmost drift end	E170085

This results in the following rough dimensions and total surface area.

North/South Length (L)	(236237 m-230944 m) = 5.3 km
East/West Width (W)	(172231m-170085m) = 2.2 km
Approximate Area (A)	5.3 km x 2.2 km = 11.6 km^2

The measured distances are rounded upward to the nearest tenth of a kilometer, and the rounding is inconsequential because a rectangular repository area is used as a calculation simplification. Also, a 0.1 km was added to the repository length to add distance to account for the construction ramp location. Using the adjusted value of 5.4, the rectangular area is approximately 11.9 km^2. Use of a rectangular area and adjustments of lengths as simplifications will result in an conservative overestimation of the repository emplacement area by a factor of about 2. In actuality, the area of the repository drifts, as seen in Figure D-2b is irregularly shaped. For the emplacement area shown on Figure D-4b and as given in Drawing 800-IED-WIS0-00103-000-00A from *D&E / PA/C IED Subsurface Facilities* (BSC 2004 [DIRS 168370]), the total of the emplacement area is given as 6,004,074 m^2, or an equivalent 6.0 km^2.

D3.3.2.2 Paintbrush Outcrop

This target area is pertinent for TSPA-LA because the Paintbrush is a key geologic unit. For TSPA-SR, the area of the repository lying below the Paintbrush outcrop area along the western edge of the repository footprint was determined to be 1.1 km by 0.1 km (BSC 2004 [DIRS 170029], Table 6-2, Figures 6-8 and 6-14, and Section 6.5.1.3). This portion of the analysis was retained herein for completeness and traceability, although the change in repository footprint from TSPA-SR to TSPA-LA shifted the repository eastward, away and from beneath the outcrop. This change in footprints can be seen by comparing Figures D-4a and D-4b.

D3.3.2.3 TSPA-LA–Siting Area

A corroborative analysis is performed using estimated dimensions for the siting area as taken from Figure D-4a. Consideration of the entire siting area increases the general area and aids in determining the sensitivity of the analysis to changes in repository footprint design. Knowledge of such sensitivity may allow application of this analysis without revision in the event the repository footprint is changed. The reference drawing shows the extent of the entire siting area. The estimated dimensions are:

North/South Length (L)	(236500 m-230500 m) = 6.0 km
East/West Width (W)	(173000 m-170000 m) = 3.0 km
Approximate Area (A)	6.0 km x 3.0 km = 18.0 km^2

D3.3.2.4 TSPA-SR Repository Footprint

The corroborative analysis for the TSPA-SR repository footprint has been retained in this analysis report because the TSPA-SR design, less the contingency area, is roughly equivalent to the longest dimension of the repository footprint to be used as the basis of the TSPA-LA. This provides a basis for examining the sensitivity of the analysis to changes in relative dimensions. The area and depth of the TSPA-SR repository was based on the design provided in CRWMS M&O (2000 [DIRS 150088]). For TSPA-SR meteor evaluation, a conservative bounding assumption regarding the repository footprint was used and was based on the shallowest depth of the repository and the largest areal footprint. The TSPA-SR meteorite FEP evaluation assumed that the repository dimensions were:

North/South Length (L)	8.6 km
East/West Width (W)	1.3 km
Approximate Area (A)	8.6 km x 1.3 km = 11.2 km^2
Minimum Depth	250 m

This length and width for the drift layouts are shown in Figure D-4a and exclude turn outs for the access drifts. The lower block was not considered in the TSPA-SR evaluation. For this analysis, the length and width values are retained. However, the minimum depth of the emplacement area is assumed to be 200 m to ensure equivalence for comparison to the TSPA-LA design.

D3.3.3 Depths and Crater Diameters of Interest

The depths and crater diameters of interest include the diameter associated with the onset of complex cratering, the depth to the Paintbrush geologic unit, and the depth to the repository.

D3.3.3.1 Simple and Complex Cratering

The amount of meteor kinetic energy acting in combination with the impacted rock properties determines the features, shape, size, and depth of any crater and any related cratering effects such as fracturing. The potential consequences are divided at the first level based on two types of observed cratering. Simple craters consist of an elevated rim and central depression. Complex cratering involves the uplift and significant vertical displacement of the central portion of the crater. Complex cratering can be initiated with crater diameters of 2 km in sedimentary rocks;

however, terrestrial simple craters may also exhibit crater diameters up to 4 km, which is the threshold for simple-to-complex cratering in crystalline rocks based on the direct inputs justified for use in Section B5.5.3.4 of Appendix B (Grieve 1987 [DIRS 135254], p. 249; Grieve et al. 1995 [DIRS 135260], p. 194; Wuschke et al. 1995 [DIRS 129326], p. 3). The threshold for FEP screening based on probability is stated as an annualized equivalence of 10^{-8} events per year for the repository area (Assumption 5.1 of the main body of this document). Based on the cratering rate distributions given in Figure D-3, a 2-km crater diameter occurs at a frequency of approximately 10^{-12} or less per year, which is four orders of magnitude less frequent than the threshold for consideration. Consequently, complex cratering features, which can onset at a crater diameter of 2 km, do not occur with sufficient frequency to be of concern for FEP screening. Because such large diameter craters are very unlikely events, complex cratering is not further considered in the FEP analysis.

D3.3.3.2 Depth of the Paintbrush Unit and Related Crater Diameters

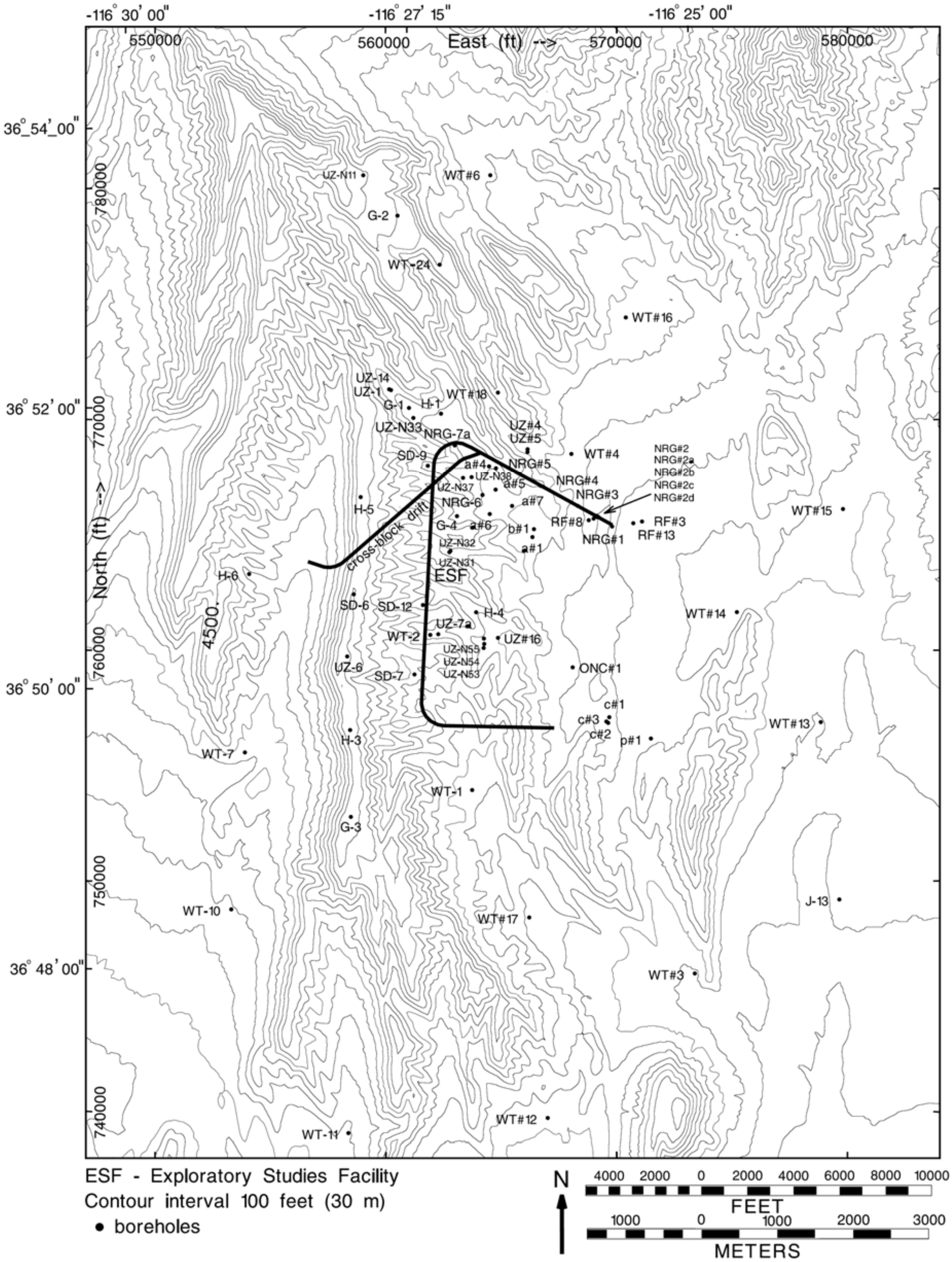
Geologic information relevant to the assessment of the repository includes the thickness and continuity of the PTn unit lying above the repository unit (BSC 2004 [DIRS 169861], Sections 6.1.2 and 6.2.2). The large storage capacity and low fracture frequency of the highly porous PTn unit may effectively dampen transient pulses of infiltration and more evenly distribute the downward flow of water. However, isotopic (chlorine-36) analysis has identified isolated pathways that provide relatively rapid water movement for small amounts of water through the Paintbrush non-welded unit to the top of the underlying Topopah Springs welded unit. Geologic data indicate that the PTn ranges in thickness from greater than 165 m (541 feet) beneath northern Yucca Mountain to about 15 m (49 feet) in the south, with breaks in area coverage along the Solitario Canyon, Iron Ridge, and Dune Wash fault systems. The underground layout incorporates a minimum PTn thickness of 10 m (33 feet). However, the primary information relevant to this analysis is the depth of the PTn below the surface, because the depth to the top of the geologic unit is used to define the maximum crater diameter, or more specifically the associated depth of increased fracturing, that can occur without the potential to significantly change the subsurface hydrogeologic fracture properties. The depth of this unit, then, is of interest.

Figures D-4b and D-5 references the location of various boreholes in relation to the repository footprint and the local coordinates. Starting with the borehole locations shown, the following inputs were used to determine the depth to sub-zones of the Paintbrush non-welded unit. The zones of interest include the Pah Canyon and Topopah Springs subzones of the Paintbrush non-welded tuff. The depths of lithostratigraphic contacts are taken from MO0004QGFMPICK.000 (BSC 2003 [DIRS 152554]) and are given in Table D-7. The data are arranged by increasing depth to the top of the Pah Canyon (Tpp) unit.

Across most of the TSPA-LA repository footprint, the Tpp unit is at depths of 60 m or greater, based on the average and 50th percentile values for the depth to the top of the Tpp unit. At all locations given, with the exception of the locations USW WT-14, USW UZ-N31, UE-25 p #1, and USW UZ-N32 (shaded in Table D-7), the depth of the Tptrv3 unit is greater than 60 m. A range of exhumation depth–to–crater diameter ratios of 0.10 to 0.33 is noted in Appendix B, and a value of 0.32 has been justified for use as direct input in Section B5.5.3.5 of Appendix B. These ratios are based on direct input provided in Wuschke et al. (1995 [DIRS 129326]) and

Grieve (1998 [DIRS 163385]). A value for fracture depth–to–crater diameter of 0.32 is realistic based on Grieve (1998 [DIRS 163385]). Because the intended use is for FEP screening and analysis, the conservative value of increased fracturing depth to 0.76 of the crater diameter, as indicated by Wuschke et al. (1995 [DIRS 129326]), is examined to ensure that the range of uncertainty in relationships is covered. The use of this value based on effects in plutonic rock is somewhat contrary to the observation made by Grieve (1998 [DIRS 163385], p. 113) that depths in sedimentary rocks tend to be shallower than in plutonic rock. However, the use of these values is consistent with use of cratering rate and crater diameter distributions from these same sources. A more complete discussion is provided in Section B5.5.3.5 of Appendix B.

Given a 60-m depth to a key hydrogeologic unit, and given the depth–to–crater diameter ratios just stated, the crater diameters of concern for exhumation for the PTn unit ranges from 188 to 600 m, and the crater diameters of interest with regard to fracturing is about 79 m.



Source: BSC 2004 (DIRS 170029), Figure 6-1.

Figure D-5. Boring Locations

Table D-7. Depth to PTn in the TSPA-LA Repository Area

Statistic/Boring	Pah Canyon Tuff nondivided (Tpp)	Topopah Spring Tuff (Tpt) crystal-rich vitric nonwelded to partially welded zones (Tptrv3)	Tpt, crystal-rich vitric densely welded zone (Tptrv1)	Thickness (m)
	Depth from Surface (m)			
Summary Statistics				
Maximum	281.6	290.8	294.7	83.1
Average	88	109	112	24
50^{th} Percentile	68	92	97	17
Minimum	31.1	32.6	37.8	5.2
By Boring				
USW UZ-14	31.1	81.7	86.1	55.0
USW UZ-1	32.0	82.9	86.6	54.6
USW WT-14	32.6	32.6	37.8	5.2
USW UZ-N31	36.5	51.3	55.2	18.8
UE-25 p #1	38.7	42.7	45.1	6.4
USW UZ-N32	39.6	56.7	60.8	21.2
USW G-1	41.1	80.8	82.3	41.1
USW UZ-N37	45.2	74.6	78.2	33.1
USW SD-9	47.4	77.9	81.8	34.4
USW G-4	51.3	68.3	72.8	21.6
UE-25 NRG #7/7a	52.4	86.7	90.3	37.9
UE-25 UZ #4	53.0	101.5	105.2	52.2
UE-25 NRG #6	53.3	74.6	79.2	25.9
UE-25 a #5	54.9	79.9	84.4	29.6
UE-25 a #6	56.7	70.0	73.7	17.0
UE-25 UZ #5	56.7	105.2	108.1	51.4
UE-25 UZ #16	57.5	66.1	69.9	12.4
USW H-1	58.0	89.9	100.6	42.6
USW UZ-N54	58.3	66.3	70.9	12.6
USW UZ-N53	59.6	67.3	70.1	10.5
UE-25 a #4	60.0	92.0	96.6	36.5
UE-25 b #1	62.3	78.9	83.8	21.5
USW UZ-7a	65.5	74.1	75.8	10.3
UE-25 NRG #5	65.5	97.8	100.6	35.1
USW H-4	65.8	73.8	76.5	10.7
USW WT-17	66.1	73.8	75.6	9.4
UE-25 a #1	66.5	81.3	84.0	17.5
USW UZ-N55	67.5	71.1	74.4	6.8
UE-25 a #7	69.0	89.0	92.8	23.8
USW WT-2	75.3	82.6	85.3	10.1
UE-25 c #3	82.6	87.2	90.8	8.2
USW H-6	84.7	91.5	100.6	15.8
USW SD-12	84.8	95.7	98.9	14.1
UE-25 NRG #2b	87.0	- -	- -	- -

Table D-7. Depth to PTn in the TSPA-LA Repository Area (Continued)

Statistic/Boring	Pah Canyon Tuff nondivided (Tpp)	Topopah Spring Tuff (Tpt) crystal-rich vitric nonwelded to partially welded zones (Tptrv3)	Tpt, crystal-rich vitric densely welded zone (Tptrv1)	Thickness (m)
UE-25 c #2	87.2	93.3	96.0	8.8
USW WT-11	87.5	93.6	96.6	9.1
UE-25 c #1	91.4	97.2	100.3	8.8
USW WT-4	98.8	135.3	139.0	40.2
USW WT-12	103.3	110.3	112.5	9.1
USW SD-7	104.5	117.1	117.7	13.2
USW WT-15	113.4	132.9	134.7	21.3
UE-25 NRG #4	114.3	145.4	147.8	33.5
USW WT-7	119.2	126.5	131.7	12.5
USW GU-3/G-3	119.4	127.3	130.4	11.0
USW H-3	127.1	132.6	135.6	8.5
USW WT-1	135.9	145.4	147.5	11.6
USW UZ-6	137.2	145.8	149.0	11.9
USW WT-13	140.2	149.4	151.8	11.6
USW WT-16	140.8	176.8	181.1	40.2
USW H-5	143.6	165.2	171.3	27.7
USW WT-24	144.5	212.0	212.4	68.0
USW G-2	150.6	230.2	233.7	83.1
USW WT-18	151.5	210.9	213.7	62.2
UE-25 ONC #1	189.3	196.0	199.3	10.1
UE-25 J-13	198.1	207.9	210.6	12.5
USW WT-10	281.6	290.8	294.7	13.1

Source: DTN MO0004QGFMPICK.000 (BSC 2003 [DIRS 152554]).

D3.3.3.3 Depth of the Repository Emplacement Area and Related Crater Diameters

With regard to the depth of the repository emplacement area, the minimum stand-off distances given in Drawing 800-IED-WIS0-00101-000-00A from *D&E / PA/C IED Subsurface Facilities* (BSC 2004 [DIRS 164519]) indicate that the overburden thickness from emplacement area to topographic surface is 215 m. A slightly shallower depth of 200 m will be used in the calculation to provide a small margin of conservatism and to allow for any future eastward extension or additions of drifts within the siting area.

A range of exhumation depth–to–crater diameter–to–ratios of 0.10 to 0.33 is noted in Appendix B, and a value of 0.32 has been justified for use as direct input in Section B5.5.3.5 of Appendix B, as previously discussed. Because the intended use is for FEP screening and analysis, the conservative value of increased fracturing depth to 0.76 of the crater diameter, as indicated by Wuschke et al. (1995 [DIRS 129326]), is examined to ensure that the range of uncertainty in relationships is covered.

Given the above ratios, the crater diameters of interest for impairing repository performance from exhumation to repository depth ranges from 625 m to about 2 km, and craters capable of fracturing to repository depth have diameters in excess of about 263 m.

D3.3.4 Cratering Distributions Adjusted for Target Area

The target area in each case is initially assumed rectangular in shape, with the dimensions described in Section D3.3.1 of this appendix. However, if a meteorite were to impact exterior to the repository boundary or an outcrop area, but within one-half of the crater diameter from the boundary, the repository could still potentially be affected. This affects the boundaries on each side of the repository and the outcrop. Assuming fracturing and exhumation effects are cylindrical below the entire crater, the target area can be expressed as:

$$\text{Area (A)} = (L + 2 \text{ x } D/2)(W + 2 \text{ x } D/2) = (L+D)(W+D) \qquad \text{(Eq. D-6)}$$

Equation D-6 further simplifies to

$$\text{Area (A)} = LW + (L+W)D + D^2 \qquad \text{(Eq. D-6a)}$$

where:

L = length of target area (km)
W = width of target area (km)
D = diameter of crater (km).

Starting with Equation D-1, the overall annual probability of meteorite impacts that could disrupt or fracture the repository is given by the product of the frequency of impact and the target area integrated over the range of possible crater diameters:

$$F = \int f(D) \, A \, dD \qquad \text{(Eq. D-7)}$$

From Equations D-2 and D-6a and with k equaling the power of the distribution for a given meteorite crater distribution:

$$F = \int (-k \, K \, D^{k-1}) \, (LW + (L+W) \, D + D^2) \, dD \qquad \text{(Eq. D-8)}$$

By removing the constants k and K and using the additive properties of integrals and exponents, the resulting integral is in the form of $\int u^n \, du$

$$F = -k \, K \int (LWD^{k-1} + (L+W)D^k + D^{k+1}) \, dD \qquad \text{(Eq. D-8a)}$$

Equation D-8a simplifies to:

$$F = -k\,K \left(\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2} \right) \Bigg|_{D}^{300} \qquad \text{(Eq. D-8b)}$$

where:

F = frequency of impacts per year capable of disrupting the repository
K = the proportionality constant (from regression analysis)
k = power of the distribution (from regression analysis)
L = length of the repository (km)
W = width of the repository (km)
D = diameter of the crater (km).

The lower limit to the integral is assumed to be 0.001 km (1 m), based on the need to capture very small crater diameters to evaluate the potential for impact in the PTn outcrop area. The choice is arbitrary based on the possible scale of interest, and larger or smaller values could have been chosen. The upper limit was set at 300 km, which corresponds to the largest recognized crater on the earth's surface. A smaller limit could have been set, but would have reduced the cumulative frequency slightly. So long as the diameter is chosen such that the chosen crater diameter occurs at an annualized frequency well below the FEP screening threshold of 10^{-8}, it makes only a minor difference in the resulting calculation. However, a 300 km crater diameter is the largest observed feature on earth, so it serves as a defensible upper bound.

Equation D-4 is coupled with Equation D-6a to construct a distribution from the equation given by Wuschke et al. (1995 [DIRS 129326], p. 4), and takes on the form of

$$F(D) = 2.0\times10^{-12}\,(D)^{-2}\,(L + D)\,(W + D) \qquad \text{(Eq. D-9)}$$

D3.3.5 Calculation of Cratering Distribution for the Repository Footprint

Equation D-8b is applied below for the target area for both the Grieve distribution and the distribution based on mass flux. The power of –1.8 and the value for K of $(1.2 \pm 0.6)\times10^{-12}$ shown in Equation D-3, are only applicable to the Grieve distribution and are used accordingly. As seen on Figure D-3, the cratering distribution derived from meteoroid flux (after Hills and Goda) has two primary components, an upper curve (for D < 0.1 km) and a lower curve (for D > 0.1 km), which are connected by an essentially vertical portion of the curve. Tables D-8a through D-8d provide the results of the regression analyses for the meteoroid flux distributions (i.e., for the upper and lower portions of the frequency curves for 15 and 20 km/s, respectively). Figures D-6a through D-6d provide representation of the analysis. Because of the offset in the cumulative-flux-derived frequency curves, the constant, K, was also determined for each portion of the curve for each velocity. Table D-9 provides example spreadsheet calculations for the results shown in Tables D-8a through D-8d.

The slope of the distribution and the constant were applied to Equation D-8b for the upper and lower portion of the curves for the two atmospheric entry velocities (V=15 km/s and 20 km/s). The use of the two portions of the curve is justified because the lower portion of the meteoroid flux curve indicates a differing distribution as shown on Figure D-3. For the upper portion of the curves, the lower limit of the integral was taken to be a lower limit of 1 m, as previously described. The upper limit for the integral for the upper portion of the curves was selected based on the breakpoint in the curves for V=15 km/s and V=20 km/s (i.e., based on crater diameters of 80 m and 20 m, respectively). These breakpoints also correspond to the curves approaching the distribution curve given by Neukum and Ivanov (1994 [DIRS 121510]). The Neukum and Ivanov curve was previously defined as an upper bound on crater diameter distribution based on lunar cratering data adjusted for “atmosphereless” earth. Use of an upper integral limit of 300 km for the upper curves would result in a calculated annualized frequency of about 3×10^{-8} for a crater diameter of 1 km. Figure D-3 clearly indicates that the value based on three different distribution curves should be on the order of 10^{-11} or 10^{-12}, a three to four order of magnitude difference. For the lower portion of the curve, the lower integral limit was taken as the breakpoints (80 m and 20 m) in the curves, and an integral limit of a 300-km crater diameter was used, consistent with its application for the Grieve distribution. To address the break in the curve between the upper and lower limits, the calculation overlaps the upper limit for the upper curve respective to the lower limit in the lower curve. This allows for annual frequency of the breakpoint (80 m and 20 m, respectively) to be calculated. The upper limit of the integration is set at 100 m and 40 m respectively, as shown in Tables D-10a through D-10d. Using the breakpoint as the upper limit would cause the calculated frequency to be “zero”, because Equation D-8b is for the cumulative frequency and describes the annual frequency of the given diameter or larger.

Tables D-10a and D-10b provide the annual probability calculations for cratering above the repository for the TSPA–LA emplacement area, and for the PTn Outcrop area. The results are shown in Figures D-6 and D-8, respectively. For corroborative and sensitivity analysis purposes, Table D-10c evaluates the probability for the TSPA-LA siting area, and for sensitivity analysis purposes, Table D-10d reassesses the TSPA-SR design. Results are shown for the TSPA-LA siting area and the TSPA-SR design in Figures D-9 and D-10, respectively.

For the various repository footprint evaluations (Figures D-7, D-9, and D-10), the figures indicate the equivalent FEP screening probability threshold (i.e., an annualized equivalence of 1×10^{-8}), the crater diameters that are of interest with respect to fracturing of the Paintbrush hydrologic unit and to depth of the repository, and the crater diameters that are of interest with respect to exhumation of those same features. The diameters of interest for fracturing and exhumation overlap, depending on which feature is being considered and which diameter-to-depth factor is assumed. Figure D-8 provides the annual probability for cratering in the outcrop area, which is the same for the TSPA–SR and TSPA–LA designs, and the annualized probability for cratering within or near the outcrop area is shown. Because it is the outcrop area (i.e., exposure at the surface), any impact in the outcrop will result in exhumation and fracturing.

Tables D-11 through D-14 provide example spreadsheet calculations for the results shown in Tables D-10a through D-10d, for the distribution curves.

Table D-8a. Regression Analysis for Crater Diameter *D* for Meteoroid Flux for Upper Portion of Curve (*D* < 0.1 km) and V = 15 km/s

Crater Diameter D_{15} (km)	**Frequency (F)**	**log(*D*)**	**log(F)**	**[log (*D*) - log $(D)_{mean}$]**	**[log(*D*) - log $(D)_{mean}]^2$**	**[log(F) - log $(F)_{mean}$]**	**[log(*D*) - log $(D)_{mean}$] x [log(F) - log $(F)_{mean}$]**
0.002	8.5E-07	-2.70	-6.07	-0.84	0.71	0.79	-0.67
0.004	5.1E-07	-2.40	-6.30	-0.54	0.29	0.57	-0.31
0.006	4.3E-07	-2.22	-6.37	-0.36	0.13	0.49	-0.18
0.008	3.6E-07	-2.10	-6.44	-0.24	0.06	0.42	-0.10
0.01	3.2E-07	-2.00	-6.49	-0.14	0.02	0.37	-0.05
0.012	3.0E-07	-1.92	-6.52	-0.06	0.00	0.34	-0.02
0.014	1.9E-07	-1.85	-6.72	0.00	0.00	0.14	0.00
0.016	8.7E-08	-1.80	-7.06	0.06	0.00	-0.20	-0.01
0.018	8.2E-08	-1.74	-7.09	0.11	0.01	-0.22	-0.03
0.02	7.7E-08	-1.70	-7.11	0.16	0.03	-0.25	-0.04
0.04	3.4E-08	-1.40	-7.47	0.46	0.21	-0.61	-0.28
0.06	2.7E-08	-1.22	-7.57	0.64	0.40	-0.71	-0.45
0.08	9.8E-09	-1.10	-8.01	0.76	0.58	-1.15	-0.87
Mean		-1.86	-6.86				
Sum					2.45		-3.00
Slope		-1.23					

$$\text{Slope} = \frac{\sum [\log(D) - \log(D)\text{mean}] \times [\log(F) - \log(F)\text{mean}]}{\sum [\log(D) - \log(D)\text{mean}]^2}$$

NOTE: Values for *D* and for F are taken from Table D-7 of this appendix.

Slope = k = -1.23: This is less steep than the Grieve slope of –1.8, which is based on observed earth cratering at crater diameters of 10 km and was extrapolated for smaller crater diameters. The slope of the Grieve distribution decreases for smaller crater diameters, but is recognized as likely underestimating the number of small diameter craters.

Constant K = 7.0 E-10.

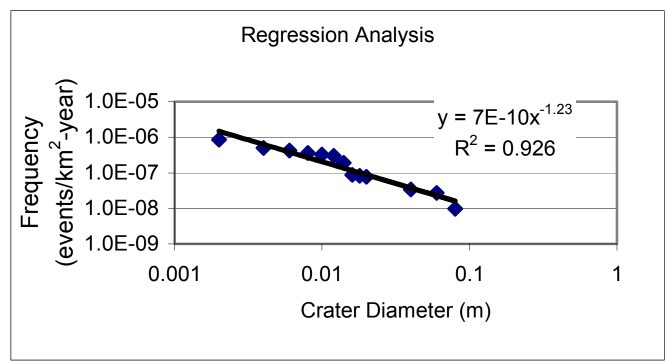


Figure D-6a. Regression Analysis for Upper Curve Portion (V = 15 km/s)

Table D-8b. Regression Analysis for Crater Diameter *D* for Meteoroid Flux for Lower Portion of Curve (*D* > 0.1 km) and V = 15 km/s

V = 15 km/sec: Lower Portion of Curve							
Crater Diameter D_{15} (km)	**Frequency (F)**	**log(*D*)**	**log(F)**	**[log(*D*) - log (*D*) $_{mean}$]**	**[log(*D*) - log (*D*)$_{mean}$]^2**	**[log(F) - log (F)$_{mean}$]**	**[log(*D*) - log (*D*)$_{mean}$] x [log(F) - log (F)$_{mean}$]**
0.1	8.5E-13	-1.00	-12.07	-0.68	0.47	0.73	-0.50
0.12	7.3E-13	-0.92	-12.14	-0.60	0.37	0.66	-0.40
0.14	6.1E-13	-0.85	-12.21	-0.54	0.29	0.58	-0.31
0.16	5.4E-13	-0.80	-12.27	-0.48	0.23	0.53	-0.25
0.18	4.9E-13	-0.74	-12.31	-0.43	0.18	0.49	-0.21
0.2	4.5E-13	-0.70	-12.34	-0.38	0.15	0.45	-0.17
0.4	2.5E-13	-0.40	-12.60	-0.08	0.01	0.19	-0.02
0.6	1.6E-13	-0.22	-12.80	0.09	0.01	-0.01	0.00
0.8	1.1E-13	-0.10	-12.98	0.22	0.05	-0.18	-0.04
1	7.3E-14	0.00	-13.14	0.32	0.10	-0.34	-0.11
1.2	6.0E-14	0.08	-13.22	0.40	0.16	-0.43	-0.17
1.4	4.7E-14	0.15	-13.33	0.46	0.21	-0.53	-0.25
1.6	3.6E-14	0.20	-13.44	0.52	0.27	-0.64	-0.34
1.8	3.1E-14	0.26	-13.51	0.57	0.33	-0.71	-0.41
2	2.6E-14	0.30	-13.58	0.62	0.38	-0.79	-0.48
Mean		-0.32	-12.80				
Sum					3.19		-3.65
Slope		-1.14					

$$\text{Slope} = \frac{\sum [\log(D) - \log(D)\text{mean}] \times [\log(F) - \log(F)\text{mean}]}{\sum [\log(D) - \log(D)\text{mean}]^2}$$

NOTE: Values for *D* and for F are taken from Table D-7 of this appendix.

Slope = k = -1.14: This is less steep than the Grieve slope of –1.8, which is based on observed earth cratering at crater diameters of 10 km and was extrapolated for smaller crater diameters. The slope of the Grieve distribution decreases for smaller crater diameters, but is recognized as likely underestimating the number of small diameter craters.

Constant K = 7.0 E-14.

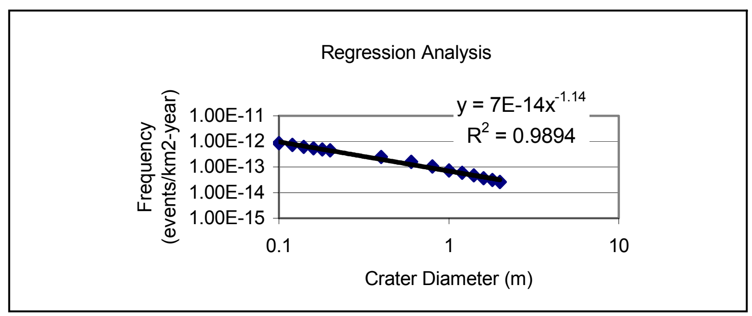


Figure D-6b. Regression Analysis for Lower Curve Portion (V = 15 km/s)

Table D-8c. Regression Analysis for Crater Diameter *D* for Meteoroid Flux for Upper Portion of Curve (*D* < 0.02 km) and V = 20 km/s

Crater Diameter D_{20} (km)	Frequency (F)	log(*D*)	log(F)	$[\log(D) - \log(D)_{mean}]$	$[\log(D) - \log(D)_{mean}]^2$	$[\log(F) - \log(F)_{mean}]$	$[\log(D) - \log(D)_{mean}] \times [\log(F) - \log(F)_{mean}]$
0.002	5.6E-07	-2.70	-6.26	-0.66	0.43	0.49	-0.32
0.004	4.3E-07	-2.40	-6.36	-0.35	0.13	0.38	-0.14
0.006	2.9E-07	-2.22	-6.53	-0.18	0.03	0.22	-0.04
0.008	1.7E-07	-2.10	-6.76	-0.05	0.00	-0.01	0.00
0.01	1.5E-07	-2.00	-6.83	0.04	0.00	-0.08	0.00
0.012	1.4E-07	-1.92	-6.85	0.12	0.01	-0.11	-0.01
0.014	1.4E-07	-1.85	-6.87	0.19	0.04	-0.12	-0.02
0.016	1.3E-07	-1.80	-6.89	0.25	0.06	-0.15	-0.04
0.018	1.2E-07	-1.74	-6.91	0.30	0.09	-0.16	-0.05
0.02	6.2E-08	-1.70	-7.21	0.34	0.12	-0.46	-0.16
Mean		-2.04	-6.75				
Sum					0.91		-0.78
Slope		-0.85					

$$\text{Slope} = \frac{\sum [\log(D) - \log(D)\text{mean}] \times [\log(F) - \log(F)\text{mean}]}{\sum [\log(D) - \log(D)\text{mean}]^2}$$

NOTE: Values for *D* and for F are taken from Table D-7 of this appendix.

Slope = k = -0.85: This is less steep than the Grieve slope of –1.8, which is based on observed earth cratering at crater diameters of 10 km and was extrapolated for smaller crater diameters. The slope of the Grieve distribution decreases for smaller crater diameters, but is recognized as likely underestimating the number of small diameter craters.

Constant K = 3.0 E-9.

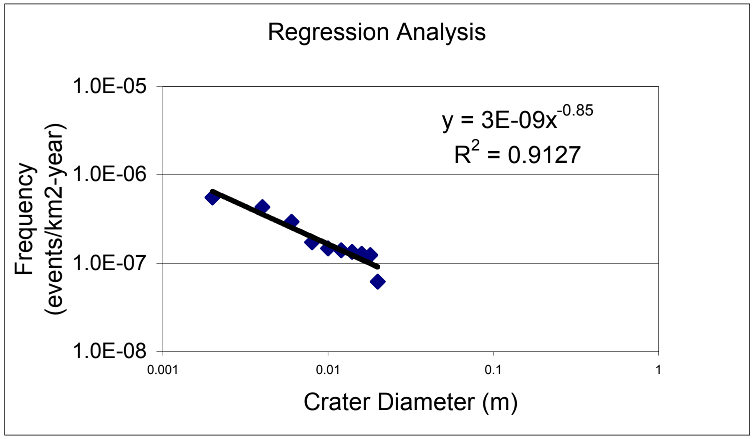


Figure D-6c. Regression Analysis for Upper Curve Portion (V= 20 km/s)

Table D-8d. Regression Analysis for Crater Diameter *D* for Meteoroid Flux for Lower Portion of Curve (*D* > 0.02 km) and V = 20 km/s

Crater Diameter D_{20} (km)	Frequency (F)	log(*D*)	log(F)	[log(*D*) - log $(D)_{mean}$]	[log(*D*) - log $(D)_{mean}]^2$	[log(F) - log $(F)_{mean}$]	[log(*D*) - log $(D)_{mean}$] x [log(F) - log $(F)_{mean}$]
0.04	5.0E-13	-1.40	-12.30	-0.93	0.86	0.62	-0.57
0.06	4.3E-13	-1.22	-12.37	-0.75	0.57	0.55	-0.41
0.08	3.9E-13	-1.10	-12.41	-0.63	0.39	0.51	-0.32
0.1	3.7E-13	-1.00	-12.44	-0.53	0.28	0.48	-0.25
0.12	3.3E-13	-0.92	-12.48	-0.45	0.20	0.44	-0.20
0.14	2.8E-13	-0.85	-12.56	-0.38	0.15	0.36	-0.14
0.16	2.5E-13	-0.80	-12.60	-0.33	0.11	0.32	-0.10
0.18	2.2E-13	-0.74	-12.65	-0.27	0.08	0.27	-0.07
0.2	2.0E-13	-0.70	-12.70	-0.23	0.05	0.22	-0.05
0.4	1.5E-13	-0.40	-12.83	0.07	0.01	0.09	0.01
0.6	1.1E-13	-0.22	-12.94	0.25	0.06	-0.03	-0.01
0.8	7.5E-14	-0.10	-13.13	0.37	0.14	-0.21	-0.08
1	4.9E-14	0.00	-13.31	0.47	0.22	-0.39	-0.18
1.2	3.9E-14	0.08	-13.41	0.55	0.30	-0.50	-0.27
1.4	3.4E-14	0.15	-13.47	0.62	0.38	-0.55	-0.34
1.6	2.6E-14	0.20	-13.59	0.67	0.45	-0.67	-0.45
1.8	2.3E-14	0.26	-13.63	0.73	0.53	-0.71	-0.52
2	1.9E-14	0.30	-13.71	0.77	0.59	-0.80	-0.61
Mean		-0.47	-12.92				
Sum					5.37		-4.58
Slope		-0.85					

$$\text{Slope} = \frac{\sum [\log(D) - \log(D)\text{mean}] \times [\log(F) - \log(F)\text{mean}]}{\sum [\log(D) - \log(D)\text{mean}]^2}$$

NOTE: Values for *D* and for F are taken from Table D-7 of this appendix.

Slope = k = -0.85: This is less steep than the Grieve slope of –1.8, which is based on observed earth cratering at crater diameters of 10 km and was extrapolated for smaller crater diameters. The slope of the Grieve distribution decreases for smaller crater diameters, but is recognized as likely underestimating the number of small diameter craters.

Constant K = 5.0 E-14.

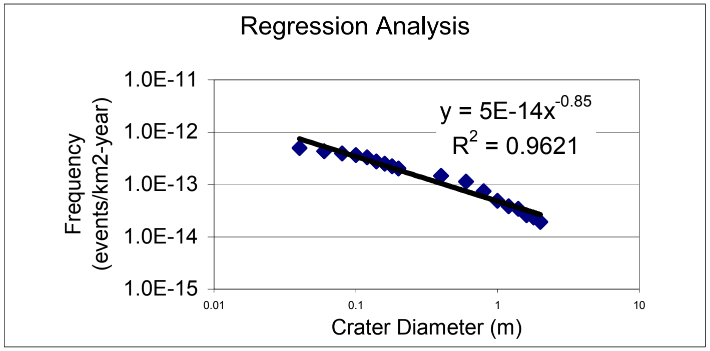


Figure D-6d. Regression Analysis for Lower Curve Portion (V = 20 km/s)

Table D-9. Example Spreadsheet Calculation for Regression Analysis

Rows/ Columns	C	D	E	F	G	H	I	J
2	**V = 15 km/sec: Upper Portion of Curve**							
3	**Crater Diameter D_{15} (km)**	**Frequency (F)**	**log(*D*)**	**log(F)**	**[log(*D*) - log (D_{mean})]**	**$[\log(D) - \log(D_{mean})]^2$**	**[log(F) - log (F_{mean})]**	**[log(*D*) - log (D_{mean})] x [log(F) - log (F)]**
4								
5	From Table D-5	From Table D-5	=LOG(C5)	=LOG(D5)	=E5-$E$19	=G5^2	=F5-$F$19	=I5*G5
6	From Table D-5	From Table D-5	=LOG(C6)	=LOG(D6)	=E6-$E$19	=G6^2	=F6-$F$19	=I6*G6
7	From Table D-5	From Table D-5	=LOG(C7)	=LOG(D7)	=E7-$E$19	=G7^2	=F7-$F$19	=I7*G7
8	From Table D-5	From Table D-5	=LOG(C8)	=LOG(D8)	=E8-$E$19	=G8^2	=F8-$F$19	=I8*G8
9	From Table D-5	From Table D-5	=LOG(C9)	=LOG(D9)	=E9-$E$19	=G9^2	=F9-$F$19	=I9*G9
10	From Table D-5	From Table D-5	=LOG(C10)	=LOG(D10)	=E10-$E$19	=G10^2	=F10-$F$19	=I10*G10
11	From Table D-5	From Table D-5	=LOG(C11)	=LOG(D11)	=E11-$E$19	=G11^2	=F11-$F$19	=I11*G11
12	From Table D-5	From Table D-5	=LOG(C12)	=LOG(D12)	=E12-$E$19	=G12^2	=F12-$F$19	=I12*G12
13	From Table D-5	From Table D-5	=LOG(C13)	=LOG(D13)	=E13-$E$19	=G13^2	=F13-$F$19	=I13*G13
14	From Table D-5	From Table D-5	=LOG(C14)	=LOG(D14)	=E14-$E$19	=G14^2	=F14-$F$19	=I14*G14
15	From Table D-5	From Table D-5	=LOG(C15)	=LOG(D15)	=E15-$E$19	=G15^2	=F15-$F$19	=I15*G15
16	From Table D-5	From Table D-5	=LOG(C16)	=LOG(D16)	=E16-$E$19	=G16^2	=F16-$F$19	=I16*G16
17	From Table D-5	From Table D-5	=LOG(C17)	=LOG(D17)	=E17-$E$19	=G17^2	=F17-$F$19	=I17*G17
18								
19	Mean		=AVERAGE(E5:E17)	=AVERAGE(F5:F17)				
20	Sum					=SUM(H5:H17)		=SUM(J5:J17)
21	Slope		=J20/H20					

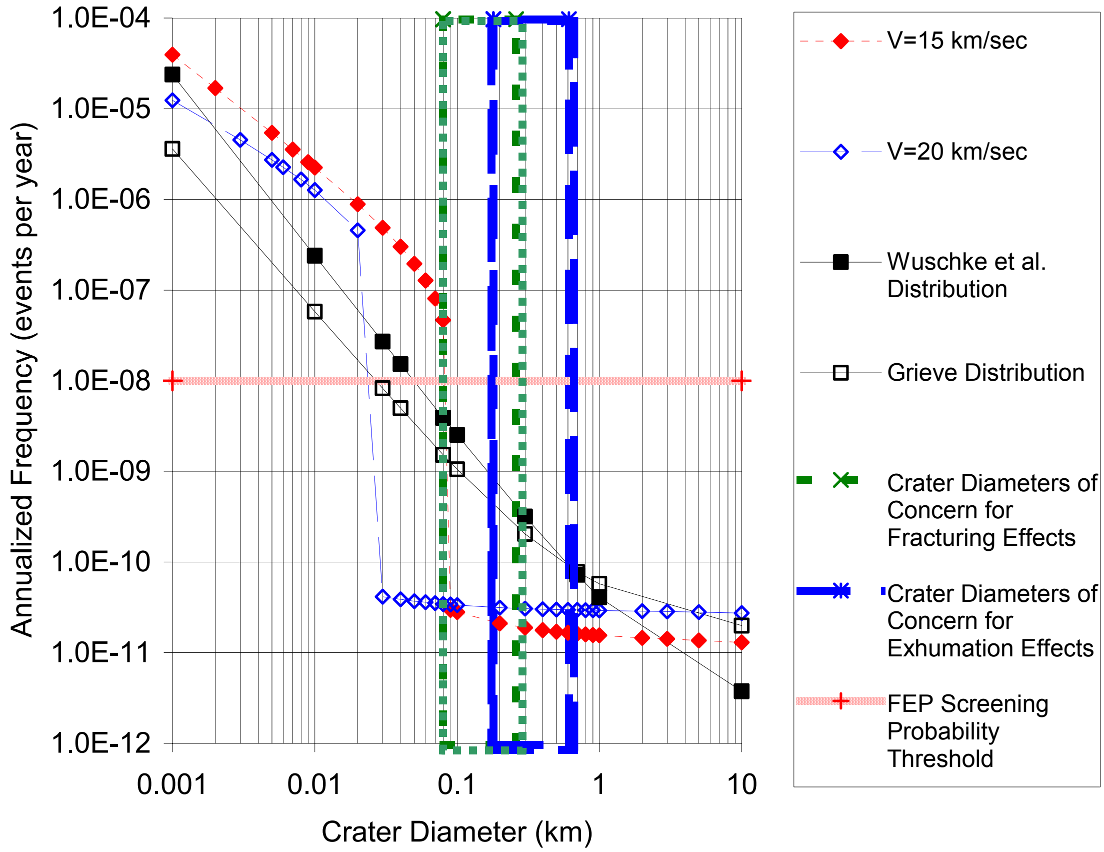


Figure D-7. Annualized Frequency of Cratering above the Repository for the TSPA-LA Emplacement Area

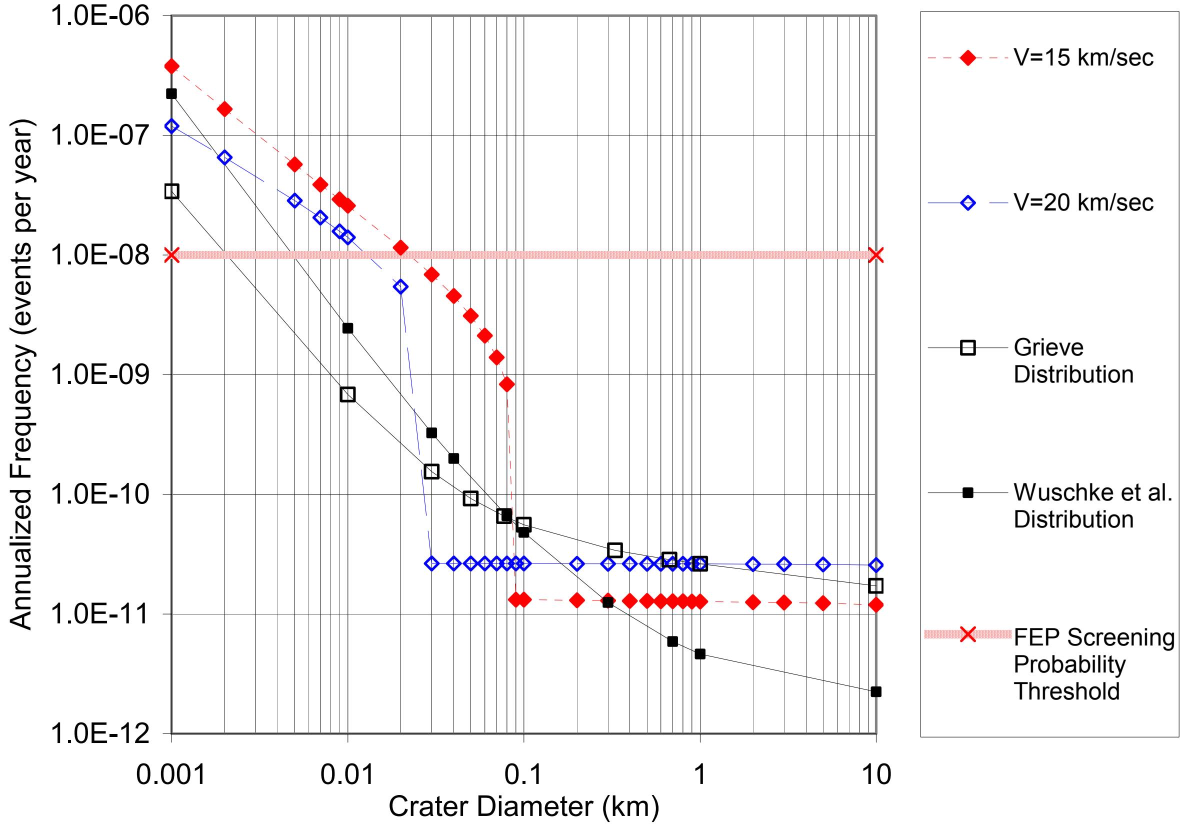


Figure D-8. Annualized Frequency of Cratering above the Paintbrush Outcrop

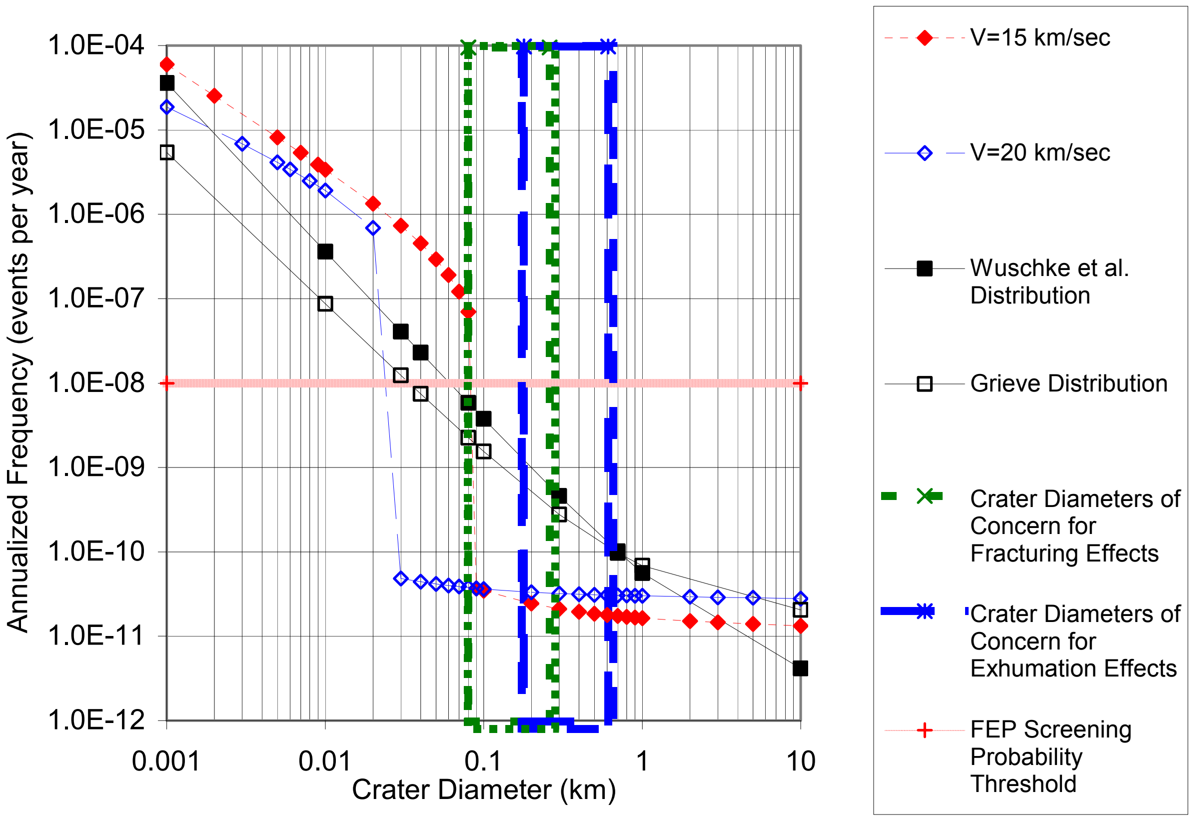


Figure D-9. Annualized Frequency of Cratering above the Repository for the TSPA-LA Siting Area

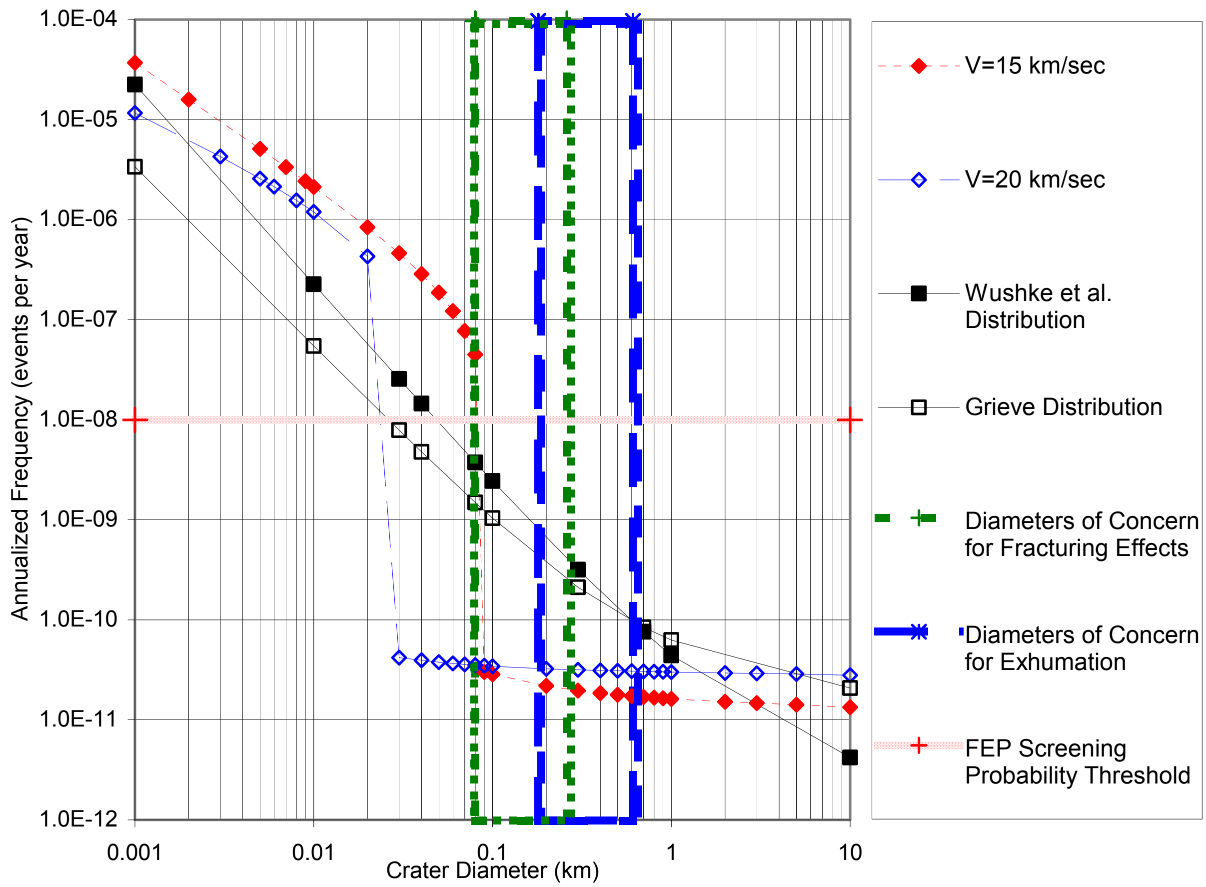


Figure D-10. Annualized Frequency of Cratering above the Repository for the TSPA-SR Design

Table D-10a. Frequency (F) of Cratering above Repository for TSPA-LA Emplacement Area

TSPA-LA Emplacement Area	L=5.4		W=2.2		V=15 km/s	
Crater Diameter *D* (km)	K	$\frac{LWD^k}{k}$	$\frac{(L+W)(D^{k+1})}{k+1}$	$\frac{D^{k+2}}{k+2}$	F(*D*) (sum of terms)	kK(F(*D*)-F(*D*)$_{max}$)
UPPER CURVE FOR V=15 km/s						
	K=7.0 E-10				k=-1.23	
0.001	7.0E-10	-4.6E+04	-1.6E+02	6.1E-03	-4.6E+04	3.9E-05
0.002	7.0E-10	-2.0E+04	-1.4E+02	1.0E-02	-2.0E+04	1.7E-05
0.005	7.0E-10	-6.4E+03	-1.1E+02	2.1E-02	-6.5E+03	5.4E-06
0.007	7.0E-10	-4.2E+03	-1.0E+02	2.8E-02	-4.3E+03	3.5E-06
0.009	7.0E-10	-3.1E+03	-9.7E+01	3.4E-02	-3.2E+03	2.6E-06
0.01	7.0E-10	-2.7E+03	-9.5E+01	3.6E-02	-2.8E+03	2.2E-06
0.02	7.0E-10	-1.2E+03	-8.1E+01	6.2E-02	-1.3E+03	8.9E-07
0.03	7.0E-10	-7.1E+02	-7.4E+01	8.5E-02	-7.9E+02	4.9E-07
0.04	7.0E-10	-5.0E+02	-7.0E+01	1.1E-01	-5.7E+02	3.0E-07
0.05	7.0E-10	-3.8E+02	-6.6E+01	1.3E-01	-4.5E+02	2.0E-07
0.06	7.0E-10	-3.0E+02	-6.4E+01	1.5E-01	-3.7E+02	1.3E-07
0.07	7.0E-10	-2.5E+02	-6.1E+01	1.6E-01	-3.1E+02	8.1E-08
0.08	7.0E-10	-2.1E+02	-6.0E+01	1.8E-01	-2.7E+02	4.6E-08
0.1	7.0E-10	-1.6E+02	-5.7E+01	2.2E-01	-2.2E+02	0.0E+00
LOWER CURVE FOR V=15 km/s						
	K=7.0 E-14				k=-1.14	
0.09	7.0E-14	-1.6E+02	-7.5E+01	1.5E-01	-2.4E+02	3.0E-11
0.1	7.0E-14	-1.4E+02	-7.4E+01	1.6E-01	-2.2E+02	2.8E-11
0.2	7.0E-14	-6.5E+01	-6.7E+01	2.9E-01	-1.3E+02	2.1E-11
0.3	7.0E-14	-4.1E+01	-6.3E+01	4.1E-01	-1.0E+02	1.9E-11
0.4	7.0E-14	-3.0E+01	-6.1E+01	5.3E-01	-9.0E+01	1.8E-11
0.5	7.0E-14	-2.3E+01	-5.9E+01	6.4E-01	-8.1E+01	1.7E-11
0.6	7.0E-14	-1.9E+01	-5.8E+01	7.5E-01	-7.5E+01	1.7E-11
0.7	7.0E-14	-1.6E+01	-5.6E+01	8.6E-01	-7.1E+01	1.6E-11
0.8	7.0E-14	-1.3E+01	-5.5E+01	9.6E-01	-6.8E+01	1.6E-11
0.9	7.0E-14	-1.2E+01	-5.4E+01	1.1E+00	-6.5E+01	1.6E-11
1	7.0E-14	-1.0E+01	-5.4E+01	1.2E+00	-6.3E+01	1.6E-11
2	7.0E-14	-4.7E+00	-4.8E+01	2.1E+00	-5.1E+01	1.5E-11
3	7.0E-14	-3.0E+00	-4.6E+01	3.0E+00	-4.6E+01	1.4E-11
5	7.0E-14	-1.7E+00	-4.3E+01	4.6E+00	-4.0E+01	1.4E-11
10	7.0E-14	-7.5E-01	-3.9E+01	8.4E+00	-3.1E+01	1.3E-11
300	7.0E-14	-1.5E-02	-2.4E+01	1.6E+02	1.3E+02	0.0E+00

Table D-10a. Frequency (F) of Cratering above Repository for TSPA-LA Emplacement Area (Continued)

TSPA-LA Emplacement Area	L=5.4		W=2.2		V=20 km/s	
Crater Diameter D (km)	**K**	**$\frac{LWD^k}{k}$**	**$\frac{(L+W)(D^{k+1})}{k+1}$**	**$\frac{D^{k+2}}{k+2}$**	**F(D) (sum of terms)**	**kK(F(D)-F(D)$_{max}$)**
UPPER CURVE FOR V=20 km/s						
			K=3.0 E-09		k=-0.85	
0.001	3.0E-09	-5.0E+03	1.9E+01	3.1E-04	-5.0E+03	1.2E-05
0.003	3.0E-09	-2.0E+03	2.2E+01	1.1E-03	-2.0E+03	4.5E-06
0.005	3.0E-09	-1.3E+03	2.4E+01	2.0E-03	-1.3E+03	2.7E-06
0.006	3.0E-09	-1.1E+03	2.4E+01	2.5E-03	-1.1E+03	2.3E-06
0.008	3.0E-09	-8.5E+02	2.5E+01	3.4E-03	-8.3E+02	1.6E-06
0.01	3.0E-09	-7.1E+02	2.6E+01	4.4E-03	-6.8E+02	1.3E-06
0.02	3.0E-09	-3.9E+02	2.9E+01	9.8E-03	-3.6E+02	4.5E-07
0.04	3.0E-09	-2.2E+02	3.2E+01	2.2E-02	-1.8E+02	0.0E+00
LOWER CURVE FOR V=20 km/s						
			K=5.0 E-14		k=-0.85	
0.03	5.0E-14	-2.8E+02	3.1E+01	1.6E-02	-2.5E+02	4.1E-11
0.04	5.0E-14	-2.2E+02	3.2E+01	2.2E-02	-1.8E+02	3.9E-11
0.05	5.0E-14	-1.8E+02	3.3E+01	2.8E-02	-1.5E+02	3.7E-11
0.06	5.0E-14	-1.5E+02	3.4E+01	3.5E-02	-1.2E+02	3.6E-11
0.07	5.0E-14	-1.3E+02	3.5E+01	4.1E-02	-1.0E+02	3.5E-11
0.08	5.0E-14	-1.2E+02	3.6E+01	4.8E-02	-8.4E+01	3.4E-11
0.09	5.0E-14	-1.1E+02	3.6E+01	5.5E-02	-7.2E+01	3.4E-11
0.1	5.0E-14	-9.9E+01	3.7E+01	6.2E-02	-6.2E+01	3.4E-11
0.2	5.0E-14	-5.5E+01	4.1E+01	1.4E-01	-1.4E+01	3.1E-11
0.3	5.0E-14	-3.9E+01	4.3E+01	2.2E-01	4.6E+00	3.1E-11
0.4	5.0E-14	-3.0E+01	4.5E+01	3.0E-01	1.5E+01	3.0E-11
0.5	5.0E-14	-2.5E+01	4.7E+01	3.9E-01	2.2E+01	3.0E-11
0.6	5.0E-14	-2.2E+01	4.8E+01	4.9E-01	2.7E+01	3.0E-11
0.7	5.0E-14	-1.9E+01	4.9E+01	5.8E-01	3.1E+01	3.0E-11
0.8	5.0E-14	-1.7E+01	5.0E+01	6.7E-01	3.4E+01	2.9E-11
0.9	5.0E-14	-1.5E+01	5.1E+01	7.7E-01	3.6E+01	2.9E-11
1	5.0E-14	-1.4E+01	5.2E+01	8.7E-01	3.9E+01	2.9E-11
2	5.0E-14	-7.7E+00	5.7E+01	1.9E+00	5.1E+01	2.9E-11
3	5.0E-14	-5.5E+00	6.1E+01	3.1E+00	5.8E+01	2.8E-11
5	5.0E-14	-3.5E+00	6.6E+01	5.5E+00	6.7E+01	2.8E-11
10	5.0E-14	-2.0E+00	7.3E+01	1.2E+01	8.3E+01	2.7E-11
300	5.0E-14	-1.1E-01	1.2E+02	6.0E+02	7.2E+02	0.0E+00

Table D-10a. Frequency (F) of Cratering above Repository for TSPA-LA Emplacement Area (Continued)

TSPA-LA Emplacement Area	L=5.4		W=2.2		V=20 km/s	
Crater Diameter *D* (km)	K	$\frac{LWD^k}{k}$	$\frac{(L+W)(D^{k+1})}{k+1}$	$\frac{D^{k+2}}{k+2}$	F(*D*) (sum of terms)	kK(F(*D*)-F(*D*)$_{max}$)
GRIEVE DISTRIBUTION						
			K=1.20 E-12		k=1.80	
0.001	1.20E-12	-1.7E+06	-2.4E+03	1.3E+00	-1.7E+06	3.6E-06
0.01	1.20E-12	-2.6E+04	-3.8E+02	2.0E+00	-2.7E+04	5.8E-08
0.03	1.20E-12	-3.6E+03	-1.6E+02	2.5E+00	-3.8E+03	8.2E-09
0.04	1.20E-12	-2.2E+03	-1.2E+02	2.6E+00	-2.3E+03	5.0E-09
0.08	1.20E-12	-6.2E+02	-7.2E+01	3.0E+00	-6.9E+02	1.5E-09
0.1	1.20E-12	-4.2E+02	-6.0E+01	3.2E+00	-4.7E+02	1.1E-09
0.3	1.20E-12	-5.8E+01	-2.5E+01	3.9E+00	-7.9E+01	2.0E-10
0.7	1.20E-12	-1.3E+01	-1.3E+01	4.7E+00	-2.1E+01	7.8E-11
1	1.20E-12	-6.6E+00	-9.5E+00	5.0E+00	-1.1E+01	5.8E-11
10	1.20E-12	-1.0E-01	-1.5E+00	7.9E+00	6.3E+00	2.0E-11
100	1.20E-12	-1.7E-03	-2.4E-01	1.3E+01	1.2E+01	7.0E-12
300	1.20E-12	-2.3E-04	-9.9E-02	1.6E+01	1.6E+01	0.0E+00
WUSCHKE ET AL. DISTRIBUTION						
Crater Diameter (km)	**Adjusted L (km)**	**Adjusted W (km)**		**Adjusted Area (km^2)**	**D^{-2}**	**F**
0.001	5.40	2.20		11.9	1.0E+06	2.4E-05
0.01	5.41	2.21		12.0	1.0E+04	2.4E-07
0.03	5.43	2.23		12.1	1.1E+03	2.7E-08
0.04	5.44	2.24		12.2	6.3E+02	1.5E-08
0.08	5.48	2.28		12.5	1.6E+02	3.9E-09
0.1	5.50	2.30		12.7	1.0E+02	2.5E-09
0.3	5.70	2.50		14.3	1.1E+01	3.2E-10
0.7	6.10	2.90		17.7	2.0E+00	7.2E-11
1	6.40	3.20		20.5	1.0E+00	4.1E-11
10	15.40	12.20		187.9	1.0E-02	3.8E-12
100	105.40	102.20		10771.9	1.0E-04	2.2E-12
300	305.40	302.20		92291.9	1.1E-05	2.1E-12

NOTES:

For distribution curves:

$$F = k\,K\left(\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right)\Bigg|_{0.001}^{max}$$

where:

F = events per year
K = proportionality constant (from regression equation)
k = power of the distribution (from regression equation)
L = length of repository (km)
W = width of the repository (km)
D = diameter of crater (km)

For Wuschke et al.: $F = 2.0 \times 10^{-12} \times D^{-2} \times (L_{adjusted} \times W_{adjusted})$

Table D-10b. Frequency (F) of Cratering in the Paintbrush Outcrop

Outcrop Area	L=1.1		W=0.1		V=15 km/s	
Crater Diameter *D* (km)	**K**	**$\frac{LWD^k}{k}$**	**$\frac{(L+W)(D^{k+1})}{k+1}$**	**$\frac{D^{k+2}}{k+2}$**	**F(*D*) (sum of terms)**	**$kK(F(D)-F(D)_{max})$**
UPPER CURVE FOR V=15 km/s						
	K=7.0 E-10				k=1.23	
0.001	7.0E-10	-4.3E+02	-2.5E+01	6.1E-03	-4.5E+02	3.8E-07
0.002	7.0E-10	-1.8E+02	-2.2E+01	1.0E-02	-2.0E+02	1.7E-07
0.005	7.0E-10	-5.9E+01	-1.8E+01	2.1E-02	-7.7E+01	5.7E-08
0.007	7.0E-10	-3.9E+01	-1.6E+01	2.8E-02	-5.6E+01	3.9E-08
0.009	7.0E-10	-2.9E+01	-1.5E+01	3.4E-02	-4.4E+01	2.9E-08
0.01	7.0E-10	-2.5E+01	-1.5E+01	3.6E-02	-4.0E+01	2.6E-08
0.02	7.0E-10	-1.1E+01	-1.3E+01	6.2E-02	-2.4E+01	1.1E-08
0.03	7.0E-10	-6.6E+00	-1.2E+01	8.5E-02	-1.8E+01	6.9E-09
0.04	7.0E-10	-4.6E+00	-1.1E+01	1.1E-01	-1.6E+01	4.5E-09
0.05	7.0E-10	-3.5E+00	-1.0E+01	1.3E-01	-1.4E+01	3.1E-09
0.06	7.0E-10	-2.8E+00	-1.0E+01	1.5E-01	-1.3E+01	2.1E-09
0.07	7.0E-10	-2.3E+00	-9.7E+00	1.6E-01	-1.2E+01	1.4E-09
0.08	7.0E-10	-2.0E+00	-9.4E+00	1.8E-01	-1.1E+01	8.3E-10
0.1	7.0E-10	-1.5E+00	-8.9E+00	2.2E-01	-1.0E+01	0.0E+00
LOWER CURVE FOR V=15 km/s						
	K=7.0 E-14				k=1.14	
0.09	7.0E-14	-1.5E+00	-1.2E+01	1.5E-01	-1.3E+01	1.3E-11
0.1	7.0E-14	-1.3E+00	-1.2E+01	1.6E-01	-1.3E+01	1.3E-11
0.2	7.0E-14	-6.1E-01	-1.1E+01	2.9E-01	-1.1E+01	1.3E-11
0.3	7.0E-14	-3.8E-01	-1.0E+01	4.1E-01	-1.0E+01	1.3E-11
0.4	7.0E-14	-2.7E-01	-9.6E+00	5.3E-01	-9.4E+00	1.3E-11
0.5	7.0E-14	-2.1E-01	-9.3E+00	6.4E-01	-8.9E+00	1.3E-11
0.6	7.0E-14	-1.7E-01	-9.1E+00	7.5E-01	-8.5E+00	1.3E-11
0.7	7.0E-14	-1.4E-01	-8.9E+00	8.6E-01	-8.2E+00	1.3E-11
0.8	7.0E-14	-1.2E-01	-8.7E+00	9.6E-01	-7.9E+00	1.3E-11
0.9	7.0E-14	-1.1E-01	-8.6E+00	1.1E+00	-7.6E+00	1.3E-11
1	7.0E-14	-9.6E-02	-8.4E+00	1.2E+00	-7.4E+00	1.3E-11
2	7.0E-14	-4.4E-02	-7.7E+00	2.1E+00	-5.6E+00	1.3E-11
3	7.0E-14	-2.7E-02	-7.2E+00	3.0E+00	-4.3E+00	1.2E-11
5	7.0E-14	-1.5E-02	-6.7E+00	4.6E+00	-2.1E+00	1.2E-11
10	7.0E-14	-6.9E-03	-6.1E+00	8.4E+00	2.3E+00	1.2E-11
300	7.0E-14	-1.4E-04	-3.8E+00	1.6E+02	1.5E+02	0.0E+00

Table D-10b. Frequency (F) of Cratering in the Paintbrush Outcrop (Continued)

Outcrop Area	**L=1.1**		**W=0.1**		**V=20 km/s**	
Crater Diameter D (km)	**K**	**$\frac{LWD^k}{k}$**	**$\frac{(L+W)(D^{k+1})}{k+1}$**	**$\frac{D^{k+2}}{k+2}$**	**F(D) (sum of terms)**	**kK(F(D)-F(D)$_{max}$)**
UPPER CURVE FOR V=20 km/s						
			K=3.0 E-09		k=-0.85	
0.001	3.0E-09	-4.7E+01	2.9E+00	3.1E-04	-4.4E+01	1.2E-07
0.002	3.0E-09	-2.6E+01	3.3E+00	7.0E-04	-2.3E+01	6.6E-08
0.005	3.0E-09	-1.2E+01	3.7E+00	2.0E-03	-8.1E+00	2.9E-08
0.007	3.0E-09	-8.9E+00	3.9E+00	2.9E-03	-4.9E+00	2.1E-08
0.009	3.0E-09	-7.2E+00	4.1E+00	3.9E-03	-3.1E+00	1.6E-08
0.01	3.0E-09	-6.5E+00	4.1E+00	4.4E-03	-2.4E+00	1.4E-08
0.02	3.0E-09	-3.6E+00	4.6E+00	9.8E-03	9.6E-01	5.4E-09
0.04	3.0E-09	-2.0E+00	5.1E+00	2.2E-02	3.1E+00	0.0E+00
LOWER CURVE FOR V=20 km/s						
			K=5.0 E-14		k=-0.85	
0.03	5.0E-14	-2.6E+00	4.9E+00	1.6E-02	2.3E+00	2.7E-11
0.04	5.0E-14	-2.0E+00	5.1E+00	2.2E-02	3.1E+00	2.6E-11
0.05	5.0E-14	-1.7E+00	5.3E+00	2.8E-02	3.6E+00	2.6E-11
0.06	5.0E-14	-1.4E+00	5.4E+00	3.5E-02	4.0E+00	2.6E-11
0.07	5.0E-14	-1.2E+00	5.5E+00	4.1E-02	4.3E+00	2.6E-11
0.08	5.0E-14	-1.1E+00	5.6E+00	4.8E-02	4.6E+00	2.6E-11
0.09	5.0E-14	-1.0E+00	5.7E+00	5.5E-02	4.8E+00	2.6E-11
0.1	5.0E-14	-9.2E-01	5.8E+00	6.2E-02	5.0E+00	2.6E-11
0.2	5.0E-14	-5.1E-01	6.4E+00	1.4E-01	6.1E+00	2.6E-11
0.3	5.0E-14	-3.6E-01	6.8E+00	2.2E-01	6.7E+00	2.6E-11
0.4	5.0E-14	-2.8E-01	7.1E+00	3.0E-01	7.2E+00	2.6E-11
0.5	5.0E-14	-2.3E-01	7.4E+00	3.9E-01	7.5E+00	2.6E-11
0.6	5.0E-14	-2.0E-01	7.6E+00	4.9E-01	7.9E+00	2.6E-11
0.7	5.0E-14	-1.7E-01	7.7E+00	5.8E-01	8.2E+00	2.6E-11
0.8	5.0E-14	-1.6E-01	7.9E+00	6.7E-01	8.4E+00	2.6E-11
0.9	5.0E-14	-1.4E-01	8.0E+00	7.7E-01	8.7E+00	2.6E-11
1	5.0E-14	-1.3E-01	8.2E+00	8.7E-01	8.9E+00	2.6E-11
2	5.0E-14	-7.1E-02	9.0E+00	1.9E+00	1.1E+01	2.6E-11
3	5.0E-14	-5.1E-02	9.6E+00	3.1E+00	1.3E+01	2.6E-11
5	5.0E-14	-3.3E-02	1.0E+01	5.5E+00	1.6E+01	2.6E-11
10	5.0E-14	-1.8E-02	1.1E+01	1.2E+01	2.4E+01	2.6E-11
300	5.0E-14	-9.9E-04	1.9E+01	6.0E+02	6.2E+02	0.0E+00

Table D-10b. Frequency (F) of Cratering in the Paintbrush Outcrop (Continued)

TSPA-SR Repository	**L=1.1**		**W=0.1**		**V=20 km/s**	
Crater Diameter *D* (km)	**K**	**$\frac{LWD^k}{k}$**	**$\frac{(L+W)(D^{k+1})}{k+1}$**	**$\frac{D^{k+2}}{K+2}$**	**F(*D*) (sum of terms)**	**kK(F(*D*)-F(*D*)$_{max}$)**
GRIEVE DISTRIBUTION						
			K=1.20E-12		k=-1.80	
0.001	1.20E-12	-1.5E+04	-3.8E+02	1.3E+00	-1.6E+04	3.4E-08
0.01	1.20E-12	-2.4E+02	-6.0E+01	2.0E+00	-3.0E+02	6.8E-10
0.03	1.20E-12	-3.4E+01	-2.5E+01	2.5E+00	-5.6E+01	1.5E-10
0.05	1.20E-12	-1.3E+01	-1.6E+01	2.7E+00	-2.7E+01	9.2E-11
0.077	1.20E-12	-6.2E+00	-1.2E+01	3.0E+00	-1.5E+01	6.6E-11
0.1	1.20E-12	-3.9E+00	-9.5E+00	3.2E+00	-1.0E+01	5.6E-11
0.33	1.20E-12	-4.5E-01	-3.6E+00	4.0E+00	-8.5E-02	3.4E-11
0.67	1.20E-12	-1.3E-01	-2.1E+00	4.6E+00	2.4E+00	2.9E-11
1	1.20E-12	-6.1E-02	-1.5E+00	5.0E+00	3.4E+00	2.6E-11
10	1.20E-12	-9.7E-04	-2.4E-01	7.9E+00	7.7E+00	1.7E-11
100	1.20E-12	-1.5E-05	-3.8E-02	1.3E+01	1.3E+01	6.7E-12
300	1.20E-12	-2.1E-06	-1.6E-02	1.6E+01	1.6E+01	0.0E+00
WUSCHKE ET AL. DISTRIBUTION						
Crater Diameter (km)	**Adjusted L (km)**	**Adjusted W (km)**		**Adjusted Area (km^2)**	**D-2**	**Frequency (per year)**
0.001	1.10	0.10		0.1	1.0E+06	2.2E-07
0.01	1.11	0.11		0.1	1.0E+04	2.4E-09
0.03	1.13	0.13		0.1	1.1E+03	3.3E-10
0.04	1.14	0.14		0.2	6.3E+02	2.0E-10
0.08	1.18	0.18		0.2	1.6E+02	6.6E-11
0.1	1.20	0.20		0.2	1.0E+02	4.8E-11
0.3	1.40	0.40		0.6	1.1E+01	1.2E-11
0.7	1.80	0.80		1.4	2.0E+00	5.9E-12
1	2.10	1.10		2.3	1.0E+00	4.6E-12
10	11.10	10.10		112.1	1.0E-02	2.2E-12
100	101.10	100.10		10120.1	1.0E-04	2.0E-12
300	301.10	300.10		90360.1	1.1E-05	2.0E-12

NOTES:

For distribution curves:

$$F = k\,K\left(\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right)\Bigg|_{0.001}^{max}$$

where:

F = events per year
K = proportionality constant (from regression equation)
k = power of the distribution (from regression equation)
L = length of repository (km)
W = width of the repository (km)
D = diameter of crater (km)

For Wuschke et al.: $F = 2.0 \times 10^{-12} \times D^{-2} \times (L_{adjusted} \times W_{adjusted})$

Table D-10c. Frequency (F) of Cratering above Repository for TSPA-LA Siting Area

TSPA-LA Siting Area	L=5.4		W=2.6		V=15 km/s	
Crater Diameter *D* (km)	K	$\frac{LWD^{k}}{K}$	$\frac{(L+W)(D^{k+1})}{k+1}$	$\frac{D^{k+2}}{k+2}$	F(*D*) (sum of terms)	$kK(F(D)-F(D)_{max})$
UPPER CURVE FOR V=15 km/s						
	K=7.0 E-10				k=-1.23	
0.001	7.0E-10	-7.0E+04	-1.9E+02	6.1E-03	-7.0E+04	6.0E-05
0.002	7.0E-10	-3.0E+04	-1.6E+02	1.0E-02	-3.0E+04	2.5E-05
0.005	7.0E-10	-9.7E+03	-1.3E+02	2.1E-02	-9.8E+03	8.2E-06
0.007	7.0E-10	-6.4E+03	-1.2E+02	2.8E-02	-6.5E+03	5.3E-06
0.009	7.0E-10	-4.7E+03	-1.2E+02	3.4E-02	-4.8E+03	3.9E-06
0.01	7.0E-10	-4.1E+03	-1.1E+02	3.6E-02	-4.3E+03	3.4E-06
0.02	7.0E-10	-1.8E+03	-9.6E+01	6.2E-02	-1.9E+03	1.3E-06
0.03	7.0E-10	-1.1E+03	-8.8E+01	8.5E-02	-1.2E+03	7.3E-07
0.04	7.0E-10	-7.6E+02	-8.2E+01	1.1E-01	-8.4E+02	4.5E-07
0.05	7.0E-10	-5.8E+02	-7.8E+01	1.3E-01	-6.6E+02	2.9E-07
0.06	7.0E-10	-4.6E+02	-7.5E+01	1.5E-01	-5.4E+02	1.9E-07
0.07	7.0E-10	-3.8E+02	-7.3E+01	1.6E-01	-4.5E+02	1.2E-07
0.08	7.0E-10	-3.2E+02	-7.1E+01	1.8E-01	-3.9E+02	7.0E-08
0.1	7.0E-10	-2.5E+02	-6.7E+01	2.2E-01	-3.1E+02	0.0E+00
LOWER CURVE FOR V=15 km/s						
	K=7.0 E-14				k=-1.14	
0.09	7.0E-14	-2.5E+02	-8.9E+01	1.5E-01	-3.4E+02	3.7E-11
0.1	7.0E-14	-2.2E+02	-8.8E+01	1.6E-01	-3.1E+02	3.5E-11
0.2	7.0E-14	-9.9E+01	-8.0E+01	2.9E-01	-1.8E+02	2.4E-11
0.3	7.0E-14	-6.2E+01	-7.5E+01	4.1E-01	-1.4E+02	2.1E-11
0.4	7.0E-14	-4.5E+01	-7.2E+01	5.3E-01	-1.2E+02	1.9E-11
0.5	7.0E-14	-3.5E+01	-7.0E+01	6.4E-01	-1.0E+02	1.8E-11
0.6	7.0E-14	-2.8E+01	-6.8E+01	7.5E-01	-9.6E+01	1.8E-11
0.7	7.0E-14	-2.4E+01	-6.7E+01	8.6E-01	-8.9E+01	1.7E-11
0.8	7.0E-14	-2.0E+01	-6.5E+01	9.6E-01	-8.5E+01	1.7E-11
0.9	7.0E-14	-1.8E+01	-6.4E+01	1.1E+00	-8.1E+01	1.7E-11
1	7.0E-14	-1.6E+01	-6.3E+01	1.2E+00	-7.8E+01	1.6E-11
2	7.0E-14	-7.1E+00	-5.7E+01	2.1E+00	-6.2E+01	1.5E-11
3	7.0E-14	-4.5E+00	-5.4E+01	3.0E+00	-5.6E+01	1.5E-11
5	7.0E-14	-2.5E+00	-5.0E+01	4.6E+00	-4.8E+01	1.4E-11
10	7.0E-14	-1.1E+00	-4.6E+01	8.4E+00	-3.8E+01	1.3E-11
300	7.0E-14	-2.3E-02	-2.8E+01	1.6E+02	1.3E+02	0.0E+00

Table D-10c. Frequency (F) of Cratering above Repository for TSPA-LA Siting Area (Continued)

TSPA-LA Siting Area	**L=5.5**		**W=2.6**		**V=20 km/s**	
Crater Diameter *D* (km)	**K**	**$\frac{LWD^k}{k}$**	**$\frac{(L+W)(D^{k+1})}{k+1}$**	**$\frac{D^{k+2}}{k+2}$**	**F(*D*) (sum of terms)**	**$kK(F(D)-F(D)_{max})$**
UPPER CURVE FOR V=20 km/s						
			K= 3.0 E-09		k= -0.85	
0.001	3.0E-09	-7.6E+03	2.2E+01	3.1E-04	-7.6E+03	1.9E-05
0.003	3.0E-09	-3.0E+03	2.6E+01	1.1E-03	-3.0E+03	6.8E-06
0.005	3.0E-09	-1.9E+03	2.8E+01	2.0E-03	-1.9E+03	4.1E-06
0.006	3.0E-09	-1.7E+03	2.9E+01	2.5E-03	-1.6E+03	3.4E-06
0.008	3.0E-09	-1.3E+03	3.0E+01	3.4E-03	-1.3E+03	2.5E-06
0.01	3.0E-09	-1.1E+03	3.1E+01	4.4E-03	-1.0E+03	1.9E-06
0.02	3.0E-09	-5.9E+02	3.4E+01	9.8E-03	-5.6E+02	6.9E-07
0.04	3.0E-09	-3.3E+02	3.8E+01	2.2E-02	-2.9E+02	0.0E+00
LOWER CURVE FOR V=20 km/s						
			K=5.0 E-14		k=-0.85	
0.03	5.0E-14	-4.2E+02	3.7E+01	1.6E-02	-3.8E+02	4.8E-11
0.04	5.0E-14	-3.3E+02	3.8E+01	2.2E-02	-2.9E+02	4.4E-11
0.05	5.0E-14	-2.7E+02	3.9E+01	2.8E-02	-2.3E+02	4.2E-11
0.06	5.0E-14	-2.3E+02	4.0E+01	3.5E-02	-1.9E+02	4.0E-11
0.07	5.0E-14	-2.0E+02	4.1E+01	4.1E-02	-1.6E+02	3.9E-11
0.08	5.0E-14	-1.8E+02	4.2E+01	4.8E-02	-1.4E+02	3.8E-11
0.09	5.0E-14	-1.6E+02	4.3E+01	5.5E-02	-1.2E+02	3.7E-11
0.1	5.0E-14	-1.5E+02	4.4E+01	6.2E-02	-1.1E+02	3.6E-11
0.2	5.0E-14	-8.3E+01	4.8E+01	1.4E-01	-3.5E+01	3.3E-11
0.3	5.0E-14	-5.9E+01	5.1E+01	2.2E-01	-7.4E+00	3.2E-11
0.4	5.0E-14	-4.6E+01	5.4E+01	3.0E-01	7.7E+00	3.2E-11
0.5	5.0E-14	-3.8E+01	5.5E+01	3.9E-01	1.8E+01	3.1E-11
0.6	5.0E-14	-3.3E+01	5.7E+01	4.9E-01	2.5E+01	3.1E-11
0.7	5.0E-14	-2.9E+01	5.8E+01	5.8E-01	3.0E+01	3.1E-11
0.8	5.0E-14	-2.6E+01	5.9E+01	6.7E-01	3.4E+01	3.0E-11
0.9	5.0E-14	-2.3E+01	6.0E+01	7.7E-01	3.8E+01	3.0E-11
1	5.0E-14	-2.1E+01	6.1E+01	8.7E-01	4.1E+01	3.0E-11
2	5.0E-14	-1.2E+01	6.8E+01	1.9E+00	5.8E+01	2.9E-11
3	5.0E-14	-8.3E+00	7.2E+01	3.1E+00	6.7E+01	2.9E-11
5	5.0E-14	-5.3E+00	7.8E+01	5.5E+00	7.8E+01	2.9E-11
10	5.0E-14	-3.0E+00	8.6E+01	1.2E+01	9.5E+01	2.8E-11
300	5.0E-14	-1.6E-01	1.4E+02	6.0E+02	7.5E+02	0.0E+00

Table D-10c. Frequency (F) of Cratering above Repository for TSPA-LA Siting Area (Continued)

TSPA-LA Siting Area	**L=5.5**		**W=2.6**		**V=20 km/s**	
Crater Diameter D (km)	**K**	**$\frac{LWD^k}{k}$**	**$\frac{(L+W)(D^{k+1})}{k+1}$**	**$\frac{D^{k+2}}{k+2}$**	**F(D) (sum of terms)**	**kK(F(D)-F(D)$_{max}$)**
GRIEVE DISTRIBUTION						
			K=1.20 E-12		k=-1.80	
0.001	1.20E-12	-2.0E+06	-2.5E+03	1.3E+00	-2.0E+06	4.2E-06
0.01	1.20E-12	-3.1E+04	-4.0E+02	2.0E+00	-3.1E+04	6.8E-08
0.03	1.20E-12	-4.3E+03	-1.7E+02	2.5E+00	-4.5E+03	9.7E-09
0.04	1.20E-12	-2.6E+03	-1.3E+02	2.6E+00	-2.7E+03	5.8E-09
0.08	1.20E-12	-7.4E+02	-7.5E+01	3.0E+00	-8.1E+02	1.8E-09
0.1	1.20E-12	-4.9E+02	-6.3E+01	3.2E+00	-5.5E+02	1.2E-09
0.3	1.20E-12	-6.8E+01	-2.6E+01	3.9E+00	-9.0E+01	2.3E-10
0.7	1.20E-12	-1.5E+01	-1.3E+01	4.7E+00	-2.3E+01	8.4E-11
1	1.20E-12	-7.8E+00	-1.0E+01	5.0E+00	-1.3E+01	6.1E-11
10	1.20E-12	-1.2E-01	-1.6E+00	7.9E+00	6.2E+00	2.0E-11
100	1.20E-12	-2.0E-03	-2.5E-01	1.3E+01	1.2E+01	7.0E-12
300	1.20E-12	-2.7E-04	-1.0E-01	1.6E+01	1.6E+01	0.0E+00
WUSCHKE ET AL. DISTRIBUTION						
Crater Diameter (km)	**Adjusted L (km)**	**Adjusted W (km)**		**Adjusted Area (km^2)**	**D^{-2}**	**F**
0.001	5.40	2.60		14.0	1.0E+06	2.8E-05
0.01	5.41	2.61		14.1	1.0E+04	2.8E-07
0.03	5.43	2.63		14.3	1.1E+03	3.2E-08
0.04	5.44	2.64		14.4	6.3E+02	1.8E-08
0.08	5.48	2.68		14.7	1.6E+02	4.6E-09
0.1	5.50	2.70		14.9	1.0E+02	3.0E-09
0.3	5.70	2.90		16.5	1.1E+01	3.7E-10
0.7	6.10	3.30		20.1	2.0E+00	8.2E-11
1	6.40	3.60		23.0	1.0E+00	4.6E-11
10	15.40	12.60		194.0	1.0E-02	3.9E-12
100	105.40	102.60		10814.0	1.0E-04	2.2E-12
300	305.40	302.60		92414.0	1.1E-05	2.1E-12

NOTES:

For distribution curves:

$$F = k\,K\left(\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right)\Bigg|_{0.001}^{max}$$

where:

F = events per year
K = proportionality constant (from regression equation)
k = power of the distribution (from regression equation)
L = length of repository (km)
W = width of the repository (km)
D = diameter of crater (km)

For Wuschke et al.: $F = 2.0 \times 10^{-12} \times D^{-2} \times (L_{adjusted} \times W_{adjusted})$

Table D-10d. Frequency (F) of Cratering above Repository for TSPA-SR Design

TSPA-SR Repository	**L=8.6**		**W=1.3**		**V=15 km/s**	
Crater Diameter *D* (km)	**K**	**$\frac{LWD^k}{k}$**	**$\frac{(L+W)(D^{k+1})}{k+1}$**	**$\frac{D^{k+2}}{k+2}$**	**F(*D*) (sum of terms)**	**kK(F(*D*)-F(*D*)$_{max}$)**
UPPER CURVE FOR V=15 km/s						
	K=7.0 E-10				k=-1.23	
0.001	7.0E-10	-4.3E+04	-2.1E+02	6.1E-03	-4.4E+04	3.7E-05
0.002	7.0E-10	-1.9E+04	-1.8E+02	1.0E-02	-1.9E+04	1.6E-05
0.005	7.0E-10	-6.0E+03	-1.4E+02	2.1E-02	-6.2E+03	5.1E-06
0.007	7.0E-10	-4.0E+03	-1.3E+02	2.8E-02	-4.1E+03	3.3E-06
0.009	7.0E-10	-2.9E+03	-1.3E+02	3.4E-02	-3.1E+03	2.4E-06
0.01	7.0E-10	-2.6E+03	-1.2E+02	3.6E-02	-2.7E+03	2.1E-06
0.02	7.0E-10	-1.1E+03	-1.1E+02	6.2E-02	-1.2E+03	8.4E-07
0.03	7.0E-10	-6.7E+02	-9.7E+01	8.5E-02	-7.7E+02	4.6E-07
0.04	7.0E-10	-4.7E+02	-9.1E+01	1.1E-01	-5.6E+02	2.9E-07
0.05	7.0E-10	-3.6E+02	-8.6E+01	1.3E-01	-4.4E+02	1.9E-07
0.06	7.0E-10	-2.9E+02	-8.3E+01	1.5E-01	-3.7E+02	1.2E-07
0.07	7.0E-10	-2.4E+02	-8.0E+01	1.6E-01	-3.2E+02	7.7E-08
0.08	7.0E-10	-2.0E+02	-7.8E+01	1.8E-01	-2.8E+02	4.5E-08
0.1	7.0E-10	-1.5E+02	-7.4E+01	2.2E-01	-2.3E+02	0.0E+00
LOWER CURVE FOR V=15 km/s						
	K=7.0 E-14				k=-1.14	
0.09	7.0E-14	-1.5E+02	-9.8E+01	1.5E-01	-2.5E+02	3.0E-11
0.1	7.0E-14	-1.4E+02	-9.7E+01	1.6E-01	-2.3E+02	2.9E-11
0.2	7.0E-14	-6.2E+01	-8.8E+01	2.9E-01	-1.5E+02	2.2E-11
0.3	7.0E-14	-3.9E+01	-8.3E+01	4.1E-01	-1.2E+02	2.0E-11
0.4	7.0E-14	-2.8E+01	-7.9E+01	5.3E-01	-1.1E+02	1.8E-11
0.5	7.0E-14	-2.2E+01	-7.7E+01	6.4E-01	-9.8E+01	1.8E-11
0.6	7.0E-14	-1.8E+01	-7.5E+01	7.5E-01	-9.2E+01	1.7E-11
0.7	7.0E-14	-1.5E+01	-7.3E+01	8.6E-01	-8.7E+01	1.7E-11
0.8	7.0E-14	-1.3E+01	-7.2E+01	9.6E-01	-8.4E+01	1.7E-11
0.9	7.0E-14	-1.1E+01	-7.1E+01	1.1E+00	-8.1E+01	1.6E-11
1	7.0E-14	-9.8E+00	-7.0E+01	1.2E+00	-7.8E+01	1.6E-11
2	7.0E-14	-4.4E+00	-6.3E+01	2.1E+00	-6.5E+01	1.5E-11
3	7.0E-14	-2.8E+00	-6.0E+01	3.0E+00	-5.9E+01	1.5E-11
5	7.0E-14	-1.6E+00	-5.5E+01	4.6E+00	-5.2E+01	1.4E-11
10	7.0E-14	-7.1E-01	-5.0E+01	8.4E+00	-4.3E+01	1.3E-11
300	7.0E-14	-1.5E-02	-3.1E+01	1.6E+02	1.2E+02	0.0E+00

Table D-10d. Frequency (F) of Cratering above Repository for TSPA-SR Design (Continued)

TSPA-SR Repository	L=8.6		W=1.3		V=20 km/s	
Crater Diameter *D* (km)	**K**	**$\frac{LWD^k}{k}$**	**$\frac{(L+W)(D^{k+1})}{k+1}$**	**$\frac{D^{k+2}}{k+2}$**	**F(*D*) (sum of terms)**	**kK(F(*D*)-F(*D*)$_{max}$)**
UPPER CURVE FOR V=20 km/s						
			K=3.0 E-09		k=-0.85	
0.001	3.0E-09	-4.7E+03	2.4E+01	3.1E-04	-4.7E+03	1.2E-05
0.003	3.0E-09	-1.9E+03	2.9E+01	1.1E-03	-1.8E+03	4.3E-06
0.005	3.0E-09	-1.2E+03	3.1E+01	2.0E-03	-1.2E+03	2.6E-06
0.006	3.0E-09	-1.0E+03	3.2E+01	2.5E-03	-1.0E+03	2.1E-06
0.008	3.0E-09	-8.0E+02	3.3E+01	3.4E-03	-7.7E+02	1.6E-06
0.01	3.0E-09	-6.7E+02	3.4E+01	4.4E-03	-6.3E+02	1.2E-06
0.02	3.0E-09	-3.7E+02	3.8E+01	9.8E-03	-3.3E+02	4.3E-07
0.04	3.0E-09	-2.0E+02	4.2E+01	2.2E-02	-1.6E+02	0.0E+00
LOWER CURVE FOR V=20 km/s						
			K=5.0 E-14		k=-0.85	
0.03	5.0E-14	-2.6E+02	4.0E+01	1.6E-02	-2.2E+02	4.2E-11
0.04	5.0E-14	-2.0E+02	4.2E+01	2.2E-02	-1.6E+02	3.9E-11
0.05	5.0E-14	-1.7E+02	4.3E+01	2.8E-02	-1.3E+02	3.8E-11
0.06	5.0E-14	-1.4E+02	4.5E+01	3.5E-02	-1.0E+02	3.7E-11
0.07	5.0E-14	-1.3E+02	4.6E+01	4.1E-02	-8.1E+01	3.6E-11
0.08	5.0E-14	-1.1E+02	4.6E+01	4.8E-02	-6.7E+01	3.5E-11
0.09	5.0E-14	-1.0E+02	4.7E+01	5.5E-02	-5.5E+01	3.5E-11
0.1	5.0E-14	-9.3E+01	4.8E+01	6.2E-02	-4.5E+01	3.4E-11
0.2	5.0E-14	-5.2E+01	5.3E+01	1.4E-01	1.6E+00	3.2E-11
0.3	5.0E-14	-3.7E+01	5.6E+01	2.2E-01	2.0E+01	3.2E-11
0.4	5.0E-14	-2.9E+01	5.9E+01	3.0E-01	3.1E+01	3.1E-11
0.5	5.0E-14	-2.4E+01	6.1E+01	3.9E-01	3.8E+01	3.1E-11
0.6	5.0E-14	-2.0E+01	6.2E+01	4.9E-01	4.3E+01	3.1E-11
0.7	5.0E-14	-1.8E+01	6.4E+01	5.8E-01	4.7E+01	3.0E-11
0.8	5.0E-14	-1.6E+01	6.5E+01	6.7E-01	5.0E+01	3.0E-11
0.9	5.0E-14	-1.4E+01	6.6E+01	7.7E-01	5.3E+01	3.0E-11
1	5.0E-14	-1.3E+01	6.7E+01	8.7E-01	5.5E+01	3.0E-11
2	5.0E-14	-7.3E+00	7.5E+01	1.9E+00	6.9E+01	2.9E-11
3	5.0E-14	-5.1E+00	7.9E+01	3.1E+00	7.7E+01	2.9E-11
5	5.0E-14	-3.3E+00	8.5E+01	5.5E+00	8.8E+01	2.9E-11
10	5.0E-14	-1.8E+00	9.4E+01	1.2E+01	1.0E+02	2.8E-11
300	5.0E-14	-1.0E-01	1.6E+02	6.0E+02	7.6E+02	0.0E+00

Table D-10d. Frequency (F) of Cratering above Repository for TSPA-SR Design (Continued)

TSPA-SR Repository	L=8.6		W=1.3		V=20 km/s	
Crater Diameter *D* (km)	**K**	**$\frac{LWD^k}{k}$**	**$\frac{(L+W)(D^{k+1})}{k+1}$**	**$\frac{D^{k+2}}{k+2}$**	**F(*D*) (sum of terms)**	**kK(F(*D*)-F(*D*)$_{max}$)**
GRIEVE DISTRIBUTION						
			K=1.20 E-12		k=-1.8	
0.001	1.20E-12	-1.6E+06	-3.1E+03	1.3E+00	-1.6E+06	3.4E-06
0.01	1.20E-12	-2.5E+04	-4.9E+02	2.0E+00	-2.5E+04	5.5E-08
0.03	1.20E-12	-3.4E+03	-2.0E+02	2.5E+00	-3.6E+03	7.9E-09
0.04	1.20E-12	-2.0E+03	-1.6E+02	2.6E+00	-2.2E+03	4.8E-09
0.08	1.20E-12	-5.9E+02	-9.3E+01	3.0E+00	-6.8E+02	1.5E-09
0.1	1.20E-12	-3.9E+02	-7.8E+01	3.2E+00	-4.7E+02	1.0E-09
0.3	1.20E-12	-5.4E+01	-3.2E+01	3.9E+00	-8.3E+01	2.1E-10
0.7	1.20E-12	-1.2E+01	-1.6E+01	4.7E+00	-2.4E+01	8.5E-11
1	1.20E-12	-6.2E+00	-1.2E+01	5.0E+00	-1.4E+01	6.3E-11
10	1.20E-12	-9.8E-02	-2.0E+00	7.9E+00	5.9E+00	2.1E-11
100	1.20E-12	-1.6E-03	-3.1E-01	1.3E+01	1.2E+01	7.1E-12
300	1.20E-12	-2.2E-04	-1.3E-01	1.6E+01	1.6E+01	0.0E+00

WUSCHKE ET AL. DISTRIBUTION					
Crater Diameter *D* (km)	**Adjusted L (km)**	**Adjusted W (km)**	**Adjusted Area (km^2)**	**D^{-2}**	**F**
0.001	8.60	1.30	11.2	1.0E+06	2.2E-05
0.01	8.61	1.31	11.3	1.0E+04	2.3E-07
0.03	8.63	1.33	11.5	1.1E+03	2.6E-08
0.04	8.64	1.34	11.6	6.3E+02	1.4E-08
0.08	8.68	1.38	12.0	1.6E+02	3.7E-09
0.1	8.70	1.40	12.2	1.0E+02	2.4E-09
0.3	8.90	1.60	14.2	1.1E+01	3.2E-10
0.7	9.30	2.00	18.6	2.0E+00	7.6E-11
1	9.6	2.3	22.1	1.0E+00	4.4E-11
10	18.6	11.3	210.2	1.0E-02	4.2E-12
100	109	101	11001	1.0E-04	2.2E-12
300	309	301	92981	1.1E-05	2.1E-12

NOTES:

For distribution curves:

$$F = k\,K\left(\frac{LW(D)^k}{k} + \frac{(L+W)(D)^{k+1}}{k+1} + \frac{(D)^{k+2}}{k+2}\right)\Bigg|_{0.001}^{max}$$

where:

F = events per year
K = proportionality constant (from regression equation)
k = power of the distribution (from regression equation)

L = length of repository (km)
W = width of the repository (km)
D = diameter of crater (km)

For Wuschke et al.: $F = 2.0 \times 10^{-12} \times D^{-2} \times (L_{adjusted} \times W_{adjusted})$

Table D-11. Spreadsheet Example: Calculation of Distribution Curves for V = 15 km/s

Repository L= 8.6 W= 1.3

From Regression Analysis Equation: K= '=Regression Analyses'!E20 k=='Regression Analyses'!E19

	K		**Coefficients for Power Distribution - Upper Curve**			
D(15)	**=E3**	**=G3**	**=C6+1**	**=C6+2**	**Sum of Terms**	**F**
0.001	=$B$6	=($C$1*$E$1*A8^$C$6)/$C$6	=($C$1+$E$1)*(A8^$D$6)/$D$6	=A8^$E$6/$E$6	=SUM(C8:E8)	=$C$6*B8*(F8-$F$23)
0.002	=$B$6	=($C$1*$E$1*A9^$C$6)/$C$6	=($C$1+$E$1)*(A9^$D$6)/$D$6	=A9^$E$6/$E$6	=SUM(C9:E9)	=$C$6*B9*(F9-$F$23)
0.005	=$B$6	=($C$1*$E$1*A10^$C$6)/$C$6	=($C$1+$E$1)*(A10^$D$6)/$D$6	=A10^$E$6/$E$6	=SUM(C10:E10)	=$C$6*B10*(F10-$F$23)
0.007	=$B$6	=($C$1*$E$1*A11^$C$6)/$C$6	=($C$1+$E$1)*(A11^$D$6)/$D$6	=A11^$E$6/$E$6	=SUM(C11:E11)	=$C$6*B11*(F11-$F$23)
0.009	=$B$6	=($C$1*$E$1*A12^$C$6)/$C$6	=($C$1+$E$1)*(A12^$D$6)/$D$6	=A12^$E$6/$E$6	=SUM(C12:E12)	=$C$6*B12*(F12-$F$23)
0.01	=$B$6	=($C$1*$E$1*A13^$C$6)/$C$6	=($C$1+$E$1)*(A13^$D$6)/$D$6	=A13^$E$6/$E$6	=SUM(C13:E13)	=$C$6*B13*(F13-$F$23)
0.02	=$B$6	=($C$1*$E$1*A14^$C$6)/$C$6	=($C$1+$E$1)*(A14^$D$6)/$D$6	=A14^$E$6/$E$6	=SUM(C14:E14)	=$C$6*B14*(F14-$F$23)
0.03	=$B$6	=($C$1*$E$1*A15^$C$6)/$C$6	=($C$1+$E$1)*(A15^$D$6)/$D$6	=A15^$E$6/$E$6	=SUM(C15:E15)	=$C$6*B15*(F15-$F$23)
0.04	=$B$6	=($C$1*$E$1*A16^$C$6)/$C$6	=($C$1+$E$1)*(A16^$D$6)/$D$6	=A16^$E$6/$E$6	=SUM(C16:E16)	=$C$6*B16*(F16-$F$23)
0.05	=$B$6	=($C$1*$E$1*A17^$C$6)/$C$6	=($C$1+$E$1)*(A17^$D$6)/$D$6	=A17^$E$6/$E$6	=SUM(C17:E17)	=$C$6*B17*(F17-$F$23)
0.06	=$B$6	=($C$1*$E$1*A18^$C$6)/$C$6	=($C$1+$E$1)*(A18^$D$6)/$D$6	=A18^$E$6/$E$6	=SUM(C18:E18)	=$C$6*B18*(F18-$F$23)
0.07	=$B$6	=($C$1*$E$1*A19^$C$6)/$C$6	=($C$1+$E$1)*(A19^$D$6)/$D$6	=A19^$E$6/$E$6	=SUM(C19:E19)	=$C$6*B19*(F19-$F$23)
0.08	=$B$6	=($C$1*$E$1*A20^$C$6)/$C$6	=($C$1+$E$1)*(A20^$D$6)/$D$6	=A20^$E$6/$E$6	=SUM(C20:E20)	=$C$6*B20*(F20-$F$23)
0.1	=$B$6	=($C$1*$E$1*A23^$C$6)/$C$6	=($C$1+$E$1)*(A23^$D$6)/$D$6	=A23^$E$6/$E$6	=SUM(C23:E23)	=$C$6*B23*(F23-$F$23)

Table D-11. Spreadsheet Example: Calculation of Distribution Curves for V = 15 km/s (Continued)

From Regression Analysis Equation: K= ='Regression Analyses'!E45 k=='Regression Analyses'!E44

	K		**Coefficients for Power Distribution - Lower Curve**			
D(15)	**=E26**	**=G26**	**=C28+1**	**=C28+2**	**Sum of Terms**	**F**
0.09	=$B$28	=($C$1*$E$1*A30^$C$28)/$C$28	=($C$1+$E$1)*(A30^$D$28)/$D$28	=A30^$E$28/$E$28	=SUM(C30:E30)	=$C$28*B30*(F30-$F$45)
0.1	=$B$28	=($C$1*$E$1*A31^$C$28)/$C$28	=($C$1+$E$1)*(A31^$D$28)/$D$28	=A31^$E$28/$E$28	=SUM(C31:E31)	=$C$28*B31*(F31-$F$45)
0.2	=$B$28	=($C$1*$E$1*A32^$C$28)/$C$28	=($C$1+$E$1)*(A32^$D$28)/$D$28	=A32^$E$28/$E$28	=SUM(C32:E32)	=$C$28*B32*(F32-$F$45)
0.3	=$B$28	=($C$1*$E$1*A33^$C$28)/$C$28	=($C$1+$E$1)*(A33^$D$28)/$D$28	=A33^$E$28/$E$28	=SUM(C33:E33)	=$C$28*B33*(F33-$F$45)
0.4	=$B$28	=($C$1*$E$1*A34^$C$28)/$C$28	=($C$1+$E$1)*(A34^$D$28)/$D$28	=A34^$E$28/$E$28	=SUM(C34:E34)	=$C$28*B34*(F34-$F$45)
0.5	=$B$28	=($C$1*$E$1*A35^$C$28)/$C$28	=($C$1+$E$1)*(A35^$D$28)/$D$28	=A35^$E$28/$E$28	=SUM(C35:E35)	=$C$28*B35*(F35-$F$45)
0.6	=$B$28	=($C$1*$E$1*A36^$C$28)/$C$28	=($C$1+$E$1)*(A36^$D$28)/$D$28	=A36^$E$28/$E$28	=SUM(C36:E36)	=$C$28*B36*(F36-$F$45)
0.7	=$B$28	=($C$1*$E$1*A37^$C$28)/$C$28	=($C$1+$E$1)*(A37^$D$28)/$D$28	=A37^$E$28/$E$28	=SUM(C37:E37)	=$C$28*B37*(F37-$F$45)
0.8	=$B$28	=($C$1*$E$1*A38^$C$28)/$C$28	=($C$1+$E$1)*(A38^$D$28)/$D$28	=A38^$E$28/$E$28	=SUM(C38:E38)	=$C$28*B38*(F38-$F$45)
0.9	=$B$28	=($C$1*$E$1*A39^$C$28)/$C$28	=($C$1+$E$1)*(A39^$D$28)/$D$28	=A39^$E$28/$E$28	=SUM(C39:E39)	=$C$28*B39*(F39-$F$45)
1	=$B$28	=($C$1*$E$1*A40^$C$28)/$C$28	=($C$1+$E$1)*(A40^$D$28)/$D$28	=A40^$E$28/$E$28	=SUM(C40:E40)	=$C$28*B40*(F40-$F$45)
2	=$B$28	=($C$1*$E$1*A41^$C$28)/$C$28	=($C$1+$E$1)*(A41^$D$28)/$D$28	=A41^$E$28/$E$28	=SUM(C41:E41)	=$C$28*B41*(F41-$F$45)
3	=$B$28	=($C$1*$E$1*A42^$C$28)/$C$28	=($C$1+$E$1)*(A42^$D$28)/$D$28	=A42^$E$28/$E$28	=SUM(C42:E42)	=$C$28*B42*(F42-$F$45)
5	=$B$28	=($C$1*$E$1*A43^$C$28)/$C$28	=($C$1+$E$1)*(A43^$D$28)/$D$28	=A43^$E$28/$E$28	=SUM(C43:E43)	=$C$28*B43*(F43-$F$45)
10	=$B$28	=($C$1*$E$1*A44^$C$28)/$C$28	=($C$1+$E$1)*(A44^$D$28)/$D$28	=A44^$E$28/$E$28	=SUM(C44:E44)	=$C$28*B44*(F44-$F$45)
300	=$B$28	=($C$1*$E$1*A45^$C$28)/$C$28	=($C$1+$E$1)*(A45^$D$28)/$D$28	=A45^$E$28/$E$28	=SUM(C45:E45)	=$C$28*B45*(F45-$F$45)

Table D-12. Spreadsheet Example: Calculation of Distribution Curves for V = 20 km/s

Repository L= 8.6 W= 1.3

From Regression Analysis Equation: K= ='Regression Analyses'!P20 k=='Regression Analyses'!P19

D(20)	**K**	**Coefficients for Power Distribution - Upper Curve**				
	=E3	**=G3**	**=C6+1**	**=C6+2**	**Sum of Terms**	**F**
0.001	=$B$6	=($C$1*$E$1*A8^$C$6)/$C$6	=($C$1+$E$1)*(A8^$D$6)/$D$6	=A8^$E$6/$E$6	=SUM(C8:E8)	=$C$6*B8*(F8-$F$15)
0.003	=$B$6	=($C$1*$E$1*A9^$C$6)/$C$6	=($C$1+$E$1)*(A9^$D$6)/$D$6	=A9^$E$6/$E$6	=SUM(C9:E9)	=$C$6*B9*(F9-$F$15)
0.005	=$B$6	=($C$1*$E$1*A10^$C$6)/$C$6	=($C$1+$E$1)*(A10^$D$6)/$D$6	=A10^$E$6/$E$6	=SUM(C10:E10)	=$C$6*B10*(F10-$F$15)
0.006	=$B$6	=($C$1*$E$1*A11^$C$6)/$C$6	=($C$1+$E$1)*(A11^$D$6)/$D$6	=A11^$E$6/$E$6	=SUM(C11:E11)	=$C$6*B11*(F11-$F$15)
0.008	=$B$6	=($C$1*$E$1*A12^$C$6)/$C$6	=($C$1+$E$1)*(A12^$D$6)/$D$6	=A12^$E$6/$E$6	=SUM(C12:E12)	=$C$6*B12*(F12-$F$15)
0.01	=$B$6	=($C$1*$E$1*A13^$C$6)/$C$6	=($C$1+$E$1)*(A13^$D$6)/$D$6	=A13^$E$6/$E$6	=SUM(C13:E13)	=$C$6*B13*(F13-$F$15)
0.02	=$B$6	=($C$1*$E$1*A14^$C$6)/$C$6	=($C$1+$E$1)*(A14^$D$6)/$D$6	=A14^$E$6/$E$6	=SUM(C14:E14)	=$C$6*B14*(F14-$F$15)
0.04	=$B$6	=($C$1*$E$1*A15^$C$6)/$C$6	=($C$1+$E$1)*(A15^$D$6)/$D$6	=A15^$E$6/$E$6	=SUM(C15:E15)	=$C$6*B15*(F15-$F$15)

Table D-12. Spreadsheet Example: Calculation of Distribution Curves for V = 20 km/s (Continued)

From Regression Analysis Equation: K= ='Regression Analyses'!P45 k== 'Regression Analyses'!P44

D(20)	**K**	**Coefficients for Power Distribution - Lower Curve**				
	=E18	**=G18**	**=C21+1**	**=C21+2**	**Sum of Terms**	**F**
0.03	=$B$21	=($C$1*$E$1*A23^$C$21)/$C$21	=($C$1+$E$1)*(A23^$D$21)/$D$21	=A23^$E$21/$E$21	=SUM(C23:E23)	=$C$21*B23*(F23-$F$44)
0.04	=$B$21	=($C$1*$E$1*A24^$C$21)/$C$21	=($C$1+$E$1)*(A24^$D$21)/$D$21	=A24^$E$21/$E$21	=SUM(C24:E24)	=$C$21*B24*(F24-$F$44)
0.05	=$B$21	=($C$1*$E$1*A25^$C$21)/$C$21	=($C$1+$E$1)*(A25^$D$21)/$D$21	=A25^$E$21/$E$21	=SUM(C25:E25)	=$C$21*B25*(F25-$F$44)
0.06	=$B$21	=($C$1*$E$1*A26^$C$21)/$C$21	=($C$1+$E$1)*(A26^$D$21)/$D$21	=A26^$E$21/$E$21	=SUM(C26:E26)	=$C$21*B26*(F26-$F$44)
0.07	=$B$21	=($C$1*$E$1*A27^$C$21)/$C$21	=($C$1+$E$1)*(A27^$D$21)/$D$21	=A27^$E$21/$E$21	=SUM(C27:E27)	=$C$21*B27*(F27-$F$44)
0.08	=$B$21	=($C$1*$E$1*A28^$C$21)/$C$21	=($C$1+$E$1)*(A28^$D$21)/$D$21	=A28^$E$21/$E$21	=SUM(C28:E28)	=$C$21*B28*(F28-$F$44)
0.09	=$B$21	=($C$1*$E$1*A29^$C$21)/$C$21	=($C$1+$E$1)*(A29^$D$21)/$D$21	=A29^$E$21/$E$21	=SUM(C29:E29)	=$C$21*B29*(F29-$F$44)
0.1	=$B$21	=($C$1*$E$1*A30^$C$21)/$C$21	=($C$1+$E$1)*(A30^$D$21)/$D$21	=A30^$E$21/$E$21	=SUM(C30:E30)	=$C$21*B30*(F30-$F$44)
0.2	=$B$21	=($C$1*$E$1*A31^$C$21)/$C$21	=($C$1+$E$1)*(A31^$D$21)/$D$21	=A31^$E$21/$E$21	=SUM(C31:E31)	=$C$21*B31*(F31-$F$44)
0.3	=$B$21	=($C$1*$E$1*A32^$C$21)/$C$21	=($C$1+$E$1)*(A32^$D$21)/$D$21	=A32^$E$21/$E$21	=SUM(C32:E32)	=$C$21*B32*(F32-$F$44)
0.4	=$B$21	=($C$1*$E$1*A33^$C$21)/$C$21	=($C$1+$E$1)*(A33^$D$21)/$D$21	=A33^$E$21/$E$21	=SUM(C33:E33)	=$C$21*B33*(F33-$F$44)
0.5	=$B$21	=($C$1*$E$1*A34^$C$21)/$C$21	=($C$1+$E$1)*(A34^$D$21)/$D$21	=A34^$E$21/$E$21	=SUM(C34:E34)	=$C$21*B34*(F34-$F$44)
0.6	=$B$21	=($C$1*$E$1*A35^$C$21)/$C$21	=($C$1+$E$1)*(A35^$D$21)/$D$21	=A35^$E$21/$E$21	=SUM(C35:E35)	=$C$21*B35*(F35-$F$44)
0.7	=$B$21	=($C$1*$E$1*A36^$C$21)/$C$21	=($C$1+$E$1)*(A36^$D$21)/$D$21	=A36^$E$21/$E$21	=SUM(C36:E36)	=$C$21*B36*(F36-$F$44)
0.8	=$B$21	=($C$1*$E$1*A37^$C$21)/$C$21	=($C$1+$E$1)*(A37^$D$21)/$D$21	=A37^$E$21/$E$21	=SUM(C37:E37)	=$C$21*B37*(F37-$F$44)
0.9	=$B$21	=($C$1*$E$1*A38^$C$21)/$C$21	=($C$1+$E$1)*(A38^$D$21)/$D$21	=A38^$E$21/$E$21	=SUM(C38:E38)	=$C$21*B38*(F38-$F$44)
1	=$B$21	=($C$1*$E$1*A39^$C$21)/$C$21	=($C$1+$E$1)*(A39^$D$21)/$D$21	=A39^$E$21/$E$21	=SUM(C39:E39)	=$C$21*B39*(F39-$F$44)
2	=$B$21	=($C$1*$E$1*A40^$C$21)/$C$21	=($C$1+$E$1)*(A40^$D$21)/$D$21	=A40^$E$21/$E$21	=SUM(C40:E40)	=$C$21*B40*(F40-$F$44)
3	=$B$21	=($C$1*$E$1*A41^$C$21)/$C$21	=($C$1+$E$1)*(A41^$D$21)/$D$21	=A41^$E$21/$E$21	=SUM(C41:E41)	=$C$21*B41*(F41-$F$44)
5	=$B$21	=($C$1*$E$1*A42^$C$21)/$C$21	=($C$1+$E$1)*(A42^$D$21)/$D$21	=A42^$E$21/$E$21	=SUM(C42:E42)	=$C$21*B42*(F42-$F$44)
10	=$B$21	=($C$1*$E$1*A43^$C$21)/$C$21	=($C$1+$E$1)*(A43^$D$21)/$D$21	=A43^$E$21/$E$21	=SUM(C43:E43)	=$C$21*B43*(F43-$F$44)
300	=$B$21	=($C$1*$E$1*A44^$C$21)/$C$21	=($C$1+$E$1)*(A44^$D$21)/$D$21	=A44^$E$21/$E$21	=SUM(C44:E44)	=$C$21*B44*(F44-$F$44)

Table D-13. Spreadsheet Example: Formulas for Calculating Grieve Distribution

Repository		L= 8.6		W= 1.3		
Grieve						
	K	k	Coefficient for Power Distribution			
	1.2 E--12	-1.8	=C4+1	=C4+2		
0.001	=$B$4	=($C$1*$E$1*A6^$C$4)/$C$4	=($C$1+$E$1)*(A6^$D$4)/$D$4	=A6^$E$4/$E$4	=SUM(C6:E6)	=$C$4*B6*(F6-$F$17)
0.01	=$B$4	=($C$1*$E$1*A7^$C$4)/$C$4	=($C$1+$E$1)*(A7^$D$4)/$D$4	=A7^$E$4/$E$4	=SUM(C7:E7)	=$C$4*B7*(F7-$F$17)
0.03	=$B$4	=($C$1*$E$1*A8^$C$4)/$C$4	=($C$1+$E$1)*(A8^$D$4)/$D$4	=A8^$E$4/$E$4	=SUM(C8:E8)	=$C$4*B8*(F8-$F$17)
0.04	=$B$4	=($C$1*$E$1*A9^$C$4)/$C$4	=($C$1+$E$1)*(A9^$D$4)/$D$4	=A9^$E$4/$E$4	=SUM(C9:E9)	=$C$4*B9*(F9-$F$17)
0.08	=$B$4	=($C$1*$E$1*A10^$C$4)/$C$4	=($C$1+$E$1)*(A10^$D$4)/$D$4	=A10^$E$4/$E$4	=SUM(C10:E10)	=$C$4*B10*(F10-$F$17)
0.1	=$B$4	=($C$1*$E$1*A11^$C$4)/$C$4	=($C$1+$E$1)*(A11^$D$4)/$D$4	=A11^$E$4/$E$4	=SUM(C11:E11)	=$C$4*B11*(F11-$F$17)
0.3	=$B$4	=($C$1*$E$1*A12^$C$4)/$C$4	=($C$1+$E$1)*(A12^$D$4)/$D$4	=A12^$E$4/$E$4	=SUM(C12:E12)	=$C$4*B12*(F12-$F$17)
0.7	=$B$4	=($C$1*$E$1*A13^$C$4)/$C$4	=($C$1+$E$1)*(A13^$D$4)/$D$4	=A13^$E$4/$E$4	=SUM(C13:E13)	=$C$4*B13*(F13-$F$17)
1	=$B$4	=($C$1*$E$1*A14^$C$4)/$C$4	=($C$1+$E$1)*(A14^$D$4)/$D$4	=A14^$E$4/$E$4	=SUM(C14:E14)	=$C$4*B14*(F14-$F$17)
10	=$B$4	=($C$1*$E$1*A15^$C$4)/$C$4	=($C$1+$E$1)*(A15^$D$4)/$D$4	=A15^$E$4/$E$4	=SUM(C15:E15)	=$C$4*B15*(F15-$F$17)
100	=$B$4	=($C$1*$E$1*A16^$C$4)/$C$4	=($C$1+$E$1)*(A16^$D$4)/$D$4	=A16^$E$4/$E$4	=SUM(C16:E16)	=$C$4*B16*(F16-$F$17)
300	=$B$4	=($C$1*$E$1*A17^$C$4)/$C$4	=($C$1+$E$1)*(A17^$D$4)/$D$4	=A17^$E$4/$E$4	=SUM(C17:E17)	=$C$4*B17*(F17-$F$17)

Table D-14. Spreadsheet Example: Formulas for Calculating Wuschke et al. Distribution

Frequency Calculation and Area Adjustment for Distribution per Wuschke et al. 1995

Repository	L= 8.3		W= 1.3

Crater Diameter (km)	Adjusted L (km)	Adjusted W (km)	Adjusted Area (km2)	D-2	Frequency per year
0.001	=$C$3+A6	=$E$3+A6	=B6*C6	=A6^-2	=D6*E6*0.000000000002
0.01	=$C$3+A7	=$E$3+A7	=B7*C7	=A7^-2	=D7*E7*0.000000000002
0.03	=$C$3+A8	=$E$3+A8	=B8*C8	=A8^-2	=D8*E8*0.000000000002
0.04	=$C$3+A9	=$E$3+A9	=B9*C9	=A9^-2	=D9*E9*0.000000000002
0.08	=$C$3+A10	=$E$3+A10	=B10*C10	=A10^-2	=D10*E10*0.000000000002
0.1	=$C$3+A11	=$E$3+A11	=B11*C11	=A11^-2	=D11*E11*0.000000000002
0.3	=$C$3+A12	=$E$3+A12	=B12*C12	=A12^-2	=D12*E12*0.000000000002
0.7	=$C$3+A13	=$E$3+A13	=B13*C13	=A13^-2	=D13*E13*0.000000000002
1	=$C$3+A14	=$E$3+A14	=B14*C14	=A14^-2	=D14*E14*0.000000000002
10	=$C$3+A15	=$E$3+A15	=B15*C15	=A15^-2	=D15*E15*0.000000000002
100	=$C$3+A16	=$E$3+A16	=B16*C16	=A16^-2	=D16*E16*0.000000000002
300	=$C$3+A17	=$E$3+A17	=B17*C17	=A17^-2	=D17*E17*0.000000000002

D3.4 UNCERTAINTY CONSIDERATIONS

Uncertainties for the meteorite impact analysis include both epistemic and aleatory uncertainties. Aleatory uncertainties in the physical properties of observed objects (e.g., density, velocities, diameters, angle of entry) are inherent in assuming such values for calculating meteor radius. Epistemic uncertainties are reflected in the distributions used for the mass flux and for the percentage of types of meteors that occur within the entire population of possible earth interceptors. This is due to observations of only a limited number of objects over a very short period compared to that involved in determining crater rate distributions.

The evaluation approach used to define the probability distribution can include consideration of probability of impact of known objects, probabilities based on empirical cratering observations from the lunar and earth's surface, or determination of probabilities based on meteor flux to the earth's atmosphere. The first option, impact of known objects, is only of limited use because space surveys are currently incomplete, and there are large uncertainties that influence the probability calculations. However, it does serve as a corroborative checkpoint for comparison for any other derived values. For the second option, empirical crater observations, uncertainties stem from uncertainty in the age of observed craters, uncertainties regarding overprinting from multiple impacts in a given area, and extrapolations required to account for differences in atmospheric and gravitational effects. In the case of earth cratering studies, the limitations also include the destruction of small diameter craters through time and/or limitations in identification of such features. For the last option, a crater distribution based on meteor flux, the analysis encounters uncertainties in accounting for multiple factors. These factors include the distribution of the mass and diameter of the meteoroids, the distribution in composition of meteoroids, the velocity of the meteoroids, their entry angle into the earth's atmosphere, and effects encountered by the meteor during passage through Earth's atmosphere (ablation and fragmentation). Each of the factors (mass or size, material, velocity, angle, and atmospheric effects) determines the kinetic energy with which the meteorite impacts the earth, and thereby influences the resulting crater diameter and depth.

The curve derived from Grieve in Figure D-3 is based on extrapolation of observable earth cratering data, but its limitation is for crater diameters larger than 10 km. For this analysis, however, the slope of the Grieve distribution was assumed constant even for the smaller crater diameters. The extrapolation of the distribution from Grieve (1998 [DIRS 163385]) for very small crater diameters likely overestimates the number of small-diameter craters, and is therefore conservative (i.e., the number of small cratering events may be overestimated in the calculation) due to the extrapolation of the curve. The number of observed small diameter craters as noted by Grieve's is substantially less than that projected by the extrapolated distribution, and would in fact be the true lower bound. The degree of conservatism, however, cannot be quantified because the number of observed small diameter craters is skewed because it does not account for atmospheric effects on small meteors, increased obscuration of smaller diameter craters by weathering and burial, and the implicit difficulty in identifying small diameter craters. The crater diameter distribution observed by Grieve and based on large crater diameters, however, at least includes the effects of ablation and fragmentation as reflected for large diameter craters.

The curve from Wuschke et al. (1995 [DIRS 129326]) is based on a subset of the Grieve information and, if comparable to the information used by Hughes (1998 [DIRS 162562]) may only be valid down to diameters of 1 km. The data derived from Wuschke et al. (1995 [DIRS 129326]) may represent a more realistic distribution of actual size and has been applied to a hypothetical Canadian repository.

Furthermore, the curves derived from the cumulative flux data in Figure D-3, and based on the modeling results from Hills and Goda (1993 [DIRS 135281], Figures 16 and 17), are dependent on the assumptions regarding composition, assumed densities, and the relative composition of the cumulative flux. The cumulative flux curves overstate the frequency of impact resulting in a given crater diameter if the relative percent of iron meteorites is lower and/or the percent of carbonaceous meteorites is greater than that assumed. Also, these curves likely overstate the frequency because it is assumed that the entire flux enters earth’s atmosphere at angles that result in the least atmospheric dissipation.

With regard to the flux of meteoroids to earth, the reported values of the cumulative number of events for a meteoroid of a given diameter or larger is provided in Figure B-1 of Appendix B of this analysis report and spans approximately two orders of magnitude, with the range in values decreasing slightly for meteor diameters on the order of 1,000 meters or greater. For the analysis, a conservative set of data for the range of interest was selected. Use of a different data set would likely result in a decreased rate of cratering of a given diameter, although the relationship is not linear due to atmospheric shield effects.

There is a large uncertainty associated with the distribution of meteoroids based on composition as shown in Table B-13 of Appendix B. Selection of a distribution that prefers a cometary composition would tend to decrease the probability of given crater diameter due to the greater effect of atmospheric shielding effects on cometary and soft stone meteoroids for a given diameter. Similarly, decreased percentage of iron meteoroids (Table B-14 of Appendix B) would also tend to decrease the cratering rate for a given diameter because iron meteors are stronger and more dense that stony meteors of the same diameter and result in larger crater diameters. A reasonable, but conservative, value of 5 percent iron meteors was selected to minimize the effects of uncertainty in the percent irons. The selected value is thought conservative, because as shown in Table B-14 of Appendix B of this analysis report, the average of the reported values was 5 percent, but only 4 of 13 of the reported values exceeded 5 percent. These higher values are likely biased because they are based on meteorite finds and iron-type meteorites are more likely to be found. One value (17.8 percent) drives the average. Excluding the extreme value of 17.8 results in an average value of 3.9 percent. For the stony/cometary percentages, an equal distribution was used for larger diameters, and a decreased percentage of stony material was used for the small masses and diameters. Selection of a more equal distribution would increase the crater diameter rates, although the increase would not be linear due to the continued effects of atmospheric shielding effects (albeit shifted based on initial diameter). However, the use of the more conservative value of 5 percent for iron meteors may also compensate in part for a preferred cometary composition for smaller meteoroids.

There is also uncertainty associated with meteoroid densities. In reality, meteoroid densities likely show some type of modal distributions based on parent bodies and origin, and vary according the range of compositions considered. The range of values from the literature search is provided in Table B-15 of Appendix B of this analysis report. To simplify the calculation, the compositions were binned into three types (metallic, stony, and carbonaceous) and reasonable but conservative values for density were assigned for each type as previously. The calculation is structured in such a way that increases or decreases in assumed density would directly affect the calculated radius of a meteoroid of a given mass, with an increase in density leading to decreased equivalent meteoroid radius. A decrease in the density by a factor of two would increase the calculated meteoroid radius by a factor of only about 1.3. A decrease in initial meteoroid radius generally would result in a decreased resulting crater diameter.

Additionally, there is little information regarding the distribution of initial velocities or entry angle of meteoroids impacting the earth's surface, although upper and lower bounds for the distributions could be established. These uncertainties are addressed, by assuming conservative values for both factors, as described for Assumption 5.4.

Regardless of the uncertainty in physical property distributions, the net effects of uncertainty are partially addressed by comparing the cratering distribution derived from meteoroid influx, to those derived based on lunar cratering rates and on observed earth cratering rates. The lunar-and earth-based cratering rates respectively represent a true upper bound, and a reasonable lower bound on cratering rates. These distributions of observed features reflect the net effect of all uncertainties in physical property distributions on the resulting crater diameter distributions. However, for crater diameters less than about 10 km, there is a high degree of uncertainty with regard to the actual cratering rate due to the inability to detect smaller scale features, and due to the destruction of smaller scale crater diameters by natural processes acting over prolonged time periods.

D4. IMPLICATIONS FOR FEP SCREENING AND CONCLUSIONS

The probability of the occurrence of crater diameters of interest (i.e., the diameters that define whether the repository is affected by direct exhumation, fracturing to repository depth, or fracturing of other overlying units of interest) is compared to the FEP screening threshold diameter of one chance in 10,000 of occurring in 10,000 years (or an annualized occurrence of 10^{-8}). If the probability of occurrence is less than this threshold, the effect can be excluded from further consideration in TSPA-LA. If not, then the effect is examined for "significance." If it can be demonstrated that the omission of the effect would not significantly change radionuclide exposure or release to the accessible environment, then the effect can be excluded from further consideration in TSPA-LA.

As shown on Figure D-7, the probability of the formation of crater diameters above or near the repository that is sufficient to result in exhumation and/or fracturing to the depth of the repository falls below the FEP screening probability threshold. Likewise, exhumation and/or fracturing to the top of the Paintbrush hydrologic unit above or near the repository is also excluded because the occurrence of such craters falls below the FEP screening probability threshold. This holds true for each of the cratering distributions considered for all but the easternmost portion of the repository. Figure D-8 addresses the potential for cratering in the Paintbrush hydrologic unit outcrop area, which is discussed separately.

Figure D-7 indicates that at an annualized probability of 10^{-8}, the corresponding crater diameter resulting from impact of the largest meteor fragment is likely to range from 20 to 80 m. The 80-m diameter represents the minimum diameter needed to fracture to the depth of the PTn unit in the easternmost portion of the repository, where the unit is shallowest, and is taken from the V=15 km/sec distribution curve. The other distribution curves indicate lesser crater diameters, suggesting that meteorite impact is of low consequence. An 80-m crater diameter corresponds to a maximum total surface area of about 0.005 km^2, or about 0.04 percent of the repository surface area of 14 km^2 for any crater resulting from the largest fragment (Hills and Goda 1993 [DIRS 135281], Figure 17). Assuming a hard stone composition, this crater diameter is associated with an initial meteor radius on the order of 50 m to 100 m, based on Hills and Goda (1993 [DIRS 135281], Figure 17), as reflected in Figure B-4b of Appendix B of this analysis report. Based on Hills and Goda (1993 [DIRS 135281], Figure 9), the radius of the associated debris swarm (i.e., the degree of scatter of all fragments, but with lesser cratering effects, if any, than the largest fragment and thus incapable of fracturing to top of the PTn or deeper) is on the order of 0.4 to 0.5 km. This suggests a debris and/or crater field with a total encompassing area of approximately 0.5 to 0.8 km^2, but with a pock-marked surface – some portion of the area is affected and some is not depending on the number of size of other fragments. This suggests that at most, only 4 to 6 percent of the total surface area of the repository (and likely significantly less) is even, potentially affected. This suggests that an argument for exclusion based on low consequence may also appropriate depending on modeling sensitivity and relative model grid size.

With regard to the Paintbrush hydrologic unit outcrop area, the probability threshold is shown on Figure D-8. The figure indicates that resulting crater diameters at the probability threshold would be less than 20 m. This represents a surface area of less than 0.001 km^2, or less than 0.01 percent, of the repository surface area. The resulting effects from the radius of the debris swarm would be at the lower end of the scale of the effects just discussed. Although the total affected area would be about the same, the width of the outcrop area is no greater than 0.1 km, thus limiting the outcrop area affected by the debris swarm to no more than 0.03 km^2. This would represent less than one-half percent of the repository surface area. Accordingly, this aspect of meteorite impact can also be excluded based on low consequence.

Such meteors could results in earthquakes with Richter magnitudes ranging from Magnitude 5 to slightly less than Magnitude 7 (Richter Scale) (Hills and Goda 1993 [DIRS 135281], Figure 18). Existing seismic analyses cover this range of magnitude of events, so a meteorite-caused earthquake component would not provide additional significant hazard and is, therefore, excluded based on low consequence.

A comparison of the annualized frequency curves for the three repository designs (Figures D-7, D-9, and D-10) indicate that there are only minor differences in probability estimates despite seemingly significant changes in the total area and the respective dimensions. The total footprint area varies from 11.2 km^2 for the TSPA-SR design, to 1 km^2 based on the TSPA-LA emplacement area, and as large as 18 km2 based on the TSPA-LA siting area. For sensitivity considerations, the probabilities derived for the Wuschke et al. distribution is further examined because it represents a constant slope in the distribution curve. For an 80 m diameter crater, the respective probabilities for the above-listed areas were calculated to be 3.7×10^{-9}, 3.9×10^{-9}, and 4.6×10^{-9}. Consequently, the range of total areas increased from the TSPA-SR repository footprint by factors of 1.25 and 1.6 respectively, but the probabilities increased by factors of 1.05 and 1.24, respectively. And with respect to the TSPA-LA emplacement area, the siting area increases by a factor of 1.29 and the probability increased by a factor of about 1.18. Thus, excluding consideration of the V=15 km/sec distribution curve, at least a doubling of the repository footprint area used for evaluating TSPA-LA would be needed before probability based on the Wuschke et al. distribution would be of concern. However, if the V=15 km/sec curve is limiting, then expansion of areas greater than that currently considered would dictate further evaluation of the consequence for potential fracturing of the PTn unit, and expansion of the repository into areas where the PTn was shallower than 60 m or non-existent would also require further examination.

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