efficiently and safely. Several activities were conducted which directly impacted the material handling and the facility layouts as they developed during the course of the ACD. It should be recognized that these efforts will be needed throughout the entire course of the MGDS design including verification during and following construction.

10.3 INDUSTRIAL SAFETY

The safety of workers and members of the public is of paramount importance for the MGDS. This means designing and operating a system that allows for continued management, handling, transfer, storage, emplacement, retrieval, and isolation of spent nuclear fuel and high level waste in a safe manner that optimally protects health, safety, and the environment under all operational conditions.

10.3.1 Policy and Process

The safety and health of workers on the project receives the highest priority. For MGDS construction and operation, both radiological safety and occupational safety and health plans and procedures are followed. Radiological control for normal operating conditions is achieved primarily through design by employing the ALARA principle. For off-normal radiological events or accidents, DBE/Design Basis Accident (DBA) analyses are used along with Probabilistic Risk Assessments, where appropriate. Occupational safety and health is addressed by application of, primarily, Occupational Safety and Health Administration standards 29 CFR 1910 and 29 CFR 1926, and Mining Safety and Health Administration standard 30 CFR 57, supplemented by other standards as appropriate to achieve an adequate level of protection for the workers as, for example, in the *Safety and Health Plan* (YMP 1995c). Consideration of safety begins at the design with YAP-30.48, *System Safety Analysis*, as described by the *System Safety Plan* (YMP 1995f). Preliminary Hazards Analyses are used to identify and mitigate hazards and this analytical process continues down to job task level which uses Job Safety Analysis methodology to assure worker protection.

10.3.2 Previous and Ongoing Work

Providing for the safety and health of workers and operating personnel on the project has already been incorporated for the ESF and is the result of an integrated interdisciplinary effort that directly affects design as well as operating practices.

These safety efforts continue for the MGDS and are not only integrated from a design discipline and operational standpoint but from a radiological and non-radiological standpoint as well. Design efforts concerning ALARA (Section 10.2, Vol. II) and DBEs and DBAs are also coordinated (Section 10.1, Vol. II). For example, the Preliminary Hazards Analysis is used as the focal point for surface, subsurface, and Waste Package (Section 8, Vol III) DBEs/DBAs from a radiological standpoint. The same Preliminary Hazards Analysis is used for non-radiological safety in the form of a System Safety Analysis to insure thoroughness and consistency. Other related deliverables being conducted in parallel are the *Preliminary MGDS System Safety Analysis* (CRWMS M&O 1996b) and the *Waste Package Off-Normal and Accident Scenario Report* (CRWMS M&O 1996c).

9902240288 Part 5 of 7

efficiently and safely. Several activities were conducted which directly impacted the material handling and the facility layouts as they developed during the course of the ACD. It should be recognized that these efforts will be needed throughout the entire course of the MGDS design including verification during and following construction.

10.3 INDUSTRIAL SAFETY

The safety of workers and members of the public is of paramount importance for the MGDS. This means designing and operating a system that allows for continued management, handling, transfer, storage, emplacement, retrieval, and isolation of spent nuclear fuel and high level waste in a safe manner that optimally protects health, safety, and the environment under all operational conditions.

10.3.1 Policy and Process

The safety and health of workers on the project receives the highest priority. For MGDS construction and operation, both radiological safety and occupational safety and health plans and procedures are followed. Radiological control for normal operating conditions is achieved primarily through design by employing the ALARA principle. For off-normal radiological events or accidents, DBE/Design Basis Accident (DBA) analyses are used along with Probabilistic Risk Assessments, where appropriate. Occupational safety and health is addressed by application of, primarily, Occupational Safety and Health Administration standards 29 CFR 1910 and 29 CFR 1926, and Mining Safety and Health Administration standard 30 CFR 57, supplemented by other standards as appropriate to achieve an adequate level of protection for the workers as, for example, in the *Safety and Health Plan* (YMP 1995c). Consideration of safety begins at the design with YAP-30.48, *System Safety Analysis*, as described by the *System Safety Plan* (YMP 1995f). Preliminary Hazards Analyses are used to identify and mitigate hazards and this analytical process continues down to job task level which uses Job Safety Analysis methodology to assure worker protection.

10.3.2 Previous and Ongoing Work

Providing for the safety and health of workers and operating personnel on the project has already been incorporated for the ESF and is the result of an integrated interdisciplinary effort that directly affects design as well as operating practices.

These safety efforts continue for the MGDS and are not only integrated from a design discipline and operational standpoint but from a radiological and non-radiological standpoint as well. Design efforts concerning ALARA (Section 10.2, Vol. II) and DBEs and DBAs are also coordinated (Section 10.1, Vol. II) . For example, the Preliminary Hazards Analysis is used as the focal point for surface, subsurface, and Waste Package (Section 8, Vol III) DBEs/DBAs from a radiological standpoint. The same Preliminary Hazards Analysis is used for non-radiological safety in the form of a System Safety Analysis to insure thoroughness and consistency. Other related deliverables being conducted in parallel are the *Preliminary MGDS System Safety Analysis* (CRWMS M&O 1996b) and the *Waste Package Off-Normal and Accident Scenario Report* (CRWMS M&O 1996c).

10.3.3 Design Inputs

The following requirements are from the RDRD. Requirements are identified in accordance with the numbering system used in the RDRD.

3.3.6.1 General requirements:

A. All Repository Segment work places shall be designed to be free from recognized hazards that are causing or are likely to cause death or serious physical harm to employees.

B. All Repository Segment work places shall be designed to comply with occupational safety and health standards promulgated under 29 CFR 1910, 29 CFR 1926, and 30 CFR 57.

3.3.6.2 System Safety Precedence

The order of precedence for satisfying system safety requirements and resolving identified hazards shall be as follows:

A. The first priority of design shall be to eliminate hazards. If the hazard cannot be eliminated, the associated risk shall be reduced shall be reduced to an acceptable level through design selection.

B. If identified hazards cannot be eliminated or their associated risks adequately reduced through design selection, that risk shall be reduced through the use of fixed, automatic, or other protective safety design features or devices. when applicable.

C. When neither design nor safety devices can effectively eliminate identified hazards or adequately reduce associated risk, devices shall be used to detect the condition and to produce an adequate warning signal to alert personnel of hazard. Warning signals and their application shall be designed to minimize the probability of incorrect personnel reaction to the signal and shall be standardized within like types of systems.

D. Only where it is impractical to eliminate residual hazards through design selection or adequately reduce the associated risk with safety and warning devices, may procedures and training be used as the only protection.

E. This Section (3.3.6) imposes requirements from 29 CFR 1910, 29 CFR 1926 and 30 CFR 57.

1. 30 CFR 57 shall apply only to underground facilities and equipment and to those mining-related surface facilities and equipment specifically addressed in 30 CFR 57.

2. 29 CFR 1910 and 29 CFR 1926 shall apply to all other surface facilities and equipment. 29 CFR 1910 and 29 CFR 1926 shall also be applied to underground facilities not addressed by 30 CFR 57 and where safety hazards analysis following the precedence in Section 3.3.6.2.A-D deems it necessary.

3.2.5.1.2 Reliability of Equipment

A failure modes and effects analysis shall be performed for all major equipment whose failure can result in personnel injury or illness. Based on this analysis, designs shall be developed to ensure reliability which minimizes safety hazards to the extent possible. Under such design conditions, failures shall not result in personnel injury or occupational illness. If designs cannot be developed to these requirements, then the reliability of systems will be shown by analysis to be such as to minimize the probability of injury or illness to personnel. In demonstrating system reliability, MIL-STD-882B shall be considered in the design, where applicable. (These requirements differ from "items important to safety" and "item important to waste isolation", both of which have very specific meanings for meeting NRC requirements. Further, these criteria do not supplant radiological standards contained in NRC or EPA requirements: e.g., the radiological standards 10 CFR 20).

(MIL-STD-882C is the latest version. The next revision of the RDRD will reflect the latest version.)

10.3.4 Methodology

A general description of the methods used to achieve a high level of industrial safety is contained in the following four activities:

- Establishing precedence
- Conducting and implementing System Safety Analyses
- Complying with regulatory requirements
- Monitoring and verifying.

10.3.4.1 Establishing Precedence (See Subsection 10.3.3)

10.3.4.2 Conducting and Implementing System Safety Analyses

Performing System Safety Analyses and implementing the results is the result of applying the process described in Attachment 9.4 of YAP-30.48, *System Safety Analysis*. The process consists of the following three principal activities:

- Safety Assessment
- Mitigation
- System Safety Working Group.

Safety Assessment: The Safety Assessment activity consists of scenario identification and safety analysis. Safety analysis is comprised of the establishment of system criteria, relevant databases, and application of these criteria to the appropriate design phase. Scenario identification is the detailed description of the identified hazards resulting from Preliminary Hazards Analyses.

Mitigation: Each hazard has one or more mitigations identified which are used to alter the design appropriately or is passed on as a procedural matter to be implemented. The mitigations must reduce the risk to a preselected level of risk.

System Safety Working Group: A System Safety Working group is established for each System Safety Analysis (consisting of designers and safety personnel as a minimum) to establish, review, and evaluate hazardous scenarios prior to sign off.

10.3.4.3 Complying with Regulatory Requirements

Occupational safety and health requirements are primarily derived from compliance with Occupational Safety and Health Administration rules found in Title 29 CFR Part 1900 through 1926. Other standards and regulations are used to supplement the Occupational Safety and Health Administration OSHA rules; their use and application is determined by the DOE Assistant Manager for Environment, Safety, and Health (AMESH) in accordance with the *Safety and Health Plan* (YMP 1995c).

A guiding principle in the use of any selected Occupational Safety and Health Administration standard is as follows: if a particular standard is specifically applicable to a condition, practice, operation or process, it prevails over any other standard that might otherwise be applicable to the same situation.

10.3.4.4 Monitoring and Verifying

Implementation of industrial safety measures is verified through surveillance and inspection of workplaces. Industrial hygiene monitoring is conducted on a continuing basis for workplace environmental agents. Employees are encouraged to bring hazardous conditions or practices to management's attention for correction. Hazardous conditions or practices that are not in compliance with requirements, or accepted safe practices identified in Job Safety Analyses, are corrected by line management. To prevent recurrence, training is conducted on a continuing basis. Regular safety meetings are held to discuss current issues and provide employees with timely information. Trend analysis of injuries and illnesses is performed to determine if the System Safety Analyses and Job Safety Analyses, applicable to the causal conditions, should be reviewed and modified.

10.3.5 Conclusions

The success of the safety efforts for the MGDS will, as in the past require close coordination not only with the design groups but with support analysis groups such as those involved in Waste Package probabilistic evaluations, DBE/DBA analysis, and Performance Assessment/Probabilistic Risk Assessment. At the same time, interfaces need to be maintained between system safety and health and safety to ensure that industrial safety is addressed thoroughly in design as well as operations.

11. OFF-SITE TRANSPORTATION WITHIN NEVADA

The 1995 systems study, *Nevada Potential Repository Preliminary Transportation Strategy Study 2* (CRWMS M&O 1995ax), recommended four rail routes for consideration as alternatives for the transportation of radioactive waste to the proposed repository at Yucca Mountain, Nevada. Routes evaluated in Study 2 were based on previous Study 1 work (CRWMS M&O 1995ay), which had eliminated several other potential routes. During Study 2, the routes were evaluated for fatal flaws primarily from the standpoint of land-use and topographic constraints. All Study 2 routes are currently recommended as reasonable alternatives for further evaluation.

The four rail routes are summarized as follows:

- Valley Modified Route – From a connection with Union Pacific in the Dike/Apex area (northeast of Las Vegas) to the repository via the Indian Springs vicinity, based on a revised Study 1 corridor. Two routing possibilities were considered in the Indian Springs area.

- Jean Route – From a connection with Union Pacific in the Jean/Borax area (south of Las Vegas) to the repository via Pahrump Valley, based on a revised and expanded Study 1 corridor. Key alternate routing possibilities are via Wilson Pass versus State Line Pass and via the northern Pahrump Valley versus Stewart Valley.

- Carlin Route – From a connection with Southern Pacific and Union Pacific at Beowawe (between Carlin and Battle Mountain), via Big Smoky Valley to a point near Mud Lake (southeast of Tonopah), from where part of the Caliente Route is used for the remaining distance to the repository. An alternate route via Monitor Valley was also studied.

- Caliente Route – From a connection with Union Pacific at Caliente to the repository via Mud Lake, based on a preliminary alignment completed by DeLeuw Cather (SAIC 1992).

Study 2 identified current land-use constraints along each rail route through extensive research of land records and field investigation. Using this land-use research data and engineering criteria, pre-conceptual design refined the corridors to a width of one to five miles, and in the process ensured that each corridor supported a feasible route with minimal land-use conflicts.

The following sections summarize the engineering analyses performed in Study 2 for each of the rail routes.

11.1 PREVIOUS WORK

11.1.1 Engineering Analysis

Engineering criteria, as described in the Design Inputs Section, were applied to the various proposed routes to yield a pre-conceptual engineering survey. Key elements of this analysis included:

- Acquiring complete map coverage of corridors and adjacent areas, including United States Geological Survey (USGS) 1:24,000 scale (7.5') topographic maps, and U.S. of Land Management (BLM) 1:100,000 scale Surface Management Status maps.

- Establishing approximate locations of feasible alignments according to land-use constraints and engineering criteria. This activity involved extensive topographic map analysis and field investigation.

- Developing quantity estimates, cost estimates, and construction schedules.

Each route was divided into a series of sections, reflecting various alternates studied within each corridor. Route Section Description sheets in Appendix F1 present details concerning the following types of constraints considered:

- Land-use constraints
- Archeological and historical sites
- Road crossings and proximity to population
- Topographic considerations
- Bridges and hydrologic considerations
- Operating considerations.

A state-wide map showing the refined corridor boundaries for the four rail routes is shown in Figure 11-1.

11.1.2 Maps and Profiles

Maps and profiles of the route corridors are included in Appendix F2. A total of 17 map sheets at a scale of 1:250,000 (1" = 4 miles approximately) provide complete coverage of the corridors, illustrating the following key features:

- Proposed rail corridors
- Existing railroads
- Highways
- Topography indicated by contour lines at 200-foot intervals
- Hydrography
- Boundaries of the Nevada Test Site and the Nellis Air Force Range.

Profiles are presented for each section, as delineated in the Route Section Description sheets. These indicate the existing ground line along a likely track alignment; actual track profiles are to

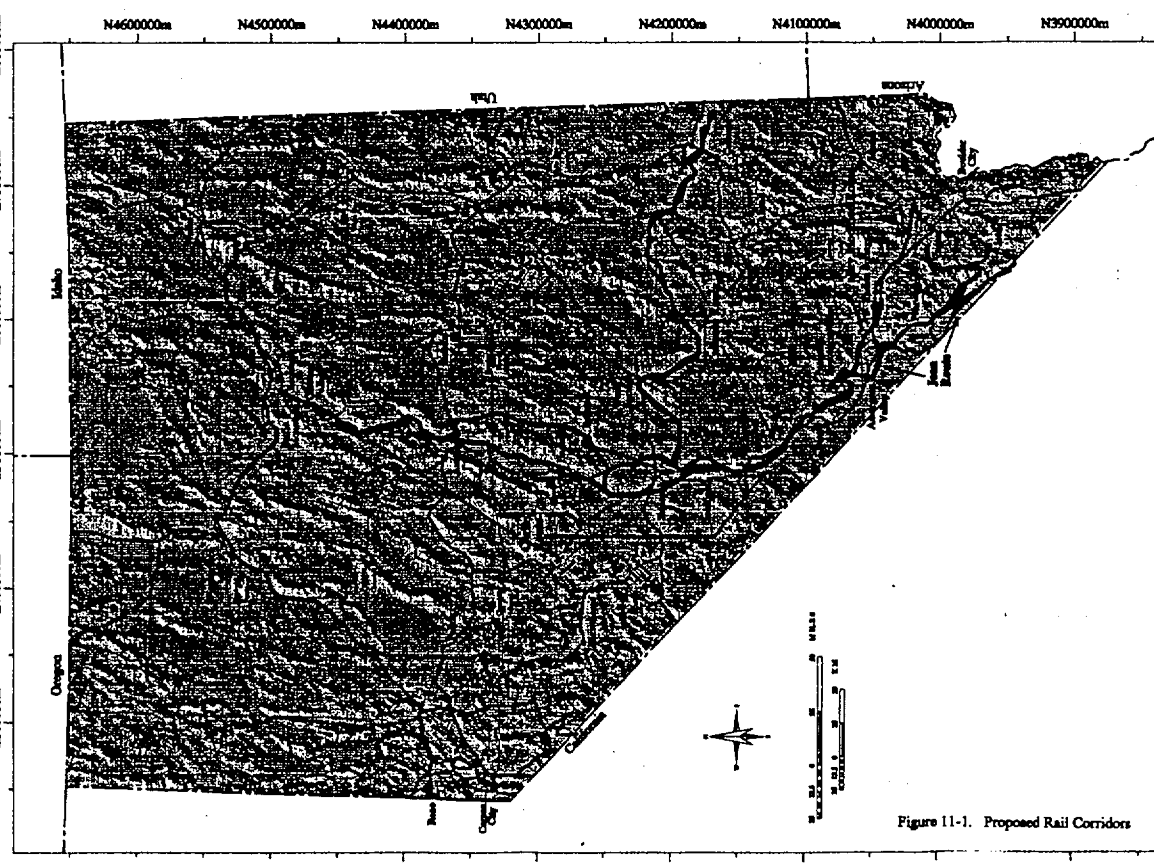


Figure 11-1. Proposed Rail Corridors

INTENTIONALLY LEFT BLANK

be developed in subsequent design work. Contiguous small-scale profiles covering the entire length of each corridor are also included in Appendix F2 for comparative purposes.

11.1.3 Quantity Estimates

Preliminary quantities for earthwork, bridges, grade separations, tunnels, and track length for each route are presented in the Quantity Takeoff sheets in Volume IV. Key assumptions used in developing these quantities are as follows:

- Right-of-Way – Acreage is based on a total right-of-way width of 400 feet throughout.
- Clearing and Grubbing – Acreage is based on an average of 10.8 acres/track mile.
- Earthwork – Roadbed width is assumed to be 24 feet. Parallel access (maintenance) roads were not considered at this time.

  Earthwork quantities were computed through a cursory survey of 1:24000 scale topographic maps. As shown on the Quantity Takeoff sheets, each route section is divided into a series of subsections at points where significant changes in the nature of the topography is apparent. Within each subsection, an approximate average height of cut or fill was estimated, upon which the average volume of earthwork per mile was based. The volume figure was reduced by up to 30 percent (through the "Balance Ratio") in areas where the proximity of cuts and fills clearly permits use of most excavated material for fills.

  Breakdown of the excavated material into common, rippable, and hardrock quantities is based on rough percentages estimated from field inspection.

- Subballast – Volume is based on 3,200 cubic yards/track mile.
- Track Length – Includes 2,500-foot sidings at 80-mile intervals, plus 1.6 miles of yard trackage.
- Signaled Grade Crossings – Assumed at all roads indicated as "Light-Duty" (typically gravel) on 1:24,000 scale maps.
- Grade Separations – Assumed at all paved public road crossings; the need for separation structures at other public roads will be evaluated during subsequent design. A three-span structure (totaling 130 feet long) was assumed for all grade separations over two-lane roads, while a five-span structure (totaling 230 feet long) was assumed for all four-lane highways.
- Bridges – The width of the watercourse (as shown on 1:24,000 scale maps) was used as the basis for bridge length.
- Major Culverts. Assumed in areas where the required culvert size and/or number of installations per mile would be significantly greater than average.

11.2 DESIGN INPUTS

Basic design criteria were established in Study 2 to govern corridor definition and facilitate consistent evaluation of alternate routes. Prior to conceptual design, these requirements will be reviewed, and applicable standards placed in the *Repository Design Requirements Document* (YMP 1994a).

11.2.1 General

Design must comply with DOE Order 6430.1A, *General Design Criteria*, and the recommendations of the American Railway Engineering Association, as prescribed in the current issue of the *Manual for Railway Engineering* (AREA 1994).

11.2.2 Traffic

Based on the Transportation Cask Arrival Scenario in the CDA Document, Key Assumption 001, (CRWMS M&O 1995a) the rail line will handle up to 600 shipments of spent nuclear fuel and HLW per year along with corresponding return movement of empty transportation casks and canisters. Maximum weight per cask (loaded) will be 125 tons; gross rail load is currently estimated at 194 tons per six-axle car.

The rail line may also handle movement of material and equipment for repository construction, maintenance, and operation, as well as other possible freight traffic. Due to the expected low volume and lighter car weights of such traffic, no design requirements beyond that for the principal traffic are envisioned at this time.

11.2.3 Grades and Curvature

Based on typical U.S. railroad practice for new construction, maximum grade and curvature limits of 2.5 percent and 8 degrees were assumed, respectively.

To the extent feasible, grades in the 1.5 percent to 2.2 percent range were assumed in order to gain a level of operating safety consistent with rail lines used by waste trains prior to reaching Nevada. Grades in tunnels are limited to 75 percent of a route's maximum grade, as recommended by American Railway Engineering Association.

To limit run-times and corresponding quantity requirements for casks, rolling stock and train crews, a design speed of 50 mph was assumed desirable over the majority of each route. Consequently, curves of 2 degrees or less were assumed in corridor development where appropriate.

11.2.4 Corridor Width

A corridor width of one to five miles was considered desirable, allowing for all reasonable alignments which may be considered during subsequent design.

11.3 ROUTE DESCRIPTIONS

Table 11-1 summarizes key characteristics of the rail corridors and significant alternates within each. The corridors are further described in the following pages and in the Route Section Description sheets in Appendix F1. Maps and profiles of the corridors are in Appendix F2.

Table 11-1. General Characteristics of Rail Routes

Route and Alternates	Length (miles)	Maximum		Rise & Fall (feet)	Notes
		Grade	Curve		
Valley Modified Route					
via Indian Hills	98.0	1.5%	6°	2,700	
via Cactus Springs	97.5	1.5%	4°	2,300	
Jean Route					
via Wilson Pass and N. Pahrump	114.0	2.2%	8°	6,200	1
via Wilson Pass and Stewart Valley	118.5	2.2%	8°	6,600	1
via State Line Pass and N. Pahrump	122.0	2.2%	8°	5,400	2
via State Line Pass and Stewart Valley	126.5	2.2%	8°	5,800	2
Carlin Route					
via Big Smoky Valley	331.0	2.4%	8°	6,800	3
via Monitor and Ralston Valleys	338.0	2.4%	8°	8,700	3
via Monitor, Baxter, and Klondike	363.0	2.4%	8°	9,600	3
Caliente Route	338.0	2.4%	8°	16,500	

Notes:

1. Design of Wilson Pass Alternate may increase grade to 2.5 percent and/or increase distance by up to 2.5 miles to reduce tunnel lengths.

2. Design of State Line Pass Alternate may increase curvature to 10 degrees to reduce earthwork.

3. Design of Mud Lake - repository portion (Goldfield Section of Caliente Route) may reduce maximum grade and curvature of Carlin Route to 2.0 percent and 6 degrees, respectively.

11.3.1 Valley Modified Route

Connection of the Valley Modified route with the Union Pacific main line would be between the Dike and Apex sidings. The route proceeds along the north side of Las Vegas Wash to the vicinity of Corn Creek Springs, generally parallels U.S. Highway 95 to Mercury Valley, and passes through Rock Valley and across Jackass Flats to the repository.

Physical characteristics are summarized as follows:

- Of the routes under consideration, the Valley Modified route is the shortest. Total distance from the Union Pacific connection to the repository is 98 miles.

- Compared to the other three routes, the Valley Modified route has the straightest alignment and flattest profile. Few curves require restriction below 50 mph, as most would be 2 degrees or less. Steepest grades are 1.5 percent, the longest of which would be the westbound ascent of the hills south of Indian Springs on the Indian Hills Alternate.

- The connection point is in close proximity to Union Pacific yards at Valley and Arden, at distances of 6 and 26 miles, respectively. This proximity, coupled with the route's short length, would permit flexibility for interchange operations.

As delineated by the Route Section Description sheets in Appendix F1, the route is composed of the Las Vegas Wash Section, either the Indian Hills Alternate or the Cactus Springs Alternate, and the Mercury Section. The following paragraphs summarize the key engineering concerns related to each of these sections.

Las Vegas Wash Section

Corridor location is highly dependent upon land-use constraints, particularly in the eastern half of the section where closest to North Las Vegas. As shown on the maps, a reasonable compromise was achieved between topographic and land-use constraints by locating the corridor on the alluvial fans north of Las Vegas Wash, along the southern border of the Desert National Wildlife Range. Acceptable distances are maintained from areas of critical concern, notably the 7,500-acre BLM parcel to be transferred to North Las Vegas. At the same time, this location provides the opportunity to design an alignment meeting acceptable engineering practices.

Further west, the corridor crosses Las Vegas Wash at a point 4 miles south of Corn Creek Springs where the wash is relatively confined. The corridor then parallels U.S. Highway 95; sufficient corridor width has been allowed to locate the rail line up to three-quarters of a mile from the highway to minimize public visibility and limit grades. Due to the close proximity of the Nellis Air Force Range boundary to the highway (as close as 500 feet), the corridor requires use of a strip of Nellis Air Force Range property up to three-quarters of a mile wide along the boundary for about 7 miles.

Indian Hills Alternate

Of the two routes possible in the vicinity of Indian Springs, the Indian Hills Alternate appears more feasible, as it bypasses both the community of Indian Springs and the Nellis Air Force Auxiliary Field by routing through the hills to the south. This routing requires 11 miles of 1.5 percent grade and separation structures over U.S. Highway 95 (four lanes in this area) at each end of the alternate. Although some curves up to 6 degrees would be required in the hills immediately south of Indian Springs, the balance of the alternate crosses large alluvial fans which permit a relatively straight alignment.

Cactus Springs Alternate

Due its relatively flat profile, the Cactus Springs Alternate is operationally more desirable than the Indian Hills Alternate. However, availability of right-of-way through the Indian Springs area may make this alternate unfeasible. Negotiation with the Air Force would be necessary to define a right-of-way through either the developed area between U.S. Highway 95 and the airfield (involving relocation of Air Force and civilian structures), or through areas immediately north of the airfield now used for target practice. Corridor maps indicate a gap in the corridor through this area, as definition is dependent upon such negotiations.

West of Indian Springs, to the eastern boundary of the Nevada Test Site near Mercury, a route along the north side of Indian Springs Valley is proposed to maximize distance from U.S. Highway 95. Due to the relatively rough topography along the north side of the valley, additional construction costs are expected compared with a possible routing immediately adjacent to U.S. Highway 95.

Mercury Section

The final 34 miles of the route traverses the Nevada Test Site. A steep descent into Mercury Valley is avoided by routing between the community of Mercury and the site of Camp Desert Rock. About 14 miles of the route generally parallels Jackass Flats Road (on the east side), using a less direct route than the road in order to keep grades moderate. Further west, routing via Rock Valley (using a 1.5 percent downgrade) avoids heavy grades that would be required by following Jackass Flats Road over Little Skull Mountain. The route proceeds upgrade across Jackass Flats about two miles southwest of Nevada Test Site facilities. Fortymile Wash is crossed at its narrowest point near the repository.

11.3.2 Jean Route

Various alternates yield four possible configurations of the Jean Route; each configuration is composed of three route sections: over the Spring Mountains (via either Wilson Pass or State Line Pass), around developed areas in the vicinity of Pahrump (via either the North Pahrump or the Stewart Valley Alternate), and across the eastern Amargosa Desert to the repository.

In any case, the physical characteristics of the route may be summarized as follows:

- The route is relatively short, being 114 to 127 miles from the Union Pacific connection to the repository.

- Mountainous territory is traversed over 30 to 40 miles, involving grades up to 2.2 percent and 8-degree curves. Most difficult is the crossing of the Spring Mountains, which will involve major earthwork and tunneling.

- Tangent track and flat curves comprise the balance of the route, permitting 50 mph operation.

- Portions of the route are in close proximity to the communities of Jean, Goodsprings, Sandy Valley, Pahrump, and Crystal.

- Possible connection points at Jean and Borax are in close proximity (21 to 26 miles) to the Union Pacific yard at Arden. This proximity, coupled with the route's short length, would permit flexibility for interchange operations.

Key engineering concerns related to each of the route sections are summarized in the following paragraphs.

Wilson Pass Alternate

Although the corridor map implies a Union Pacific connection site up to three miles north of Jean, grade separations over Interstate 15 and the old highway are more difficult in the northern half of the corridor due to the elevation of the highways relative to Union Pacific track. On the other hand, connection near the southern corridor boundary would be within one-half mile of casinos and industrial buildings in Jean. In Goodsprings, the probable track location is about one mile from the main portion of the town, and about one-half mile from new housing northeast of the community.

Although shorter than the State Line Pass Alternate by approximately eight miles, the Wilson Pass Alternate requires much longer 2.2 percent grades on both the east and west approaches to the Spring Mountains due to the greater elevation gain. Extra distance in the alignment, achieved by looping around the north end of Goodsprings Valley, is instrumental in keeping the grade reasonable on the east side of the range.

Two major tunnels are currently envisioned, approximately 2.0 and 0.5 miles in length, the longer being through the summit of the range. However, in considering tradeoffs involved in raising the elevation of the line (through additional distance or grades up to 2.5 percent), subsequent design may greatly shorten these tunnels.

The Table Mountain Pass Alternate (listed in Study 1), southwest of Goodsprings, has more severe topography than the Wilson Pass Alternate and is not recommended for further consideration as a feasible corridor.

State Line Pass Alternate

Ample space in the vicinity of Borax permits flexibility for connections with Union Pacific, but location of grade separation structures to the west (over Interstate 15) may be dictated by a large archeological site in the vicinity.

As State Line Pass is the lowest summit in the Spring Mountains, the 2.2 percent grades are much shorter than those on the Wilson Pass Alternate. However, California must be entered for about six miles to access the pass, and construction costs will be high due to difficult topography on both approaches.

East of State Line Pass, heavy earthwork will be required through rocky terrain for three miles around the southern tip of the range. A large alluvial fan from a canyon on the north side forms the summit; due to the apparent high runoff, any cut through the summit will require considerable flood protection measures.

The west side of the Spring Mountains will require more difficult construction than the east side. To avoid entering the California Wilderness Area to the southwest, the route follows the north side of the canyon leading from the summit. Slopes are very steep; cuts and fills up to 100 feet high will be required through hard rock and some tunneling may be necessary. In contrast with the 8-degree curvature limit noted in the Design Inputs Section, use of 10-degree curves in this area may have significant construction cost benefits. Over a distance of about three miles to the north of the summit, all washes from the Spring Mountains have the appearance of significant flash flooding.

In the vicinity of Sandy Valley, the probable track location would parallel Cherokee Street and would be less than one mile from some dwellings. A new school on Hopi Street (about one-quarter mile north of Quartz Avenue) is about one mile south of the probable rail line location; some housing to the north is less than one-half mile from the probable location.

North Pahrump Alternate

In the extreme eastern portion of Pahrump, elimination of a short tunnel through a branch of the Spring Mountains is feasible by using an alternate corridor crossing undeveloped private lands in the south one half of Section 2 and the northeast quarter of Section 11.

The route climbs alluvial slopes along the east side of Pahrump to avoid urbanized areas. Closest proximity of the probable track location to developed areas in central Pahrump would be about 1.5 miles in the vicinity of the winery on North Homestead Road.

Proper development of the North Pahrump Alternate would necessitate purchase of right-of-way through private (but largely vacant) lands for about five miles in the northern part of Pahrump Valley. Most critical is a parcel of private land at the summit of the Last Chance Range, upon which a new dwelling is under construction that would be less than one-quarter mile from the probable track location through the summit. Routing to avoid all private lands in northern Pahrump Valley would lengthen the line about three miles, unreasonably increase grade lengths and curvature, and substantially increase earthwork due to rough topography.

The descent from the summit of the Last Chance Range (north of Johnnie) is through very rough topography, requiring 2.2 percent grades and 8-degree curves over a distance of about two miles. Cuts and fills up to 60 feet high and approximately 1,800 feet of tunneling would be necessary.

Stewart Valley Alternate

Longer than the North Pahrump Alternate by 4.5 miles, the Stewart Valley Alternate skirts Pahrump by using the BLM-proposed utility corridor along the state line. This utility corridor minimizes private land acquisition, but a rail line centered in the corridor would pass within 800 feet (0.15 mile) of homes in the developing Homestead Road area near Thorne Drive, making suitability of the BLM corridor for rail line use questionable. A feasible alternate route may be through the north half of Section 25 which, although private land, is undeveloped. A rail line centered through this area would be about 0.3 mile from existing housing.

In the Highway 372 vicinity, the probable track location is within one-half mile of a home under construction in the southeast quarter of Section 26; distance is slightly greater to various other dwellings in the immediate area. Beyond the northern limit of Sections 25 and 26 there are numerous mobile homes, the most southerly of which would be about one mile from the probable track location.

In Stewart Valley, six new homes have been constructed immediately west of Ash Meadows Road in S16 T24N R8E; at least 30 others are planned in the immediate vicinity. Although this development is in California, close proximity to the probable track location (within one-half mile) is a concern. Dwellings present along the west side of Ash Meadows road in Sections 6 and 7 of T20S R52E are within one-half mile of the probable track location.

A short tunnel may be required through the knob in the soutwest quarter of S9 T24N R8E, which appears to be hardrock. Further west, construction of the rail line parallel to, and within 500 feet east of, Ash Meadows Road would be the most economical location, as the road is relatively straight and has little grade. Location further up the hillside would entail significant curvature and earthwork through rocky material.

Amargosa Desert Section

The route through this section is relatively free from land-use and topographic constraints. Private land holdings north of the community of Crystal are easily avoided, although route length is slightly increased in order to do so. The last 14 miles of the route traverses the Nevada Test Site east of Fortymile Wash, crossing the wash at a narrow point near the repository.

11.3.3 Carlin Route

The Carlin Route connects with Southern Pacific and Union Pacific at Beowawe; connection at Palisade (assumed in Study 1) is not considered feasible due to various land-use conflicts. The route traverses the length of Crescent Valley and either Big Smoky Valley or Monitor Valley to Mud Lake, from where the Caliente Route is assumed the remaining distance to the repository. Routing via Monitor Valley connects with the Caliente Route via either the Ralston Valley Alternate or via the southern end of Big Smoky Valley using the combined Baxter Springs and Klondike Alternates.

Physical characteristics are summarized as follows:

- The route is relatively long, being 331 miles from Beowawe to the repository. Routing via Monitor Valley and Ralston Valley would add seven miles of length, while routing via Monitor Valley and the southern portion of Big Smoky Valley would result in a total length of about 363 miles.

- Mountainous territory over 50 miles (65 miles if via Monitor Valley) of the route involves grades up to 2.4 percent (steepest grades are south of Mud Lake on the Caliente Route). Some of these heavy grade areas also include curves up to 8 degrees.

- Tangent track and flat curves comprise the balance of the route, permitting 50 mph operation.

- Beowawe is reasonably close to Southern Pacific and Union Pacific yards at Carlin and Elko (25 miles and 50 miles, respectively). This proximity provides flexibility for interchange operations. However, operations may be complicated by the Southern Pacific/Union Pacific paired-track arrangement, which routes all westbound movements over Southern Pacific and all eastbound movements over Union Pacific. The planned Union Pacific/Southern Pacific merger will likely move Southern Pacific operations in Carlin to Elko, but will not affect the paired-track arrangement.

- Proximity to major mining operations in the Tenabo, Gold Acres, Cortez, and Round Mountain areas may be significant to possible shared-use concerns.

Key engineering concerns related to each of the route sections are summarized in the following paragraphs.

Crescent Valley Section

The primary site under consideration for rail connections is one to two miles east of Beowawe townsite. Alternatively, the most northerly 10 miles of the rail line could be located through the hills east of Crescent Valley (using 1.5 percent grades), making Southern Pacific/Union Pacific connections about four miles east of Beowawe. Connection further east is impractical due to increasing topography. In either case, ample space is available for connecting tracks and other terminal facilities which may be required. The Humboldt River, being north of the Union Pacific main line, would not be crossed.

Much of the eastern portion of Crescent Valley is normally dry lake bed, which may accumulate significant water during periods of runoff. These areas should be avoided by rail construction due to the soft subgrade and resulting maintenance problems. The optimum route appears to be on the western slopes of the valley, about one mile east of the town of Crescent Valley.

The most critical issue in Crescent Valley is the growth of the Cortez and Gold Acres mining operations, particularly the planned "Pipeline" Mine Development. The corridor, as currently envisioned, passes between these mining operations to the south of the growing tailings piles. Additional input from the mining companies may possibly shift the corridor further south in this vicinity.

From the southern end of Crescent Valley, the route climbs to Dry Canyon Summit using a 2.0 percent grade. Grades of up to 2.0 percent characterize the downgrade from Dry Canyon Summit to Grass Valley. The route then follows the west side of the valley, crossing alluvial fans until it passes west of Grass Valley Ranch where a 2.0 percent upgrade begins to the top of Rye

Patch Canyon. An alternate location is possible east of the ranch through more rugged topography. A downgrade of about 1.5 percent brings the route into Big Smoky Valley.

Big Smoky Valley Alternate

North of the Round Mountain/Hadley/Carvers area, there are numerous ranches and privately owned grazing lands along the west side of the valley, between Highway 376 and the approximate valley centerline. The most favorable rail route is therefore along the east side of the valley at the foot of the alluvial fans, thereby avoiding private lands and recreational aspects of the west side, as well as the lakebed and marsh areas of the valley bottom.

Potential land-use conflicts exist in the vicinity of Round Mountain, Hadley and Carvers, which are within 8 miles of each other. The valley narrows significantly in this area, limiting the opportunity to avoid private lands. The most critical point is between the Round Mountain mining properties and the new community of Hadley. The tailings pile for the Round Mountain mine is apparently growing toward Highway 376.

The currently envisioned route crosses Highway 376 north of Hadley and proceeds along the west side of the valley. An alternate route to the east, between the airport and Highway 376, rejoins the other route just south of Hadley. This alternate is closer to the Round Mountain mining operation. From this point south of Hadley the route crosses back to the east side of the valley and parallels Highway 376.

Monitor Valley Alternate

This route traverses Hickison Summit using 2.0 percent grades and proceeds south along the west side of Monitor Valley. Between Highway 50 and Dianas Punch Bowl (approximately 30 miles south of the highway), broad sloping planes on either side of the valley floor permit avoidance of the few private land holdings encountered.

South of Dianas Punch Bowl, the valley floor is so flat that routing directly up the center should be avoided due to accumulation of water during runoff periods. At the time of the field inspection, Dry Lake was filled with water and appeared somewhat larger than shown on the BLM map. Further south, private land holdings in the bottom of the valley can generally be avoided while retaining an acceptable rail alignment. The route leaves Monitor Valley via a short ascent to Horse Heaven Summit.

Ralston Valley Alternate

To keep grades reasonable, additional distance of up to two miles will be required in the descent from Horse Heaven Summit to the Hunts Canyon vicinity. Several routing arrangements, using loops with 6-degree curves, are possible within the proposed corridor.

Considerable development has taken place in the 12 mile stretch of Ralston Valley north of Highway 6, forcing the corridor up onto alluvial slopes along the east side of the valley. These developments include several private land holdings and homesites on the east side of Highway 376 (notably in Section 32 of T5N R44E). South of Highway 6, route length is increased about two miles to avoid the Tonopah Airport.

From Mud Lake, the Goldfield Section of the Caliente Route is used for the remaining distance to the repository.

Baxter Springs Alternate

Routing from Monitor Valley via the Baxter Springs Alternate (and connecting to the Klondike Alternate) provides a reasonable, although very circuitous, option to the Ralston Valley Alternate. Total length of the Carlin Route would be increased by approximately 25 miles. The principal advantage of this alternate is to enable routing via Monitor Valley while avoiding potential conflict with development further south in Ralston Valley.

As with the Ralston Valley Alternate, additional distance will be required in the descent from Horse Heaven Summit to keep grades reasonable. A key routing possibility may involve crossing Toiyabe National Forest land for less than one mile. The balance of the route proceeds in a westerly direction, traversing the southern end of the Toquima Range on a relatively straight alignment. A separation structure will be required over Highway 376 near the point where the alternate enters Big Smoky Valley.

Klondike Alternate

The southern portion of Big Smoky Valley provides a straight, direct route with no significant obstacles to rail line construction. The few private lands in the valley floor can easily be avoided. Sand dunes in Section 24 of T7N R41E appear stable as some vegetation is present, while Crescent Dunes (15 miles to the south) are east of any likely route; blowing sand may therefore not be a significant concern for a rail line in this area.

The route passes west of Tonopah and proceeds southeast to a point west of Mud Lake. Two grade separations over U.S. Highway 95 would be necessary (west and south of Tonopah, respectively). From Mud Lake, the Goldfield Section of the Caliente Route is used for the remaining distance to the repository.

11.3.4 Caliente Route

The Caliente Route is the most mountainous of the routes under consideration, with seven major mountain crossings and three minor summits. The balance of the route generally follows the bottom of large desert valleys, notably Sand Spring Valley, Reveille Valley, Ralston Valley, and Sarcobatus Flat.

Physical characteristics are summarized as follows:

- At 338 miles from Union Pacific connection at Caliente to the repository, the Caliente Route is the longest of all routes considered (except for the Carlin Route using a Monitor Valley/Baxter Springs/Klondike routing).

- Mountainous territory over approximately 80 miles of the route involves grades up to 2.4 percent. Some heavy grade areas include curves up to 8 degrees. As shown in Table 11-1, total rise and fall of the Caliente Route is more than double that of the Carlin and Jean Routes.

- Tangent track and flat curves comprise the balance of the route, permitting 50 mph operation.

- The distance from Caliente to the nearest Union Pacific yards at Milford and Las Vegas (Valley and Arden) is over 115 miles. Coupled with the route's long length, this distance may limit interchange possibilities.

- The Caliente route is unique in that it is by far the most circuitous of the routes studied; more than 100 miles of additional length are required to keep the route out of the Nellis Air Force Range.

As indicated by the Route Section Description sheets, the route is divided into two key sections at Mud Lake. The Reveille Section (from Caliente to Mud Lake) is exclusive to the Caliente route, while the Goldfield Section (from Mud Lake to the repository) is common to the Caliente and Carlin routes.

Reveille Section

Most of the heavy grade areas are in the eastern portion nearest Caliente; the two most difficult mountain crossings are Bennett Pass and Timber Mountain Pass. Significant extra distance in the form of large loops is necessary to achieve acceptable grades in these and other cases. Further engineering work may find that the heavy grades may be reduced to 2.0 percent with some construction cost penalty. Such reduction would be most difficult in the case of Timber Mountain Pass due to the rough topography of the east slope of the Seaman Range and its close proximity to White River.

A significant route option is indicated on the corridor maps by a split corridor between Coal Valley and Garden Valley. The route may use either Water Gap or a somewhat higher pass through the Golden Gate Range about four miles to the north. The key advantage of routing through Water Gap is the avoidance of 3.5 miles of grades over 2.0 percent.

In the more westerly portions of the Reveille Section, the route traverses the length of Sand Spring Valley, Reveille Valley, and Stone Cabin Valley through a series of long tangents and relatively little grade. The north-south orientation of much of Reveille Valley, however, results in over 30 miles of circuity.

The Reveille Section is notable in being more isolated than any other route section in the study; Caliente and Panaca are the only communities along this part of the route, and access from paved public roads is very limited.

Goldfield Section

Heavy grade areas (up to 2.4 percent) extend over both the Goldfield Hills and the western portion of Yucca Mountain near Beatty Wash. Further engineering work may find that these grades may be reduced with some construction cost penalty.

Due to the depth of the canyon encompassing Beatty Wash and the rugged nature of the adjacent branch of Yucca Mountain, negotiating this area will be one of the more difficult portions of the Caliente (or Carlin) Route. However, DeLeuw Cather's proposed route leading to this area, through the northern portion of Crater Flat, is clearly far more circuitous than necessary. The corridor has therefore been widened sufficiently to permit investigation of improved alignments through both the Crater Flat and Beatty Wash areas.

Significant route options are indicated on the corridor maps by split corridors in two key areas:

- In the vicinity of Goldfield, a route through part of the Nellis Air Force Range (over a distance of about 14 miles) would greatly improve the route by using a much lower summit and avoiding mining patent areas. Grades would be less than 1.5 percent versus 2.4 percent required for the higher summit near Espina Hill. Curvature would likewise be greatly reduced.

- Across Sarcobatus Flat (in the vicinity of Scottys Junction), two options are available to avoid private lands and housing in the area. These options parallel U.S. Highway 95 to the west and east, respectively.

Routing on the west side will require three highway grade separations; a route east of the highway would have, at most, two grade separations. However, this route would require penetration of the Nellis Air Force Range to bypass the private lands. A third possible routing would be via the alignment abandoned by the Las Vegas & Tonopah Railroad further west through Bonnie Claire; such routing would lengthen the line at least two miles.

In the event that routing is kept east of the highway, it may be feasible to avoid the two grade separations over U.S. Highway 95 proposed by DeLeuw Cather near Tolicha Wash; routing higher on the alluvial fan of the wash is possible, although some heavy earthwork may be required through the hills to the south.

Crestline Alternate

Pending further investigation of land status, the Crestline Alternate may be a potential option at the extreme eastern end of the Caliente Route. Currently, land ownership data is incomplete concerning the portion of the route which uses the abandoned 200-foot wide right-of-way of the former Union Pacific Pioche branch between Caliente and a point near Panaca (a distance of approximately 10.5 miles).

In the event that the former Union Pacific right-of-way is unavailable for rail use, another origin point for the Caliente route may be justified. DeLeuw Cather evaluated a route from Crestline with the following general characteristics:

- 15 miles additional length
- Heavy grades and sharp curvature
- Extensive earthwork
- Approximately $88 million additional cost
- Additional operating and maintenance cost.

This alternate was originally eliminated from the study due to the additional cost. However, it may be an attractive option if land ownership becomes an obstacle to routing from Caliente.

11.4 OPERATING PLANS

The typical dedicated train is assumed to be two 3,000-horsepower diesel-electric locomotives with a maximum of three spent nuclear fuel transportation cask cars or five high-level waste transportation cask cars, with two or more buffer cars (gondolas) and an escort car (CRWMS M&O 1995a, Key Assumption 001). Trailing train weight would probably not exceed 2,500 tons, and train lengths would not likely exceed 800 feet.

Locomotive power should be ample to maintain speeds of 50 mph, with excellent braking and train handling characteristics. Projected tonnages suggest that frequencies could vary from one train each way every ten days (1,000 ± net metric tons of uranium per year) to two trains each way per week under peak conditions (3,000 ± net metric tons of uranium per year).

Operating plans depend upon route lengths and corresponding run times from the junction point to the repository. Run times indicated in the following sections are based on the train assumed above, the individual route's physical characteristics, and a maximum speed of 50 mph.

For both the Carlin and Caliente Routes, the "hours of service" 12-hour limit (required by 49 CFR 228, Subpart B) is a major operating consideration. Due to the length of these runs, crews would have a programmed layover (a least 10 hours) at the repository before returning to the home terminal. Transporting crews between the repository and the home terminal would be impractical due to the distance involved. The length of these routes therefore introduces disadvantages in the form of layover costs and the necessity of carefully scheduling train movements to avoid extended layovers.

11.4.1 Interchange with Line-Haul Carriers

A key operating issue to be determined is whether dedicated trains or general freight service is to be used in interchanging with Union Pacific (or Southern Pacific). Dedicated trains would offer greater opportunity to schedule and control movement of cask cars and may result in cost benefits through enhanced use of crews and equipment. "Run-through" motive power would also be possible, simplifying interchange and enabling the use of Union Pacific locomotives. Trains arriving at the connection point would then stop only to secure movement authority and change crews.

If general freight service is used, cask cars would be set out at the junction point by Union Pacific (or Southern Pacific) trains and subsequently assembled into a train for movement to the repository. The more random nature of general freight service would likely result in shorter, more frequent trains than in the case of dedicated train service.

A conceptual layout of the interchange yard and connecting trackage is applicable to any of the possible connection sites, but should be modified depending on the specific site and the selection of interchange via either dedicated or general freight service.

In the case of Jean, Borax, or Caliente, the existing main line passing siding would serve as the siding shown on the drawing adjacent to the main line. Two storage tracks are included for interchange of loaded and empty cars with general freight service; these tracks may be unnecessary if dedicated trains are used with motive power run-through. The "Y" track enables run-through movements from either direction, as well as turning of any captive locomotives. One leg of the " Y" may therefore be unnecessary if all interchange is to be accomplished using run-through service from one direction only.

11.4.2 Valley Modified Route

Close proximity to North Las Vegas makes Dike suitable as a home terminal for Yucca Mountain crews; Union Pacific crews would terminate at the Union Pacific Arden yard, traveling to and from Dike by motor vehicle.

Run times between Dike and the repository should be under three hours in each direction. Speed would be limited to about 25 mph upgrade and restricted to 40 mph downgrade on the steepest grades of 1.5 percent. A crew could operate from Dike to the repository and return within the 12-hour limit, allowing two hours at the repository for switching and make-up of the outbound train.

In the event that a return movement is not available when switching is completed at the repository, the crew could return to their home terminal by motor vehicle, leaving the motive power idle at the repository until needed. The crew would be recalled when required and transported back to the repository to operate the empty train to Dike. Depending upon the length of delay at the repository, this may be less costly than requiring the crew to remain at the repository until a return movement is available.

11.4.3 Jean Route

Jean's proximity to Goodsprings (7 miles) and Las Vegas (30 miles) makes it acceptable as a home terminal for Yucca Mountain crews. Union Pacific crews would terminate at the Union Pacific terminal at Arden, travelling to and from Jean by motor vehicle.

Normal run times between Jean and the repository should be under four hours in each direction. Speed would be limited to 15 to 20 mph upgrade and restricted to 25 mph downgrade on the steepest grades of 2.2 percent. A crew could operate from Jean to the repository and return within the 12-hour limit, allowing two hours at the repository for switching and make-up of the outbound train.

As described for the Valley Modified route, transporting the crew to the home terminal may be appropriate when a return movement is not immediately available at the repository.

11.4.4 Carlin Route

Beowawe's proximity to Crescent Valley (10 miles) and Carlin (25 miles) makes it acceptable as a home terminal for Yucca Mountain crews. Southern Pacific and Union Pacific crews would terminate at their respective yards in Carlin and Elko, travelling to and from Beowawe by motor vehicle.

Normal run times between Beowawe and the repository should be under nine hours in each direction. Speed would be limited to 15 to 20 mph upgrade and restricted to 25 mph downgrade on the steepest grades of 2.0 to 2.4 percent. A crew could operate from Beowawe to the repository (or return) within the 12-hour limit, allowing over an hour at the repository for switching.

11.4.5 Caliente Route

Caliente would serve as a home terminal for train crews, as well as a layover point for Union Pacific crews operating the trains between Caliente and Milford, the next Union Pacific crew-change point.

Normal run times between Caliente and the repository should be under 10 hours in each direction. Speed would be limited to 15 to 20 mph upgrade and restricted to 25 mph downgrade on the steepest grades of 2.4 percent. A crew could operate from Caliente to the repository (or return) within the 12-hour limit, allowing over an hour at the repository for switching.

12. DEVELOPMENT TASKS AND ISSUES

At the completion of the repository advanced conceptual design (ACD), major design issues and development tasks have been identified. The report provides feasible concepts to most of these issues through assumptions or engineering judgment and acknowledges that some of these issues remain to be resolved as design and site characterization move forward. A discussion of issues related to the repository design is presented in this section.

Some of these issues encompass more than repository design; an example of this is the thermal loading issue which spans repository design, Engineered Barrier System design, site characterization program, and pre- and postclosure performance assessment. However, the impact of this issue on repository design only is discussed here. Some issues are confined to repository design. For example, the issue of the disposability of spent nuclear fuel assemblies. Each major design issue is discussed as shown below:

- Description of the issue
- Assumption used for ACD
- Risk considerations, including a qualitative description of cost and design impact
- Tasks required to resolve the issue (e.g., substantiate the assumption).

12.1 SURFACE DESIGN ISSUES

Issues that are expected to pose the greatest risk to the repository surface facilities design are described below. None of the issues is expected to be unsolvable (i.e., adequate facilities can be designed and constructed regardless of how the issue is resolved). These issues present program risk in that the cost of construction or operations could be significantly affected.

12.1.1 Disposability of Spent Fuel Assembly Canisters

12.1.1.1 Description

The repository may receive spent fuel assemblies (SFAs) in a variety of configurations, including bare fuel in GA-4 and GA-9 legal weight truck casks, disposable canisters in rail casks, and non-disposable canisters in rail casks (e.g., dual purpose canisters). The primary issue involves whether the SFA canisters, which are used to deliver 98 percent of the SFAs (70 percent of the waste), will be disposable. A disposable canister can be transferred directly to a disposal container as a sealed unit and subsequently emplaced in the repository. Nondisposable canisters would need to be opened and the 12 to 40 SFAs, depending on the canister capacity, would be individually removed and transferred to a disposal container. The residual nondisposable canister would require processing as a solid low-level waste and disposal off site.

12.1.1.2 Assumption Used for ACD

The repository ACD is based on receiving 8,593 disposable SFA canisters. The detailed waste form arrival scenario is provided as a controlled design assumption (Key Assumption 002, Waste Form Arrival Scenario) and is provided in Table 7.1.2-3.

12.1.1.3 Risk Considerations

If the canisters are not disposable, the following Waste Handling Building (WHB) design changes would be required: two hot cells would be added to open the canisters and transfer the SFAs; the single ACD hot cell dedicated to disposable canister waste transfers would be deleted; the number of shipping cask preparation stations would increase by two receipt and two exit stations; and the cask unloading ports would increase from two to five. These collective changes to the major features of the WHB configuration would increase the size of the facility footprint by about 45 percent.

Transfers of uncanistered SFAs inherently lead to more contamination being dispersed within the confinement zones as opposed to transfers of canistered SFAs. For this reason it is estimated that the liquid low-level waste generated from more frequent decontamination operations would increase approximately threefold. The solid low-level waste generation rate would therefore also increase threefold because the liquid low-level waste is mixed with grout, solidified in drums, and disposed of as a solid low-level waste. The amount of solid low-level waste drums requiring disposal would increase from approximately 32,000 cubic feet per year to 90,000 cubic feet per year. The unloaded nondisposable canisters would conservatively generate approximately 1.75 million cubic feet of additional solid low-level waste. The increases in secondary waste generation would result in expanding the Waste Treatment Building size and numbers of process equipment, or operating the present facility for an additional shift, or both.

The projected increases to the WHB and Waste Treatment Building (WTB) life cycle costs are estimated to be about $570 million and $345 million, respectively. The WTB life cycle costs include all solid low-level waste disposal costs. Based on the design impacts described above, the use of non-disposable canisters will have a significant impact on repository cost.

There is a high probability that in the future the repository waste form arrival scenario will be predominantly based on nondisposable canisters (i.e., dual purpose canisters licensed for storage and transportation) due to a number of recent programmatic decisions that favor the adoption of existing nondisposable canister technologies.

12.1.1.4 Tasks Required For Resolution

A revised basis for the repository waste form arrival scenario must be developed by Waste Acceptance and incorporated in the *Repository Design Requirements Document* (RDRD) (YMP 1994a). The WHB, WTB, and portions of the Cask Maintenance Facility (CMF) will need to be updated in order to develop a defensible design and a sufficiently accurate cost estimate in support of the next design phase.

12.1.2 Waste Form Assay for Measurements

12.1.2.1 Description

The repository design assumes SFA burn-up credit will be achieved based on accurate records taken at the reactor sites prior to shipment. Without this credit it is expected that the current waste package design would need to be resized and/or redesigned. The current program position is that it will not be necessary to perform additional measurements of SFA burn-up; although measurements to verify the existing spent fuel burn-up records may be considered in the future to mitigate the risk of the program position acceptance by the U.S. Nuclear Regulatory Commission (NRC).

It is expected that other waste forms, such as severely degraded SFA and/or other U.S. Department of Energy- (DOE) owned waste, may need to be assayed at the repository. Industry currently provides assay measurement technology that may be suitable for performing an assay that will be acceptable to the NRC. Certain technology operates underwater on uncanistered individual fuel assemblies. Other technologies may be available but have not been identified.

12.1.2.2 Assumption Used for ACD

The repository ACD does not include provisions for conducting SFA burn-up or other waste form assay measurements. The bulk of the SFAs are transferred to disposal containers in sealed canisters, which does not accommodate operations requiring access to uncanistered SFAs. Also, the SFA and other waste form transfer operations are conducted dry, in a hot cell, which would not directly accommodate current underwater assaying technologies without some modification for shielding background radiation and/or local neutron scatter in air.

12.1.2.3 Risk Considerations

Three different alternatives should be considered, depending on the requirements of the selected assaying technology. The impact of each technology alternative is described below:

- *Dry Technology Operating on Sealed Canisters* – If this type of technology is used, assay equipment and hot cell assay stations would need to be added to the WHB. There would be an impact on the waste throughput due to the additional time required for set-up, calibration, maintenance, and conducting the assay measurements. These changes would result in a moderate increase in the cost of the WHB construction and operation. Sealed SFA canisters are not expected to be suitable for assaying due to the probable use of internal borated materials. Other DOE-owned waste forms, however, may arrive at the repository sealed in specially designed canisters.

- *Dry Technology Operating on Individual SFAs* – If this type of technology is used, burn-up measurement equipment and hot cell stations would need to be added to the WHB. In addition, hot cells and equipment would need to be added to cut open canisters and handle/transfer individual SFAs, as described for the alternative in Section 12.1.1. The additional time required for equipment set-up, calibration, maintenance and conducting the burn-up measurements would impact the facility size based on maintaining the same waste throughput. These changes would result in a significant increase in the cost of the WHB construction and operation. Other impacts are described in Section 12.1.1.

- *Wet Assay Technology Operating on Individual SFAs* – If this type of technology is used, burn-up measurement pools and equipment would need to be added to the design. In addition, hot cells and/or fuel handling pools and equipment would need to be added to cut open canisters and handle/transfer individual SFAs. With this alternative, consideration should also be given to using a wet transfer system for all fuel handling operations and integrating this system with the wet system provided for conducting cask maintenance. The impacts on cost are unknown because the design would be radically different from the design provided in the ACD.

Of the 19 buildings in the North Portal area, the WHB, WTB, and CMF contribute approximately 64 percent to the construction cost and 59 percent to the operating cost of the repository surface facilities. The potential impacts described above are significant drivers to the repository cost.

There is a low probability that in the future some burn-up measurement capability for SFAs would become a requirement for the repository design based on the current program position. There is a moderate probability that some DOE-owned waste form assay capability would become a functional repository requirement. There is also a high probability that the selected technology would operate on individual SFAs and other non-SFA waste form canisters. There is a high probability that a technology exists or could be developed to perform the SFA assays in a dry environment.

12.1.2.4 Tasks Required for Resolution

Assay and/or burn-up measurement technologies need to be identified, possibly modified, and approved. A technology needs to be selected, and the facility and equipment requirements need to be established. The major repository nuclear facilities would need to be redesigned and the total system life cycle cost would need to be updated.

12.1.3 Repository Collocation with Interim Storage

12.1.3.1 Description

Congress is currently considering amending the Nuclear Waste Policy Act of 1982 to allow, or require, interim storage of spent nuclear fuel (SNF) and defense high-level waste (DHLW) near the repository. Interim storage (referred to as monitored retrievable storage) involves receiving shipping casks, transferring the waste to a storage mode, and transferring the storage mode to a storage pad. When the repository begins operation, the waste is transferred from the storage mode to a disposal container for emplacement.

It is expected that most of the facilities required to conduct repository operations would also be required to conduct interim storage operations. It is also expected that the repository could conduct all the interim storage operations if a storage pad were added and a storage mode loading capability were added to the WHB. Due to space limitations adjacent to the North Portal, the storage pad may need to be remote.

12.1.3.2 Assumption Used for ACD

The repository ACD does not include considerations for collocation with interim storage operations.

12.1.3.3 Risk Considerations

Adding the interim storage mission to the MGDS (i.e., collocation) would significantly impact the current repository design scope, as well as planned schedules, budgets and program milestones. Project redirection to a phased licensing and construction approach would be considered to promote early receipt of waste forms at lowest initial cost. The repository surface waste handling designs would be impacted by the added functional requirement to accommodate handling of the waste storage modes and interface with the storage mode transporters. A suitable location for the storage pad would also need to be identified, and the complexities of licensing a single facility under both 10 CFR 60 and 10 CFR 72 would need to be addressed.

The design impacts described above will increase the construction and operating cost of the repository surface facilities, although a collocated design will also be significantly more cost efficient for the overall waste management system as compared to providing separate (i.e., non-collocated) facilities.

There is a moderate probability that interim storage will be collocated with the repository in the future. A determination that the Yucca Mountain site is not suitable for a repository would likely deter a decision to provide interim storage within the Nevada Test Site. However, there has been no indication to date that the Yucca Mountain site would not be suitable for a repository. Interim storage collocated with the repository is an attractive waste management option because the waste would not need to be transported twice, it accommodates early receipt of waste, and it has a relatively small impact on the repository construction cost. Another advantage of this alternative is that the storage pad could likely be used to support a repository retrieval mission or accommodate surface waste cooling (aging).

12.1.3.4 Tasks Required for Resolution

Congressional action is required to revise the current Nuclear Waste Policy Act of 1982 to allow interim storage at the proposed repository site. The repository surface facilities design would then need to be modified to incorporate disparate interim storage features from the monitored retrieval storage design. A phased construction approach would need to be addressed in the design so that early waste receipt and minimum initial construction costs may be achieved.

12.1.4 Integrated Nuclear Operations

12.1.4.1 Description

Surface nuclear operations at the repository include waste handling operations, cask maintenance operations, and waste treatment operations. These major operations are performed in separate structures, each with unique individual systems and components. Each major operation also requires a variety of support systems. Many of these support systems are common to all three of the major operations and could be combined in an integrated facility design that serves all operations more efficiently and economically. Integrating these operations into a single facility could take advantage of economy of scale by using fewer large facilities, eliminating multiple like support systems, increasing facility utilization, promoting the sharing of staff, and facilitating personnel and materials movement.

12.1.4.2 Assumption Used for ACD

The repository ACD provides separate structures (i.e., WHB, CMF, and WTB) for conducting the nuclear material handling operations. Each building contains common support areas such as offices, tool and equipment storage, maintenance shops, health physics areas, and change rooms. This non-integrated approach was selected for the ACD because the repository surface facilities design, schedule, and budget were inadequate to develop integrated facility designs.

12.1.4.3 Risk Considerations

Integrating the facilities for waste handling operations, cask maintenance operations, and waste treatment operations is expected to reduce the quantity of construction (i.e., total building area) and optimize the operating staff.

Of the 19 buildings in the North Portal area, the WHB, WTB, and CMF contribute approximately 64 percent to the construction cost and 59 percent to the operating cost of the repository surface facilities. Integrating the operations should moderately reduce the capital and operating cost.

There is a high probability that future design optimizations will select an integrated approach for the nuclear operations.

12.1.4.4 Tasks Required for Resolution

Design integration of these facilities is currently planned for FY 1997.

12.1.5 Frequency of Waste Package Disassembly for Performance Confirmation

12.1.5.1 Description

Performance confirmation is a program of baseline data acquisition and ongoing monitoring which will ensure that assumptions made during the repository licensing process are correct. This program will provide confidence that the repository system is functioning, and will continue to function, as it was presented at the time of licensing.

Requirements to guide the development of a performance confirmation program are not yet in place. Uncertainties exist as to the types of data to be collected and how often this data needs to be collected. The program is expected to rely on some combination of in situ monitoring, in situ experiments, and laboratory and/or field testing of seals, barriers, and waste packages.

12.1.5.2 Assumption Used for ACD

The repository WHB is designed to support the retrieval and disassembly of one disposal container (waste package) every 10 years, starting ten years after the first waste package is emplaced.

The WHB design includes one hot cell that is expected to be adequately sized to conduct disposal container disassembly operations specifically in support of a performance confirmation program. This cell would also be used to add filler material to SFA canisters and to help mitigate off-normal situations with canisters, disposal containers and fuel assemblies.

During the caretaker phase, the repository maintains a skeleton crew of about 32 full-time employees to secure and maintain the facilities and conduct in situ performance confirmation monitoring. When a disposal container internals are to be examined, the staffing level for the surface operations increases to 195 full-time employees, the crews are retrained, and the affected buildings and support systems are restarted. A disposal container is brought to the WHB from the emplacement drift and transferred to the performance confirmation cell. In this cell the disposal container is opened, waste is removed, and testing and sampling activities are conducted. After examination and testing, the waste is repackaged and then returned to the emplacement area. When the above-ground performance confirmation operations are complete, the staff is reduced to 150 full-time employees, and the WHB and other affected facilities are decontaminated. Following decontamination, the repository is returned to a standby caretaker mode (i.e., maintenance and monitoring) and the staffing level reduces again to 32 full-time employees. The durations for each operating period is as follows: seven years for standby, two years for restart and waste package disassembly, and one year for decontamination. During the emplacement phase, performance confirmation activities can be performed without an increase in staffing levels.

12.1.5.3 Risk Considerations

Three options for performance confirmation are considered below:

- *Disposal Containers Do Not Require Opening* – There is no impact on the size of the facilities or construction cost because the same hot cell will be provided to support off-normal operations. The operating cost during the caretaker phase would be reduced approximately 65 percent. There is a moderate probability that this approach will ultimately be selected for the repository because other in situ methods of monitoring may be adequate to confirm system performance.

- *Disposal Containers Must Be Opened More Frequently* – There is no impact on the size of the facilities or construction cost, if the available cell can accommodate the higher throughput without impact to other functions this cell performs. It is expected that rates of approximately two disposal container openings per year or fewer could be accommodated with the present design. The operating costs during caretaker phase could double. There is a moderate chance this alternative will be selected. If it is decided that disposal containers need to be opened to collect data, it may also be decided that more openings are required because of the variety of waste forms emplaced at the repository.

- *Disposal Containers Must Be Opened So Frequently That More Cells Are Required* – The cell configurations and overall size of the WHB, construction cost, and the staff during emplacement and caretaker phases would increase. There is a low probability that this alternative will be selected.

12.1.5.4 Tasks Required For Resolution

Data are being collected from the Exploratory Studies Facility (ESF) and the Surface Based Testing programs that will provide much of the baseline information needed to initiate the formal performance confirmation program once it is developed.

A systems study concerning performance confirmation is underway during FY 1996. The objective of the study report is to provide the technical bases for recommendations for performance confirmation program-related updates to the RDRD (YMP 1994a) and/or *Engineered Barrier Design Requirements Document* (EBDRD) (YMP 1994c), with primary emphasis on the identification of the key drivers. The report will also contain an overview of the performance confirmation approach in the form of a draft performance confirmation plan. This study is the first step in defining requirements for the performance confirmation program.

When the performance confirmation disposal container opening rates are selected, the number of cells required would need to be calculated, and the WHB may require redesign.

12.2 SUBSURFACE DESIGN ISSUES

12.2.1 Thermal Loading – Emplacement Area Required

12.2.1.1 Description

Thermal loading has a great potential to impact the reference design. Section 8.2 contains a description of thermal loading and the different ways in which it can be expressed. The magnitude of the potential impact of the thermal loading decision on the subsurface repository is best defined by showing the range of repository sizes that would result from thermal loads at the opposite ends of the possible range. A repository having a low thermal loading of 25 MTU/acre would require emplacement area totaling approximately 1,134 hectares (2,800 acres) in order to emplace the 70,000 MTU waste inventory. This is approximately three times the area available in the current primary area being characterized at Yucca Mountain. At the other end of the range, a thermal load of 100 MTU/acre requires only 283 hectares (700 acres) to emplace 70,000 MTU. A repository of this size would fit entirely within the upper block of the primary area with additional space remaining.

Figure 12-1 shows these bounds. The primary area and all optional areas are required for a 25 MTU/acre loading. In contrast, only the cross-hatched area in the upper block of the primary area is needed for a high loading of 100 MTU/acre.

12.2.1.2 Assumption Used in ACD

As discussed in Section 8, a loading of 83 MTU/acre was used to develop the ACD reference design layout. This loading requires 341 hectares (843 acres) of usable emplacement area. This can be accommodated within the primary area, using the upper and lower blocks, with approximately 10 percent extra space available.

12.2.1.3 Risk Considerations

As can be seen by the wide range of possible areal requirements, the thermal loading decision has the potential to make the repository area large or compact. Potential impact is greater with a low loading because the primary area cannot accommodate the 70,000 MTU inventory at less than approximately 72 MTU/acre. If the loading were to be lower than 72 MTU/acre, additional space outside the primary area would have to be characterized and developed. A high loading would allow development of a very compact subsurface repository. Approximately 324 hectares (800 acres) is available in the upper block of the primary area. Loadings of 88 MTU/acre and above could be placed completely within the upper block.

12.2.1.4 Tasks Required for Solution

The selection of the thermal load is driven by multiple factors including long-term performance and preclosure operational needs. Field data from thermal testing in the Exploratory Studies Facility combined with long-term performance modeling will provide the primary information from which the thermal loading decision will be made. Volume I, Section 9.1, contains a discussion of the thermal loading issue. A description of the thermal strategy is contained in Section 8.2.3.

12.2.2 Thermal Loading – Maintaining Flexibility

12.2.2.1 Description

An issue related to the question of thermal loading is that of maintaining the flexibility to change thermal load if the need to do so is indicated by performance confirmation testing or modeling. Changes in the thermal loading strategy can be accommodated with relative ease prior to the receipt of NRC construction authorization and the start of repository subsurface construction. After the start of construction, however, such changes may impact both the cost of the facility and the schedule of emplacement.

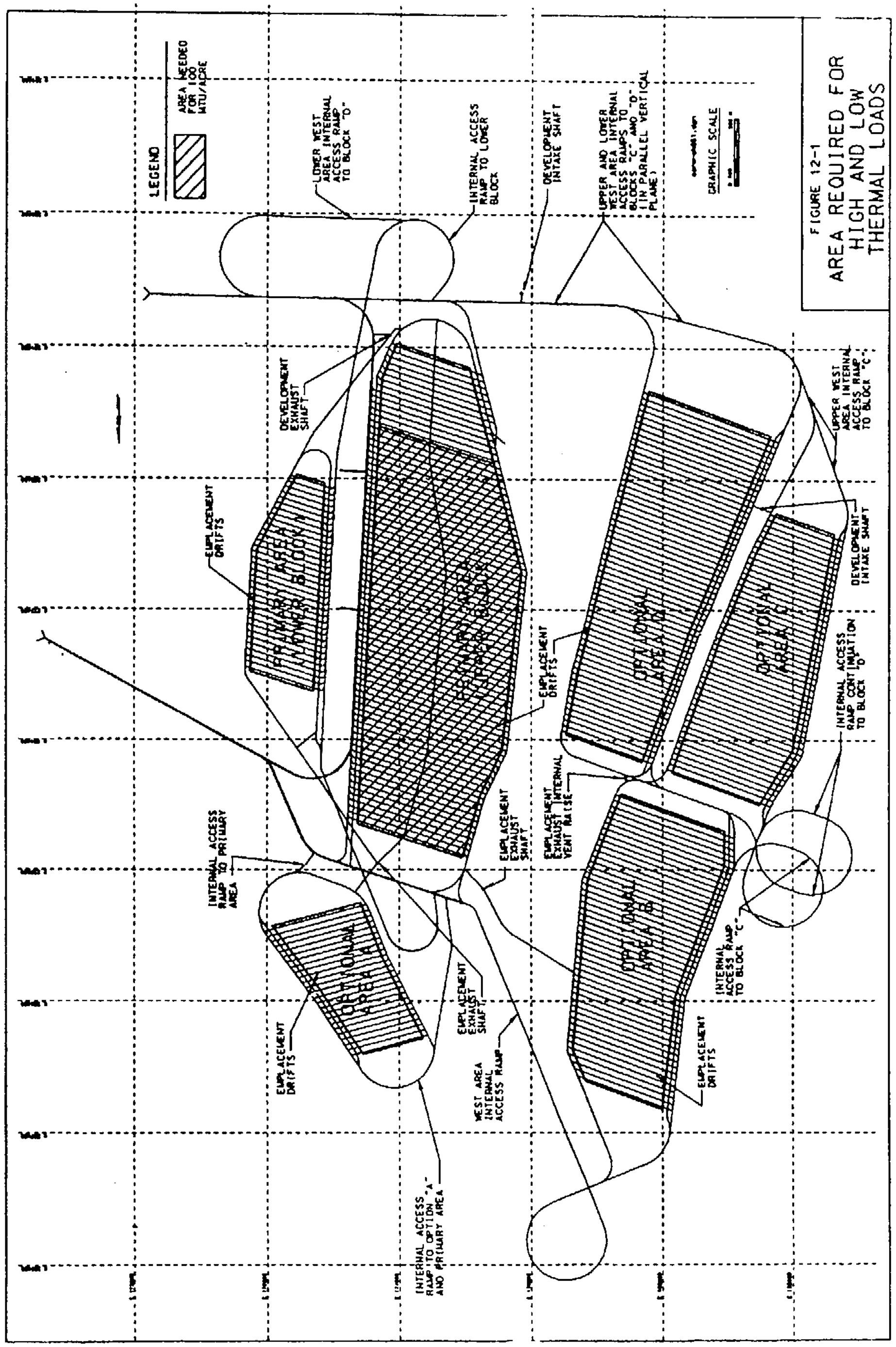


Figure 12-1. Area Required for High and Low Thermal Loads

The primary factor causing the impact is that the spacing between the emplacement drifts would not be the same for high and low thermal load strategies. A high thermal load requires emplacement drifts on relatively close spacings to achieve the waste package density needed for a high thermal load without placing the waste packages too closely together within the emplacement drifts (placing the waste packages too closely together could cause them to overheat, potentially degrading long-term performance). A low thermal load does not require such close drift spacing but, as noted in the previous section, requires significantly more total area to be developed.

A potential strategy that would allow the program to begin the emplacement process at a low thermal loading while maintaining the option to switch to a high thermal load is described the *Waste Emplacement Management Evaluation Report* (CRWMS M&O 1995at). This strategy is summarized here.

Development of the repository would be started with an emplacement drift spacing needed for a high thermal load. Waste emplacement, however, would be done at a low areal load. Two possible waste package arrangements are shown in Figures 12-2 and 12-3. Figure 12-4 shows the waste package arrangement for the high thermal loading case. As can be seen by comparing the figures, the emplacement drifts are under-used in the low loading cases, with some drifts having no waste packages, and others having packages on larger-than-minimum spacings. This does, however, maintain the option to change to a high thermal load by simply emplacing in the empty drifts and decreasing the waste package spacing in those drifts containing waste.

A downside to this strategy is that, because there is a logistical limit to the number of tunnel boring machines (TBM) that can be operated from a single service main, the development operation could not excavate emplacement drifts at a high enough rate to support the currently planned annual waste receipt and emplacement schedule. This schedule is shown in Section 8.2. As long as the emplacement drifts are being developed on close spacing, and the waste emplaced at a low loading, the annual emplacement rate would be constrained to well below the currently planned rate of 3,400 MTU/year.

Once the final thermal loading decision is made, high or low, the waste emplacement rate could be increased to the planned level. If the decision is for high thermal load, the emplacement drifts would simply be fully used. If the decision is for low thermal load, the spacing of the subsequently developed emplacement drifts would be increased, reducing the amount of under-used emplacement drift space. Figure 12-5 indicates how the primary area would appear under a scenario in which the decision was made to stay with a low thermal loading after approximately half of the upper block had been developed to maintain a high thermal loading option.

12.2.2.2 Assumption Used in ACD

The ACD reference layout is developed with closely spaced emplacement drifts, providing the ability to begin emplacement at any loading up to approximately 100 MTU/acre. As discussed above, the selection of a low loading would constrain the annual waste emplacement rate until a final loading decision was in place.

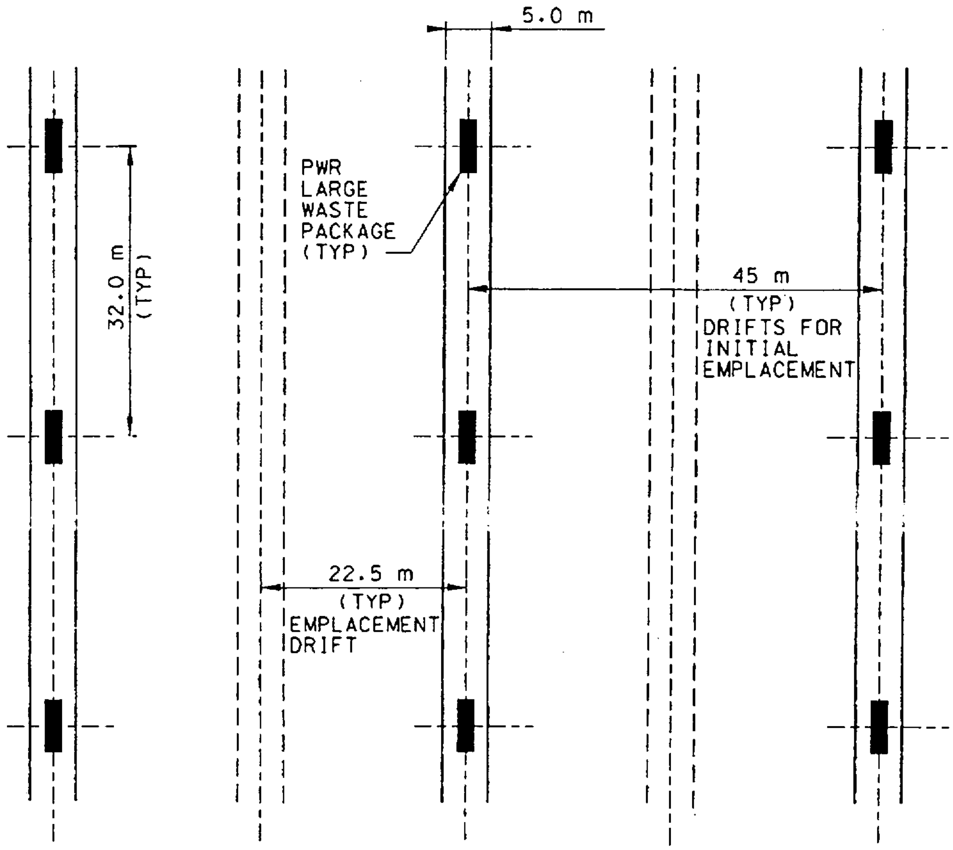


Figure 12-2. Minimal Disturbance Emplacement Pattern

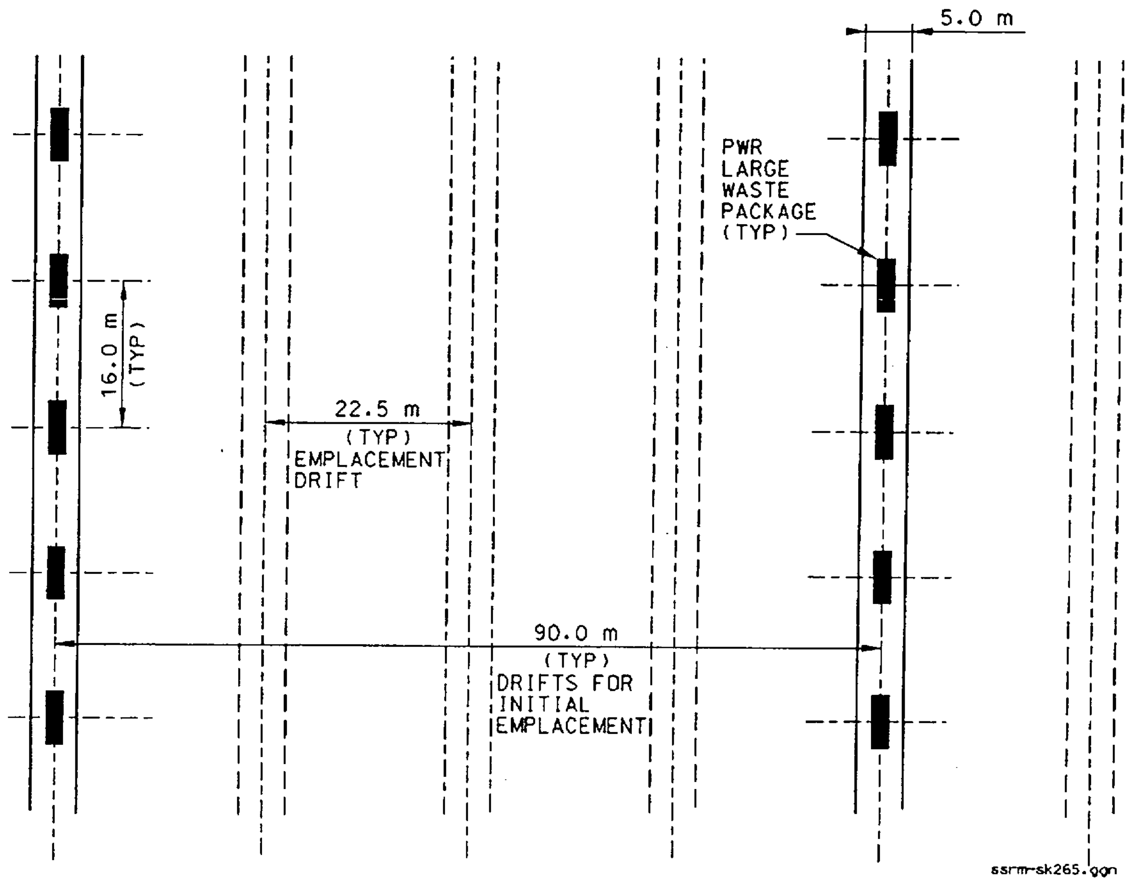


Figure 12-3. Localized Disturbance Emplacement Pattern

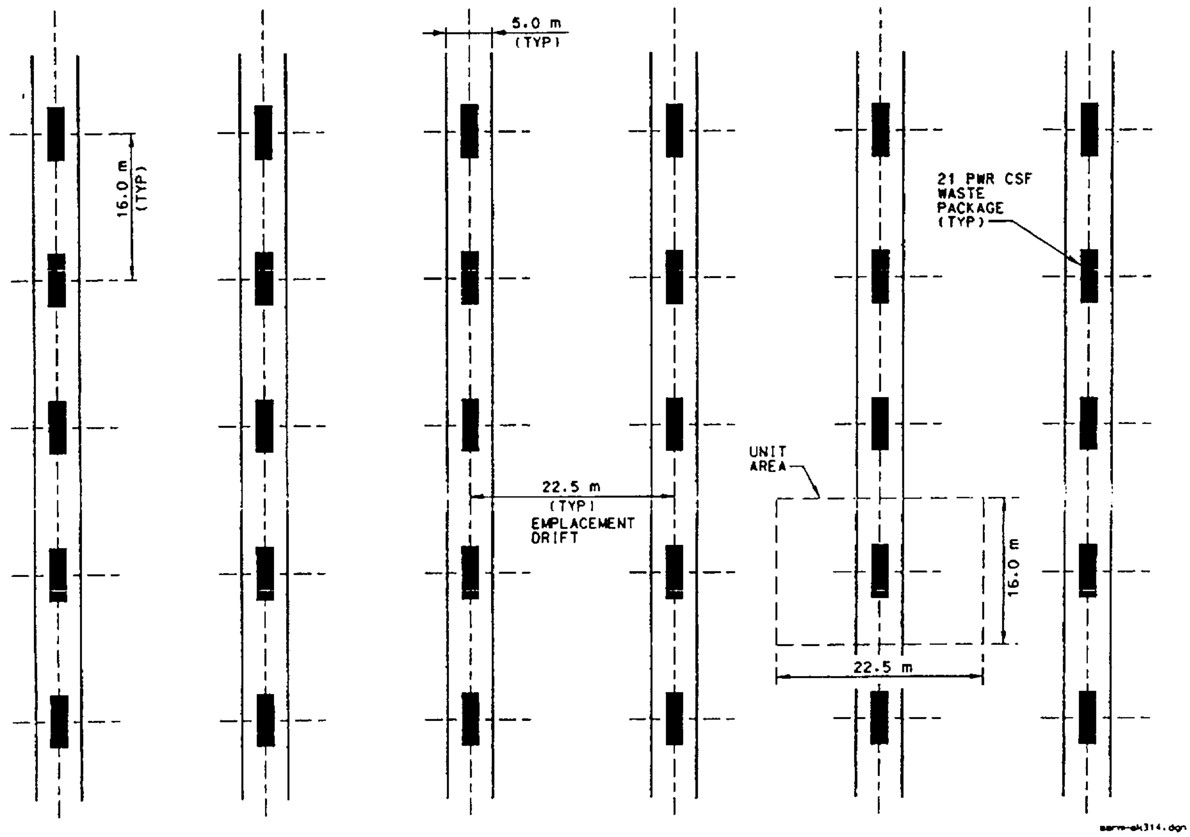


Figure 12-4. 100/MTU Emplacement Pattern

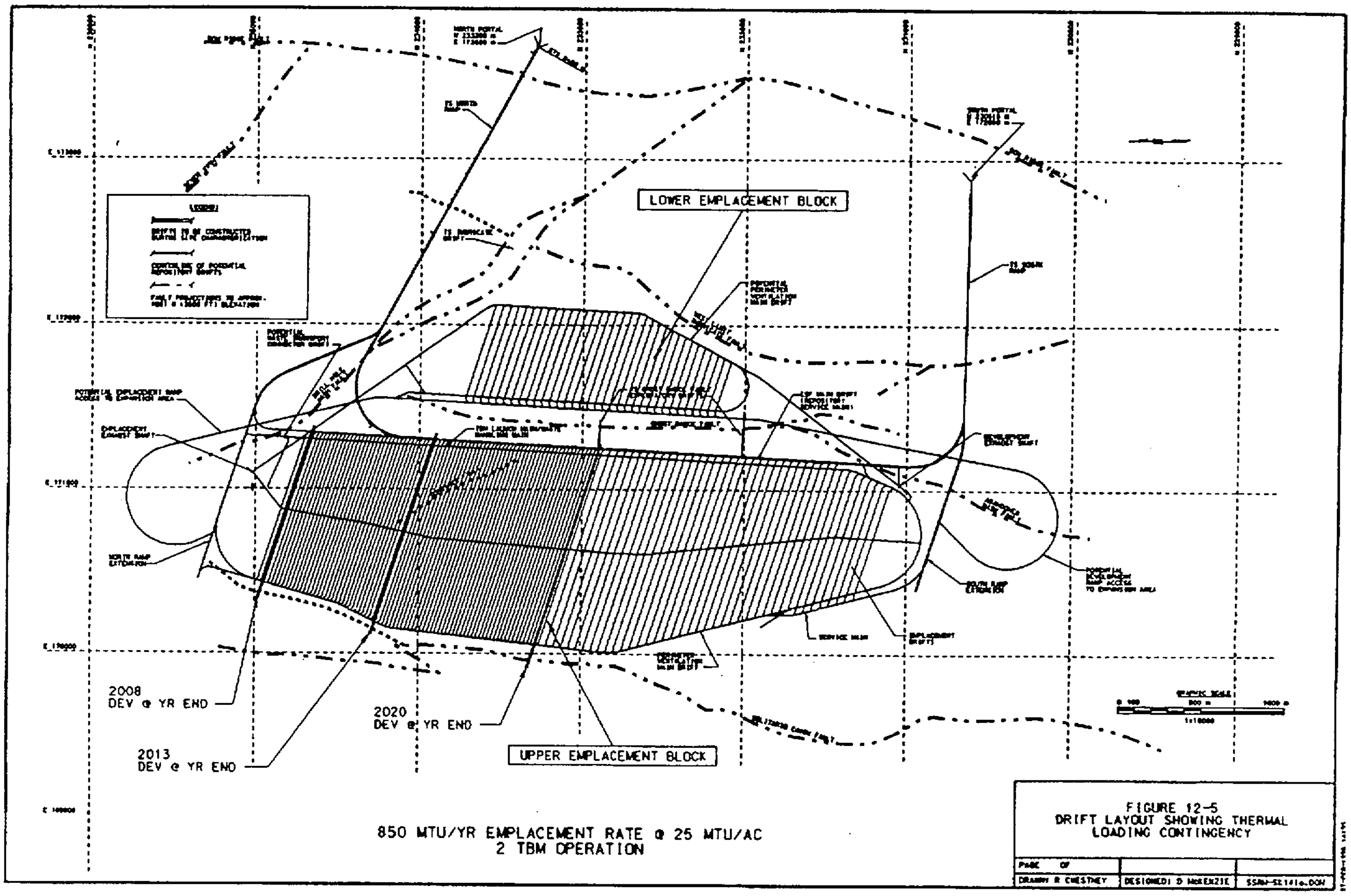


Figure 12-5. Drift Layout Showing Thermal Loading Contingency

12.2.2.3 Risk Considerations

The risk of pursuing this strategy is that some emplacement drift excavation could be wasted if the decision is made to stay with a low thermal load. Additionally, the annual waste emplacement rate would be constrained until the final decision is made. This constraint would begin in approximately the fourth year of emplacement operations. The waste receipt rate is sufficiently low in the first three years that it can be accommodated. The longer the decision is delayed, the larger the potential impact. It is preferable, therefore, to have the thermal loading decision in place prior to, or immediately following, the start of construction.

12.2.3 Thermal Loading – Thermal Goals

12.2.3.1 Description

A number of thermal goals have been developed to minimize the possible effects of increased temperature on the repository host rock and over- and underlying units. Thermal goals are discussed in Volume II, Section 8.2. Although these goals are tentative, some have become important to the repository design as their application influences repository configuration. Confirmation or revision of these goals is needed because a change in one or more of the goals may have a sizable impact on subsurface design.

12.2.3.2 Assumption Used in ACD

As described in Section 8.2, the three thermal goals influencing the current design are:

- Limit maximum temperature of the TSw3 unit to 115°C
- Limit maximum emplacement drift wall rock temperature to 200°C
- Limit maximum temperature of main access drift wall rock to 50°C.

The impacts on the layout of observing these limits are summarized below.

Limiting TSw3 temperature to 115°C involves maintaining an approximate 30 m vertical separation between the top of the TSw3 and the nearest emplaced waste packages, thus impacting the layout in the southwest area of the upper block. An area of approximately 100 acres is lost to emplacement in order to maintain the 30 m vertical separation.

The limit of 200°C for emplacement drift wall rock does not currently introduce any major limitation due to the selection of a thermal load of 83 MTU/acre for the reference design. At the reference thermal load, this temperature limit would be constraining only for large waste packages containing young (i.e., just over ten years out of reactor) fuel. The peak wall rock temperature estimated for emplacement of waste having the average characteristics of an oldest fuel first acceptance strategy (Volume II, Section 8.2) is in the 150 to 160°C range. The 200°C wall rock goal would become more important under a 100 MTU/acre scenario because more waste packages would have the potential to cause wallrock temperatures in excess of the goal.

The goal of limiting main access wall rock temperatures to 50°C involves the use of thermal buffer zones. These thermal buffers are areas of the emplacement drifts immediately adjacent to the main drifts which are left empty. This results in loss of potential emplacement area of the repository and an increase in cost. The empty areas allow the mains to remain cool because the process of thermal conduction through the rock takes many years to result in a rise of the rock temperature in the main. The fact that ventilation is maintained in the mains also tends to reduce the temperature rise of the main drifts.

12.2.3.3 Risk Considerations

The primary risk to the reference design of these goals is that a significant change in one or more of the goals could cause a change in the layout. If the TSw3 temperature limit were to be eliminated, additional emplacement space would be available in the primary area. Conversely, if it were lowered, the available space would be further reduced. Similarly, a change in the peak emplacement drift wall rock temperature goal could impact the allowable level of thermal loading and therefore change the size of the repository. A change in the main drift thermal goal could involve alteration of the width of the thermal buffers, again changing the repository size and resulting in loss or gain of emplacement area.

12.2.3.4 Tasks Required for Solution

Thermal goals are tied to the overall thermal loading strategy and will be defined (or eliminated) as a part of the final thermal loading decision.

12.2.4 Retrievability

12.2.4.1 Description

As discussed in Section 9.2, the ability to retrieve any or all of the emplaced waste must be maintained for 100 years after the start of emplacement. This retrieval operation would have to be conducted under adverse initial conditions including high temperature and radiation levels, and may have to contend with inoperative rail systems, areas of collapsed emplacement drift, and radioactive contamination from breached waste packages. Considerable effort will be required to demonstrate that retrieval is possible under the most adverse credible conditions that might be encountered. The retrievability issue encompasses issues related to long-term ground stability, including the longevity of material used for ground control. The issues related to long-term ground control requiring further investigation during the post-ACD are discussed below.

12.2.4.1.1 Materials Behavior

Information is needed to understand the potential for chemical and structural degradation of engineered materials at temperatures up to about 200°C and for time periods up to at least 150 years. Evaluation should consider the effects of site geochemistry, moisture, temperature (including temperature-induced mechanical loads), and time on construction materials (e.g., steel, concrete, shotcrete, and grout). Such data collected from in situ and laboratory tests and literature analysis are considered to have applicability to the assessment of preclosure as well as postclosure conditions.

12.2.4.1.2 Rock Mass Performance Parameters

The in situ measurement of rock and ground support deformation, stress, and temperature during ESF excavation and thermal testing (e.g., heater tests) is needed to develop criteria for the design of repository structures and operations. In addition to verification of design and the further development of acceptance criteria for subsurface openings, these data provide input to a database as the first step in a performance confirmation program as described in Subpart F of 10 CFR 60.

12.2.4.2 Assumption Used in ACD

A thermal load of 83 MTU/acre, near the lower end of the high range (80 to 100 MTU/acre), was used in the reference design. This should result in peak wall rock temperatures in the 150 to 160°C range in the emplacement drifts during the preclosure period. This is well below the current thermal goal of 200°C.

Emplacement drifts will not be ventilated after they are fully emplaced. However, the emplacement ventilation system is sized to be able to provide adequate airflow to emplacement drifts on a sequential basis to cool the drifts sufficiently for retrieval equipment to enter the drift.

No backfilling of emplacement drifts is planned. The emplacement drifts will remain unobstructed throughout the preclosure period. Retrieval equipment will have unimpaired access after ventilation is re-established to cool the drift.

The waste emplacement mode of in-drift emplacement of waste packages on railcars makes retrieval a straightforward operation under normal conditions. Retrieval would be accomplished in the reverse of the emplacement sequence.

12.2.4.3 Risk Considerations

If a determination is made that retrieval is not possible under the reference design conditions described above, the repository design would require change in order to preserve the retrieval option. The changes could involve altering certain design parameters such as the thermal loading; or basic changes to primary concepts, such as in-drift emplacement; the use of long parallel emplacement drifts; or the practice of not ventilating emplacement drifts after emplacement.

12.2.4.4 Tasks Required for Resolution

Prior to license application, the retrievability of waste under the conditions expected for the repository design must be shown to be feasible. Tasks required will include investigation of the behavior and longevity of the manmade materials that will be relied upon to preserve the retrievability option. These items are listed below.

- Ground Control – The behavior of both the subsurface openings and their installed ground control measures will be important. Field test information, primarily from ESF-based heater testing, coupled with numerical analyses of potential ground control measures and rock conditions, will help provide confidence that the drifts will remain stable. Investigation of the longevity of various construction materials should help in selecting those with projected long service lives and avoidance of those exhibiting rapid deterioration.

- Drift Invert and Rail System – The drift invert material and its installed rail haulage system must remain stable and functional in order to accommodate normal retrieval. As with ground control above, the issues of selecting proper construction materials, and in developing designs appropriate for the expected conditions, will be central to issue resolution.

- Waste Package Railcar – Retrieval under normal conditions will require that emplacement railcars remain functional throughout the preclosure period. An additional issue is that of metallurgical compatibility between the railcar and the waste package. The railcar must not detract from the long-term performance of the system. Design is needed to help ensure continued operability of the railcars, to provide compatibility, and to investigate potential enhancement of performance by the use of favorable materials and/or configurations.

12.2.5 Performance Confirmation

12.2.5.1 Description

A program of performance confirmation must be executed throughout the life of the repository. As discussed in Section 9.3, requirements for this program have not yet been defined. The eventual form that this program takes may have significant impact on the reference design. If requirements are developed that involve continuous monitoring of emplacement drifts, a significant research and development program will be needed to develop instrumentation capable of withstanding the emplacement drift environment for long time periods. Permanent in situ monitoring areas, if required, would involve changes to the subsurface layout.

12.2.5.2 Assumptions Used in ACD

While no special accommodation has been made for performance confirmation monitoring, it is felt that the layout could accommodate a reasonable program without major re-work. A combination of intermittent mobile remote monitoring and accessible in situ monitoring stations could be incorporated into the design as it now exists.

12.2.5.3 Risk Considerations

The primary risk to the design lies in the degree to which emplacement areas must be monitored. Continuous monitoring of all emplacement areas would be extremely impactive and would require a vast program of monitoring, data collection, and maintenance. Programs involving lesser levels of monitoring would have less impact on the design.

12.2.5.4 Tasks Required for Resolution

A systems engineering study currently underway is the first step in the process of defining performance confirmation program requirements. This study should produce a listing of requirements related to parameters of interest, proposed sampling frequencies, and proposed monitoring methodologies. A draft performance confirmation plan is also expected to result from this work. Subsequent repository design work will incorporate these recommendations.

12.2.6 Definition of the Repository Block

12.2.6.1 Description

The reference design presented in this MGDS ACD Report is based on the best mapping and geologic information available from ESF, surface mapping, drilling, and laboratory testing. While it is not expected that major changes will result from additional information, it is desirable to base the geologic model and, therefore, the subsurface design on the most complete information base possible.

12.2.6.2 Assumptions Used for ACD

The three-dimensional stratigraphic model described in Section 8.1 forms the basis for the reference layout, and is based on the best available geologic information.

12.2.6.3 Risk Considerations

The primary risk to the reference design of failing to acquire sufficient geologic information is that, if the design is well advanced, or construction is started, when a major feature (fault or large zone of fractured ground) is discovered, the layout may have to undergo significant modification, or even a complete change of approach. The impact of this degree of change is more severe when the design has reached its final stages, especially if construction has already begun.

12.2.6.4 Tasks Required for Resolution

The obvious solution in this situation is to continue gathering site information. Specific needs can be addressed by:

- Developing one or more cross-block drifts during site characterization to discover any major unknown north-south trending geologic features, and to explore the lower sub-units in the TSw2. The current Topopah Spring Main Drift remains in the upper part of the TSw2 along its entire length and traverses the east edge of the upper emplacement block. Such cross-block drifting is described in *Description and Rationale for Enhancement to the Baseline ESF Configuration* (CRWMS M&O 1993d).

- Performing some drilling in the southwest part of the block where geologic information is lacking to define the boundary of the block in that area.

12.2.7 Seismic Design Issues

12.2.7.1 Description

The design of the subsurface openings and ground control system must take into account ground motion from credible seismic events. A seismic design methodology has been developed and reported in two topical reports: *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain* (CRWMS M&O 1994t), and *Topical Report – Seismic Design Methodology for a Geologic Repository at Yucca Mountain* (YMP 1995d).

12.2.7.2 Assumptions Used in ACD

The reference design described in the MGDS ACD Report was developed using the methodology described in the above-referenced topical reports. The emplacement drifts were designed using the parameters for Performance Category 3.

12.2.7.3 Risk Considerations

The design of the ACD ground support systems could be affected if either of two events occur: a change in the magnitude of the design seismic event, or a change in the performance category in which repository subsurface openings have been placed.

12.2.7.4 Tasks Required for Resolution

A series of three topical reports was originally planned to be developed to address the seismic design issue. The first two reports, cited above, have been completed. A third report was originally planned for FY 1996, but has been deferred due to funding limitations. The completion of the third topical report is fundamental to the development of a robust licensing argument in the seismic design area. The first report dealt with the concept and methodology by which probabilistic estimation of the magnitude of the potential ground motion and fault displacement hazards at Yucca Mountain would be done. The second report contains a design methodology for estimating the design loads on subsurface openings, given a design seismic event. The third report is to contain definition of the magnitude of the design seismic event and corresponding ground motion parameters which can be used, in conjunction with the design methodology, to design the subsurface openings. The reference ACD design is based on the information used in the ESF design. This information can be found in *Seismic Design Inputs for the Exploratory Studies Facility at Yucca Mountain* (CRWMS M&O 1994d). The completion of the third topical report in the series is recommended to conclude the design for seismic hazards.

12.2.8 Secondary Excavation

12.2.8.1 Description

Approximately 20,000 m of the repository subsurface layout shown in this report will require excavation by means other than TBM. It is a stated assumption that mechanical excavations will be used when practical, as stated in Key Assumption 027 and Design Concept Subsurface (DCSS) 005 in the CDA Document (CRWMS M&O 1995a). There are currently no proven non-TBM mechanical excavation methods available to excavate rock having the compressive strength of the repository emplacement horizon rock, the TSw2. This unit has an unconfined compressive strength of approximately 179 megapascals (MPa) (SNL 1995a). Numerous concepts exist and have been conceptually evaluated (CRWMS M&O 1995aj). None have been proven via long-term operation in underground applications in rock of the strength of the TSw2.

12.2.8.2 Assumption used for ACD

The mobile miner, a hardrock excavation system based on disc cutter technology similar to TBMs, has been assumed for secondary (non-TBM) mechanical excavation. It is recognized that the mobile miner does not have a long history of proven use, but it has had three versions that have been used in actual mining and construction applications with varying degrees of success.

12.2.8.3 Risk Considerations

The risk to the ACD subsurface design is primarily in the operational methodology. The subsurface configuration shown can be excavated by numerous secondary excavation methods, should they prove feasible. In addition, drill and blast is an option. If drill and blast is used, some features of the design may need to be adapted to account for the movement, storage, and initiation of explosives, and the effects of blasting induced pressure waves on subsurface installations.

12.2.8.4 Tasks Required for Resolution

Further investigation into these methods, and field trials of the methods showing the most promise, would be required to base subsequent design work on any particular concept. Drill and blast excavation is the alternative to mechanical excavation and would likely be used if no non-TBM mechanical excavation methods prove feasible.

12.2.9 Emplacement Drift Backfill

12.2.9.1 Description

The use of backfill in emplacement drifts is not currently anticipated as indicated by Key Assumption 046 in the CDA Document (CRWMS M&O 1995a). However, the use of backfill as an enhancement to waste isolation is being evaluated, along with other Engineered Barrier System enhancements, in an ongoing systems engineering study. A decision to employ backfill in emplacement drifts could have the following potential effects on the design:

- If excavated tuff is to form some or all of the backfill material, the excavated rock storage area may have to provide protection of the rock to reduce the likelihood of deleterious changes over a 100-year period while stored on the surface.

- The closure period would be reconsidered because there would be approximately 250 km of drift to backfill as opposed to 25 to 30 km if only the main drifts and ramps are filled.

- A method would have to be developed to emplace backfill remotely in the emplacement drifts. A concept is discussed in Section 8.8, but significant additional work would be needed to prove the concept.

12.2.9.2 Assumption Used for ACD

As noted above, it is assumed in the ACD that no backfilling of emplacement drifts is required. However, it was considered inappropriate to present a design that did not support at least some form of emplacement drift backfill. The currently ongoing systems engineering study and the draft waste isolation strategy, which discusses backfill in numerous places, prompted the repository designers to consider adjusting the emplacement mode from a center in-drift mode, that may not support backfill, to an off-center in-drift mode which supports the placement of some types of backfill. The off-center in-drift mode also possesses other favorable attributes, including flexibility in potential retrieval actions and access for performance confirmation.

12.2.9.3 Risk Considerations

With the off-center in-drift emplacement mode, the risk to the design of changing to a backfill scenario is reduced. The closure phase of repository operations would have to be addressed again, as would the cost of construction of emplacement drifts. Additional design activity would be needed to more fully develop the concept of backfilling via a remote operation.

12.2.9.4 Tasks Required for Solution

The long-term performance of the site must be further evaluated to assess the potential benefits of backfill. Such performance assessment activity would, if backfill proves necessary or desirable, ultimately result in the development of requirements concerning backfill that would then be incorporated in subsequent design activity.

13. REFERENCES

* preceding a reference indicates document is pending DOE approval.

13.1 DOCUMENT REFERENCES

Anderson, J. G.; Brune, J. N.; Louie, J. N.; Zeng, Y.; Savage, M.; Yu, G.; Chen, Q.; and dePolo, D. 1994. "Seismicity in the Western Great Basin Apparently Triggered by the Landers, California, Earthquake, 28 June 1992." *Bulletin of the Seismological Society of America,* Vol. 84, 3.

AREA (American Railway Engineering Association) 1994. *Manual for Railway Engineering.*

Barton, N.; Lien, R.; and Lunde, J. 1977. "Estimation of Support Requirements for Underground Excavations." *Proceedings Sixteenth Symposium on Rock Mechanics: Design Methods in Rock Mechanics.* American Society of Civil Engineers.

B&W (B&W Fuel Company) 1991. *BR-100 100 Ton Rail/Barge Spent Fuel Shipping Cask Final Design Package.* 51-1203400-01.

Buesch, D. C.; Dickerson, R. P.; Drake, R. M.; and Spengler, R. W. 1993. "Integrated Geology and Preliminary Cross Section Along the North Ramp of the Exploratory Studies Facility, Yucca Mountain." *Proceedings of the Fourth Annual International Conference on High Level Radioactive Waste Management.* American Nuclear Society.

Calizaya, F.; Mousett-Jones, P.; and Casten, T. 1995. "Monitoring of Environmental Factors at the San Manuel Mine." *Proceedings of the 7th U.S. Mine Ventilation Symposium.* Society for Mining, Metallurgy, and Exploration, Inc.

Clear 1993. *allCLEAR Users Guide.* Clear Software, Inc.

Conca, J.; Zhou, W.; Arthur, R.; and Apted, M. J. 1995. *Analysis and Confirmation of Robust Performance for the Flow-Diversion Barrier System Within the Yucca Mountain Site.* IED 9408. Intera Information Technologies, Inc.

CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) 1992a. *Advanced Conceptual Design Work Plan.* ACD 93-0001 REV 0.

CRWMS M&O 1992b. Vawter, R. G. *DE-AC01-91RW00134; Waste Acceptance Support Deliverable 4A: Draft Waste Acceptance Criteria and DOE Position Recommendation for Failed Fuel.* TSO.920127.0118.

CRWMS M&O 1992c. Reserved.

CRWMS M&O 1993a. N. W. Hodgson. *Minutes of LV SCCB Meeting #004.* Interoffice Correspondence LV.SCM.NWH.10/93-031. October 14, 1993.

CRWMS M&O 1993b. *Monitored Retrievable Storage Facility Cask Maintenance Facility Design Study Report Final Draft.* D.I. No. MRSR-0001.

CRWMS M&O 1993c. *Site Characterization Plan Thermal Goals Reevaluation.* D.I. No. B00000000-01717-5705-00005, REV 00.

CRWMS M&O 1993d. *Description and Rationale for Enhancement to the Baseline ESF Configuration.* D.I. No. B00000000-01717-0200-00089 REV 01.

CRWMS M&O 1993e. *Repository Subsurface Layout Options and ESF Interface.* D.I. No. B00000000-01717-5705-00009 REV 00.

CRWMS M&O 1993f. *Repository Underground Ventilation System Concepts.* D.I. No. B00000000-01717-5705-00003 REV 00.

CRWMS M&O 1993g. *Non-Gassy Mine Classification Analysis.* D.I. No. BABE00000-01717-0200-00115 REV 00.

CRWMS M&O 1993h. *Alternatives for Waste Package Emplacement, Retrieval, and Backfill Emplacement.* D.I. No. B00000000-01717-5705-00006 REV 00.

CRWMS M&O 1993i. *Multi-Purpose Canister (MPC) Implementation Program Conceptual Design Phase Report, Volume II.C - MPC MRS Facility Conceptual Design Report: Final Draft.* D.I. No. A20000000-00811-5705-00004.

CRWMS M&O 1993j. *Preliminary Investigation of Disposal and Treatment Options for Low-Level Radioactive Mixed and Conventional Hazardous Wastes.* D.I. No. B00000000-01717-6700-00003 REV 00.

CRWMS M&O 1994a. *Initial Summary Report for Repository/Waste Package Advanced Conceptual Design.* D.I. No. B00000000-01717-5705-00015 REV 00.

CRWMS M&O 1994b. *Definition of Repository Block Limits.* D.I. No. BC0000000-01717-0200-00004 REV 00.

CRWMS M&O 1994c. *Yucca Mountain Project Draft Stratigraphic Compendium.*

CRWMS M&O 1994d. *Seismic Design Inputs for the Exploratory Studies Facility at Yucca Mountain--Technical Report.* D.I. No. BAB000000-01717-5705-00001 REV 01.

CRWMS M&O 1994e. Kelly, R. F. *Design Input Data for Repository Surface Designs.* Interoffice Correspondence VA.TD.VSM.7/94.436. July 27, 1994.

CRWMS M&O 1994f. Stringer, J. B. *QAP-3-12 Design Input Data Transmittal.* Interoffice

Correspondence VA.DES.JBS.12/94.019. December 20, 1994.

CRWMS M&O 1994g. *Retrievability Period Systems Study Report.* D.I. No. B00000000-01717-5705-00017 REV 00.

CRWMS M&O 1994h. Bahney, R. H, III. *Waste Package Thermal Analyses to Support System Studies.* Interoffice Correspondence LV.WP.RHB.06/94-167. June 30, 1994.

CRWMS M&O 1994i. Reserved.

CRWMS M&O 1994j. Williamson, D. *SNF Assembly Data.* Interoffice Correspondence WA.VA.DW.11/94.167. November 21, 1994.

CRWMS M&O 1994k. Wallin, W. E. *Revision #1 to Design Input Data Request Dated March 23, 1994.* Interoffice Correspondence LV.WP.WEW.6/94.124. June 23, 1994.

CRWMS M&O 1994l. Segrest, A. M. *Submittal of ESF/GROA Interface Drawings, D.I. No. BC0000000-01717-2100-89100 through 89105 Rev. 00 (SCP: N/A).* Letter LV.SB.KKB.2/94-024. February 25, 1994.

CRWMS M&O 1994m. *Generic Subsurface Layouts for Various Repository Thermal Loadings.* D.I. No. BC0000000-01717-5705-00002 REV 00.

CRWMS M&O 1994n. *Repository Shafts and Ramps Design Concepts Report for FY 1994.* D.I. No. BC0000000-01717-5705-00005 REV 00.

CRWMS M&O 1994o. *Subsurface Ventilation Analysis - Construction Phase.* D.I. No. B00000000-01717-2200-00001 REV 00.

CRWMS M&O 1994p. *FY 93 Thermal Loading Systems Study Final Report.* D.I. No. B00000000-01717-5705-00013 REV 01.

CRWMS M&O 1994q. *Repository Emplacement and Backfill Concepts and Operations Report.* D.I. No. BC0000000-01717-5705-00001 REV 00.

CRWMS M&O 1994r. *Data Sheet for Belt Conveyors - Bulk Handling.* Appendix A of Specification 14555, D.I. No. BABFCA000-01717-6300-14555 REV 04.

CRWMS M&O 1994s. *Repository Retrieval Concepts and Operations Report.* D.I. No. BC0000000-01717-5705-00003 REV 00.

CRWMS M&O 1994t. *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain.* D.I. No. BA0000000-01717-2200-00002 REV 00.

CRWMS M&O 1994u. Tsai, F. C. *Thermomechanical Calculations for FY93 Thermal Loading System Study.* Letter LV.PA.FCT-03/94-041. March 16, 1994.

CRWMS M&O 1995a. *Controlled Design Assumptions Document.* D.I. No. B00000000-01717-4600-00032 REV 02.

CRWMS M&O 1995b. *Develop Repository Technical Documents and Reports.* D.I. No. BC0000000-01717-2200-00010 REV 00.

CRWMS M&O 1995c. *Technical Document Preparation Plan for the Mined Geologic Disposal System Advanced Conceptual Design (Revised) Report.* D.I. No. B00000000-01717-4600-00057 REV 00.

CRWMS M&O 1995d. *MGDS Repository Status Reports, Implementation and Engineering Plans, Cost Estimates, and Information Gathering.* D.I. No. BC0000000-01717-2200-00007 REV 01.

CRWMS M&O 1995e. *Develop Scoping Technical Documents for Q-Items.* D.I. No. BC0000000-01717-2200-00008 REV 00.

CRWMS M&O 1995f. *Repository Design Basis Accident and Design Analyses.* D.I. No. BC0000000-01717-2200-00011 REV 00.

CRWMS M&O 1995g. *Perform Repository Design Basis Accident Analyses on Items Classified as Non-Q.* D.I. No. BC0000000-01717-2200-00012 REV 00.

CRWMS M&O 1995h. *Develop Repository Technical Documents for Non-Q Items.* D.I. No. BC0000000-01717-2200-00014 REV 00.

CRWMS M&O 1995i. *QA Classification Analysis of the Starter Tunnel Portion of Portals (CI: BABEAA000).* D.I. No. BABEAA000-01717-2200-00098 REV 00.

CRWMS M&O 1995j. *QA Classification Analysis of Main Access Openings (CI: BABEAD000).* D.I. No. BABEAD000-01717-2200-00002 REV 01.

CRWMS M&O 1995k. *QA Classification Analysis of Operation Support Areas (CI: BABEAE000).* D.I. No. BABEAE000-01717-2200-00001 REV 00.

CRWMS M&O 1995l. *QA Classification Analysis of Test Support Areas (CI: BABEAF000).* D.I. No. BABEAF000-01717-2200-00001 REV 00.

CRWMS M&O 1995m. *QA Classification Analysis of Ground Support Systems (CI: BABEE0000).* D.I. No. BABEE0000-01717-2200-00001 REV 02.

CRWMS M&O 1995n. *Definition of Potential Repository Block.* D.I. No. BC0000000-01717-5705-00009 REV 00.

*CRWMS M&O 1995o. *Repository Design Data Needs.* D.I. No. BC0000000-01717-5705-00012 REV 00.

CRWMS M&O 1995p. *Site Facilities Interface Final Report.* D.I. No. BCB000000-01717-4600-00003 REV 00.

*CRWMS M&O 1995q. *Emplacement Equipment/Concept Development Report.* D.I. No. BC0000000-01717-5705-00015 REV 00.

CRWMS M&O 1995r. Wallin, W. E. *Response to QAP-3-12 Request, Waste Package Closure Envelope Requirements and Cost Estimates.* Interoffice Correspondence LV.WP.WEW.1/95.012. January 9, 1995.

CRWMS M&O 1995s. *Repository Surface Waste Handling Concept of Operations.* D.I. No. BCB000000-01717-5705-00004 REV 01.

CRWMS M&O 1995t. *Preliminary Dose Assessment for the MGDS Surface Facility Waste Handling Operations.* D.I. No. B00000000-01717-5705-00022 REV 01.

CRWMS M&O 1995u. *Waste Handling Building Preliminary Estimation of the Internal Radiation Streaming for the MPC.* D.I. No. BCB000000-01717-5705-00006 REV 01.

CRWMS M&O 1995v. *Waste Handling Building Selection of Optimum Cask-Cell & Disposal Container-Cell Interface Method.* D.I. No. BCB000000-01717-5705-00002 REV 00.

CRWMS M&O 1995w. *Spent Nuclear Fuel Operations Analysis Report.* D.I. No. BCB000000-01717-5705-00001 REV 00.

CRWMS M&O 1995x. *Waste Handling Building Advanced Conceptual Design Study for FY 1995.* D.I. No. BCB000000-01717-5705-00003 REV 00.

CRWMS M&O 1995y. *Review of Designs and Requirements for Cask Operations.* D.I. No. BCB000000-01717-5705-00008 REV 00.

CRWMS M&O 1995z. *Low-Level Waste Treatment Analysis Report.* D.I. No. B00000000-01717-0200-00005 REV 00.

CRWMS M&O 1995aa. *Hazardous and Low-Level Mixed Waste Treatment Analysis Report.* D.I. No. BCB000000-01717-0200-00001 REV 00.

CRWMS M&O 1995ab. *Waste Treatment Building Interim Design Study for FY 1995.* D.I. No. BCB000000-01717-5705-00007 REV 00.

CRWMS M&O 1995ac. *Thermal Loading Study for FY 1995.* D.I. No. B00000000-01717-5705-00016 REV 00.

CRWMS M&O 1995ad. *Repository Ground Control Evaluation.* D.I. No. BC0000000-01717-5705-00017 REV 00.

CRWMS M&O 1995ae. Fleming, M. and King, J. *MGDS CDA Follow-On Data: MTU per Package.* Interoffice Correspondence SA.VA.JK.10/95.073. October 13, 1995.

CRWMS M&O 1995af. Davis, J.; Fleming, M.; King, J.; and Rose, M. *System Logistics and Waste Stream Data for MGDS CDA Update.* Interoffice Correspondence VA.SA.JK.03/95.038. March 28, 1995.

*CRWMS M&O 1995ag. *Emplacement Mode Evaluation Report.* D.I. No. BCA000000-01717-5705-00002 REV 00.

CRWMS M&O 1995ah. *Repository Layout Options Analyses Report.* D.I. No. BC0000000-01717-5705-00008 REV 00.

*CRWMS M&O 1995ai. *Recommended Layout Concepts Report.* D.I. No. BCAA00000-01717-5705-00001 REV 00.

CRWMS M&O 1995aj. *Excavation Systems Parameters.* D.I. No. BCAJ00000-01717-5705-00002 REV 00.

CRWMS M&O 1995ak. *Thermomechanical Analyses.* D.I. No. BC0000000-01717-5705-00013 REV 00.

CRWMS M&O 1995al. *ESF Ground Support Design Analysis.* D.I. No. BABEE0000-01717-0200-00002 REV 00.

*CRWMS M&O 1995am. *Retrieval Conditions Evaluation.* D.I. No. BCA000000-01717-5705-00003 REV 00.

CRWMS M&O 1995an. Bennett, S. M. and Zekai Ceylan. *WP Static Evaluation for Gantry Concept.* Interoffice Correspondence LV.WP.SMB.03/95.103. March 24, 1995.

CRWMS M&O 1995ao. *Subsurface Repository Remote Handling & Robotics Evaluation Report.* D.I. No. BC0000000-01717-5705-00016 REV 00.

CRWMS M&O 1995ap. Wallin, W. E. *Mass Estimations for Loaded Waste Packages and Transporter Shield Areal Density Values.* Interoffice Correspondence LV.WP.WEW.12/94.263. December 5, 1994.

CRWMS M&O 1995aq. *Subsurface Ventilation Concepts Report for Repository ACD - FY 94.* D.I. No. BC0000000-01717-5705-00004 REV 01.

CRWMS M&O 1995ar. *Repository Subsurface Ventilation Scoping Evaluation Report.* D.I. No. BCAD00000-01717-5705-00001 REV 00.

CRWMS M&O 1995as. *Repository Heating and Cooling Scoping Analysis Report.* D.I. No. BC0000000-01717-5705-00007 REV 00.

CRWMS M&O 1995at. *Waste Emplacement Management Evaluation Report.* D.I. No. BC0000000-01717-5705-00011 REV 00.

CRWMS M&O 1995au. *Layout and Sizing of ESF Alcoves and Refuge Chambers.* D.I. No. BABEA0000-01717-0200-00001 REV 00.

CRWMS M&O 1995av. *Total System Performance Assessment - 1995: Evaluation of the Potential Yucca Mountain Repository.* D.I. No. B00000000-01717-2200-00136 REV 01.

CRWMS M&O 1995aw. *Status Report on Systems Study to Evaluate Technical Basis for Project Decision on Use of Backfill in Emplacement Drifts at the Potential High-Level Nuclear Waste Repository at Yucca Mountain, Nevada.* D.I. No. BB0000000-01717-5703-00003 REV 00.

CRWMS M&O 1995ax. *Nevada Potential Repository Preliminary Transportation Strategy, Study 2.* D.I. No. B00000000-01717-4600-00050 REV 00.

CRWMS M&O 1995ay. *Nevada Potential Repository Preliminary Transportation Strategy, Study 1.* D.I. No. B00000000-01717-4600-00023 REV 01.

CRWMS M&O 1995az. Davis, J.; Fleming, M.; and King, J. *FY95 CDA Update Waste Stream Follow On Data.* Interoffice Correspondence VA.SA.JD.04/95.046. April 7, 1995.

CRWMS M&O 1995ba. *Controlled Design Assumptions (CDA) Key Assumptions Meeting Minutes.* Interoffice Correspondence LV.SER.ELC.11/95-102. November 21, 1995.

CRWMS M&O 1995bb. Foust, L. D.; Heath, C.; and Kubo, A. *Criticality Control Material in MPC Design.* Interoffice Correspondence VA.SE.GUR.8/95.016. August 11, 1995.

CRWMS M&O 1995bc. Balady, M. A. *Update to Rationale for Selection of First Procurement MPCs to be Opened.* Interoffice Correspondence LV.SEA.MB.04/95.047. April 24, 1995.

CRWMS M&O 1995bd. *Initial Waste Package Probabilistic Criticality Analysis: Uncanistered Fuel with Disposal Container (TBV-059-WPD).* D.I. No. B00000000-01717-2200-00079 REV 00.

CRWMS M&O 1995be. *Initial Waste Package Probabilistic Criticality Analysis: Multi-Purpose Canister with Disposal Container (TBV-060-WPD).* D.I. No. B00000000-01717-2200-00080 REV 00.

CRWMS M&O 1995bf. *Waste Package/Engineered Barrier Segment Conceptual Design Report.* D.I. No. BBA000000-01717-5705-00006 REV 00A.

CRWMS M&O 1996a. Booth, L. E. *Preliminary Hazards Analyses.* Interoffice Correspondence LV.SESE.LEB.01/96-001. January 4, 1996.

CRWMS M&O 1996b. *Preliminary MGDS System Safety Analysis.* D.I. No. BAB000000-01717-0200-00152 REV 00.

CRWMS M&O 1996c. *Waste Package Off-Normal and Accident Scenario Report.* D.I. No. BBA000000-01717-5705-00008 (In Process).

CSI (Construction Specifications Institute) 1988. *MASTERFORMAT, Master List of Titles and Numbers for the Construction Industry.* CSI MP-2-1-88.

DOE (U.S. Department of Energy) 1987a. "Transportation System Interface," *Generic Requirements Document for a Mined Geologic Disposal System (OGR/B-2).* DOE/RW-0090, Rev. 3, Appendix B.2. Office of Civilian Radioactive Waste Management.

DOE 1987b. Schneider, K. J., *Analysis of Radiation Doses from Operation of Postulated Commercial Spent Fuel Transportation Systems.* DOE-CH/TPO-001. Pacific Northwest Laboratory.

DOE 1987c. "Department of Energy Position on Retrievability and Retrieval for a Geologic Repository," *Generic Requirements Document for a Mined Geologic Disposal System (OGR/B-2).* DOE/RW-0090, Rev. 3, Appendix D. Office of Civilian Radioactive Waste Management.

DOE 1988a. *Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada.* DOE/RW-0199. Office of Civilian Radioactive Waste Management.

DOE 1988b. *Draft 1988 Mission Plan Amendment.* DOE/RW-0187. Office of Civilian Radioactive Waste Management.

DOE 1989. *Report to Congress on Reassessment of the Civilian Radioactive Waste Management Program.* DOE/RW-0247. Office of Civilian Radioactive Waste Management.

DOE 1991. *Draft Mission Plan Amendment.* DOE/RW-0316P. Office of Civilian Radioactive Waste Management.

DOE 1992. *Characteristics of Potential Repository Wastes.* DOE/RW-0184-R1. Office of Civilian Radioactive Waste Management.

DOE 1994a. Simecka, W. B. *Key Assumptions for Focused Mined Geologic Disposal System (MGDS) Development.* Letter AMEFO:PDS-3545. Office of Civilian Radioactive Waste Management. May 18, 1994.

DOE 1994b. *Civilian Radioactive Waste Management Program Plan.* DOE/RW-0458. Office of Civilian Radioactive Waste Management.

DOE 1995a. *Civilian Radioactive Waste Management System Requirements Document.* DOE/RW-0406P, Rev. 2E (D.I. No. A00000000-00811-1708-00003). Office of Civilian Radioactive Waste Management.

DOE 1995b. *Mined Geologic Disposal System Requirements Document.* DOE/RW-0404, Rev. 1, DCN 01 (D.I. No. B00000000-00811-1708-00002). Office of Civilian Radioactive Waste Management.

DOE 1995c. *Quality Assurance Requirements and Description for the Civilian Radioactive Waste Management Program.* DOE/RW-0333P, Rev. 5. Office of Civilian Radioactive Waste Management.

DOE 1995d. Dreyfus, D. A. *INFORMATION ONLY: Initiation of National Environmental Policy Act Requirements for the Potential Repository at Yucca Mountain.* Memorandum for the Secretary. Office of Civilian Radioactive Waste Management. June 22, 1995.

DOE 1996. *Site Characterization Progress Report, Number 13, April 1, 1995 - September 30, 1995.* (In Process). Office of Civilian Radioactive Waste Management.

EG&G (EG&G Energy Measurements) 1995. *Yucca Mountain Site Characterization Project Site Atlas 1995.*

Farr 1994. "Absolute HEPA Filters." *HVAC Products Bulletin B-1304-10B.* Farr Company.

General Atomics 1993a. *GA-4 Legal Weight Truck From-Reactor Spent Fuel Shipping Cask Final Design Report.* 910353/0.

General Atomics 1993b. *GA-9 Legal Weight Truck From-Reactor Spent Fuel Shipping Cask Final Design Report.* 910354/0.

Gombert, J. and Bodin, P. 1994. "Triggering of the M_S=5.4 Little Skull Mountain, Nevada, Earthquake With Dynamic Strains." *Bulletin of the Seismological Society of America.* Vol. 84, No. 3. June 1994.

Hardy, M. P. and Bauer, S. J. 1992. "Design of Underground Repository Openings in Hard Rock to Accommodate Vibratory Ground Motions." *Dynamic Analysis and Design Considerations for High-Level Nuclear Waste Repositories.* American Society of Civil Engineers.

Hartman; Howard, L.; Mutmansky, J. M.; and Wang, Y. J. 1982. *Mine Ventilation and Air Conditioning.* 2nd Edition. John Wiley & Sons, Inc. New York.

Hesketh; Howard, E.; and Cross, F. L., Jr 1983. *Fugitive Emissions and Controls.* Ann Arbor Science Publishers.

Itasca 1993a. *FLAC Version 3.2 User's Manual.* Volumes I, II, and III. Itasca Consulting Group, Inc.

Itasca 1993b. *UDEC Version 2.0 User's Manual.* Volumes I and II. Itasca Consulting Group, Inc.

Jaeger, J. C. and Cook, N. G. W. 1976. *Fundamentals of Rock Mechanics.* 3rd Edition. Chapman and Hall.

LLNL (Lawrence Livermore National Laboratory) 1993. Wilder, D. G. *Preliminary Near-Field Environment Report.* UCRL-LR-107476.

LLNL 1994. Buscheck, T. A.; Nitao, J. J.; and Saterlie, S. F. *Evaluation of Thermo-Hydrological Performance in Support of the Thermal Loading Systems Study.* UCRL-JC-115352.

LLNL 1995. *Metal Barrier Selection and Testing.* SIP-CM-01, Rev. 2.

NAC (Nuclear Assurance Corporation) 1987. *Cask Fleet Operations Study.*

NRC (U.S. Nuclear Regulatory Commission) 1984. *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants.* NUREG-0800, Rev. 5. Division of High-Level Waste Management, Office of Nuclear Material Safety and Safeguards.

NRC 1988. Duncan, A. B.; Bilhorn, S. G.; and Kennedy, J. E. *Technical Position on Items and Activities in the High-Level Waste Geologic Repository Program Subject to Quality Assurance Requirements.* NUREG-1318. Division of High-Level Waste Management, Office of Nuclear Material Safety and Safeguards.

NRC 1989a. *NRC Staff Site Characterization Analysis of the Department of Energy's Site Characterization Plan, Yucca Mountain Site, Nevada.* NUREG-1347. Division of High-Level Waste Management, Office of Nuclear Material Safety and Safeguards.

NRC 1989b. *Stability of Disposal Rooms During Waste Retrieval.* NUREG/CR-5335. Division of High-Level Waste Management, Office of Nuclear Material Safety and Safeguards.

NRC 1990. *Draft Regulatory Guide DG-3003: Format and Content for the License Application for a High Level Waste Repository.* Office of Nuclear Regulatory Research.

NRC 1994. McConnell, K. I. and Lee, M. P. *Staff Technical Position on Consideration of Fault Displacement Hazards in Geologic Repository Design.* NUREG-1494. Division of Waste Management, Office of Nuclear Material Safety and Safeguards.

NWTRB (Nuclear Waste Technical Review Board) 1990. *First Report to the U.S. Congress and the U.S. Secretary of Energy.*

ORNL (Oak Ridge National Laboratory) 1988a. A *Cask Fleet Operations Study.* ORNL/Sub/87-06604/1. Transnuclear Inc.

ORNL 1988b. Attaway, C. R. *Transportation Operations System Cask Maintenance Facility: Systems Requirements and Description.* ORNL/TM-10855 (ORO/TOP-5401.0).

ORNL 1991a. Rennich, M. J.; Medley, L. G.; and Attaway, C. R. *Feasibility Study for a Transportation Operations System Cask Maintenance Facility.* ORNL/TM-11019 (ORO/TOPO-5404.0).

ORNL 1991b. *Estimated Times for Annual Cask Maintenance.* White Paper.

ORNL 1992. Danese, F. L. and Schmid, S. P. *Cask Maintenance Operations.* White Paper.

Peng, S. S. 1992. *Surface Subsidence Engineering.* Society for Mining, Metallurgy, and Exploration, Inc.

Pritsker, Alan B. 1992. *SLAM II Quick Reference Manual.* Pritsker Corporation.

SAIC (Science Applications International Corporation) 1991. Peck, J. M.; Clanton, U. S.; Rautman, C. A.; Spengler, R. W.; and Vaniman, D. *Core Evaluation to Determine Contacts Between Thermal-Mechanical Units TSw1 and Tsw2.* Letter JHP-BP-L91-9642. May 15, 1991.

SAIC 1992. *Yucca Mountain Rail Access Study: Caliente Route Conceptual Design Report.*

SAIC 1993. *Yucca Mountain Site Characterization Project Meteorological Monitoring Program Summary Report January 1992 Through December 1992.*

Sawyer, D. A.; Fleck, R. J.; Lanphere, M. A.; Warren, R. G.; Broxton, D. E.; and Hudson, M. R. 1994. "Episode Caldera Volcanism in the Miocene Southwestern Nevada Volcanic Field: Revised Stratigraphic Framework, ^{40}AR/^{39}AR Geochronology, and Implications for Magmatism and Extension." *Geological Society of America Bulletin.* Vol. 106.

Scott, R. B. 1990. "Tectonic Setting of Yucca Mountain, Southwest Nevada." *Basin and Range Extensional Tectonics Near the Latitude of Las Vegas, Nevada.* Memoir 176, B. P. Wernicke, Ed. Geological Society of America.

SME (Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc.) 1973. Cummins; Arthur, B.; Chairman; and Given, I. A., Editor. *SME Mining Engineering Handbook.* New York.

SNL (Sandia National Laboratories) 1982. Lappin, A. R.; VanBuskirk, R. G.; Enniss, D. O.; Butters, S. W.; Prater, F. M.; Muller, C. B.; and Bergosh, J. L. *Thermal Conductivity, Bulk Properties, and Thermal Stratigraphy of Silicic Tuffs from the Upper Portion of Hole USW-G1, Yucca Mountain, Nye County, Nevada.* SAND81-1873.

SNL 1984a. Mansure, A. J. and Ortiz, T. S. *Preliminary Evaluation of the Subsurface Area Available for a Potential Nuclear Waste Repository at Yucca Mountain.* SAND84-0175.

SNL 1984b. Johnstone, J. K.; Peters, R. R.; and Gnirk, P. F. *Unit Evaluation at Yucca Mountain, Nevada Test Site, Summary Report and Recommendation.* SAND83-0372.

SNL 1984c. Nimick, F. B. and Williams, R. L. *Three-Dimensional Geologic Model of Yucca Mountain, Southern Nevada.* SAND83-2593.

SNL 1985a. Ortiz, T. S.; Williams, R. L.; Nimick, F. B.; Whittet, B. C.; and South, D. L. *A Three-Dimensional Model of Reference Thermal/Mechanical and Hydrological Stratigraphy at Yucca Mountain, Southern Nevada.* SAND84-1076.

SNL 1985b. Rautman, C. A. *Potential Problems with Topopah Spring Stratigraphy.* Letter to S. Sinnock. December 11, 1985.

SNL 1987. *Site Characterization Plan Conceptual Design Report (SCP-CDR).* SAND84-2641.

SNL 1989. Hardy, M. P. and Bauer, S. J. *Drift Design Methodology and Preliminary Application for the Yucca Mountain Site Characterization Project.* SAND89-0837.

SNL 1990. Richardson, S. S. *Preliminary Shaft Liner Design Criteria and Methodology Guide.* SAND88-7060.

SNL 1991. Dennis, A. W., Editor. *Exploratory Studies Facility Alternatives Study: Final Report.* SAND91-0025.

SNL 1992. Ma, C. W.; Sit, R. C.; Zavoshy, S. J.; and Jardine, L. J. *Preclosure Radiological Safety Analysis for Accident Conditions of the Potential Yucca Mountain Repository: Underground Facilities.* SAND88-7061.

SNL 1993a. Lin, M.; Hardy, M. P.; and Bauer, S. J. *Fracture Analysis and Rock Quality Designation Estimation for the Yucca Mountain Site Characterization Project.* SAND92-0449.

SNL 1993b. Bennett, P. C.; Doughty, D. H.; and Chambers, W. B. *Transportation Cask Contamination Weeping: A Program Leading to Prevention.*

SNL 1993c. Fernandez, J. A.; Case, J. B.; Tyburski, J. R. *Initial Field Testing Definition of Subsurface Sealing and Backfilling Tests in Unsaturated Tuff.* SAND92-0960.

SNL 1994. Fernandez, J. A. and Richardson, A. M. *A Review of the Available Technologies for*

Sealing a Pottial Underground Nuclear Waste Repository at Yucca Mountain, Nevada. SAND93-3997.

SNL 1995a. Brechtel, C. E.; Lin, M.; Martin, E.; and Kessel, D. S. *Geotechnical Characterization of the North Ramp of the Exploratory Studies Facility.* SAND95-0488.

SNL 1995b. Arnold, B. W.; Altman, S. J.; Robey, T. H.; Barnard, R. W.; and Brown, T. J. *Unsaturated-Zone Fast-Path Flow Calculations for Yucca Mountain Groundwater Travel Time Analyses (GWTT-94).* SAND95-0857.

SNL 1995c. Martin, R. J., III; Price, R. H.; Boyd, P. J.; and Noel, J. S. *Creep in Topopah Spring Member Welded Tuff.* SAND94-2585.

Spengler, R. W.; Braun, C. A.; Linden, R. M.; Martin, L. G.; Ross-Brown, D. M.; and Blackburn, R. L. 1993. "Structural Character of the Ghost Dance Fault, Yucca Mountain, Nevada." *Proceedings of the Fourth Annual International Conference on High Level Radioactive Waste Management.* American Nuclear Society.

USBR (U.S. Bureau of Reclamation) 1995a. *ESF - North Ramp, Station 1+00.00 to Station 2+00.00 As Built Geology and Geotechnical Data.* Drawing OA-46-181.

USBR 1995b. *ESF - North Ramp, Station 2+00.00 to Station 3+00.00 As Built Geology and Geotechnical Data.* Drawing OA-46-182.

USGS (U.S. Geological Survey) 1966. Lipman, P. W.; Christiansen, R. L.; and O'Connor, J. T. *A Compositionally Zoned Ash-Flow Sheet in Southern Nevada.* Professional Paper 524-F.

USGS 1976. Byers, F. M., Jr.; Carr, W. J.; Orkild, P. P.; Quinlivan, W. D.; and Sargent, K. A. *Volcanic Suites and Related Cauldrons of Timber Mountain-Oasis Valley Caldera Complex, Southern Nevada.* Profession Paper 919.

USGS 1980. Spengler, R. W. and Rosenbaum, J. G. *Preliminary Interpretations of Geologic Results Obtained from Boreholes UE25a-4, -5, -6 and -7, Yucca Mountain, Nevada Test Site.* Open-File Report 80-929.

USGS 1981. Spengler, R. W.; Byers, F. M., Jr.; and Warner, J. B. *Stratigraphy and Structure of Volcanic Rocks in Drill Hole USW G-1, Yucca Mountain, Nye County, Nevada.* Open-File Report 81-1349.

USGS 1984a. Carr, W. J. *Regional Structural Setting of Yucca Mountain, Southwestern Nevada, and Late Cenozoic Rates of Tectonic Activity in Part of the Southwestern Great Basin, Nevada and California.* USGS-OFR-84-854.

USGS 1984b. Scott, R. B. and Bonk, J. *Preliminary Geologic Map of Yucca Mountain with Geologic Sections, Nye County, Nevada.* Open-File Report 84-494.

USGS 1984c. Swadley, W. C.; Hoover, D. L.; and Rosholt, J. N. *Preliminary Report on Late Cenozoic Faulting and Stratigraphy in the Vicinity of Yucca Mountain, Nye County, Nevada.* Open-File Report 84-788.

USGS 1984d. Squires, R. R. and Young, R. L. *Flood Potential of Fortymile Wash and its Principal Southwestern Tributaries, Nevada Test Site, Southern Nevada.* Water-Resources Investigations Report 83-4001.

USGS 1984e. Scott, R. B and Castellanos, M. *Stratigraphic and Structural Relations of Volcanic Rocks in Drill Holes USW GU-3 and USW G-3, Yucca Mountain, Nye County, Nevada.* Open-File Report 84-491.

USGS 1984f. Spengler, R. W. and Chornack, M. P. *Stratigraphic and Structural Characteristics of Volcanic Rocks in Core Hole USW G-4, Yucca Mountain, Nye County, Nevada.* Open-File Report 84-789.

USGS 1986. *Geology of Drill Hole UE25p#1: A Test Hole Into Pre-Tertiary Rocks Near Yucca Mountain, Southern Nevada.* Open-File Report 86-175.

USGS 1992. Barton, C. C.; Page, W. R.; and Morgan, T. L. *Fractures in Outcrops in the Vicinity of Drill Hole USW G-4, Yucca Mountain, Nevada.* Open-File Report 89-92.

USGS 1993. Taylor, E. M. and Huckins, H. E. *Lithology, Fault Displacement, and Origin of Secondary Calcium Carbonate and Opaline Silica at Trenches 14 and 14D on the Bow Ridge Fault at Exile Hill, Nye County, Nevada.* Open-File Report 93-477.

USGS 1994a. Moyer, T. C. and Geslin, J. K. *Lithostratigraphy of the Calico Hills Formation and Prow Pass Tuff (Crater Flat Group) at Yucca Mountain, Nevada.* Open-File Report 94-460.

USGS 1994b. Spengler, R. W.; Braun, C. A.; Martin, L. G.; and Weisenberg, C. W. *The Sundance Fault: A Newly Recognized Shear Zone at Yucca Mountain, Nevada.* Open-File Report 94-49.

USGS 1994c. Ervin, E. M.; Luckey, R. R.; and Burkhardt, D. J. *Revised Potentiometric-Surface Map, Yucca Mountain and Vicinity, Nevada.* Water-Resources Investigations Report 93-4000.

USGS 1994d. *Documentation for Distribution of Lithostratigraphic Units Within the Central Block of Yucca Mountain, Nevada, Version YMP.R1.1.*

USGS 1994e. *Streamflow and Selected Precipitation Data for Yucca Mountain Region, Southern Nevada and Eastern California, Water Years 1986-1990.* Open-File Report 94-312.

USGS 1995a. Buesch, D. C.; Spengler, R. W.; Moyer, T. C.; and Geslin, J. K. *Revised Stratigraphic Nomenclature and Macroscopic Identification of Lithostratigraphic Units of the Paintbrush Group Exposed at Yucca Mountain, Nevada.* Open-File Report 94-469.

USGS 1995b. Craig, R. W. *Interception of Proposed Repository Horizon in the ESF North Ramp--Exploratory Studies Facility (ESF), Yucca Mountain Project, Nevada.* Letter to S. B. Jones. November 20, 1995.

USGS 1995c. Potter, C. J.; Dickerson, R. P.; and Day, W. C. *Nature and Continuity of the Sundance Fault, Yucca Mountain, Nevada.* Administrative Report.

USGS 1995d. *Precipitation Data for Water Years 1992 and 1993 from a Network of Nonrecording Gages at, Yucca Mountain, Nevada.* Open-File Report 95-146.

Voegle, M. D. 1993. "Photogeologic Reconnaissance of X-Tunnel at Little Skull Mountain." *Proceedings of the Fourth Annual International Conference on High Level Radioactive Waste Management.* American Nuclear Society.

YMP (U.S. Department of Energy Yucca Mountain Site Characterization Project Office) 1991. *Documentation of the Evaluation of Findings of the ESFAS Used to Develop a Reference Design Concept.* YMP/91-28.

YMP 1993. *Topical Report: Evaluation of the Potentially Adverse Condition, "Evidence of Extreme Erosion During the Quaternary Period" at Yucca Mountain, Nevada.* YMP/92-41-TR.

YMP 1994a. *Repository Design Requirements Document.* YMP/CM-0023, Rev. 0, ICN 1.

YMP 1994b. *Q-List.* YMP/90-55Q, Rev. 3.

YMP 1994c. *Engineered Barrier Design Requirements Document.* YMP/CM-0024, Rev. 0, ICN 1.

YMP 1995a. *Reference Information Base.* YMP/93-02, Rev. 3, ICN 1.

YMP 1995b. *Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion.* YMP/TBR-0001.

YMP 1995c. *Safety and Health Plan.* YMP/90-37, Rev. 2, ICN 2.

YMP 1995d. *Topical Report: Seismic Design Methodology for a Geologic Repository at Yucca Mountain.* YMP/TR-003-NP.

YMP 1995e. *Existing and Planned Boreholes With Geologic Structure.* YMP-93-172.0. EG&G/EM Remote Sensing Laboratory.

YMP 1995f. *System Safety Plan.* YMP/94-13, Rev. 0.

YMP 1995g. *Site Design and Test Requirements Document.* YMP/CM-0021, Rev. 2.

YMP 1995h. *Operation and Maintenance Management Plan.* YMP/93-01, Rev. 1.

YMP 1995i. *Exploratory Studies Facility Design Requirements.* YMP/CM-0019, Rev. 1, ICN 3.

13.2 LAWS, CODES, AND STANDARDS

Federal Facility Compliance Act of 1992. 42 USC 6901 et seq.

Low-Level Radioactive Waste Policy Amendments Act of 1985. 42 USC 2021b et seq.

National Environmental Policy Act of 1969. 42 USC 4321 et seq.

Nuclear Waste Policy Act of 1982 as amended by the Nuclear Waste Policy Amendments Act of 1987. 42 USC 10101 et seq.

Resource Conservation and Recovery Act of 1976. 42 USC 6901 et seq.

DOE (U.S. Department of Energy) Order 4330.4B. *Maintenance Management Program.* U.S. Government Printing Office. 1994.

DOE Order 4700.1. *Project Management System.* U.S. Government Printing Office. 1992.

DOE Order 5480.4. *Environmental Protection, Safety, and Health Protection Standards.* U.S. Government Printing Office. 1993.

DOE Order 5820.2A. *Radioactive Waste Management.* U.S. Government Printing Office. 1988.

DOE Order 6430.1A. *General Design Criteria.* U.S. Government Printing Office. 1989.

DOE Order HQ 1321.1. *Civilian Radioactive Waste Management Facilities--Exemption from Departmental Directives.* U.S. Government Printing Office. 1993.

DOE Order O 440.1. *Worker Protection Management for DOE Federal and Contractor Employees.* U.S. Government Printing Office. 1995.

DOE-STD-1020-94. *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities.* U.S. Government Printing Office. 1994.

DOE-STD-1021-93. *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components.* U.S. Government Printing Office. 1993.

10 CFR 20. "Standards for Protection Against Radiation." *Title 10, Energy, Code of Federal Regulations, Part 20.* U.S. Government Printing Office. January 1, 1995 Edition.

10 CFR 50. "Domestic Licensing of Production and Utilization Facilities." *Title 10, Energy, Code of Federal Regulations, Part 50.* U.S. Government Printing Office. January 1, 1995 Edition.

10 CFR 60. "Disposal of High-Level Radioactive Wastes in Geologic Repositories." *Title 10, Energy, Code of Federal Regulations, Part 60.* U.S. Government Printing Office. January 1, 1995 Edition.

10 CFR 61. "Licensing Requirements for Land Disposal of Radioactive Waste." *Title 10, Energy, Code of Federal Regulations, Part 61.* U.S. Government Printing Office. January 1, 1995 Edition.

10 CFR 71. "Packaging and Transportation of Radioactive Material." *Title 10, Energy, Code of Federal Regulations, Part 71.* U.S. Government Printing Office. January 1, 1995 Edition.

10 CFR 72. "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste." *Title 10, Energy, Code of Federal Regulations, Part 72.* U.S. Government Printing Office. January 1, 1995 Edition.

10 CFR 73. "Physical Protection of Plants and Materials." *Title 10, Energy, Code of Federal Regulations, Part 73.* U.S. Government Printing Office. January 1, 1995 Edition.

10 CFR 435. "Energy Conservation Voluntary Performance Standards for New Buildings; Mandatory for Federal Buildings." *Title 10, Energy, Code of Federal Regulations, Part 435.* U.S. Government Printing Office. January 1, 1995 Edition.

10 CFR 960. "General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories." *Title 10, Code of Federal Regulations, Part 960.* U.S. Government Printing Office. January 1, 1995 Edition.

10 CFR 961. "Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste." *Title 10, Energy, Code of Federal Regulations, Part 961.* U.S. Government Printing Office. January 1, 1995 Edition.

29 CFR 1910. "Occupational Safety and Health Standards." *Title 29, Labor, Code of Federal Regulations, Part 1910.* U.S. Government Printing Office. July 1, 1995 Edition.

29 CFR 1926. "Safety and Health Regulations for Construction." *Title 29, Labor, Code of Federal Regulations, Part 1926.* U.S. Government Printing Office. July 1, 1994 Edition.

30 CFR 57. "Safety and Health Standards--Underground Metal and Nonmetal Mines." *Title 30 Mineral Resources, Code of Federal Regulations, Part 57.* U.S. Government Printing Office. July 1, 1994 Edition.

40 CFR 191. "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes." *Title 40, Protection of Environment, Code of Federal Regulations, Part 191.* U.S. Government Printing Office. July 1, 1995 Edition.

40 CFR 260. "Hazardous Waste Management System: General." *Title 40, Protection of Environment, Code of Federal Regulations, Part 260.* U.S. Government Printing Office. July 1, 1995 Edition.

40 CFR 264. "Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities." *Title 40, Protection of Environment, Code of Federal Regulations, Part 264.* U.S. Government Printing Office. July 1, 1995 Edition.

40 CFR 265. "Interim Status for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities." *Title 40, Protection of Environment, Code of Federal Regulations, Part 265.* U.S. Government Printing Office. July 1, 1995 Edition.

40 CFR 268. "Land Disposal Restrictions." *Title 40, Protection of Environment, Code of Federal Regulations, Part 268.* U.S. Government Printing Office. July 1, 1995 Edition.

49 CFR 173. "Shippers--General Requirements for Shipments and Packagings." *Title 49, Transportation, Code of Federal Regulations, Part 173.* U.S. Government Printing Office. October 1, 1994 Edition.

49 CFR 178. "Specifications for Packaging." *Title 49, Transportation, Code of Federal Regulations, Part 178.* U.S. Government Printing Office. October 1, 1994 Edition.

49 CFR 228. "Hours of Service of Railroad Employees." *Title 49, Transportation, Code of Federal Regulations, Part 228.* U.S. Government Printing Office. October 1, 1994 Edition.

NRS Title 40, Public Health and Safety. Chapter 444 "Sanitation", Parts 440-620 'Collection and Disposal of Solid Waste'. Nevada Revised Statutes. 1993.

NRS Title 40, Public Health and Safety. Chapter 445 "Water Controls; Air Pollution", Parts 401-710 'Air Pollution'. Nevada Revised Statutes. 1994.

NRS Title 40, Public Health and Safety. Chapter 445 "Hazardous Material." Nevada Revised Statutes. 1993.

NRS Title 45, Wildlife. Chapter 501 "Administration and Enforcement." Nevada Revised Statutes. 1994.

ACI 301 Specification for Structural Concrete for Buildings. American Concrete Institute. 1989.

All Applicable Standards of American Concrete Institute.

All Applicable Standards of American Institute of Steel Construction.

All Applicable Standards of American National Standards Institute.

All Applicable Standards of American Nuclear Society.

All Applicable Standards of American Railway Engineering Association.

All Applicable Standards of American Society for Testing and Materials.

All Applicable Standards of American Society of Civil Engineers.

All Applicable Standards of American Society of Heating, Refrigeration and Air-Conditioning Engineers.

All Applicable Standards of Sheet Metal and Air-Conditioning Contractors National Association.

All Applicable Standards of Underwriters Laboratory.

All Applicable Standards of Uniform Building Code.

ANSI-N510 Testing of Nuclear Air Treatment Systems. American National Standards Institute. 1995.

ANSI/ANS 1991. *American National Standard: Neutron and Gamma-Ray Flux-to-Dose-Rate Factors.* ANSI/ANS-6.1.1-1991. American Nuclear Society.

APPENDIX A
ACRONYMS

A.1 DOCUMENT ACRONYMS

AC	Alternating Current
ACD	Advanced Conceptual Design
ACGLF	Automatic Center of Gravity Lift Fixture
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
ALARA	As Low As Reasonably Achievable
AML	Areal Mass Loading
ANS	American Nuclear Society
ANSI	American National Standards Institute
AREA	American Railway Engineering Association
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society of Testing and Materials
B&W	B&W Fuel Company
BLM	U.S. Bureau of Land Management
BOP	Balance of Plant
BWR	Boiling Water Reactor
CDA	Controlled Design Assumptions
CFR	Code of Federal Regulations
CHn	Calico Hills Nonwelded Thermal/Mechanical Unit
CI	Configuration Item
CIG	Configuration Item Group
CID	Center-In-Drift
CMAA	Crane Manufacturers Association of America, Inc.
CMF	Cask Maintenance Facility
CRD	Civilian Radioactive Waste Management System Requirements Document
CRWMS	Civilian Radioactive Waste Management System
CSCI	Computer Software Configuration Item
CSF	Canistered Spent Fuel (see canistered fuel, Vol. III)
CSI	Construction Standards Institute
CSS	Carrier Staging Shed
DB	Dry-Bulb
DBA	Design Basis Accident
DBE	Design Basis Event
DBT	Design Basis Tornado
DCS	Design Concept Assumption Surface
DCSS	Design Concept Assumption Subsurface

DHLW	Defense High-Level Radioactive Waste
DOE	U.S. Department of Energy
EBDRD	Engineered Barrier Design Requirements Document
EBS	Engineered Barrier System
ESF	Exploratory Studies Facility
ESFAS	Exploratory Studies Facility Alternatives Study
ESFDR	Exploratory Studies Facility Design Requirements
FLAC	Fast Lagrangian Analysis of Continua
FY	Fiscal Year
GROA	Geologic Repository Operations Area
HE	Human Error
HEPA	High Efficiency Particualte Air
HLW	High-Level Waste
HLWC	High-Level Waste Canister
HVAC	Heating, Ventilation and Air Conditioning
HW	Hazardous Waste
IOC	Interoffice Correspondence
ITEL	International Tunnel Equipment Limited
LLNL	Lawrence Livermore National Laboratory
LLW	Low-Level Radioactive Waste
LYNX	Lynx Geoscience Modeling Software System
M&O	Management and Operating Contractor
MGDS	Mined Geologic Disposal System
MGDS-RD	Mined Geologic Disposal System Requirements Document
MPC	Multi-Purpose Canister
MRS	Monitored Retrievable Storage
MTIHM	Metric Tons of Initial Heavy Metal
MTU	Metric Tons of Uranium
MW	Mixed Waste
N/A	Not Applicable
NEPA	National Environmental Policy Act
NNWSI	Nevada Nuclear Waste Storage Investigations
NRC	U.S. Nuclear Regulatory Commission
NTS	Nevada Test Site
NUREG	Nuclear Regulatory Commission Regulation (or position preface)

NWPA	Nuclear Waste Policy Act of 1982
NWPAA	Nuclear Waste Policy Amendments Act of 1987
NWTRB	Nuclear Waste Technical Review Board
OCID	Off-Center In-Drift
OCRWM	Office of Civilian Radioactive Waste Management
OFF	Oldest Fuel First
ORNL	Oak Ridge National Laboratory
PTn	Paintbrush Tuff Nonwelded Thermal/Mechanical Unit
PWR	Pressurized Water Reactor
QARD	Quality Assurance Requirements and Description
RCA	Radilogically Controlled Area
RCRA	Resource Conservation and Recovery Act
RDRD	Repository Design Requirements Document
RW	Radioactive Waste
SCP	Site Characterization Plan
SCP-CD	Site Characterization Plan Conceptual Design
SCP-CDR	Site Characterization Plan Conceptual Design Report
SD&TRD	Site Design and Test Requirements Document
SFA	Spent Fuel Assembly
SFC	Spent Fuel Canister
SNF	Spent Nuclear Fuel
SNL	Sandia National Laboratories
SRB	Sulfate-Reducing Bacteria
SSC	Structures, Systems, and Components
TBD	To Be Determined
TBM	Tunnel Boring Machine
TBR	To Be Resolved
TBV	To Be Verified
TCw	Tiva Canyon Welded Thermal/Mechanical Unit
TDPP	Technical Document Preparation Plan
TDS	Technical Data Assumption Surface
TDSS	Technical Data Assumption Subsurface
TMB	Transporter Maintenance Building
TS	Topopah Spring Tuff Geologic Unit
TSw	Topopah Spring Welded Thermal/Mechanical Unit
UCF	Uncanistered Fuel
UDEC	Univeral Distinct Element Code
UE	Underground, exploratory (drill hole designation)

USC	United States Code
USF	Uncanistered Spent Fuel (also see Uncanistered Fuel -UCF)
USGS	U.S. Geological Survey
USW	Underground, southern Nevada waste (drill hole designation)
VNETPC	Ventilation Network Simulation Program for Personal Computer
V-TOUGH	Computer program
WHB	Waste Handling Building
WTB	Waste Treatment Building
YMP	Yucca Mountain Site Characterization Project
YMSCO	Yucca Mountain Site Characterization Office

A.2 DEFINITIONS OF UNITS

BTU/hr	British Thermal Unit per hour
°C	degree Celcius
°C/m	degree Celcius per meter
CF	cubic feet
cfm	cubic feet per minute
cm/millenium	centimeter per millenium
cm/ka	centimeter per thousand years
cm/yr	centimeter per year
cu. m	cubic meter
dpm/cm^2	disentigration per minute per square meter
°F	degree Farenheit
ft	foot
ft^2	square foot
ft^3	cubic foot
ft-lb	foot-pound
g	gram
gals	gallons
g/cm^3	grams per cubic centimeter
GHz	gigahertz
GJ/m^2	gigajoules per square meter
GPa	gigapascal
gpd	gallons per day
gpm	gallons per minute
GWd/MTU	gigawatt-day per metric tons of uranium
hr	hour
HP	horsepower
in	inch
J/m^{3}K	joule per cubic meter-degree Kelvin
kg	kilogram
kg/m	kilogram per meter
kg/m^3	kilogram per cubic meter
kJ/m^{3}K	kilojoule per cubic meter-degree Kelvin
km	kilometer
km/h	kilometer per hour
km/hr	kilometer per hour
kN	kilonewton
kPa	kilopascals
kV	kilovolt
kW	kilowatt
kW/acre	kilowatt per acre
kWh	kilowatt-hour
kW/Pkg	kilowatt per waste package
lb	pound

lbs/ft^3	pounds per cubic foot
m	meter
m^3	cubic meter
MB	megabyte
mbar	millibar
Mbps	megabits per second
Mbtu/hr	million British Thermal Unit per hour
μCi/cm^2	microcuries per square centimeter
MeV	(10.2.2.2)
m^3/hr	cubic meter per hour
MHZ	megahertz
m^3/min	cubic meter per minute
min	minute
mm	millimeter
mm/millenium	
μm	micrometer or micron
MPa	megapascal
mph	miles per hour
mR/Hr	millirem per hour
mrem	millirem
m/s	meter per second
(m^3/s)/kW	cubic meter per second per kilowatt
m^3/s	cubic meter per second
mSv	millisievert
MT	metric tons
MTU	metric tons of uranium
MTU/acre	metric tons of uranium per acre
MTU/WP	metric tons of uranium per waste package
MVA	megavolt-ampere
MW	megawatt
MWd/IHM	(10.2.2.2)
Pa	pascals
psi	pounds per square inch
rem/hr	rem per hour
R/Hr	rem per hour
rpm	revolutions per minute
VAC	(7.2.2.5.9)
V	volt
W/mK	watt per meter-degree Kelvin
W/m^2	watt per square meter
wt %	percent weight by volume
yr	year

APPENDIX B

ANALYSIS OF GROUND STABILITY AND SUPPORT

CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

FIGURES

FIGURES (Continued)

Page

FIGURES (Continued)

THIS PAGE INTENTIONALLY LEFT BLANK

TABLES

ANALYSIS OF GROUND STABILITY AND SUPPORT

B.1 PREVIOUS WORK

Documents providing background information applicable to repository ground control include reports by Sandia National Laboratories (SNL) and the Civilian Radioactive Waste Management System Management and Operating Contractor (CRWMS M&O) documents on Exploratory Studies Facility and repository design. These reports are discussed in Section 8.5, Ground Control.

B.2 ANALYSIS INPUTS

Modeling inputs include geologic information, thermal/mechanical properties, repository layout design parameters, ground support types, in situ stress, thermal loads, dynamic loads, and temperature histories. Sources for this information, mainly CRWMS M&O and CRWMS M&O/Sandia reports, are referenced. Some of these data are qualified sources and some are not; however, these data are considered the most appropriate data for the modeling that was performed.

B.2.1 Loading Conditions

B.2.1.1 In Situ Stress

Components of the in situ-stress state at the approximate depth of the repository are given in Table B-1. These stresses, caused by the weight of the overlying geologic units, lateral confinement, and past stress history, are the initial stress condition for modeling. The vertical normal stress σ_v is considered equal to the weight of the overlying rock and is expressed as

$$\sigma_v = -\sum_{i=1}^{n} \rho_i g Y_i \tag{1}$$

where ρ_i = the average density of ith layer rock, kg/m^3
g = the gravitational acceleration, m/s^2
Y_i = the average thickness of ith layer rock, m
n = number of overlying rock layers

The magnitude of the horizontal stress σ_h is expressed as a function of the vertical stress and given as the horizontal-to-vertical stress ratio K, which is

$$K = \frac{\sigma_h}{\sigma_v} \tag{2}$$

Values for the ratio K are given in Table B-1 and show that horizontal stresses are expected to be lower than the vertical stress. Minimum and maximum horizontal stress ratios are close in value and indicate a weak horizontal stress anisotropy. A value of $K = 0.5$ has been assumed to be representative of initial horizontal repository stress and is used for this analysis. As shown in Table B-1, in situ stress at the proposed repository horizon is an average vertical stress of 7.0 MPa and a horizontal stress of 3.5 MPa.

Table B-1. Rock In Situ Stress at Proposed Repository Horizon

Parameter	Average Value	Range
Vertical Stress (MPa)	7.0	5.0 - 10.0
Minimum Horizontal/Vertical Stress (MPa)	0.5	0.3 - 0.8
Maximum Horizontal/Vertical Stress (MPa)	0.6	0.3 - 1.0
Bearing - Minimum Horizontal Stress	N57W	N50W - N65W
Bearing - Maximum Horizontal Stress	N32E	N25E - N40E
Source: *Controlled Design Assumptions*, TDSS-001 (CRWMS M&O 1995a)		

B.2.1.2 Thermal Load and Heat Transfer

A thermal load of 83 metric tons of uranium (MTU)/acre is used as the reference design load based on a programmatic decision. Drift spacing and waste package spacing associated with this thermal load are listed in Table B-2, based on the horizontal in-drift emplacement mode and the areal mass loading (AML) approach. Heat transfer in an emplacement drift involves thermal conduction, convection, and radiation. A detailed description regarding these three heat transfer mechanisms is given in Thermomechanical Analyses (CRWMS M&O 1995b).

Table B-2. Drift and Waste Package Spacings Used in Analysis

	Spacing (at 83 MTU/acre)
	83
Drift (m)	22.5
Waste Package (m)	19.12

B.2.1.3 Seismic Loads

Following the seismic design methodology described in a topical report, *Seismic Design Methodology For a Geologic Repository at Yucca Mountain* (YMP 1995b), a peak ground velocity (PGV) of 23 cm/second was selected as being appropriate for the analysis of the emplacement drifts. This PGV value corresponds to performance category 3, of the performance-goal-based seismic design method proposed in the topical report (YMP 1995b). The corresponding peak ground acceleration (PGA) is 0.37g where "g" is the gravitational acceleration. Dynamic loads on the underground repository openings have been analyzed by idealizing the seismic ground motion as a sinusoidal wave. Peak wave values are based on peak ground accelerations, and a typical earthquake frequency range has been used.

In carrying out numerical simulation using FLAC models, both PGV and PGA values were further assumed to be the same for horizontal and vertical directions. Furthermore, depth attenuation of ground motions was not considered. Seismic loading was expressed in terms of a combination of sinusoidal pressure and shear waves with an amplitude equal to 23 cm/second, frequency varying between 0.2 to 10 Hz, and duration of 0.5 to 2 seconds. At present, a frequency of 5 Hz was chosen along with a duration time of 0.5 seconds. In addition, a PGV value of 46 cm/sec and a frequency value of 10 Hz were used as an upper bound to examine the dynamic response of drift and ground support.

B.2.2 Thermal and Mechanical Rock Properties

Thermal and mechanical properties for the TSw2 thermal/mechanical unit are listed in Tables B-3 through B-6. As shown in Table B-6, mechanical properties are given for rock mass quality categories (RMQ) ranging from 1 to 5. The RMQ categories, first presented by Hardy and Bauer (SNL 1991) and used for Exploratory Studies Facility analyses (CRWMS M&O 1995e) represent the distribution of rock properties for a given rock unit. Each category is associated with a frequency of occurrence of a certain range of Q-values. For example, category RMQ=3 for rock unit Tsw2 has a typical Q-value of 1.91 for which rock properties have been derived and ground support categories have been developed (Table B-6). Also, category RMQ=3 is considered representative of the most frequently occurring range of Q-values (see Table 8.5-1 and Table 8.5-3) and is thus used as a reference case for the numerical modeling.

B.2.3 Layout Parameters

Emplacement drift orientation is a feature of the layout design that has a potential impact on ground control. Typically, a stable drift orientation is one that minimizes the occurrence of open joints or faults parallel to the drift axis, especially in rock with low horizontal stresses. As stated by DCSS 001 and explained in the *Initial Summary Report for Repository/Waste Package Advanced Conceptual Design* (CRWMS M&O 1994a, Section 8.2.1.3), emplacement drifts will be oriented at least 30 degrees from the dominant strike of vertically-dipping joints, and maintainable drifts and accesses will be oriented, if practicable, to have intersections of 70-90 degrees with the dominant strike of the joint systems. However, in situ lateral stresses at Yucca Mountain are expected to be low (CRWMS M&O 1994, Section 5.1.3), resulting in low confining stress and reduced joint strength during excavation. This condition is expected to be improved as thermally-induced horizontal stress increases following emplacement of waste packages. Both the excavation stress condition and the post-emplacement stress condition are examined by numerical stress analysis.

Horizontal center-in-drift emplacement is the reference emplacement mode, based on preliminary assessments of waste package design and repository criteria and requirements (CRWMS M&O 1995a Key 011). The current conceptual layout shows emplacement drift excavation by TBMs, which produce drifts with a circular cross section. The 5.0-m-diameter drift used in the stability analyses was chosen based on waste package size, emplacement equipment size, and invert and ground support considerations. Waste package length and diameter are assumed to be 5.68 m and 1.80 m, respectively, based on the CDA (EBDRD 3.7.1.J.1). These two parameters were used in numerical modeling with ANSYS to determine rock-mass temperature distributions.

Table B-3. Contact Depths, Thermal Conductivity, and Capacitance for TSw2 Thermal/ Mechanical Unit

Units	Upper Contact (m)	Lower Contact (m)	Thermal Conductivity (W/m·°K)	Thermal Capacitance (J/cm³·°K) (averaged over temperature range)		
				T≤94°C	94°C≤T≤114°C	T>114°C
TSw2	204.2	393.5	2.10	2.1414	10.4786	2.1839
Source: RIB, Rev. 3, Sections: 1.1326a (YMP 1995a)						

Table B-4. Thermal Expansion Coefficient for TSw2 Thermal/Mechanical Unit

Temperature Range (°C)	Thermal Expansion Coefficient (10^{-6}/°C)
25 - 50	5.07
50 - 100	7.30
100 - 150	8.19
150 - 200	8.97
Source: SNL 1995	

Table B-5. Rock In Situ Density for TSw2 Thermal/Mechanical Unit (g/cm^3)

Thermal/Mechanical Unit	At In Situ Saturation
TSw2	2.274
Source: YMP 1995a, Sec. 1.1325a	

Table B-6. Rock Mass Mechanical Properties for TSw2 Thermal/Mechanical Unit

Rock Mass Mechanical Properties		Rock Mass Quality Category				
		1	2	3	4	5
Q		0.3	0.65	1.91	3.75	8.44
Average RMR		42	48	54	59	65
Elastic Modulus (GPa)		6.37	8.95	12.55	17.11	23.51
Poisson's Ratio		0.21	0.21	0.21	0.21	0.21
Mohr-Coulomb Strength Parameters	Cohesion (MPa)[1]	1.3	1.6	2.2	2.8	3.8
	Friction Angle (degrees)[1]	49	49	50	50	50
	Dilation Angle (degrees)[1]	25	25	25	25	25
Tensile Strength (MPa)[2]		0.65	0.8	1.1	1.4	1.9
[1] Data not qualified. [2] Assumed to be one half of cohesion.						
Source: CRWMS M&O 1995c						

B.2.4 Candidate Ground Support

Ground support materials considered for emplacement drifts consist primarily of rock bolts, welded wire mesh (WWM) (not modeled), shotcrete, and structural steel sets. Three ground support types were assumed for these analyses and are used as examples to provide guidance in determining likely support behavior:

- Type I: Fully grouted rock bolts (30 mm outside diameter), 2.5 m long on a 1.0-m-square pattern plus 100 mm of shotcrete
- Type II: Shotcrete lining, 150 mm thick
- Type III: Structural steel sets, W5×19, spaced at 1.2 m intervals

Parameters and properties used to characterize the ground support elements include cross-sectional area, elastic modulus, tensile strength, bond stiffness, bond strength of the grout annulus for steel bolts, and moment of inertia for both shotcrete and steel sets. (Formulations and additional information on bond stiffness and strength are provided in Itasca 1993). Values for these parameters, grouped by ground support type, are listed below in Table B-7.

Table B-7. Ground Support Parameters and Values

Parameter	Value
Steel Rock Bolt (30-mm outside diameter):	
• Length (m)	2.5
• Cross-Sectional Area (m^2)	4.39×10^{-4}
• Elastic Modulus (GPa)	200.0
• Tensile Strength (kN)	267.0
• Bond Stiffness of Grout Annulus (GN/m/m)	10.62
• Bond Strength of Grout Annulus (MN/m)	0.556
Shotcrete (100-mm thick):	
• Cross-Sectional Area (m^2/meter of drift)	0.10
• Moment of Inertia (m^4/meter of drift)	8.33×10^{-3}
• Elastic Modulus (GPa)	27.58
• Compressive Strength (MPa)	34.5
Steel Set (W5×19):	
• Cross-Sectional Area (m^2)	3.57×10^{-3}
• Moment of Inertia (m^4)	1.09×10^{-5}
• Elastic Modulus (GPa)	200.0
• Strength (MPa)	248.0
Sources: CRWMS M&O 1995d; AISC 1989	

B.3 NUMERICAL MODELING

B.3.1 Computer Programs

Two commercially available computer programs, ANSYS and FLAC (described below), were used for the numerical analysis of rock temperature and opening stability. The ANSYS program is installed on a SGI Indigo^2 Power Extreme workstation with 320 MB RAM, and the FLAC code runs on 90-MHz Pentium microcomputers. The release of the ANSYS program used in the thermal analysis is Revision 5.2. ANSYS Revision 5.1 has been verified and validated according to the QAP-SI-series of CRWMS M&O *Computer Software Quality Assurance* procedures, but Revision 5.2 has not been verified and validated. The FLAC code, Version 3.22, on the other hand, is approved for design use in accordance with the Quality Assurance procedures and carries the appropriate CSCI number (given below), its installation on the machines used for these analyses, however, has not been documented. Additional documentation would be required before these computer results would be considered qualified.

ANSYS, introduced in 1970 by Dr. John Swanson and Swanson Analysis Systems, Incorporated (SASI), is a general-purpose program, meaning that the program can be used in many disciplines of engineering, that deal with topics including structural, geotechnical, mechanical, thermal, and fluids. The ANSYS Revision 5.2 is a menu-driven computer program and uses the Graphical User Interface (GUI) of the Unix X Window System (ANSYS 1995).

FLAC (Fast Lagrangian Analysis of Continua) is a two-dimensional explicit finite difference code that simulates the behavior of structures built of soil, rock, and other materials that are subjected to static, dynamic, and thermally induced loads (Itasca 1993). Modeled materials respond to applied forces or boundary restraints according to prescribed linear or non-linear stress/strain laws, and undergo plastic flow when a limiting yield condition is reached. FLAC is based on a Lagrangian calculation scheme, especially suited for modeling large displacements, and has several built-in constitutive models that permit the simulation of highly non-linear, irreversible responses typical of many geologic materials. The FLAC program was initially developed by Dr. Peter Cundall and Itasca Consulting Group, Inc. in 1986. The program version used to analyze opening stability is Version 3.22 (CSCI # 20.93.3001-AAu3.22), which has been verified and validated in accordance with applicable CRWMS M&O procedures.

The FLAC code computes fully-dynamic responses to seismic loadings on an explicit finite different solution scheme of the full equations of motion. Displacement and load changes brought out by ground shaking on ground support systems are calculated in the same way. A seismic event is translated into the dynamic input by one of the following four ways: (1) an acceleration history, (2) a wave velocity history, (3) a stress or pressure wave history, and (4) a dynamic force history. The history data are expressed either in a table or in functions. Different damping can be introduced into the run during the program execution to help rapidly mobilize the ground vibration after the seismic waves have passes through the model. The velocity history approach was adopted for analysis.

B.3.2 Features of the Model

B.3.2.1 Yield Criterion

The Mohr-Coulomb yield criterion was used in the analysis to judge whether or not the rock mass experiences failure. The criterion is defined as

$$\tau = c - \sigma_n \tan\phi \tag{3}$$

where τ = shear stress on a failure or yield plane, Pa
σ_n = normal stress on a failure plane (tensile stress is positive), Pa
c = cohesion, Pa
ϕ = friction angle, degrees

The yield criterion is used to represent the rock mass strength in FLAC. The ratio of Mohr-Coulomb strength to rock stress (strength/stress ratio) is evaluated for every element and is especially useful in assessing rock mass stability in the vicinity of the drift. An element is considered to perform satisfactorily when its strength/stress ratio is larger than 1.0 and is thought to fail structurally if the strength/stress ratio is equal to or less than 1.0.

The concept of factor-of-safety was used as the criterion to assess ground support performance under in situ stress, thermal and seismic loads. The factor-of-safety for ground support components is defined as the ratio of material strength to stress or force. A ground support component is in a stable state when its strength/stress (or force) ratio is larger than 1.0 and is of structural failure if the strength/stress ratio is equal to or less than 1.0.

B.3.2.2 Initial and Boundary Conditions

Initial Conditions

Initial stress condition in the analysis is assumed to be consistent with the in situ stress given in Table B-1. Initial temperature in the TSw2 thermal/mechanical unit is based on a rock temperature at the ground surface of 18.7°C and a rock thermal gradient as listed in Table B.8.

Table B-8. Rock Mass Thermal Gradient

Depth (m)	Thermal Gradient (°C/m)
0 - 150	0.019
150 - 400	0.018
400 - 541	0.030
Source: CRWMS M&O 1995a, TDSS-002	

Boundary Conditions for Thermomechanical Model

Boundary conditions for the thermomechanical model with FLAC are illustrated in Figure B-1. The half-drift-spacing geometry is appropriate for the thermomechanical model because the model is symmetric along a vertical plane through the center of the drift. The model dimension in the vertical dimension is the entire thickness of the TSw2 unit. As shown by the bar-and-roller symbols along the sides and bottoms of the models (Figure B-1), displacements in the horizontal direction on two vertical boundaries and in the vertical direction at the TSw2 lower boundary are zero (or fixed). Overburden stress is applied to the TSw2 upper contact, which is free to move vertically. The surface of the drift is stress and constraint free.

Rock temperatures after waste emplacement are time-dependent and were evaluated with the ANSYS program. Due to limitations of the thermal options in the FLAC code, rock temperature distributions are calculated based on the boundary temperature histories obtained from the thermal analyses with ANSYS. Based on thermal symmetry, the vertical model boundaries are prescribed as adiabatic, or zero heat flow, boundaries.

Boundary Conditions for Seismic Model

Boundary conditions for the seismic model with FLAC are shown in Figure B-2, and differ from those for the thermomechanical model. Symmetrical conditions for stress, displacement and velocity fields of the seismic model do not exist because the direction of seismic wave propagation varies with time. In addition, the model dimensions should be large enough to minimize wave reflection and achieve free-field conditions at boundaries so that seismically-induced response can be corrected simulated.

As illustrated in Figure B-2, the horizontal and vertical dimensions for the seismic model are 202.5 and 189.3 meters, respectively. For the 5-meter-diameter-drift with 22.5-meter-drift-spacing, the model contains 9 emplacement drifts. The center drift is reinforced with ground supports, while its neighboring drifts are not supported in order to examine the maximum influence of multiple drift excavation and waste package emplacement on the center drift. The underlying rationale is that any ground support systems which work for the center drift will automatically work for all the adjacent drifts. Figure B-3 illustrates the mesh refinement near the emplacement drifts for the seismic model.

Viscous boundary conditions are used at the base and top of the seismic model to prevent the outward propagating waves from reflecting back into the model at those boundaries, and free field conditions are set on two vertical boundaries. Seismic loads, which are in the form of sinusoidal velocity waves (P-wave and S-wave), are imposed on the model after the equilibrium has been reached under both in situ stress and thermal loads. Therefore, the initial velocity for each grid point prior to the application of seismic loads is zero. The sinusoidal velocity waves (P-wave and S-wave) are applied at the bottom of the model and propagate upwards. The S-wave, or shear wave, causes ground vibration (shaking) in the horizontal direction. The P-wave, on the other hand, causes ground oscillation in the vertical direction and results in variations of compression and tension. As was the case for the thermomechanical model, all other displacement and stress boundary conditions are still applied for the seismic model.

B.3.2.3 Sign Convention

In the FLAC program, the sign convention for stress and strain is "tension is positive and compression is negative" (as indicated in Figure B-4). For shear stress, also shown in Figure B-4, a positive shear stress points in the positive direction of the coordinate axis if the shear stress acts on a surface with the outward normal in the positive direction. Conversely, if the outward normal of the surface is in the negative direction, then the positive shear stress points in the negative direction of the coordinate axis. All stresses shown in Figure B-4 are positive. For displacement or seismic velocity, positive displacement or velocity is upward and to the right. Axial forces in ground support elements are negative in tension and positive in compression, as shown in the figures of Appendix B of the *Repository Ground Control Evaluation* report (CRWMS M&O 1995ad). For consistency, the sign of axial forces and stresses of structural members discussed in this section are reversed to positive for tension and negative for compression, unless otherwise specified.

B.4 OPENING AND GROUND SUPPORT BEHAVIOR

Numerical modeling for emplacement drifts has been carried out with Version 3.22 of FLAC. This computer program allows only two-dimensional thermomechanical analysis. Thermally-induced displacements and stresses in the rock mass and in ground support elements were calculated for up to 150 years after waste emplacement.

B.4.1 Pre-emplacement Behavior

Pre-emplacement behavior of openings discussed in this section is referred to as drift closure and rock mass yield during excavation before installation of ground support components. The pre-emplacement behavior of drifts was modeled by assuming that the rock stresses had fully relaxed prior to installation of ground supports. This is considered a conservative overestimation of the drift closures and rock mass yield for supported openings, but may result in an underestimation of the ground support load induced by in situ stress.

Drift Closure

Vertical closure, defined as the relative vertical displacement between the floor and crown, varies from less than 3 mm for RMQ=5 to about 10 mm for RMQ=1. Horizontal closure, defined as the relative horizontal displacement between the drift walls, ranges from less than 1 mm for RMQ=5 to about 2 mm for RMQ=1. Deformations for supported cases are similar due to the assumption of 100 percent stress relaxation in modeling. The values of closure shown by these results are relatively small elastic deformation resulting from the response of drift excavation to the in situ stress field.

Rock Mass Yield

As an indication of potential rock mass yield, contours of Mohr-Coulomb strength-to-stress ratios have been determined for cases of unsupported drifts (Figures B-5a, b, and c). These plots show that the factor of safety contour of 1.0, below which value yield occurs, is at a shallow depth, less than a meter, around the drift for all three RMQ categories, indicating that the drift is in stable elastic conditions following stress redistribution, and apparently self-supporting.

Ground Supports

Loads in ground support components, rock bolts, shotcrete, and steel sets, induced by the response of drift excavation to the in situ stress field, are extremely low due to the assumption of full rock stress relaxation before installation of ground support components in modeling. Higher loads may be anticipated in ground support components before waste emplacement, and to better understand the response of ground supports to the in situ stress field, a different magnitude of percentage of the rock stress relaxation, such as 50 percent, should be assumed in modeling. A previous study for the repository ground control evaluation (CRWMS M&O 1995d) indicated that with 50 percent of the rock stress relaxation before installation of ground support components, all three types of ground supports, rock bolts, shotcrete, and steel sets, appear to perform satisfactorily for the three RMQ categories, 1, 3 and 5, under excavation-induced loads.

B.4.2 Emplacement Behavior

Temperature histories of the drift wall and TSw2 boundary contacts due to a thermal load of 83 MTU/acre from waste emplacement, as shown in Figure B-6, were calculated with the ANSYS code. The heat transfer mechanism in modeling with ANSYS involves both radiation and conduction, and the thermal radiation process is simulated explicitly. Thermal analyses for FLAC models calculate time-dependent temperature distributions resulting from boundary temperature inputs, and the heat transfer mechanism involved is limited to conduction only. Coupled thermomechanical analyses with FLAC have been performed for a period of 150 years after waste emplacement. This period of time, called the overall thermal time, is divided into a number of thermal time steps. At each thermal time step, the temperature distributions are determined first, and stress and displacement fields around the supported drift opening, strength-to-stress ratios, and axial forces or moments if applicable in ground supports are then obtained by conducting a quasi-static mechanical analysis. Owing to temperature dependence of thermomechanical properties of rock, such as specific heat and thermal expansion coefficient, each thermal time step has been further divided into a number of sub-thermal time steps. At the beginning of each sub-thermal time step, the values of specific heat and thermal expansion coefficient are updated for every zone based on its corresponding temperature and the temperature dependence of the properties, as illustrated in Tables B-3 and B-4.

Depending upon mechanical properties and the magnitude of thermomechanical loads, the continuous rock model used in FLAC may behave elastically or elasto-plastically. The Mohr-Coulomb failure criterion is used in the analysis to judge whether or not the stress level reaches the yield limit, which varies with the rock mass quality (RMQ) categories.

Rock Temperature

Two-dimensional analysis with ANSYS shows that average peak temperature experienced on the drift wall for a thermal load of 83 MTU/acre, as shown in Figure B-6, is about 146°C, which occurs at about 64 years after waste emplacement. Due to decay of the heat output from waste packages and thermal conduction within the rock mass, temperatures of the drift wall undergo a slight decrease, even though drift heating by the waste packages lasts for the entire 150-year modeling time. The average wall temperature drops only 2°C to about 144°C at 150 years after waste emplacement.

Three-dimensional analysis, presented in Section 8.2.4, gives somewhat higher temperatures for both in-center and off-center emplacement modes. Maximum sidewall temperatures for in-center emplacement, for example, are about 155°C. Note that temperatures used for FLAC models are from two-dimensional analysis, rather than from three-dimensional ANSYS analysis.

Drift Closure

Thermally-induced vertical closures, as illustrated in Figure B-7a and on Table B-9 for 83 MTU/acre and ground support Type I, are in the opposite direction to closures induced by in situ loads at excavation. Maximum vertical closures induced by thermal load are about 8 mm outward for all rock mass quality (RMQ) categories. Combined in situ and thermal loads result in net vertical closures of about 1 mm inward for RMQ category 1, and about 4 and 6 mm outward for RMQ categories of 3 and 5, respectively. Maximum thermally-induced horizontal closures, as shown in Figure B-7b, are inward and are about 10 mm for RMQ category 1, 9 mm for RMQ categories 3 and 5. Combined in situ and thermal loads result in net horizontal closures of about 12 mm for the RMQ category of 1, and 10 mm for RMQ categories of 3 and 5.

As can be seen from these results, horizontal closures for the 83 MTU/acre case are about 5 to 24 times those for the in situ case. Vertical closures, on the other hand, are relatively small and are about 0.9, 1.8 to 3.4 times the in situ values for three RMQ categories of 1, 3 and 5, respectively.

It is also indicated that thermally-induced vertical and horizontal closures, as shown on Tables B-10 and B-11, for 83 MTU/acre and ground support Types II and III for three RMQ categories of 1, 3 and 5 are about the same magnitude as those for ground support Type I.

Rock Mass Yield

Time histories of major and minor principal stresses at the drift crown are shown in Figure B-8a and b for the thermal loading of 83 MTU/acre, ground support Type I, and RMQ categories of 1, 3 and 5. At 50 years following waste emplacement, the major principal compressive stress (tangential to the crown) is close to its maximum value of -30 MPa (RMQ=3) and the minor principal stress is close to its maximum value of -3 MPa. These values are about 9 and 6 times the in situ case values, respectively.

Rock mass yield is indicated by Figures B-9a, b, and c, which give strength-to-stress-ratio contour plots and failure surface envelopes at 10, 50 and 150 years after emplacement (ground support Type I and RMQ= 3). The plots of strength-to-stress ratios indicate potential rock yield to a depth of about one meter from the periphery of the drift (Figures B-9a through c). In addition, Figures B-9b and c show an increasing strength-to-stress ratio into the rock away from the drift wall, then a decrease, then a constant value as the line of symmetry (i.e., the center of the pillar) between the drifts is approached. Strength also decreases as the confining stress in the pillar decreases. Beyond 50 years, the strength-to-stress ratio in the majority of the pillar is at or above a value of 4.0 for all cases. The decrease in strength-to-stress ratio within the pillar apparently results from a stress decrease or "stress shadow" effect that occurs between multiple parallel drifts that are subjected to a high horizontal stress field perpendicular to the drifts (see for example Hoek and Brown 1980, p. 124). It is also indicated according to the analyses that the strength-to-stress ratios in the pillar are dependent on the variation of RMQ categories, decreasing with the increase of the RMQ categories under the thermal load of 83 MTU/acre.

Maximum major and minor principal stresses at the drift crown for 83 MTU/acre and ground support Types II and III, as shown on Tables B-10 and B-11, are about the same magnitude as those for the ground support Type I for three RMQ categories, 1, 3 and 5, which means that the strength-to-stress ratios of rock mass with the ground support Types II and III are similar to those with the Type I, as illustrated in Figures B-9a through c.

The analysis also shows that the vertical and horizontal closures, major and minor principal stresses, and strength-to-stress ratios of the drift opening without ground supports at 83 MTU/acre are about the same magnitude as those for the supported opening due to the flexibility of ground supports used in modeling.

Results of the analysis of loads induced in ground support components by thermal stress are given in the following:

Rock Bolts

Axial forces in rock bolts at 83 MTU/acre vary with RMQ categories, as shown in Figure B-10a and on Table B-9. Rock bolt loads reach about 267 kN, 196 kN, and 185 kN, which is approximately 100 percent, 73 percent, and 69 percent of the bolt tensile strength of 267 kN, at about 150 years after waste emplacement for the RMQ categories of 1, 3 and 5, respectively. It is indicated that at 83 MTU/acre, maximum axial forces in rock bolts are dependent of the variation of RMQ categories, decreasing with the RMQ categories. Plots of factors of safety for rock bolts at 83 MTU/acre, as shown in Figure B-10b, indicate that the factors of safety drop to or below 1.5 at about 50 years following waste emplacement for three RMQ categories, and a potential rock bolt yield may occur for the RMQ category of 1. The distribution of bolt axial force, for bolts at the crown, can be observed in Figures B-11a through c, for ground support Type I for RMQ=3 at 10, 50 and 150 years after waste emplacement. Note that not all bolts have such high axial loads; only bolts near springline have high loads, about 30 percent, 22 percent and 26 percent higher than those at crown at about 10, 50, and 150 years, respectively, after emplacement for the RMQ category of 3.

Shotcrete

Axial forces in shotcrete, for 83 MTU/acre, at 10, 50 and 100 years after waste emplacement, are presented in Figures B-11a through c for ground support Type I with RMQ=3. Axial forces increase with time; depending on location shotcrete may be in tension or compression. All shotcrete begins in compression, but the portion along the sidewalls quickly changes to tension and remains in tension. Figures B-12a and b show time histories of maximum shotcrete compressive axial stresses and its factors of safety for three RMQ categories. It is indicated that at 83 MTU/acre, the stresses in shotcrete are dependent of the variation of RMQ categories, increasing with the RMQ categories. Maximum compressive axial stresses in 100-mm thick shotcrete, as shown in Table B-9, occur at about 150 years after emplacement and are about 29 MPa for RMQ=1, 36 MPa for RMQ=3, and 40 MPa for RMQ=5. Axial stresses in the shotcrete for both rock categories of 3 and 5 exceed the compressive strength of 34.5 MPa at about 70 years after waste emplacement. Maximum compressive axial stresses in 150-mm thick shotcrete, as shown in Figure B-13a and Table B-10, are about 73 percent, 92 percent and 106 percent of the compressive strength of 34.5 MPa for the RMQ categories of 1, 3 and 5, respectively. Only axial stresses in the shotcrete for the RMQ category of 5 exceed the compressive strength at about 50 years following waste emplacement.

Both tensile and compressive stresses are developed in shotcrete at thermal loads of 83 MTU/acre. Though compressive stresses are below the strength of 34.5 MPa for the RMQ category of 1, tensile stresses for all RMQ categories are of a similar magnitude and may result in tensile failures.

Steel Sets

Time histories of axial stresses in steel sets (W5×19) are illustrated in Figure B-14a for three RMQ categories, 1, 3 and 5. Maximum compressive axial stresses at 83 MTU/acre, as shown in Table B-11, are 309 MPa, 340 MPa and 368 MPa for the RMQ categories of 1, 3 and 5, respectively, exceeding the yield limit of 248 MPa. Factors of safety for steel sets, as shown in Figure B-14b, drop to or below 1.0 at about 20 years after emplacement for three RMQ categories.

Table B-9. Results from FLAC Analysis for Thermal Load for Ground Support Type I

Ground Support Type I: 1.0 m Spacing Pattern Steel Bolt Plus 100 mm Thick Shotcrete			
Items	Thermal Load: 83 MTU/acre		
	RMQ=1	RMQ=3	RMQ=5
Horizontal Closure (mm)	12.3 (150)[1]	10.0 (150)[1]	9.5 (150)[1]
Vertical Closure (mm)	1.3 (150)[1]	-3.7 (150)[1]	-6.0 (150)[1]
Max. Major Principal Stress at Crown (MPa)	-16.8 (150)[1]	-31.1 (150)[1]	-55.8 (150)[1]
Max. Minor Principal Stress at Crown (MPa)	-2.1 (150)[1]	-3.2 (150)[1]	-5.0 (150)[1]
Max. Bolt Axial Force (kN)	267 (150)[1]	196 (150)[1]	185 (150)[1]
Bolt Strength to Axial Force Ratio	1.0 (150)[1]	1.4 (150)[1]	1.4 (70)[1]
Max. Tensile Axial Stress in Shotcrete (MPa)	20.8 (150)[1]	32.8 (150)[1]	36.2 (150)[1]
Ratio of Shotcrete Tensile Strength to Tensile Axial Stress	0.2 (150)[1]	0.1 (150)[1]	0.1 (150)[1]
Max. Compressive Axial Stress in Shotcrete (MPa)	-29.4 (150)[1]	-35.5 (150)[1]	-40.4 (150)[1]
Ratio of Shotcrete Compressive Strength to Compressive Axial Stress	1.2 (150)[1]	1.0 (150)[1]	0.9 (150)[1]

[1] Time in years after emplacement to reach a maximum value during preclosure.

Table B-10. Results from FLAC Analysis for Thermal Load for Ground Support Type II

Ground Support Type II: 150 mm Thick Shotcrete or Concrete Liner			
Items	Thermal Load: 83 MTU/acre		
	RMQ=1	RMQ=3	RMQ=5
Horizontal Closure (mm)	12.9 (150)[1]	10.5 (150)[1]	9.7 (150)[1]
Vertical Closure (mm)	1.5 (150)[1]	-3.6 (150)[1]	-6.1 (150)[1]
Max. Major Principal Stress at Crown (MPa)	-16.1 (150)[1]	-30.1 (150)[1]	-55.6 (150)[1]
Max. Minor Principal Stress at Crown (MPa)	-2.2 (150)[1]	-3.3 (150)[1]	-5.0 (150)[1]
Max. Tensile Axial Stress in Shotcrete (MPa)	12.9 (150)[1]	24.8 (100)[1]	31.6 (150)[1]
Ratio of Shotcrete Tensile Strength to Tensile Axial Stress	0.3 (150)[1]	0.1 (150)[1]	0.1 (150)[1]
Max. Compressive Axial Stress in Shotcrete (MPa)	-25.1 (150)[1]	-31.7 (150)[1]	-36.7 (150)[1]
Ratio of Shotcrete Compressive Strength to Compressive Axial Stress	1.4 (150)[1]	1.1 (150)[1]	0.9 (150)[1]

[1] Time in years after emplacement to reach a maximum value during preclosure.

Table B-11. Results from FLAC Analysis for Thermal Load for Ground Support Type III

Ground Support Type III: 1.2 m Spacing W5×19 Steel Sets			
Items	Thermal Load: 83 MTU/acre		
	RMQ=1	RMQ=3	RMQ=5
Horizontal Closure (mm)	11.8 (150)[1]	9.8 (150)[1]	9.4 (150)[1]
Vertical Closure (mm)	1.3 (150)[1]	-3.4 (150)[1]	-5.5 (150)[1]
Max. Major Principal Stress at Crown (MPa)	-17.7 (150)[1]	-31.1 (150)[1]	-52.6 (150)[1]
Max. Minor Principal Stress at Crown (MPa)	-1.6 (150)[1]	-2.7 (150)[1]	-4.5 (150)[1]
Max. Steel Set Axial Stress (MPa)	-308.8 (150)[1]	-339.5 (150)[1]	-368.4 (150)[1]
Steel Set Strength to Axial Stress Ratio	0.8 (150)[1]	0.7 (150)[1]	0.7 (150)[1]

[1] Time in years after emplacement to reach a maximum value during preclosure.

B.4.3 Seismically-induced Behavior

Numerical results for seismic load cases are given according to the type of ground support systems. Primary focus is on stability response of the drift and load response of ground supports to the seismic loads. The maximum change in ground stress, support load and displacement due to seismic loads is expressed in terms of the percentage increase or decrease in the parameter following application of seismic load.

B.4.3.1 Drift Reinforced with Rock Bolts and Shotcrete

Figure B-15 illustrates 2.5 m long, fully-grouted rock bolts and a 100 mm thick shotcrete layer in the drift. Seismic loads are applied to the model after the completion of computer simulation of thermal loads for 10, 30 and 50 years after waste package emplacement. The rock temperature nearly reaches its peak at the drift wall after 50 years. As was the approach for static and thermal loading, three different rock mass quality categories (RMQ=1, 3 and 5) were used to represent the rock mass, with case RMQ=1 being the poorest rock and RMQ=5 being the most competent.

Figure B-16 shows input velocity profiles for P- and S-waves at the base of model and the output velocity profiles at the top of model as the wave propagates through the 189-meter-thick TSw2 rock unit. Figure B-17 shows additional drift closures produced by seismic loads. Both ground vibration and drift closure diminish rapidly after the specified duration time for seismic waves, indicating that the ground remains primarily within the elastic range of deformation. The maximum dynamic drift closure caused by seismic loads is 1.6 mm between crown and invert and 0.8 mm along the springline. Figure B-18 illustrates contours of Mohr-Coulomb strength to stress ratios near the center drift under three different rock mass categories and shows no development of yielding near the drift.

As tabulated in Table B-12, fully-grouted rock bolts experience a maximum increase in axial load of 10 percent, and the shotcrete liner shows a load increase of up to 8.4 percent. The increase is not considered significant. These results are realistic because underground drifts are confined and are therefore less sensitive to earthquake-induced ground shaking than surface structures. In addition, the seismic wave is characterized by a long wave length and low frequency. The dimension of the drift is a fraction of the typical seismic wave length, consequently the rock mass and the drift tend to move together rather than undergo differential movements. Seismic-induced load maximums can occur at any point within a ground support system.

To further examine the dynamic response of the drift to seismic loadings, two more computer runs were made: one increased the input frequency for P- and S-waves from 5 to 10 Hz, and the other doubled the peak ground velocity (PGV) value to 46 cm/second as an upper bound loading case. Both runs were for RMQ=3 rock conditions. In comparison with the numerical results obtained using the PGV value of 23 cm/second, frequency of 5 Hz and duration of 0.5 seconds, doubling the frequency only slightly changed loads on bolts and shotcrete. The maximum increase in bolt loads is less than 2 percent while the maximum increase in shotcrete load is 3 percent. The strength-to-stress ratio near the drift changed noticeably during the seismic loading, however, no failure zone developed. On the other hand, doubling the PGV value caused greater change in ground support load, but did not significantly change the strength-to-stress ratio near the drift. The maximum increase detected is nearly 10 percent in bolt force and 12 percent for the compressive load in shotcrete. Figures B-19 and B-20 further illustrate these comparisons.

Table B-12. Summary of Numerical Results for Seismic Load and/or Ground Support Type I (Rock bolts plus 100 mm of shotcrete)

	Rock Mass Quality (RMQ) Category		
Item	RMQ = 1	RMQ = 3	RMQ = 5
Change in Horizontal Closure (mm)	+0.3 or -0.4	+0.4 or -0.2	+0.8 or -0.6
Change in Vertical Closure (mm)	+1.6 or -1.4	+1.2 or -1.0	+1.0 or -1.2
Change in Major Princ Stress at Crown (%)	1.5	2.5	4.5
Change in Minor Princ Stress at Crown (%)	5.0	5.2	7.0
Change in Max. Axial Bolt (%)	10.0	5.6	8.3
Change in Max. Tensile Shotcrete stress (%)	2.0	5.0	8.4
Change in Max. Compressive Shotcrete stress (%)	-18.5	-10.8	-19.2

B.4.3.2 Drift Supported by Shotcrete Liner

A shotcrete liner, as in the case for Ground Support Type II, was numerically represented by elastic beam elements bonded onto the drift wall. The liner has a thickness of 150 mm and is uniformly continuous along the drift wall. Figures B-21 and B-23 and Table B-13 summarize some of numerical results due to the seismic loads.

Table B-13. Summary of Numerical Results for Seismic Load and/or Ground Support Type II

	Rock Mass Quality (RMQ) Category		
Item	**RMQ = 1**	**RMQ = 3**	**RMQ = 5**
Change in Horizontal Closure (mm)	+0.3 or -0.5	+0.4 or -0.3	+0.8 or -0.6
Change in Vertical Closure (mm)	+1.8 or -1.5	+1.3 or -1.1	+1.1 or -1.2
Change in Major Princ Stress at Crown (%)	1.1	2.6	3.8
Change in Minor Princ Stress at Crown (%)	6.7	7.4	7.5
Change in Max. Tensile Load in Shotcrete (%)	2.1	6.3	7.3
Change in Max. Compre Load in Shotcrete (%)	-27.8	-10.0	-21.8

These results are similar to the results shown in Table B-9. In general, the additional effect of seismic loads on drift stability and ground support systems is insignificant.

B.4.3.3 Drift Supported with Steel Sets

Dynamic results obtained for a drift supported with full-circle steel sets are shown in Figures B-24 and B-26 and in Table B-14. Changes due to the addition of seismic load are small. An exception is the relatively high 16.5 percent change in axial load due to the high rock stiffness for category RMQ=5. Steel sets, which are not specified for use in such good ground, show initial overstress by thermally-induced mechanical loads and would experience some additional stress, although not significant, due to seismic loads.

Table B-14. Summary of Numerical Results for Seismic Loads for Ground Support Type III (Steel Sets)

	Rock Mass Quality (RMQ) Category		
Item	RMQ = 1	RMQ = 3	RMQ = 5
Change in Horizontal Closure (mm)	+0.3 or -0.5	+0.4 or -0.3	+0.8 or -0.6
Change in Vertical Closure (mm)	+1.8 or -1.5	+1.4 or -1.1	+1.1 or -1.2
Change in Major Princ Stress at Crown (%)	0.5	3.0	4.1
Change in Minor Princ Stress at Crown (%)	4.0	4.1	5.1
Change in Max. Axial Load in Steel Set (%)	2.2	6.1	16.5

B.5 SUMMARY

Uniformly-spaced emplacement 5-meter-diameter drifts have been analyzed using both ANSYS and FLAC codes under combinations of static, thermal and seismic loading conditions. Three sets of material properties, simulating poor to good rock mass states, were considered. Fully-grouted rock bolts, shotcrete and steel sets were incorporated in numerical models as candidate ground support for the drift. The main objective of the analysis is to examine the response of emplacement drifts to the addition of long-term thermal loading and potential earthquake events, so that the drift stability can be assessed.

Input data to numerical analyses reflect the best documented information currently available on elastic properties, strength parameters, thermal properties, in situ stresses, thermal loads, and seismic loading. These properties and their time dependent behavior, if any, have been considered in modeling as realistically as possible. Careful attention was also given to mesh refinement and boundary conditions in order to minimize the effect of mesh dimensions on numerical output.

Numerical results indicate that upon excavation, prior to waste emplacement, the unsupported drift will experience no failure of rock mass surrounding the drift. The maximum closure between crown and invert is about 10 mm. However, numerical results does indicate a potential overstressed zone which extends about 1 m into the rock where block loosening along discontinuities could occur. No discontinuities were explicitly considered in numerical models at present.

Under the thermal load of 83 MTU/acre, the drift experiences higher horizontal closure than vertical closure. In fact, the drift will elongate vertically for RMQ = 3 and RMQ = 5. The maximum horizontal closure detected is 12.8 mm while the maximum vertical elongation is 5.9 mm. These values for closure indicate that rock mass behaves essentially elastically, though the normal components of the stress state have increased significantly. Load development in fully-grouted rock bolts is below the yield capacity of the bolt, except for the bolt closest to the springline for RMQ=1 where the bolt has reached its yield strength. For fully-grouted steel bolts, yielding in steel will not substantially reduce their effectiveness. For the shotcrete lining, tension occurs in the side walls while compression occurs at the crown and invert. Regardless of the rock mass category, tensile load in shotcrete liner is high enough for tensile cracks to develop, eventually reducing the effectiveness of the shotcrete. Light steel sets are also shown to exceed their yield strength in tension and in compression. In this respect, high thermal loads indicate the need for structurally flexible support systems.

In general, underground drifts are confined and are therefore less sensitive to earthquake-induced ground shaking than surface structures. In addition, the typical seismic wave is characterized by a long wave length and low frequency. The dimension of the drift is a fraction of the typical seismic wave length, consequently the rock mass and the drift tend to move together rather than undergo any significantly differential movements. However, seismic-induced load maximums can occur at any location within the ground support system as compressional and shear waves propagate through the drift. Such a dynamic feature is important to the design of ground support connections such as shotcrete to invert and steel set to invert connection.

The seismic loading, characterized by a combination of sinusoidal P- and S-wave of velocities, was superimposed onto FLAC models after 50 years of thermal loading generated from waste packages in the emplacement drift. These seismic waves of long wave length and low frequency propagate upwards. The dynamic response of the drift and associated ground support systems to seismic loading is best described in terms of the change by percentage in stress, displacement and loads in ground support systems. Drift closure and elongation caused by seismic loading is less than 2 mm regardless of ground support types and RMQ categories. Fully-grouted rock bolts experience a maximum increase of 10 percent in axial load. Shotcrete shows a maximum tensile load increase of 8.4 percent and a compressive load decrease of 27.8 percent at different locations along the lining. Steel sets show a 16.4 percent increase in axial load in one case. These changes are noticeable but are not considered significant from the standpoint of ground control aspects.

B.6 REFERENCES

AISC (American Institute of Steel Construction) 1989. *Manual of Steel Construction Allowable Stress Design.* 9th Edition. Chicago, Illinois: American Institute of Steel Construction, Inc.

ANSYS 1995. *User's Manual Revision 5.2.* Vols. I, II, III, and IV. ANSYS, Inc.

CRWMS M&O 1994. *Initial Summary Report for Repository/Waste Package Advanced Conceptual Design.* B00000000-01717-5705-00015, Rev. 01. Las Vegas, Nevada.

CRWMS M&O 1995a. *Controlled Design Assumption Document.* B00000000-01717-4600-00032, Rev. 01. Las Vegas, Nevada.

CRWMS M&O 1995b. *Thermomechanical Analyses.* BC0000000-01717-5705-00013, Rev. 00. Las Vegas, Nevada.

CRWMS M&O 1995c. *Geology of the Exploratory Studies Facility TS Loop.* BAB000000-01717-0200-0002, Rev. 00. Las Vegas, Nevada.

CRWMS M&O 1995d. *Repository Ground Control Evaluation.* BC0000000-01717-5705-00017, Rev. 00. Las Vegas, Nevada.

CRWMS M&O 1995e. *ESF [Exploratory Studies Facility] Ground Support Design Analysis.* BABEE0000-01717-0200-00002, Rev. 00. Las Vegas, Nevada.

Hoek, E. and Brown, E. T. 1980. *Underground Excavations in Rock.* London: The Institution of Mining and Metallurgy.

Itasca 1993. *FLAC Version 3.2 User's Manual.* Three volumes. Itasca Consulting Group, Inc.

SNL 1991. Hardy, M. P. and Bauer, S. J. *Drift Design Methodology and Preliminary Application for the Yucca Mountain Site Characterization Project.* SAND89-0837. Albuquerque, New Mexico: Sandia National Laboratories.

SNL 1995. Lin, M.; Hardy, M. P.; and Ryder, E. E. *Repository Design Data: Update Through August 1995.* Sandia Letter Report SLTR95-0009. Albuquerque, New Mexico: Sandia National Laboratories.

YMP (Yucca Mountain Site Characterization Project) 1995a. *Yucca Mountain Site Characterization Project Reference Information Base.* YMP/93-02, Rev. 3. Las Vegas, Nevada.

YMP 1995b. *Seismic Design Methodology For a Geologic Repository at Yucca Mountain.* YMP/TR-003-NP, Rev. 00. Las Vegas, Nevada.

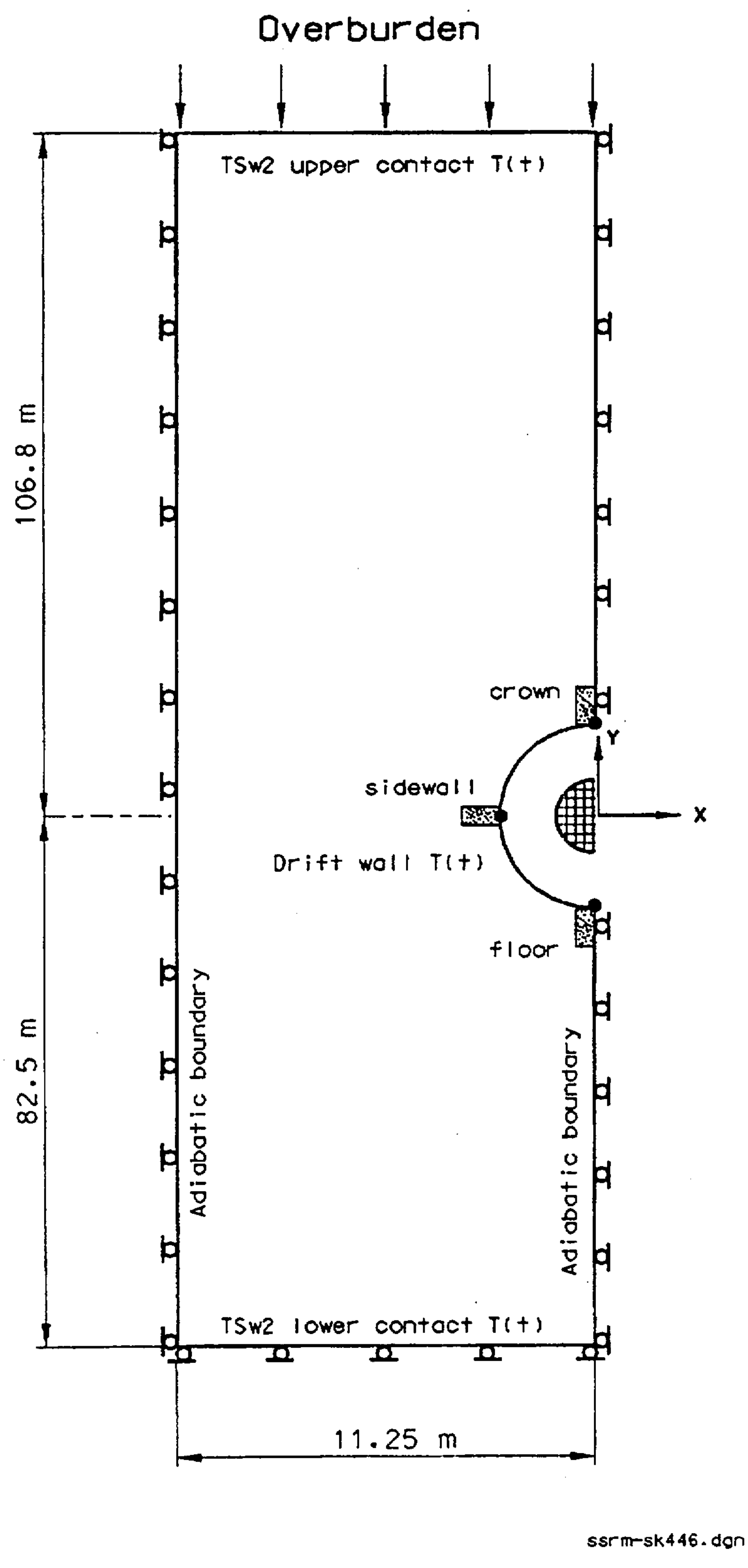


Figure B-1. Geometry and Boundary Conditions for Thermomechanical Modeling Using FLAC

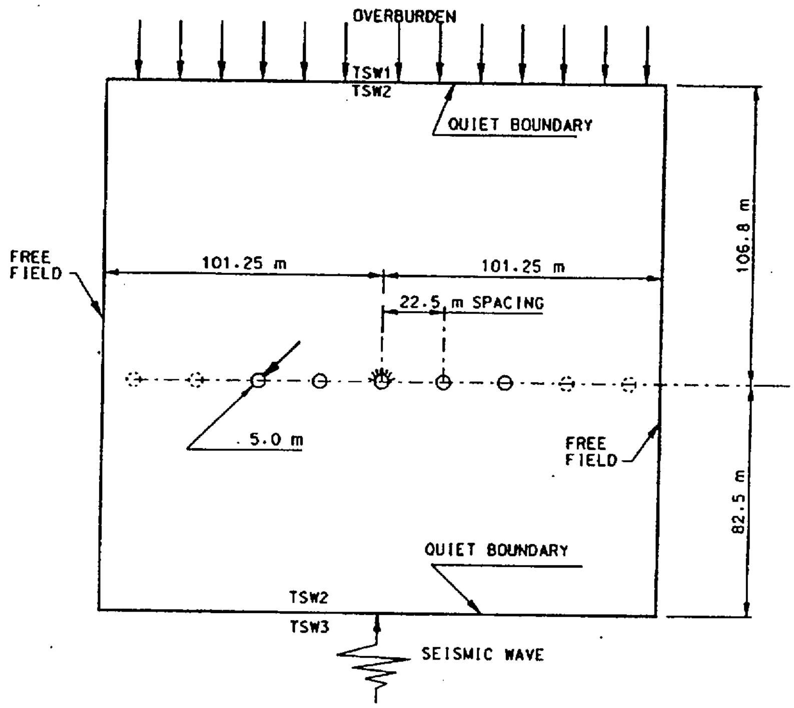


Figure B-2. Mesh Dimensions and Boundary Conditions of The FLAC Model for Seismic Analysis

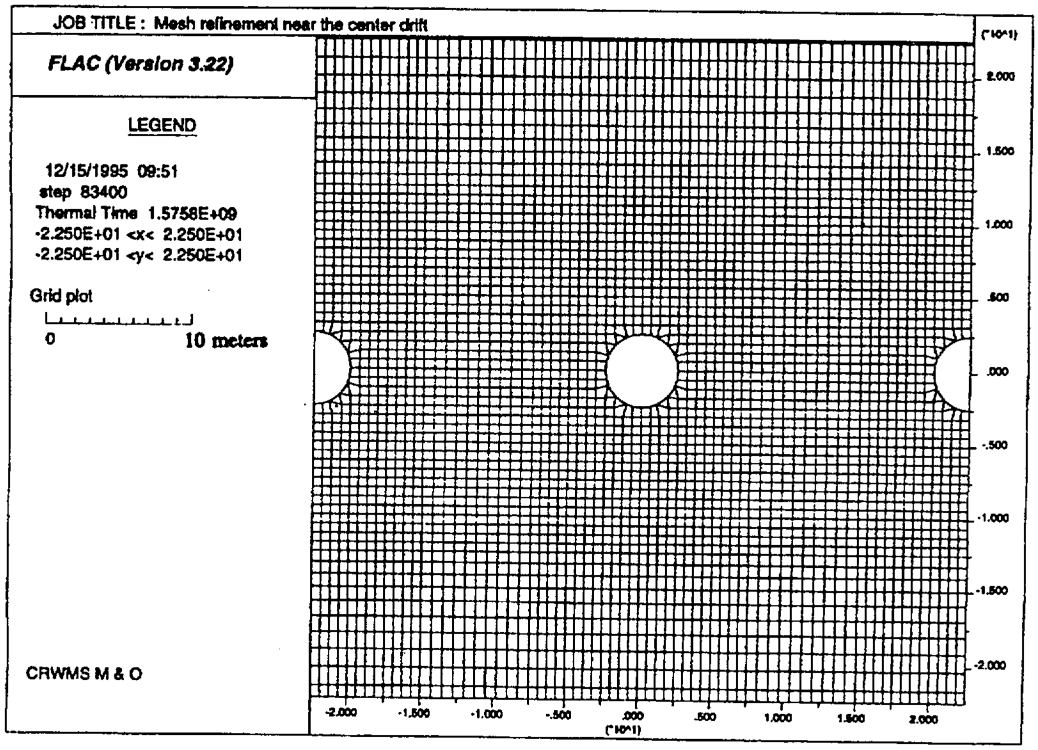


Figure B-3. Mesh Refinement Near the Center Drift

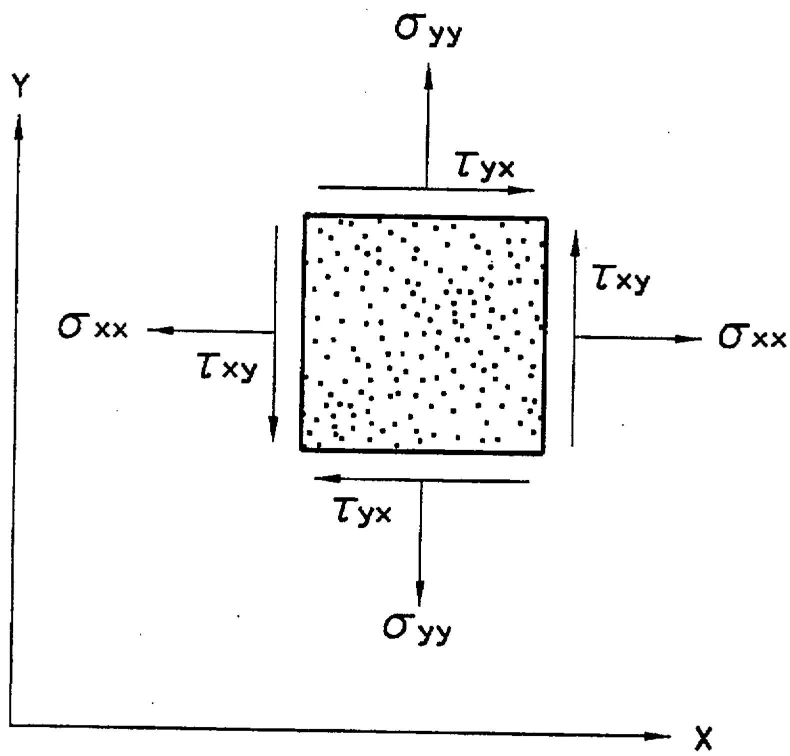


Figure B- 4. Sign Convention for Positive Stresses

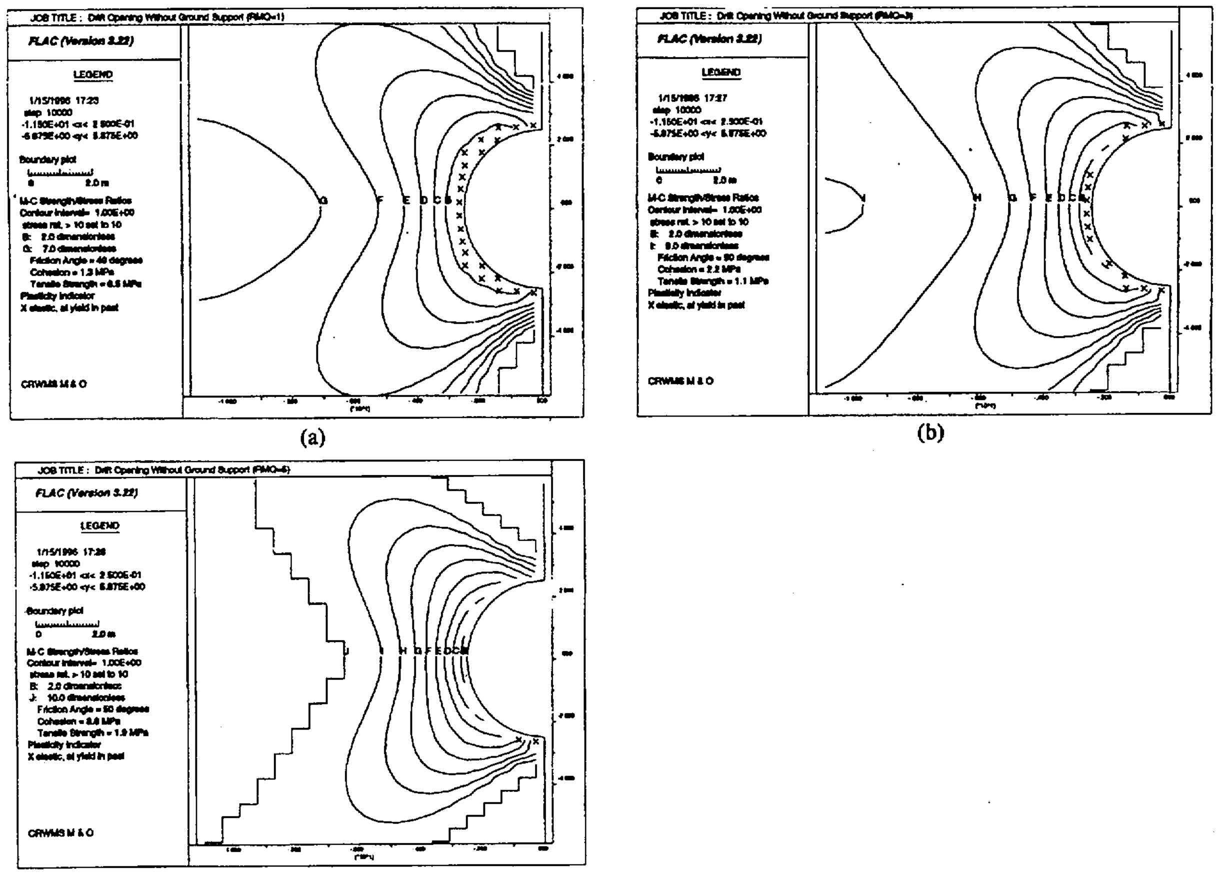


Figure B-5. Strength/Stress Ratio Contours and Plasticity Indicators around Opening without Ground Support: (a) RMQ=1; (b) RMQ=3; (c) RMQ=5

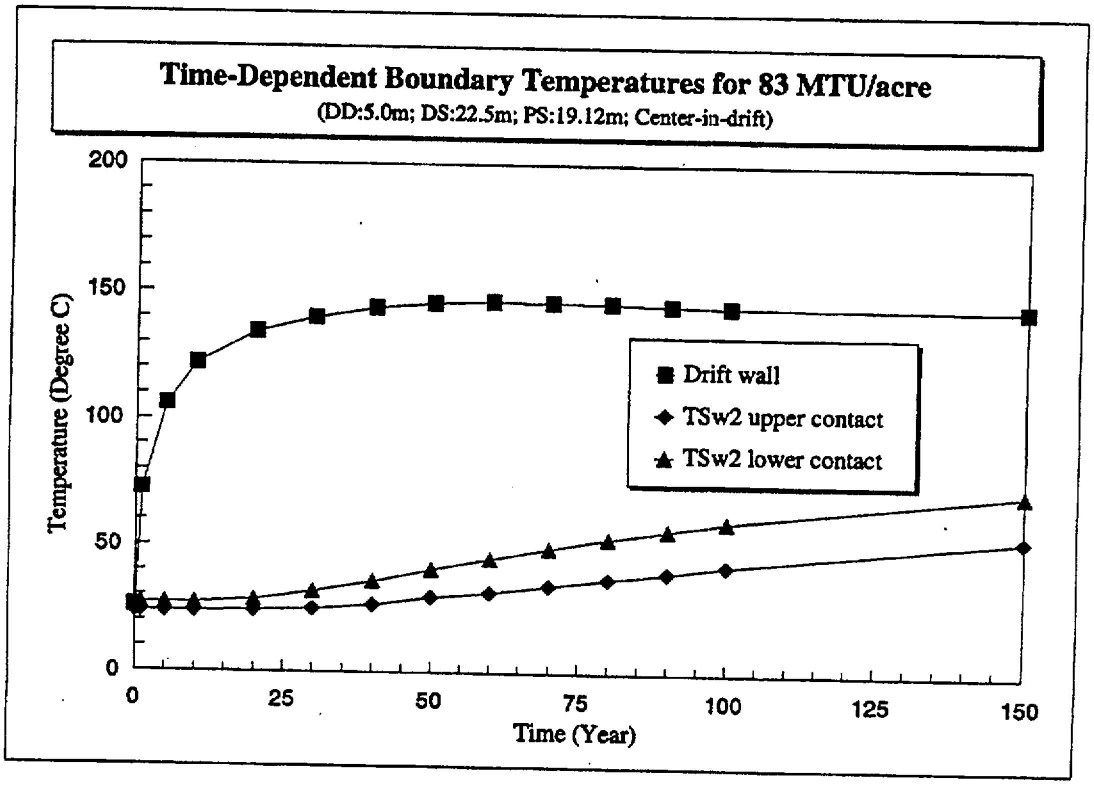
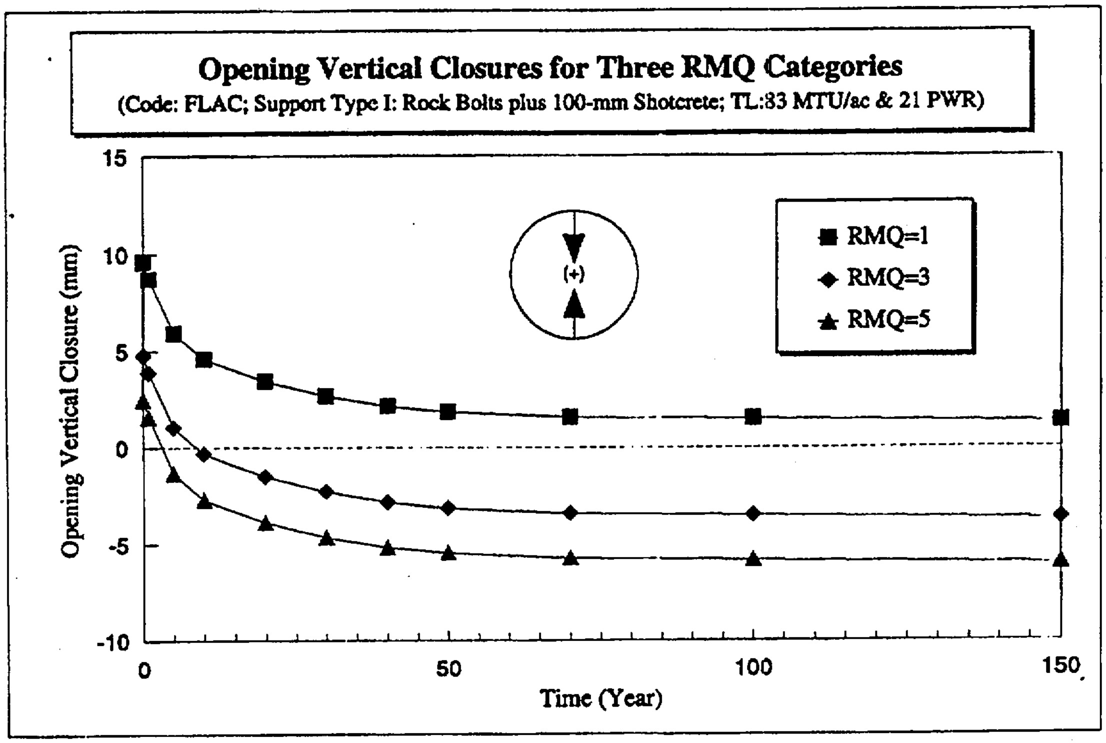
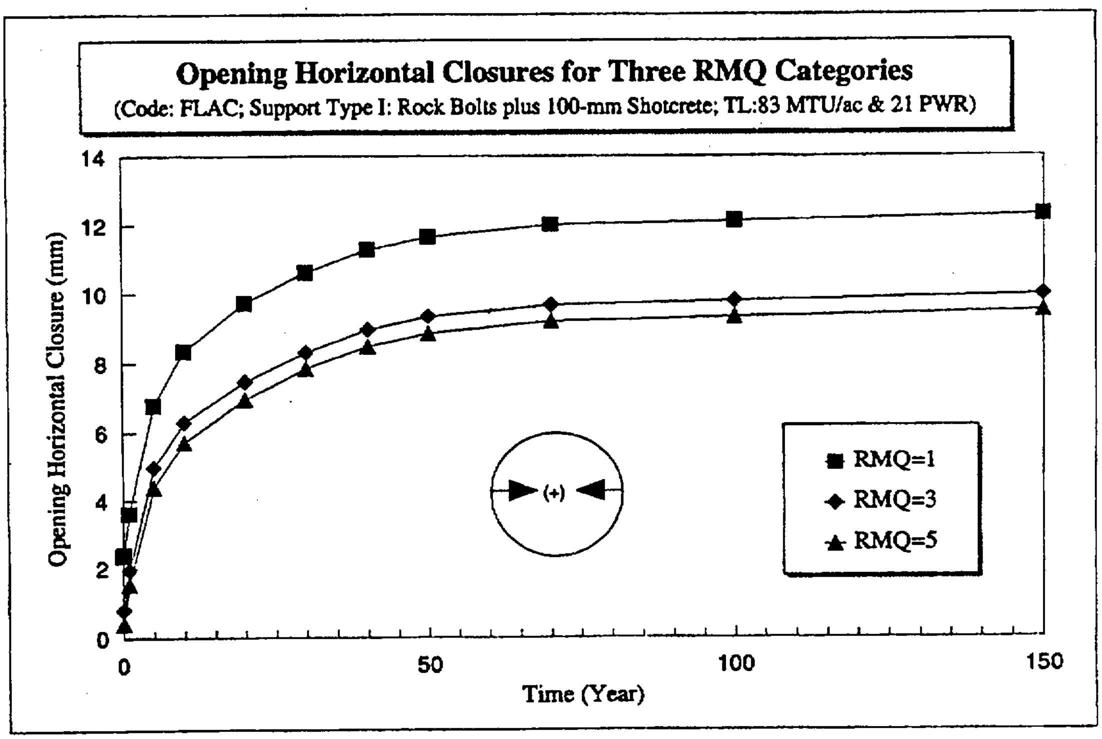


Figure B-6. Temperature Histories of TSw2 Upper and Lower Contacts and Drift Wall for 83 MTU/acre

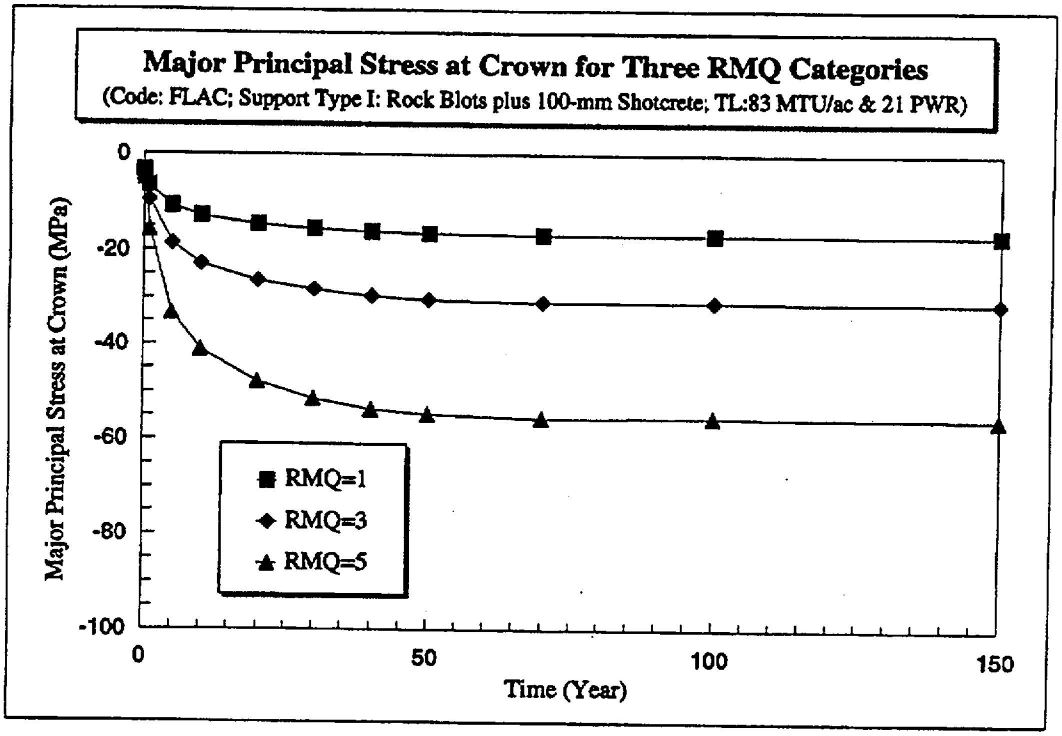


(a)

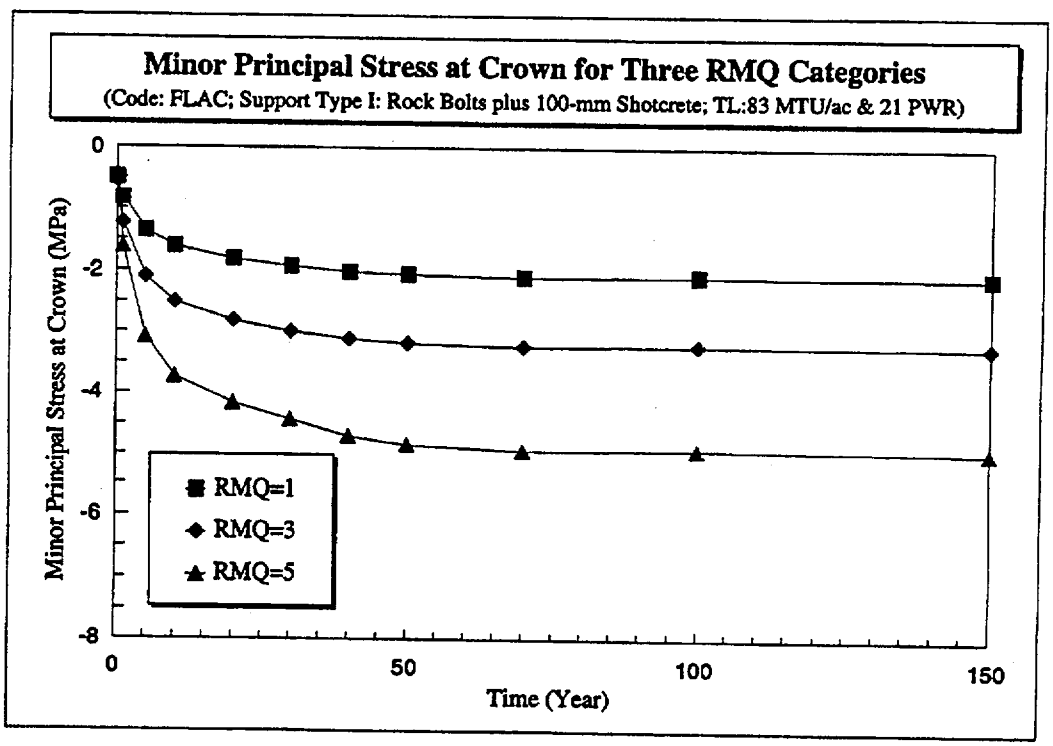


(b)

Figure B-7. Time Histories of Opening Closures for Different RMQ Categories for 83 MTU/acre: (a) Vertical Closures; (b) Horizontal Closures

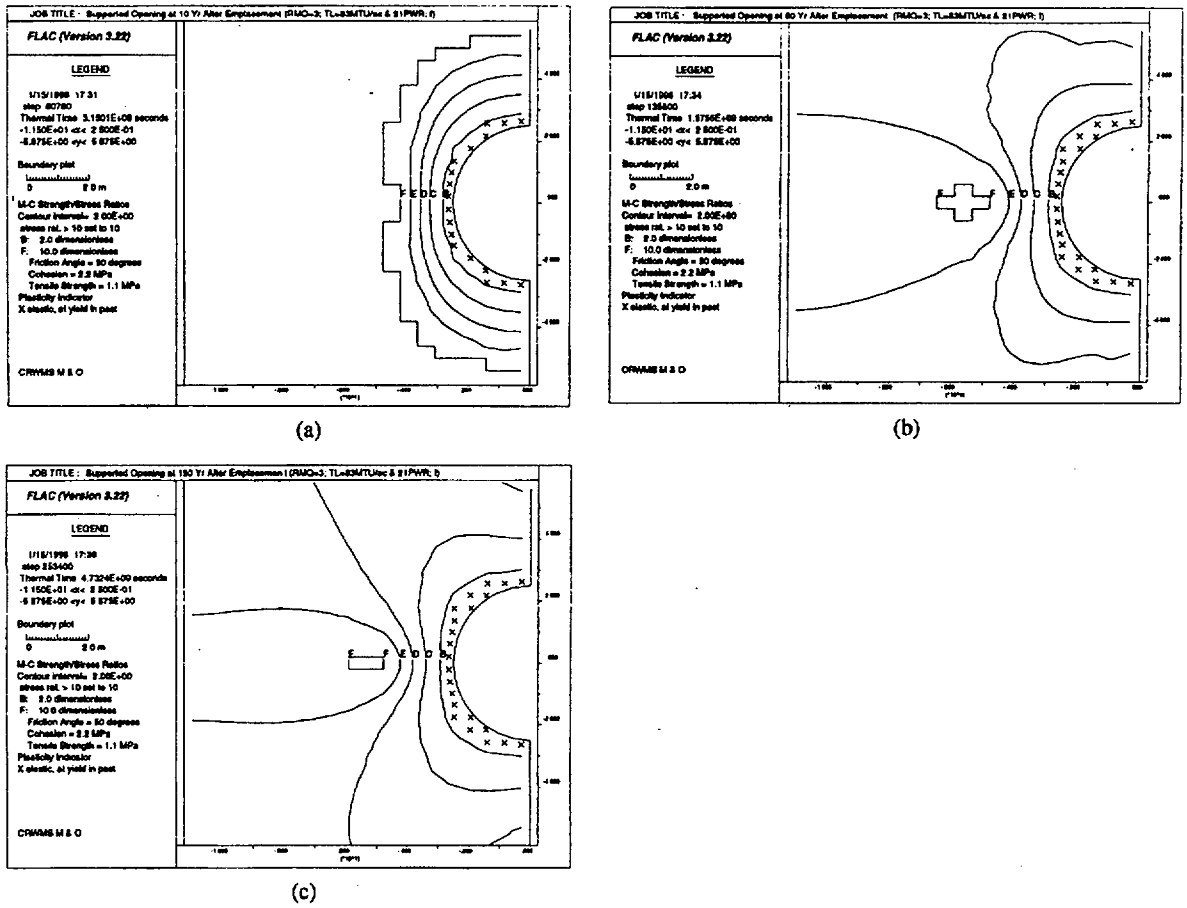


(a)



(b)

Figure B-8. Time Histories of Principal Stresses at Crown for Different RMQ Categories for 83 MTU/acre: (a) Major Principal Stress; (b) Minor Principal Stress



(a) (b) (c)

Figure B-9. Factors of Safety Contours and Plasticity Indicators around Opening with Ground Support Type I for RMQ=3 and 83 MTU/acre: (a)10 Years after Emplacement; (b) 50 Years after Emplacement; (c)150 Years after Emplacement

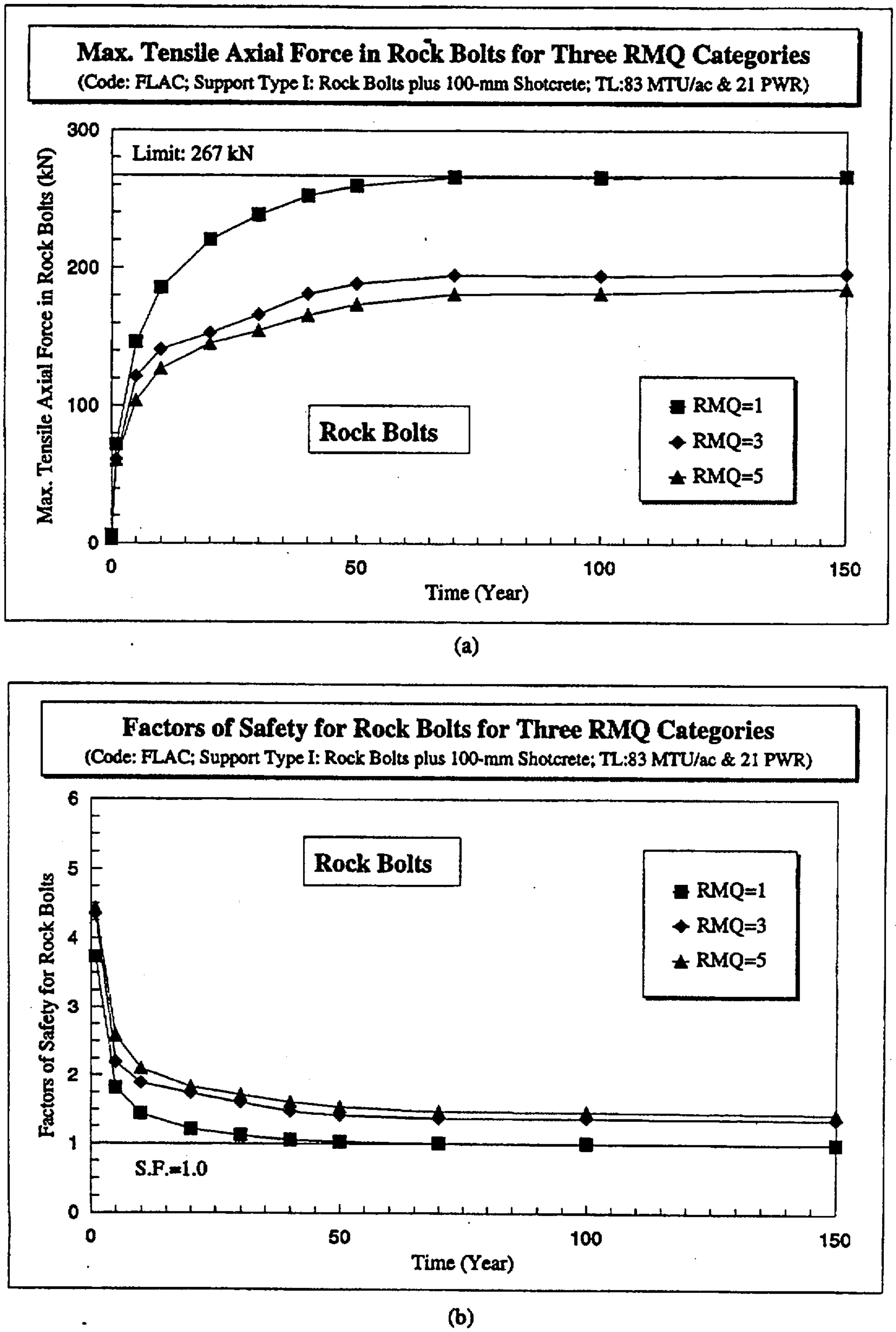


Figure B-10. Time Histories of Max. Axial Forces in Rock Bolts and Their Factors of Safety for Different RMQ Categories for 83 MTU/acre: (a) Max. Axial Forces; (b) Factors of Safety

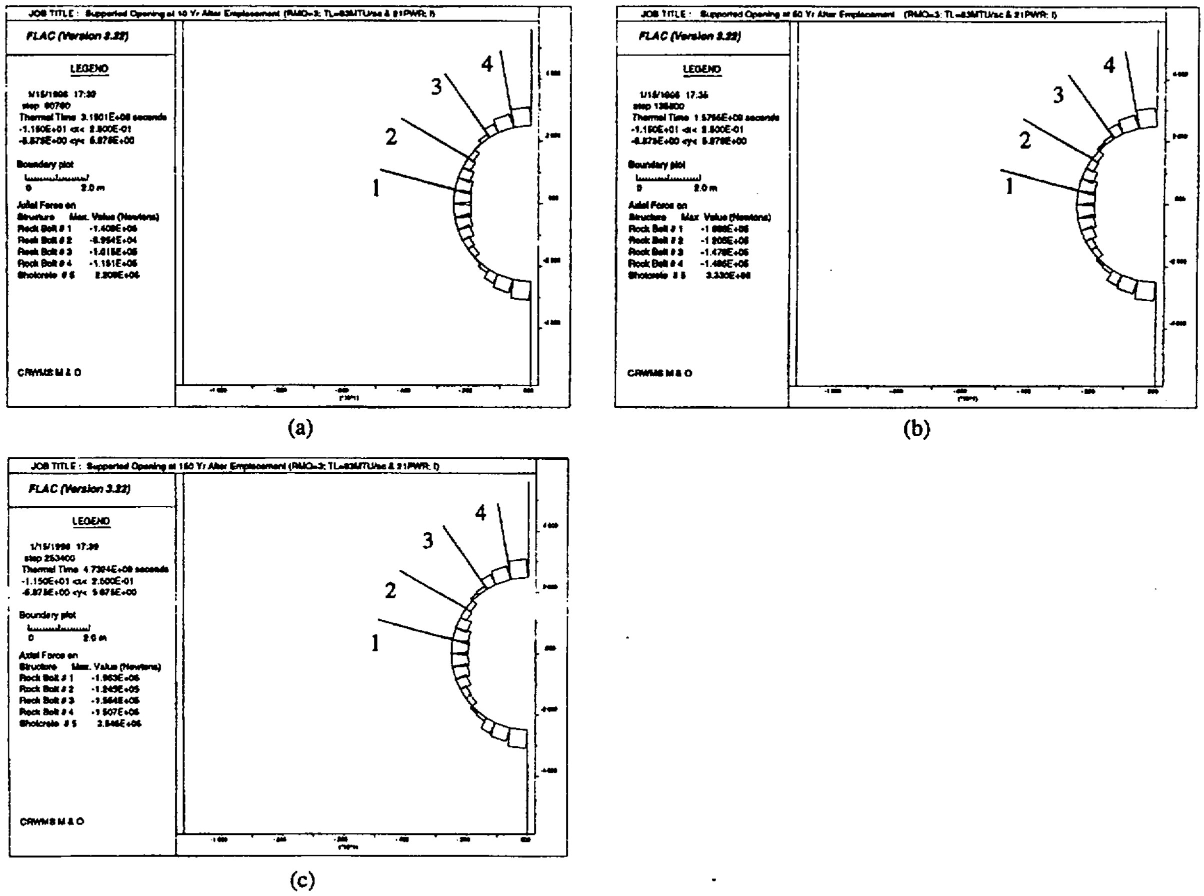
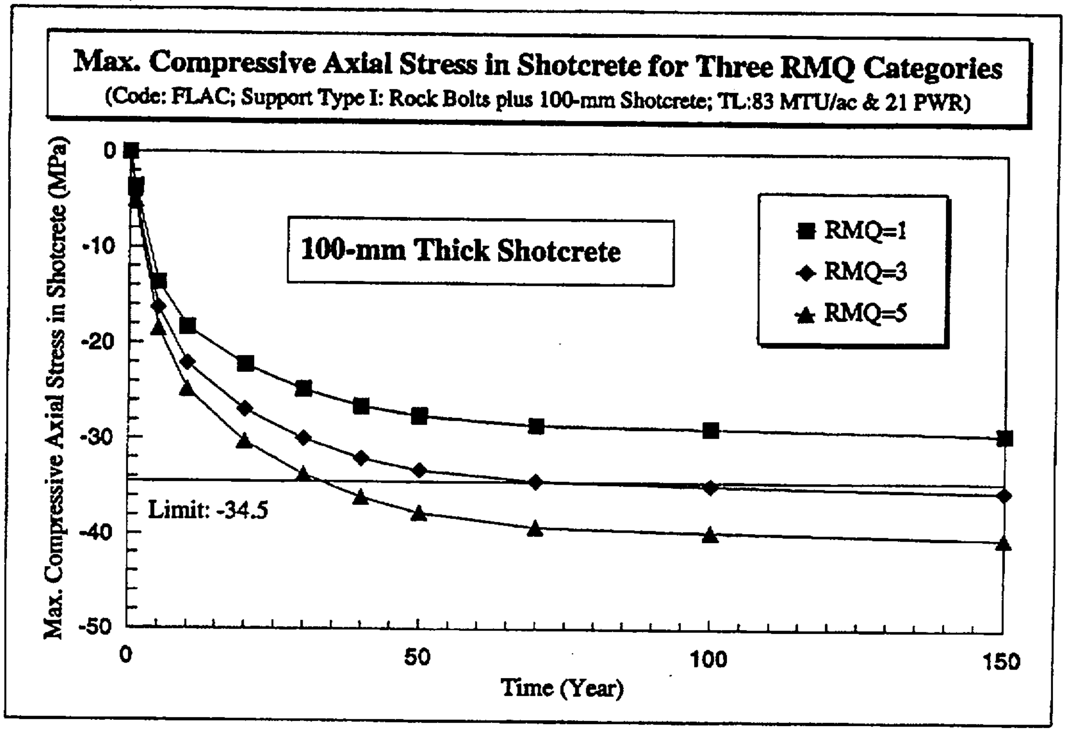
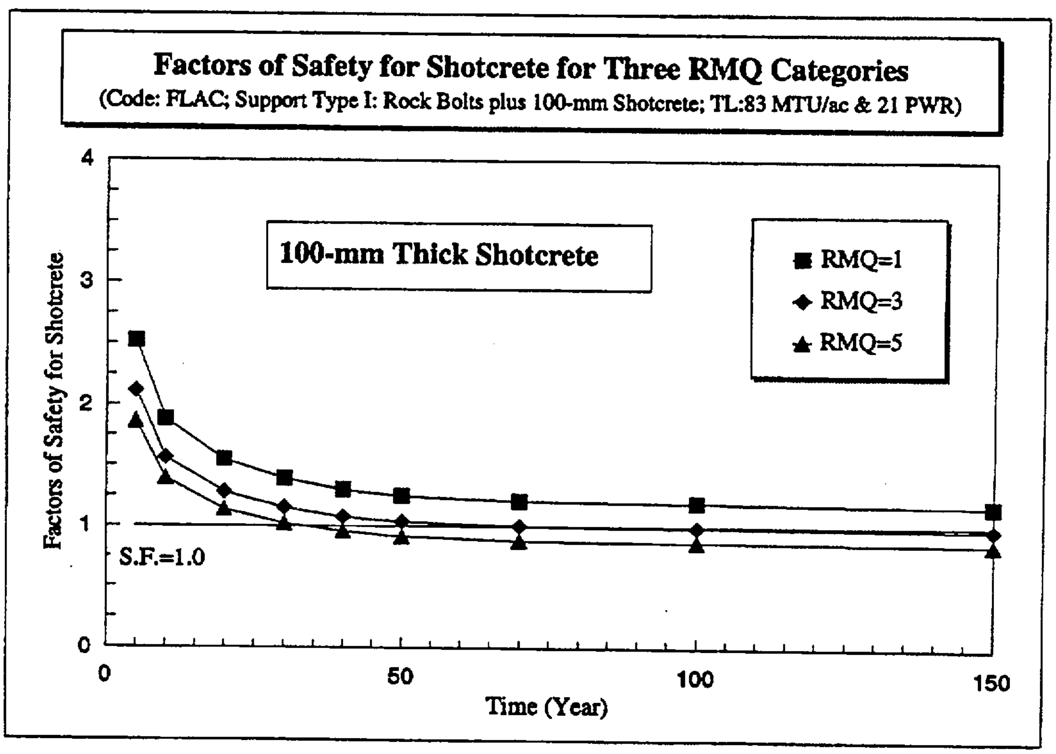


Figure B-11. Axial Forces in Rock Bolts and Shotcrete for Ground Support Type I, RMQ=3 and 83 MTU/acre: (a) 10 Years after Emplacement; (b) 50 Years after Emplacement; (c) 150 Years after Emplacement

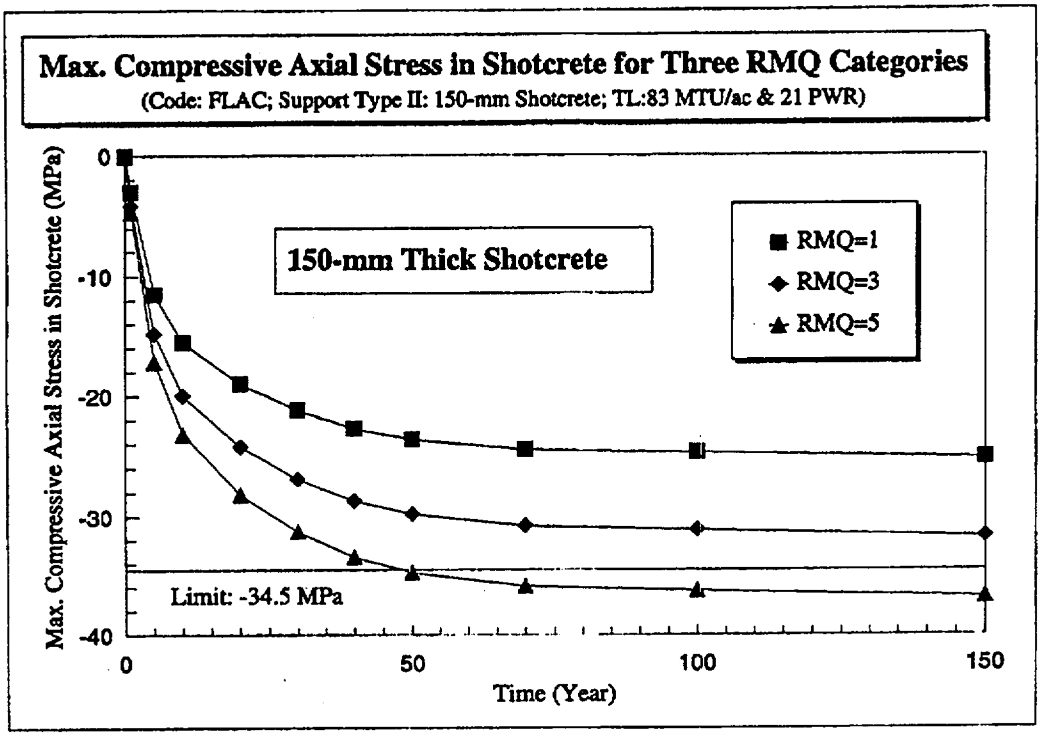


(a)

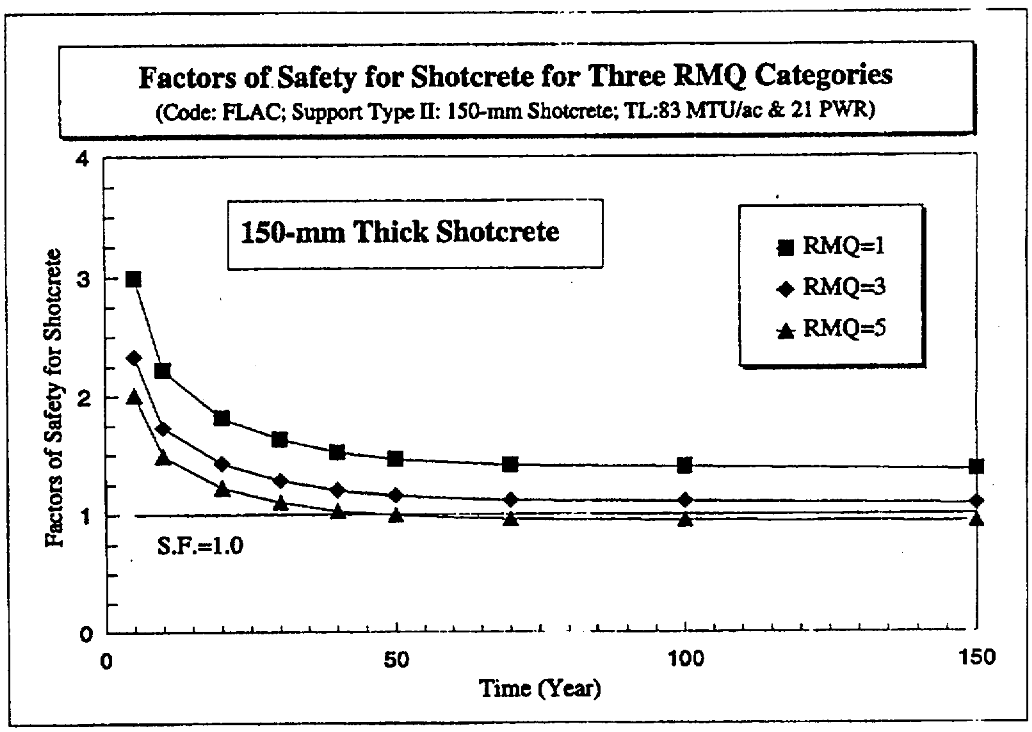


(b)

Figure B-12. Time Histories of Max. Compressive Axial Stress in Shotcrete and its Factors of Safety for Ground Support Type I, Different RMQ Categories and 83 MTU/acre (a) Max. Compressive Axial Stress; (b) Factors of Safety

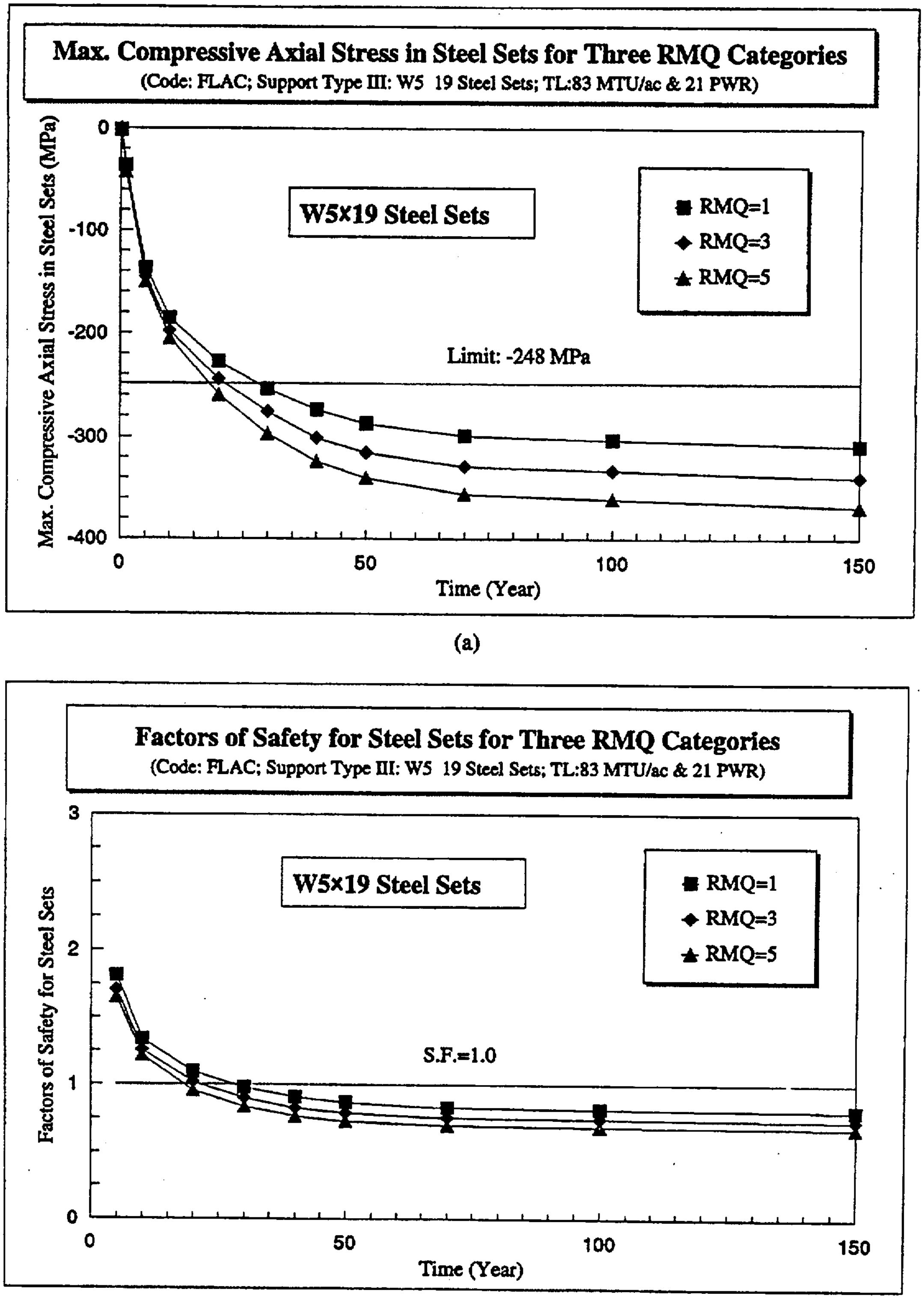


(a)



(b)

Figure B-13. Time Histories of Max. Compressive Axial Stress in Shotcrete and its Factors of Safety for Ground Support Type II, Different RMQ Categories and 83 MTU/acre (a) Max. Compressive Axial Stress; (b) Factors of Safety



(a)

(b)

Figure B-14. Time Histories of Max. Compressive Axial Stress in Steel Sets and Their Factors of Safety for Ground Support Type III, Different RMQ Categories and 83 MTU/acre (a) Max. Compressive Axial Stress; (b) Factors of Safety

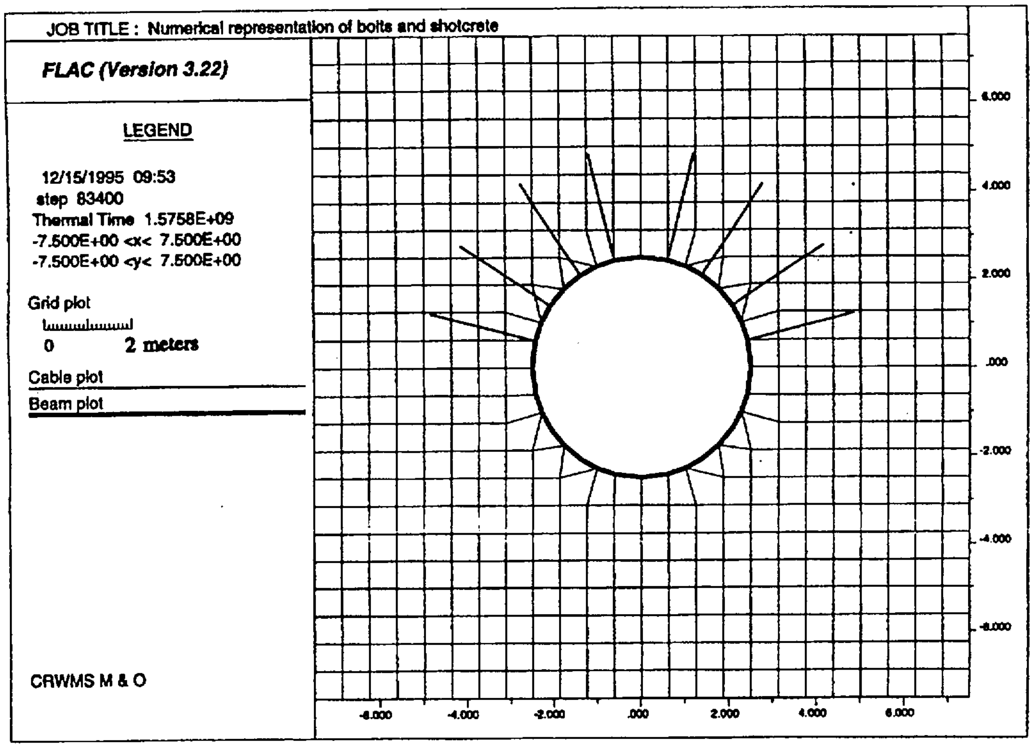


Figure B-15. Numerical Representation of Bolts and Shotcrete in the Center Drift

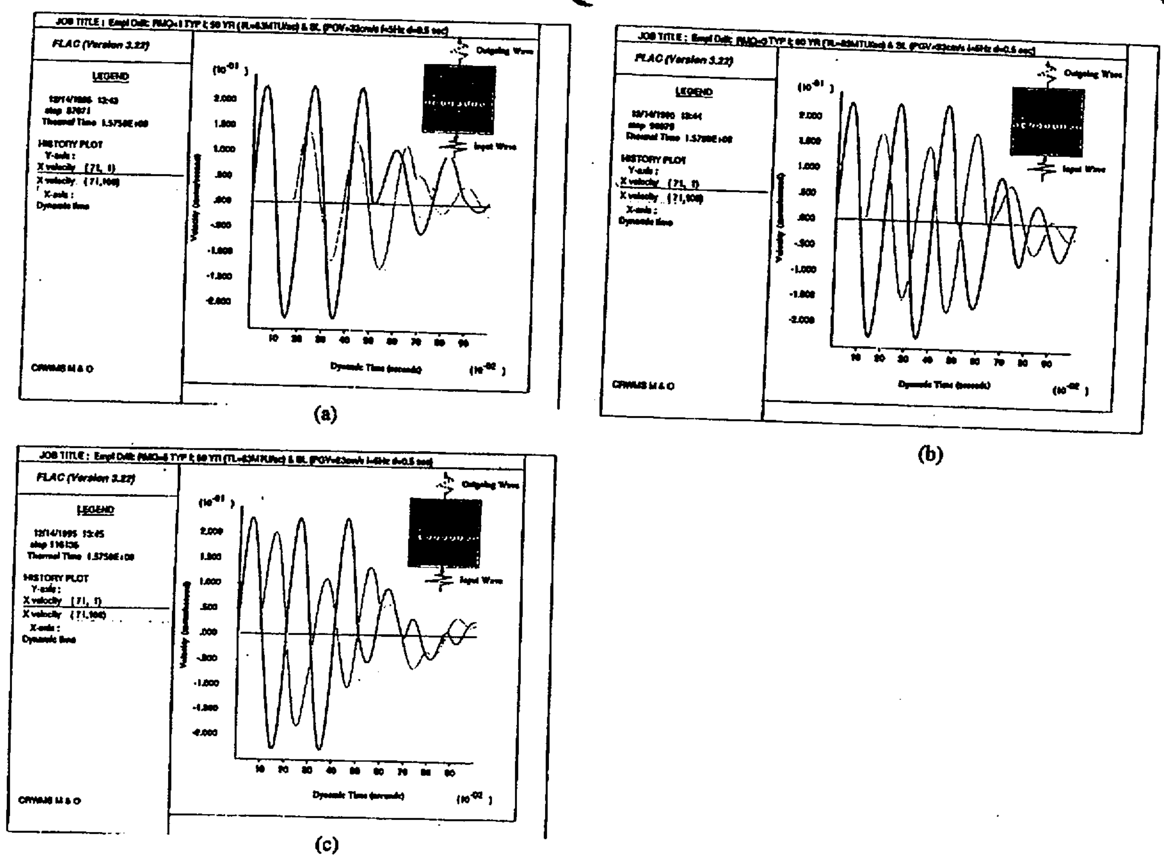


Figure B-16. Input Seismic Wave (PGV=23 cm/s, freq.=5 Hz) at the Base of FLAC Model and Outgoing Seismic Wave Monitored at the Top of FLAC Model When the Center Drift Is Reinforced with Bolts on 1.0 m Spacing and 100 mm Thick Shotcrete (Ground Support Type I): (a) Under RMQ = 1; (b) Under RMQ = 3; (c) Under RMQ = 5.

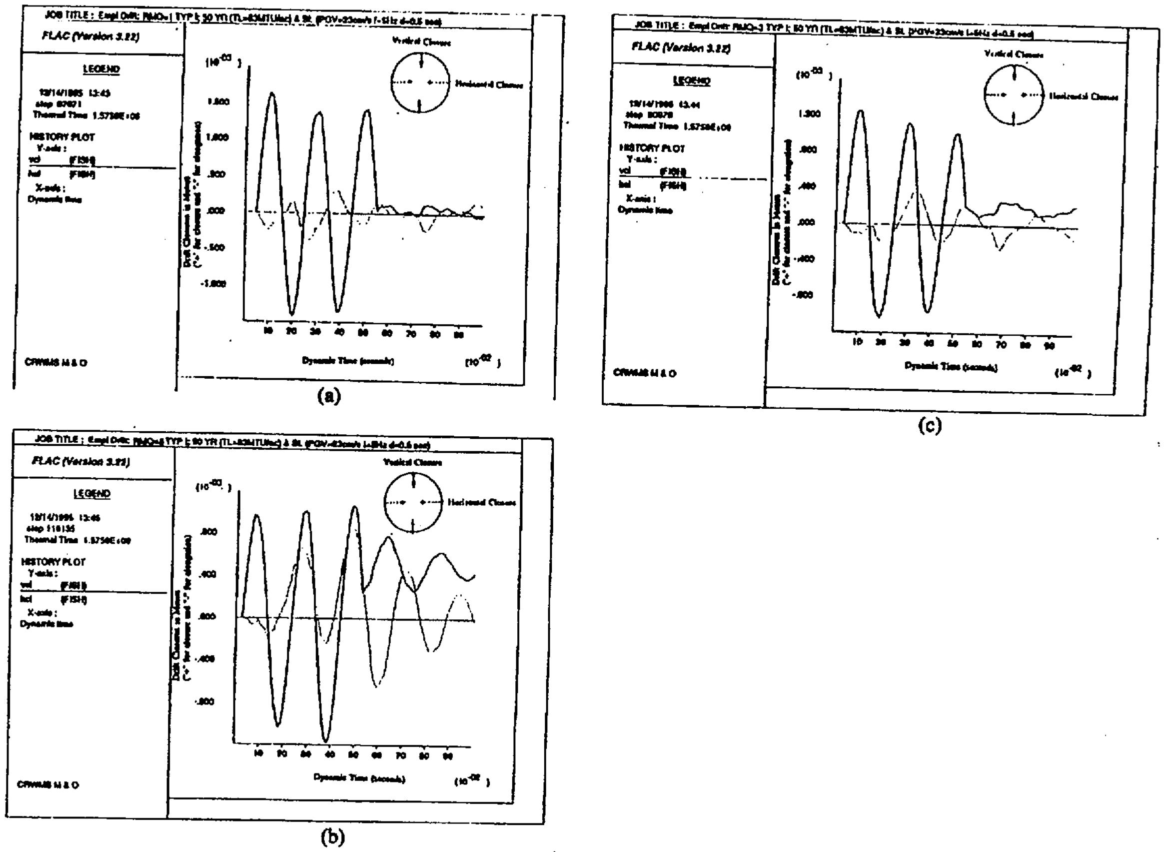


Figure B-17. Vertical and Horizontal Closures Caused during the Seismic Loading (PGV=23 cm/s, freq.=5 Hz) for the Center Drift with Ground Support Type I: Horizontal Axis Shows the Dynamic Time in Seconds and Vertical Axis Shows the Closure in Meters. (a) Under RMQ = 1; (b) Under RMQ = 3; (c) Under RMQ = 5.

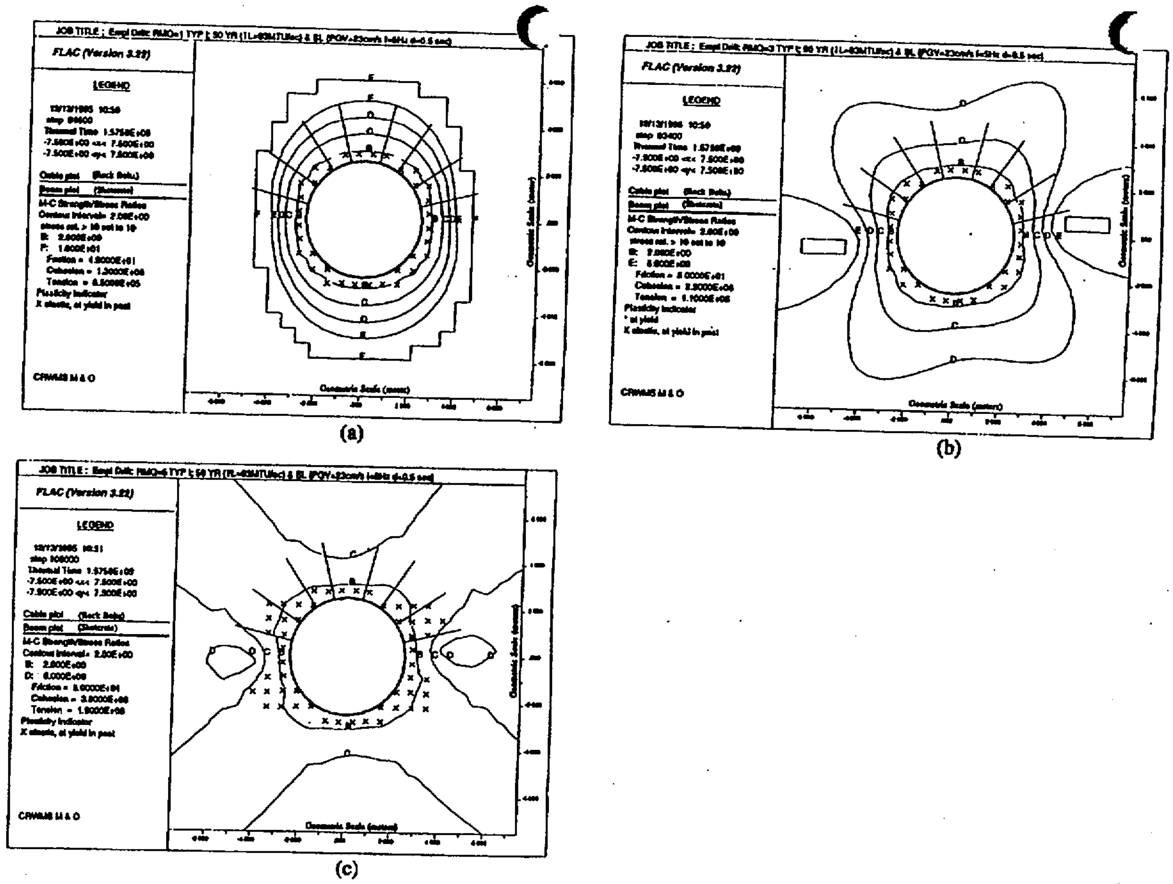


Figure B-18. Safety Factor Contour Plots and Rock Mass Plasticity Location Indicators about the Center Drift under the Seismic Loading (PGV=23 cm/s, freq.=5 Hz) and with Ground Support Type I: (a) Under RMQ = 1; (b) Under RMQ = 3; (c) Under RMQ = 5.

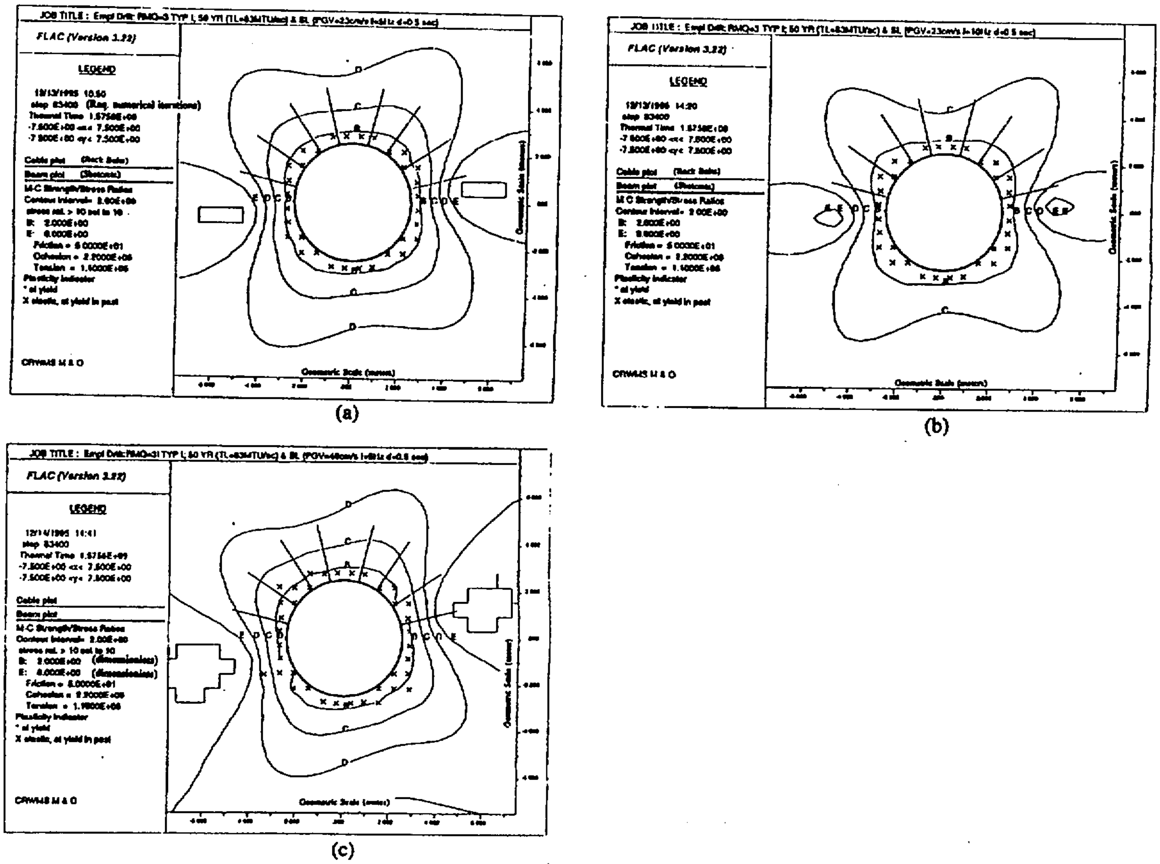


Figure B-19. Safety Factor Contour Plots and Rock Mass Plasticity Location Indicators about the Center Drift under the Different Seismic Loadings, for RMQ=3, and with Ground Support Type I: (a) Under Seismic Loading with PGV=23 cm/s, freq.=5 Hz; (b) Under Seismic Loading with PGV=23 cm/s, freq.=10 Hz; (c) Under Seismic Loading with PGV=46 cm/s, freq.=5 Hz.

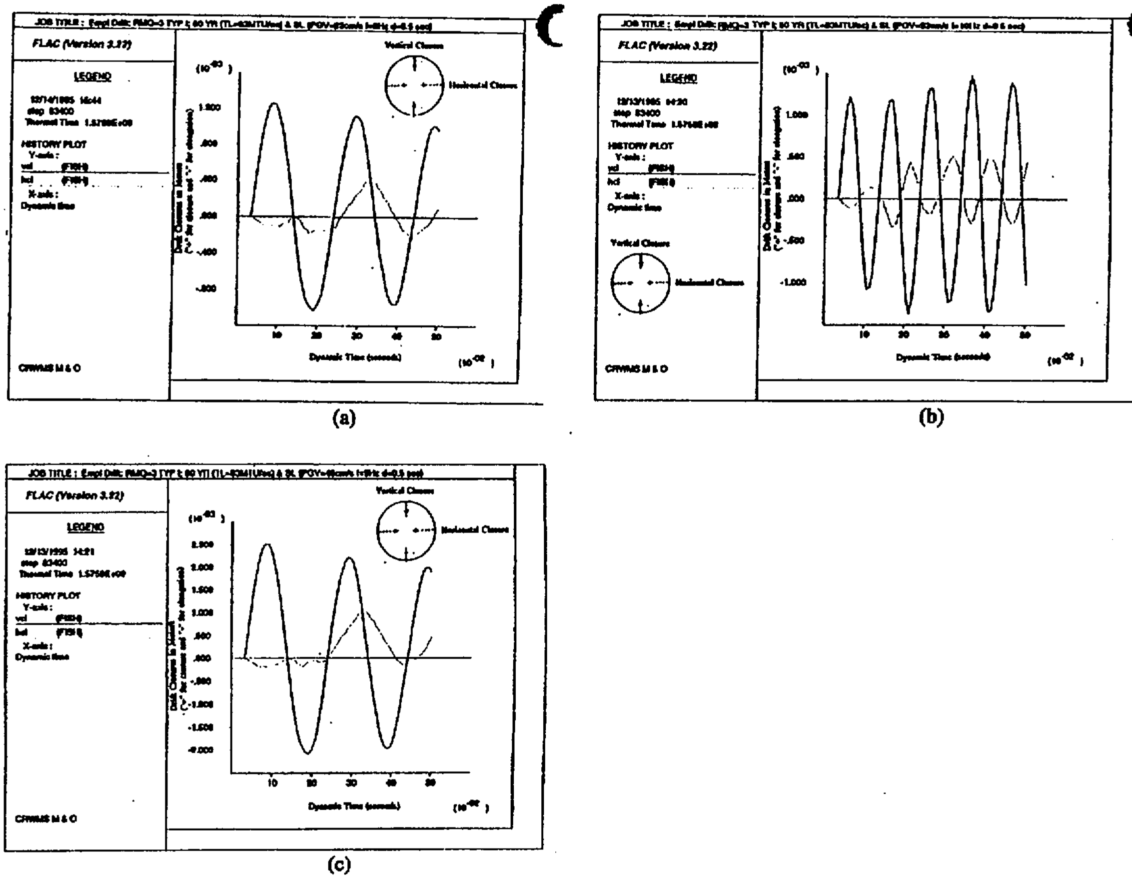
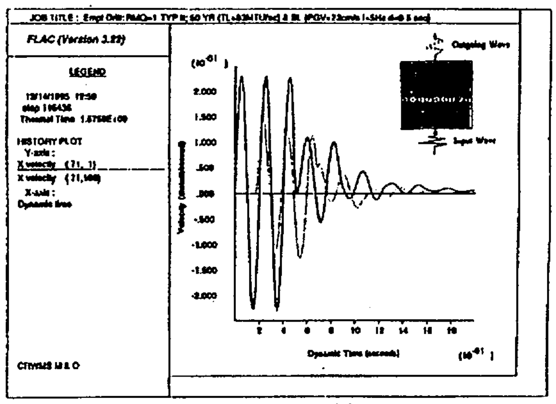
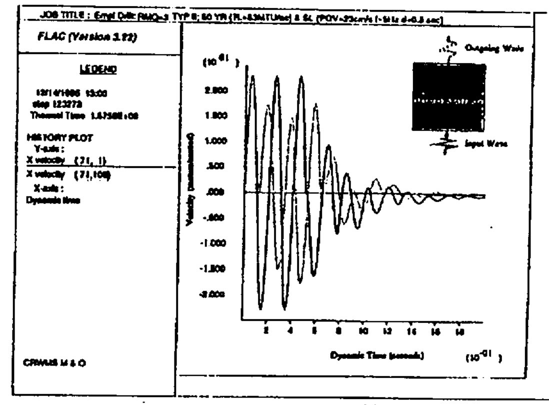


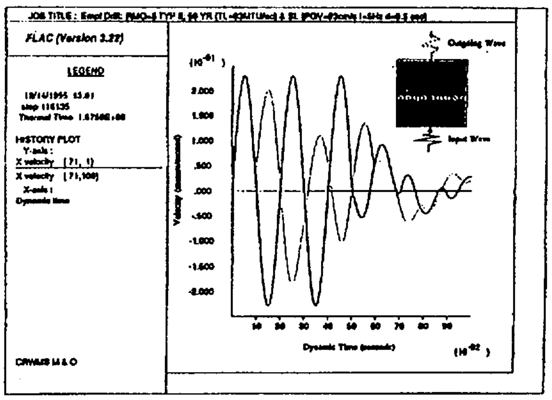
Figure B-20. Vertical and Horizontal Closures Caused about the Center Drift under three Different Seismic Loadings for RMQ=3, and with Ground Support Type I: Horizontal Axis Shows the Dynamic Time in Seconds and Vertical Axis Shows the Closure in Meters: (a) Under Seismic Loading with PGV=23 cm/s, freq.=5 Hz; (b) Under Seismic Loading with PGV=23 cm/s, freq.=10 Hz; (c) Under Seismic Loading with PGV=46 cm/s, freq.=5 Hz.



(a)



(b)



(c)

Figure B-21. Input Seismic Wave (PGV=23 cm/s, freq.=5 Hz) at the Base of FLAC Model and Outgoing Seismic Wave Monitored at the Top of FLAC Model When the Center Drift Is Reinforced with 150 mm Thick Concrete or Shotcrete Liner (Ground Support Type II): (a) Under RMQ = 1; (b) Under RMQ = 3; (c) Under RMQ = 5.

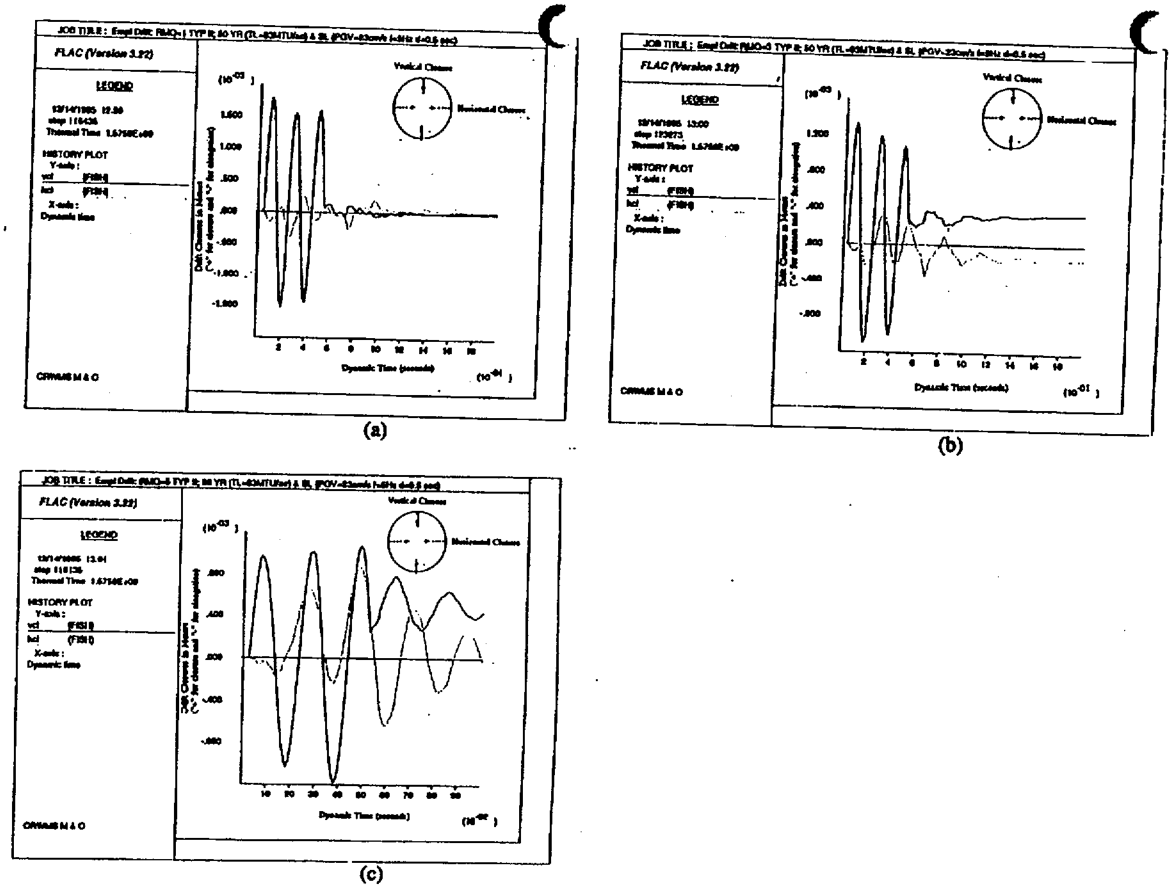
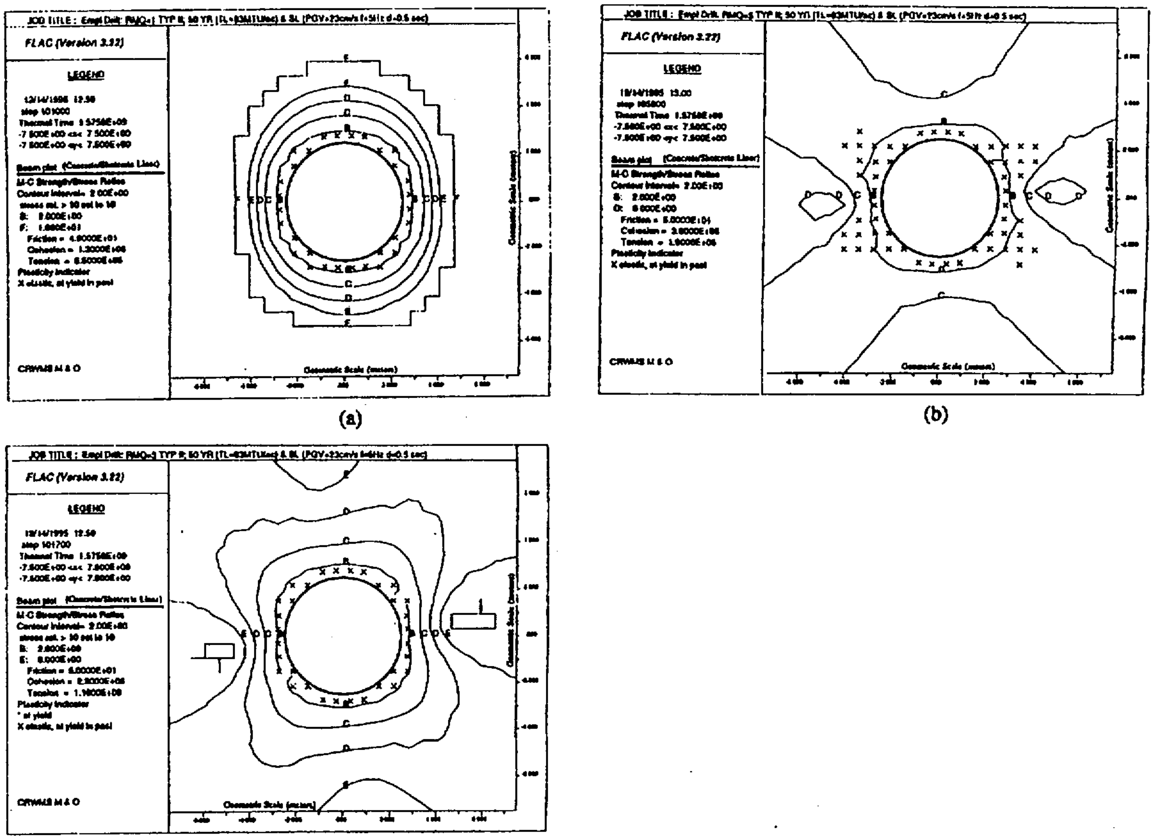


Figure B-22. Vertical and Horizontal Closures Caused during the Seismic Loading (PGV=23 cm/s, freq.=10 Hz) for the Center Drift with Ground Support Type II: Horizontal Axis Shows the Dynamic Time in Seconds and Vertical Axis Shows the Closure in Meters. (a) Under RMQ = 1; (b) Under RMQ = 3; (c) Under RMQ = 5.



(a) (b) (c)

Figure B-23. Safety Factor Contour Plots and Rock Mass Plasticity Location Indicators about the Center Drift under the Seismic Loading (PGV=23 cm/s, freq.=5 Hz) and with Ground Support Type II: (a) Under RMQ = 1; (b) Under RMQ = 3; (c) Under RMQ = 5.

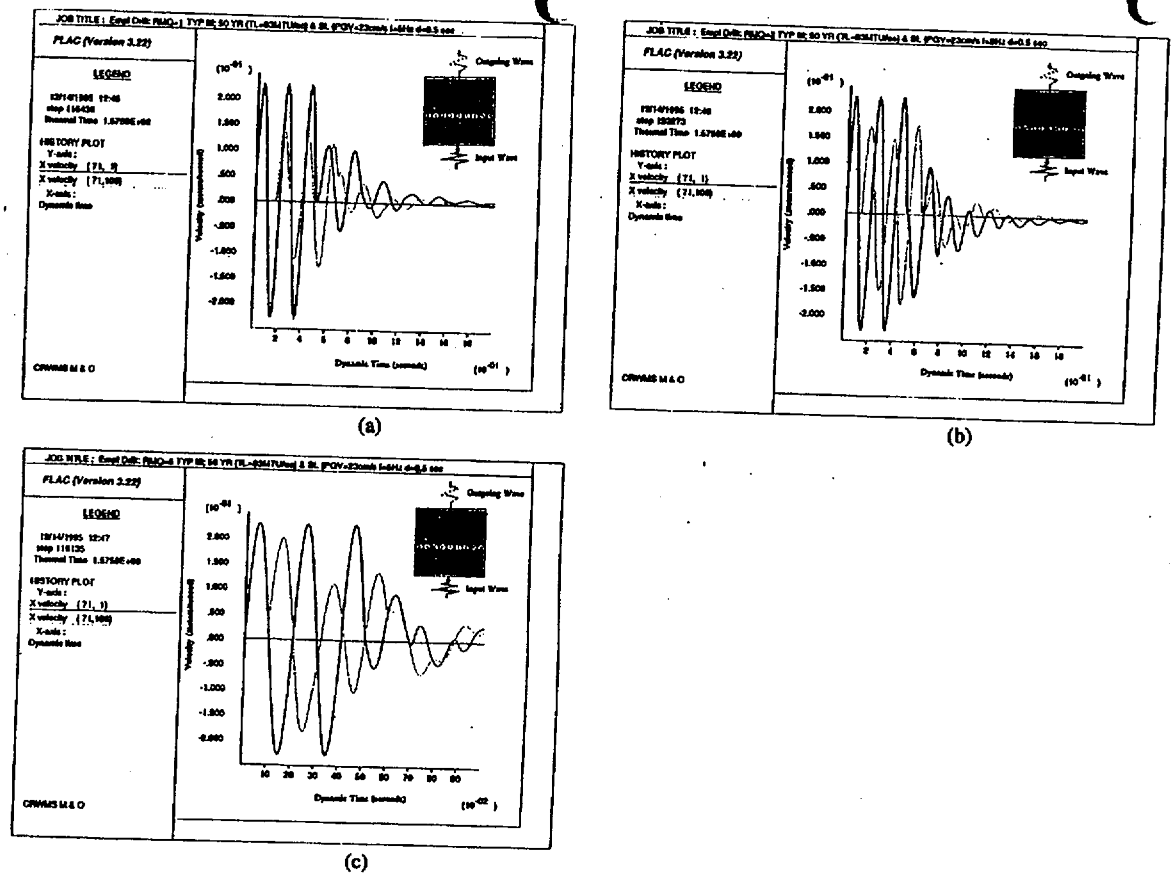
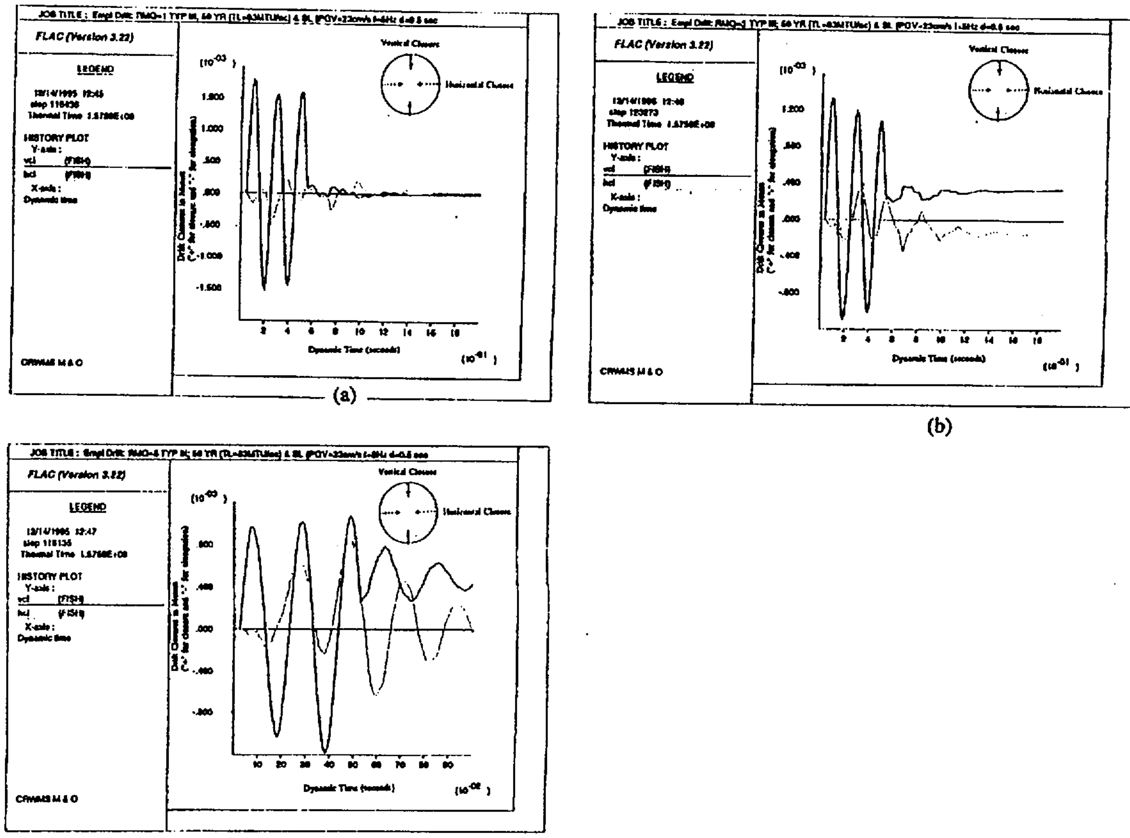


Figure B-24. Input Seismic Wave (PGV=23 cm/s, freq.=5 Hz) at the Base of FLAC Model and Outgoing Seismic Wave Monitored at the Top of FLAC Model When the Center Drift Is Reinforced with W5X19 Steel Sets on 1.2 m Spacing (Ground Support Type III): (a) Under RMQ = 1; (b) Under RMQ = 3; (c) Under RMQ = 5.



(a)

(b)

(c)

Figure B-25. Vertical and Horizontal Closures Caused during the Seismic Loading (PGV=23 cm/s, freq.=10 Hz) for the Center Drift with Ground Support Type III: Horizontal Axis Shows the Dynamic Time in Seconds and Vertical Axis Shows the Closure in Meters. (a) Under RMQ = 1; (b) Under RMQ = 3; (c) Under RMQ = 5.

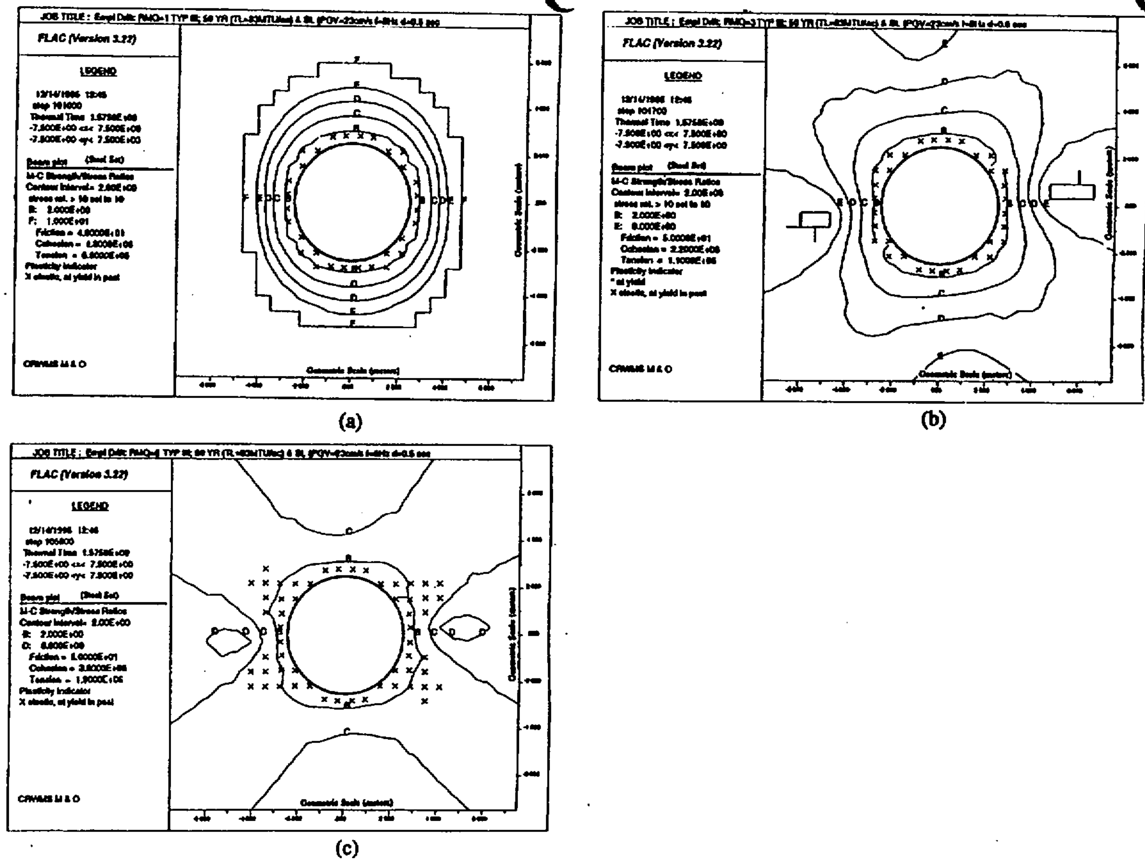


Figure B-26. Safety Factor Contour Plots and Rock Mass Plasticity Location Indicators about the Center Drift under the Seismic Loading (PGV=23 cm/s, freq.=5 Hz) and with Ground Support Type III: (a) Under RMQ = 1; (b) Under RMQ = 3; (c) Under RMQ = 5.

APPENDIX C

MATERIALS EVALUATION

CONTENTS

TABLES

MATERIALS EVALUATION

C.1 INTRODUCTION

Repository ground control design must ensure that the waste emplacement drifts are stable and accessible during the mandated 144-year retrievability period. The stability of subsurface openings is essential for shaft and ramp access, ventilation, emplacement, maintenance, monitoring, and materials handling. The performance of the ground support materials is directly affected by the waste emplacement environment. When studying this environment, the primary considerations are thermal, radiation, and biological factors.

Because organic materials are limited for use as ground support, the primary available materials are steel and concrete (items such as epoxy resin grout, timber blocking, and certain organic additives used in cementitious materials will be excluded from use). During their service life, the steel and concrete components will be exposed to elevated temperatures and radiation flux. Consequently, the effects these factors have on performance characteristics and component behavior must be examined. In addition to thermal and radiation effects, this study addresses concerns regarding the resistance of steel and concrete to bacterially mediated degradation.

The analysis of degradation factors is presented below, beginning with the potential uses of steel and an analysis of its tolerance to the thermal, radiation, and bacterial mechanisms to which it will be exposed. A similar discussion is then presented for concrete. The effect of bacterial degradation on steel and concrete is summarized in this document.

C.2 STEEL

Steel used for repository ground support may be present in various forms including:

- Structural steel sets (also referred to as ring beams and as arch supports)
- Rock bolts (including face plates)
- Welded-wire fabric and chain-link mesh
- Bar, fabric (welded wire), or fiber reinforcement in concrete and shotcrete
- Straps, channel, and lagging.

The following discussion evaluates the effects of temperature (including corrosion), radiation, and biological processes on steel.

C.2.1 Temperature Effects on Steel

Temperature can affect steel's strength, toughness and ductility, and thermal expansion. This section examines these effects and the potential for steel corrosion.

C.2.1.1 Strength

The yield point of structural steel (carbon or low-alloy) generally decreases linearly from its value at 20°C to about 80 percent of that value at 430°C, and to about 70 percent at 540°C (Merritt 1983). By interpolation, the value at 200°C is about 91 percent of that at 20°C. The modulus of elasticity of structural steel decreases from an initial value of 200 GPa at 20°C to about 172 GPa at 480°C, or 86 percent of the room-temperature value (Merritt 1983).

These results are similar to those reported by the American Institute of Steel Construction (AISC 1989). The AISC notes that the tensile strength of elevated-temperature carbon steel at 430°C is approximately 77 percent of room-temperature strength; at 540°C, tensile strength is 63 percent of room temperature strength. In contrast, a report on the elevated-temperature properties of ferritic steels (ASM 1990, p. 930) states that carbon steels are used extensively in pressure vessels up to about 370°C, and given the yield and ultimate strength of carbon steels at the maximum service temperature (370°C), they can be used essentially as they would for design of components at room temperature. Creep is not observed in these steels until temperatures are above 370°C.

Based on the above information, carbon steels at 200°C may experience modest, but insignificant, decreases in strength (about 10 percent) and deformability (about 15 percent) in comparison to these same parameters at 20°C.

C.2.1.2 Toughness and Ductility

Toughness is the ability of a metal to absorb energy and deform plastically before fracturing. A measure of toughness is notch toughness, which is measured (energy in Joules) by impact testing. Toughness decreases as the strength, hardness, and carbon content of steel are increased (ASM 1990, p. 737). At 200°C the notch toughness of a steel with 0.11-percent carbon is about six times that of a steel with 0.80-percent carbon. The 0.80-percent carbon steel exhibits the least ductility of the carbon steels and has the highest transition temperature from brittle to ductile behavior. For maximum toughness and ductility, the carbon content should be kept as low as possible, consistent with strength (ASM 1990, p. 737). The brittle-ductile transition temperature and the carbon content are the principal factors in determining the appropriate toughness and ductility for steel.

Steel set supports for Exploratory Studies Facility design typically have a carbon content of 0.07 percent (Kiewit/PB 1995) and are relatively tough and ductile, with a yield strength of 248 MPa. Rock bolt steel has a carbon content of 0.38 percent (Kiewit/PB 1995) and has moderate ductility and toughness, with a yield strength of about 483 MPa. If a more ductile rock bolt is desired to accommodate higher strain, steel with a lower carbon content may be preferred as an alternative to, for example, changes in fabrication. The trade-off would be a somewhat lower yield strength.

C.2.1.3 Thermal Expansion

Differences in thermal expansion between steel, concrete, and tuff can result in bonding failures between these components and cracking in the concrete materials. (See Appendix A, Section 5, of the *Repository Ground Control Evaluation* report (CRWMS M&O 1995a) for further discussion regarding concrete.)

Carbon steels have a coefficient of thermal expansion that varies from about 11.5 x 10^{-6}/°C at 20°C to 13.8 x 10^{-6}/°C at 200°C (ASM 1990, Figure 58, p. 652). The thermal expansion coefficient for tuff for near-field considerations is shown to vary from about 5 x 10^{-6}/°C at 25°C to 11 x 10^{-6}/°C at 250°C (SNL 1995). Table C-1 lists somewhat different values, ranging from 5.4 x 10^{-6}/°C to 17 x 10^{-6}/°C, for a similar temperature interval. These data show differences in expansion coefficients between tuff and steel of 7 x 10^{-6}/°C at 25°C, decreasing to about 3 x 10^{6}/°C at 200°C. In cases where steel expands at a greater rate than concrete, steel-to-concrete bonds may be broken and concrete cracking induced (for example, in grouted rock-bolt installations and in concrete reinforcing bars).

More severe conditions are indicated by test results reported in the report, *Thermal Goals Reevaluation* (CRWMS M&O 1993), which shows a tuff specimen reaching an expansion coefficient of approximately 12×10^{-6}/°C at 145°C and, after an abrupt increase, values between 25 and 32×10^{-6}/°C in the interval up to 200°C. An increase beyond 200°C gives a value of 53×10^{-6}/°C at 250°C. Additional testing is required to evaluate these results and, if applicable, to determine the limiting temperature at which an abrupt increase in expansion occurs.

Table C-1. Thermal Expansion Coefficient for TSw2 Thermal/Mechanical Unit

Temperature Range (°C)	Thermal Expansion Coefficient (10^{-6}/°C)
25 - 50	5.07
50 - 100	7.30
100 - 150	8.19
150 - 200	8.97
Source: SNL 1995 (average of means of tables 2-10, 2-11, and 2-12)	

C.2.1.4 Corrosion

Rock bolts or other iron-bearing components can corrode. When oxygen is present, rusting can occur. Rusting is an abiotic electrochemical process that requires a flow of electrical current for the chemical corrosion reaction to proceed. For electrochemical (galvanic) corrosion to occur, two dissimilar metals must come into electrical contact in the presence of moisture.

A separate cathodic metal is not required for steel corrosion to occur. An isolated steel bar can spontaneously rust if different areas of the bar develop active sites with different electrochemical potentials (different tendencies for oxidation), thus setting up anode-cathode pairs (or galvanic couples). Corrosion occurs in localized anodic areas. Local anodic and cathodic areas are caused by several conditions including different impurity levels in the steel, different amounts of residual strain, or different concentrations of oxygen or electrolyte in contact with the metal.

The findings of Karhnak (1984) demonstrate that steel corrosion in mines is often caused by the sulfuric acid generated by the oxidation of ore-bearing and pyritic sulfide phases. These sulfuric acid solutions are extremely corrosive to steel. The corrosion potential is enhanced if soluble copper is present in the acid solutions (as copper plates out on the steel), causing the dissolution of iron (for example, corroded train rails in underground copper mines). This type of aggressive corrosion will not occur in the waste emplacement drifts due to the absence of sulfide phases in the host formation. Moreover, it will be shown that production of bacterial sulfide is improbable (Section C.3.3).

C.2.1.4.1 Types of Corrosion

The two types of corrosion are uniform corrosion and pitting corrosion. Pitting corrosion can be further subdivided into three corrosion processes: galvanic, concentration, and crevice. These corrosion types are described below.

Uniform Corrosion occurs at a generally equal rate over the surface. The loss in weight is directly proportional to the time of exposure, and the rate of corrosion is constant. Uniform corrosion is usually associated with acids or waters having a very low pH, for example, the uniform rusting of mild steel in contact with neutral, low calcium, and low-alkalinity salt water.

Pitting Corrosion is non-uniform and more common than uniform corrosion. Pitting corrosion occurs in an environment which offers some, but not complete, protection. The pit develops at a localized anodic point on the surface and continues via a large cathodic area surrounding the anode. Chloride ions are particularly known for their association with this type of steel corrosion. Even stainless steel is subject to pitting corrosion with relatively concentrated chloride-bearing solutions. Pits may be sharp and deep or shallow and broad, and can occur without chlorides. In water that contains dissolved oxygen, the oxide-corrosion products are deposited over the site of the pitting action and form tubercles. Pitting corrosion is formed by three distinct processes:

- *Galvanic Corrosion* – Galvanic corrosion is associated with the contact of two different types of metals or alloys in the same environment. Almost all metals and substances have different solution potentials, whether in the same or in different environments. When two metals come together, the difference in potential results in current flow, and one of the metals becomes anodic and the other cathodic. The anodic metal corrodes and the cathodic metal does not (or if so, at a relatively low rate). The cathodic metal is "protected" at the expense of the anodic metal (for example, the protectiveness zinc metal affords to iron).

- *Concentration-Cell Corrosion* – The most prevalent corrosion, concentrated-cell corrosion, occurs when differences in acidity (pH), metal-ion concentrations, anion concentrations, or dissolved oxygen cause solution differences in the same metal. In water containing dissolved oxygen, the corrosion products are deposited at the anode, and in the subsequent hydrolysis of ferrous ion, hydrogen ions are formed. This greater acidity at the anode results in a hydrogen-ion concentration cell at this point and increases the corrosion rate. In the same instance, dissolved oxygen cannot diffusively penetrate to the anode surface because it first reacts with solubilized ferrous ion, resulting in an absence of oxygen at the anode. But oxygen can diffuse to the cathode area and result in an oxygen-concentration cell, also increasing the corrosion rate. Furthermore, hydroxyl ions accumulate at the cathode, drastically reducing the hydrogen ion concentration, which enhances the concentration cell related to the development of hydrogen ions at the anode.

- *Crevice Corrosion* – Crevice corrosion results when oxygen, because it is spent on corrosion in a crevice, does not diffuse into the crevice depths. The crack, crevice, or the uneven joint between two surfaces of the same metal that are bound together face-to-face behaves as a pit where oxygen can reach the exposed surface but is deficient in the crevice. An oxygen-concentration gradient is created that results in corrosion.

C.2.1.4.2 Corrosion Rates

Based on the theory of corrosion, mathematical models can be developed to predict material corrosion rates under given conditions. Tilman et al. (1989) developed a model that generally predicts the corrosion rate of rock bolts or Split Set® stabilizers in underground mines. To develop the model, non-galvanized (EX-TEN-H60 and KAI-WELL-55) and galvanized Split Set stabilizers were exposed to oxygenated and non-oxygenated mine waters (actual and synthetic) from seven mines. Based on the behavior of the stabilizers when exposed to these waters, corrosion rate equations were derived that quantify (1) the impact of variable dissolved oxygen, chloride, sulfate, and magnesium content on non-galvanized stabilizers and (2) the impact of dissolved oxygen content and temperature on galvanized stabilizers. The derived equations are shown below (corrosion rate reported in thousandths of an inch per year):

- EX-TEN-H60 Steel:
  Ln corrosion rate = 0.303 (O_2 Conc., ppm) - 0.0309 (Cl^- Conc., ppm) + 0.00187 (SO_4^{-2} Conc., ppm) - 0.0435 (Mg^{+2} Conc., ppm)

  R^2 = 0.96 [Linear regression coefficient of actual versus predicted corrosion rates.]

- KAI-WELL-55 Steel:
  Ln corrosion rate = 0.352 (O_2 Conc., ppm) - 0.0740 (Cl^- Conc., ppm) + 0.00202 (SO_4^{-2} Conc., ppm) - 0.0415 (Mg^{+2} Conc., ppm)

  R^2 = 0.96

- Galvanized Steel
  Ln corrosion rate = (Ln O_2 Conc., ppm) + 2.557 (Ln Temp., °F) - 11.333

  R^2 = 0.83

These equations show that non-galvanized steel in contact with a dilute, non-oxygenated water may result in only a slow rate of corrosion, less than 1 thousandth of an inch per year. Conversely, non-galvanized steel in contact with a well-oxygenated, briny solution could have a corrosion rate of 80 thousandths of an inch per year. At this accelerated rate, a 0.092-inch-thick Split Set stabilizer would be penetrated by corrosion in just over a year.

The mathematics of the individual equations can be qualitatively explained based on known geochemical principles:

- Corrosion can occur in the absence of oxygen, as the following chemical reactions demonstrate:
  Anode: $Fe = Fe^{+2} + 2e^-$
  Cathode: $2e^- + 2H_2O = H_2 + 2OH^-$

- When dissolved oxygen is present, the cathode reaction may be represented as:
  $2e^- + H_2O + \frac{1}{2}O_2 = 2OH^-$

  Therefore, with or without dissolved oxygen, the same amount of hydroxide ion is formed at the cathode, and alkaline conditions prevail.

- The effect of dissolved oxygen is reflected at the anode where the following side reaction occurs:
  $2\,Fe^{+2} + H_2O + \frac{1}{2}O_2 = 2Fe^{+3} + 2OH^-$

- Ferric hydroxide can now precipitate generating hydronium ion:
  $Fe^{+3} + 3H_2O = Fe(OH)_3 + 3H^+$

  The resulting acidity increases the solution rate of iron and maintains a high potential difference between the anode and cathode areas.

Under these conditions, the corrosion rate is limited by the supply (typically by diffusion) of dissolved oxygen to the anode corrosion product. The greater the rate of dissolved oxygen diffusion to the anode, the greater the rate of corrosion. This chemical fact is captured in the above equations for non-galvanized steel. The above equations assume a constant pH for the contacting solution and do not directly address acidic attack.

Ferric hydroxides deposited by corrosion can inhibit oxygen diffusion. Beneath the ferric oxide surface within water-filled pipes, anaerobic conditions can develop that, under certain circumstances, can support sulfate-reducing bacteria (SRB). In the absence of the water, oxygen can freely diffuse into this region and prevent SRB activity, as diffusion-based transport calculations will demonstrate. With an absence of water, the source of sulfate ion is also removed, thus suspending SRB activity. This issue is further discussed in Section C.3.3.

An analysis of the corrosion rate equation for galvanized metal shows that temperature changes far outweigh incremental changes in dissolved oxygen content. (Oxygen has a limited solubility in ambient temperature water, a solubility that decreases as temperature increases.) The temperature-dominated equation generally shows that the corrosion rate increases approximately two-fold with each temperature increase of 10°C, which is consistent with the van't Hoff relationship.

It should be noted that the steel composition of rock bolts for ground support of emplacement drifts has not yet been explicitly specified; therefore, the steel corrosion rates predicted by the mathematical models mentioned above are for reference purposes.

C.2.1.4.3 Corrosion Rate and Strength Loss

A corrosion-related strength decay curve can be derived from the tensile and yield strength data of Tilman et al. (1989). Both EX-TEN-H60 and KAI-WELL-55 steel have linear strength-versus-thickness relationships; therefore, loss of material by corrosion also translates into a linear loss in strength, as shown in Table C-2.

By estimating a corrosion rate, the annual strength loss and the residual strength at the end of any given year can be calculated. The above analysis assumes uniform corrosion and does not address isolated pit corrosion.

Table C-3 lists the temperature-dependent corrosion rates predicted for galvanized steel under oxygenated conditions (dissolved oxygen content of 7 ppm).

Table C-2. Relationship Between Corrosion Rate and Strength Loss for Non-Galvanized Steel

Corrosion Rate per Year (thousandths of an inch)	Strength Loss in EX-TEN-H60 Steel per Year (psi)	Residual Strength in EX-TEN-H60 Steel After One Year (psi)	Strength Loss in KAI-WELL-55 Steel per Year (psi)	Residual Strength in KAI-WELL-55 Steel After One Year (psi)
1	290	28,700	298	29,462
10	2,899	26,091	2,976	26,784
20	5,798	23,192	5,952	23,808
40	11,596	17,394	11,904	17,856
80	23,192	5,798	23,808	5,952

Table C-3. Temperature Dependence on the Corrosion Rate of Galvanized Steel Under Oxygenated Conditions

Temperature (°F)	Corrosion Rate per Year (thousandths of an inch)
50	2
100	11
150	31
200	64

The corrosion rate estimates stop at 200°F. Although the emplacement drifts will likely reach higher temperatures, the above relationship is predicated on the presence of liquid water that will not exist at temperatures greater than 212°F. Consequently, another corrosion mechanism will predominate at an unknown rate.

In summary, Tilman et al. (1989) found that (1) deoxygenated water is seven times less aggressive than oxygenated water to non-galvanized steel and (2) galvanized steel is much more resistant to corrosion, with comparatively low corrosion rates even at elevated temperatures. Galvanizing offers two advantages: up to 1/60th the corrosion rate of non-galvanized steel under similar conditions and greater resistance to pitting corrosion. Even when the galvanizing is marred (e.g., during rock bolt emplacement) it acts as a sacrificial anode and provides protection.

Stainless steel is resistant to corrosion over a wide range of water chemistry, exceeding the range even of galvanized bolts (Kaiser et al. 1990). This is particularly important for friction rock bolts. Because of their thin walled construction and large surface area, friction rock bolts are more susceptible to corrosion damage than conventional bolts. Additionally, austenitic stainless steels are more ductile than conventional carbon steels, providing both high strength and ductility. Kaiser et al. (1990) have advocated using stainless steel friction rock bolts to increase the useful life of rock support systems.

Kaiser et al. (1990) also found that in addition to acidic mine waters, elevated humidity and solubilized engine exhaust tend to increase the corrosion rates of carbon steel rock bolts. This is consistent with the understanding of water being a prerequisite for corrosion. Sulfur dioxide in the exhaust can cause accelerated pit corrosion. During their analysis of rock bolt longevity in Canadian underground mines, Kaiser et al. (1990) determined the life spans of forged-head mechanical rock bolts to be 18 to 240 months, averaging 68.7 months, while resin grouted bolts had lifespans of 18 to 60 months, averaging 38 months. Lifespans of Split Set and Swellex friction rock bolts ranged from 3 to 72 months and 3.5 to 120 months, respectively, with both averaging about 25 months.

Mechanisms to further prevent rock bolt corrosion include protectively coating the steel and suppressing the electrochemical process. An example of a protective steel coating is zinc galvanizing. Suppressing the electrochemical corrosion of steel involves cathodic protection. Zinc or cadmium bars are electrically connected to the steel, causing it to act as a cathode and prevent corrosion. High-strength structural steels can be alloyed with copper and other elements to produce high resistance to atmospheric deterioration. These steels develop a tight oxide that inhibits further atmospheric corrosion (Mindess and Young 1980).

Steel can also be protected from the corrosion caused by moisture and temperature changes by embedding it in shotcrete or concrete, as in the case of steel reinforcement bars. For worst-case moisture and temperature conditions, the ACI Building Code (ACI 1989) specifies a minimum concrete cover of about 75 mm for concrete "...cast against and permanently exposed to earth." The minimum cover specified for precast concrete is 38 mm. The ACI Building Code also states that denseness and nonporosity of protecting concrete shall be considered for corrosive environments or other severe exposure conditions. These standard code provisions are not intended to deal with the elevated temperature conditions or exposure durations in the repository environment; they are referenced as a starting point for further analysis beyond the scope of this evaluation.

Degradation of the grout surrounding the rock bolts will be limited because the expected temperatures are below those required to cause serious grout deterioration. (Section C.3.1 examines deterioration mechanisms when grout is exposed to elevated temperature.) The rock bolts will be protected from chloride-related corrosion (due to chloride ions in the grout) by appropriately limiting the use of chloride-based set accelerators. Rock bolt and steel set deterioration should also be limited by the protective coating of shotcrete or grout. Additionally, the dry conditions of the shotcrete or grout environment will limit bacterial activity (further discussed in Section C.2.3).

C.2.2 Radiation Effects on Steel

Radiation hazards from the waste packages will come from different radiation types including alpha-particles, beta-particles, and neutrons and photons (gamma- and x-rays) (CRWMS M&O 1994, Section 6). The primary radiation from the waste package is neutron and gamma because the alpha and beta radiation are stopped by the disposal container (CRWMS M&O 1995b). Neutrons and gamma radiation can produce ionization when they pass through materials because the energy of these particles can eject electrons from the elements they contact. Organic compounds, such as lubricants and electrical insulation, will suffer fragmentation that results in the formation of different material, and integrated circuits in computer systems can be damaged. Metals such as steel are less affected by such irradiation (ASM 1990). Generally, the only type of radiation emanating from the high-level waste packages that may affect steel is the neutron field. The remainder, namely beta, gamma, and alpha radiation, have no known significant effect upon the structural properties of steel.

Irradiation is described in terms of (1) the flux of neutrons striking the material, measured as the number of neutrons per square meter per second ($n/[m^2 \cdot s]$) and (2) the fluence, which is flux integrated over time or the number of neutrons per square meter (n/m^2). Based on a 100-year service life for the underground facilities, the neutron fluence for a waste package has been conservatively estimated to not exceed 2.2×10^{20} n/m^2 (CRWMS M&O 1995b). This value is about $3.2 \times 10^{20} n/m^2$ for a 144-year service life, which includes retrievability preparation time and closure operations (YMP 1994, Section 6.2).

Radiation effects from the waste packages are not expected to be a design concern for steel materials used in the emplacement drift, as reported in report title (CRWMS M&O 1995b):

> Irradiation effects on steels include swelling, hardening, and embrittlement. Swelling is not detectable at neutron fluences of less than 1×10^{26} n/m^2 even in austenitic steel (ASM 1990, p. 655, Figure 2), and ferritic steels, such as those expected to be used in the repository, are much more resistant to swelling (ASM 1990, p. 656, column 3). Increases in hardness, and thus strength, are not harmful. For a manganese-molybdenum low-alloy steel (ASTM A 302, grade B), measurable embrittlement occurs at neutron fluences as low as 1×10^{22} n/m^2. For fluences up to about 3×10^{22} n/m^2, the effect appears to be approximately proportional to the fluence. The increase in the ductile-brittle transition temperature, as measured by a 41 J Charpy V-notch impact test, is approximately 25×10^{-22} K·m^2 F, where F is the neutron fluence (ASM 1990, p. 659, Fig. 7). Because the neutron fluence over the service life of the underground facilities is less than 2.2×10^{20} n/m^2 (considering a 100-year service life), the expected increase in the ductile-brittle transition temperature is not more than 0.6 K (0.8 K for a 144-year service life).

In summary, the neutron radiation field expected from any single waste package is not expected to exceed 2.2×10^{20} n/m^2 for 100 years (or 2.2×10^{18} n/[m^2·yr]) based upon estimated values from bare fuel assemblies. This value is very conservative because in practice the radiation field would be expected to be several orders of magnitude lower due to shielding from the waste package walls, decay of radioactivity, and geometric divergence. Therefore, radiation effects are believed to be insignificant and not expected to degrade the steel properties.

C.2.3 Biological Effects on Steel

In aqueous, oxygen-free, reduced environments, the lifetime of steel and iron material is diminished by SRB. Although the deleterious effects of SRB have been demonstrated in both laboratory and natural settings, special conditions that do not exist at the Yucca Mountain repository are required for SRB to corrode steel. In addition to the anaerobic, aqueous environment, these conditions require the availability of sulfate, an electron acceptor, and a carbon source.

Steel biodegradation occurs when SRB consume hydrogen during sulfate reduction. Iron immersed in water releases Fe^{++}-cations, and the metal surface becomes negatively charged by the remaining electrons. The dissolving process continues only if the electrons are removed, for example by an oxidizing agent. Under aerobic conditions, oxygen acts as an electron acceptor and rust is formed. Under anaerobic conditions, the electrons left on the metal surface reduce protons, from the dissociation of water, to hydrogen, which forms a protective layer over the submerged iron surface. SRB oxidize the elemental hydrogen with sulfate as the electron acceptor. Removal of the hydrogen protons by SRB disrupts the natural equilibrium and causes cathodic depolarization of the iron surface (Cord-Ruwisch and Widdel 1986). The presence of liquid-phase water is critical to this process. Elevated temperatures in the emplacement drifts will ultimately eliminate liquid water. Concrete will be formulated with a sufficiently low water-to-cement ratio to prevent free water in the pore spaces.

In the laboratory setting, *Desulfovibrio* (a hydrogenase-positive SRB) did not break down steel and produce sulfide unless a favorable organic energy source, such as lactate, was present. Experimental results indicate that the availability of organic electron donors may be an important factor influencing the removal of cathodic hydrogen from iron surfaces; and anoxic aqueous environments that are rich in anaerobically degradable organic matter should be more corrosive than environments that are mainly inorganic. In the natural environment, biodegradation of steel has been demonstrated in off-shore oil pipes, sewage pipes, and oil tanks (Cord-Ruwisch and Widdel 1986) which meet the above bacterial requirements. These requirements are absent within the waste emplacement drifts, thus eliminating SRB activity.

SRB may penetrate the concrete and come into contact with the steel. The presence of oxygen, excessively high temperatures, and inadequate sources of sulfate and carbon create an environment hostile to SRB. In the absence of the specialized environment required for SRB metabolism, corrosion of steel by SRB is expected to be limited.

C.3 CONCRETE

Concrete for ground support may be used in the following forms:

- Shotcrete – Full-circle structural lining, 100 to 150 mm thick; or to secure fractured rock, less than 100 mm.

- Concrete lining – Pre-cast segments, cast-in-place, with or without reinforcement such as steel bars, mesh, or fibers.

- Grout – typically to encapsulate and secure rock bolts, but also to consolidate and strengthen the rock mass.

Additionally, concrete may be used for invert fill and waste package pedestals. Both of these applications and most of those listed above were considered in the materials review documented in Appendix A, Concrete Stability at Elevated Temperatures, of *Repository Ground Control Evaluation* (CRWMS M&O 1995a). Conclusions from this literature review are summarized below.

Ground control measures typically emphasize rigid confinement of the supported rocks. Previous thermomechanical modeling results have suggested that a ground support that provides light to moderate confinement, yet still prevents rock loosening and fallouts, may be preferable. Rather than design to resist a thermally induced stress, ground support components can be fabricated for ductility and structural flexibility. An example of this type of component is fiber-reinforced concrete (described below). The relatively low tensile strength of concrete is well known. In fact, tensile stresses are expected to be carried entirely by the steel reinforcing bars (Mindess and Young 1980).

One development that improves the tensile strength of concrete is the use of fiber-reinforcing additives. Mindess and Young (1980) define fiber-reinforced concrete as concrete made from Portland cement which incorporates discrete fibers. Fibers suitable for reinforcing concrete include steel, organic polymers, ceramics, and asbestos. These fibers differ in both performance characteristics and costs and are briefly described below.

- Steel fibers may be produced either by cutting wire, shearing sheets, or from a hot-melt extract; they may be smooth or deformed in a variety of ways to improve the bond. Steel fibers will rust at the concrete surface but appear to be very durable within the concrete mass.

- Using iron as an admixture to function as either a fiber reinforcement or as an agent to increase grout density is in contrast with using iron filings as a grout expanding agent, which is not being proposed.

- Glass fibers are generally available as "chopped strand," where each strand may consist of 100 to 4,000 separate filaments. Ordinary glass is not suitable for use because the highly alkaline environment will attack and rapidly reduce the fiber strength. Glass fibers are manufactured with significant amounts of ZrO_2 which is highly alkali resistant.

- Naturally occurring asbestos fibers have long been used with cement and water to manufacture pipe and other building components. However, there are significant health hazards associated with the production and handling of asbestos fiber.

- Most polymeric fibers, such as nylon and polypropylene, have lower elastic moduli than concrete. Therefore, these fibers cannot increase the strength of the composite material and may reduce the strength. They are effective in increasing the impact and shatter resistance of the concrete.

- Kevlar, which is an aromatic polyamide, has both a high tensile strength and a high modulus of elasticity and shows considerable promise as a reinforcement media, but is very expensive.

- Carbon fibers also have a very high elastic modulus, tensile strength, and cost. Like organic fibers, they are not attacked chemically by the cement.

- Natural organic fibers, such as sisal and jute, are cellulosic compounds and may not be suitable for use. They have low tensile strengths and elastic moduli and tend to deteriorate in damp or alkaline environments. Additionally, their ability to potentially support bacterial activity prevents their usage.

- Typical properties of these fibers are shown in Table C-4.

The direct tensile strength of concrete can be increased considerably by the addition of appropriate fibers. The increase is dependent on the aspect ratio of the fibers. The effects on flexural strength are less clear. Some investigators (Mindess and Young 1980) have found both an increase in the first crack strength and in the ultimate strength, the latter being up to three times the strength of plain concrete. A real advantage of fiber-reinforced concrete is that a certain amount of flexural strength can be relied upon, even after some cracking of the matrix occurs.

A limitation of the information database is the behavior of fiber-reinforced concrete under elevated temperatures and radiation flux. Arguably, little impact may be measured for a steel-reinforced concrete. The behavior of other materials, including organic-based compounds, may be less resilient under the high temperature and radiation environment of the waste emplacement drifts, as discussed below.

Table C-4. Typical Properties of Fibers and Cement Matrix

Fiber	Diameter (Thousandths of an inch)	Specific Gravity	Modulus of Elasticity (GPa)	Tensile Strength (GPA)	Elongation at Break (%)
Asbestos	0.02 - 20	2.55	165	3 - 4.5	2 - 3
Glass	9 - 15	2.60	70 - 80	2 - 4	2 - 3.5
Graphite	8 - 9	1.90	240 - 415	1.5 - 2.6	0.5 - 1.0
Steel	5 - 500	7.84	200	0.5 - 2.0	0.5 - 3.5
Poly-propylene	20 - 200	0.91	5 - 77	0.5 - 0.75	20
Kevlar	10	1.45	65 - 133	3.6	2.1 - 4.0
Sisal	10 - 50	1.50	—	0.8	3.0
Cement matrix	—	2.50	10 - 45	$3 - 7 \times 10^{-3}$	0.02

C.3.1 Temperature Effects on Concrete

The review of temperature effects on concrete in Appendix A of *Repository Ground Control Evaluation* (CRWMS M&O 1995a) found that:

> At temperatures below 300°C, Portland cement does not lose enough strength (unconfined compressive strength) to necessitate the substitution of a more thermally resistant material. Consequently, Portland cement-based concrete with "standard" aggregate should be adequate for all concrete used for ground support.

The *Repository Ground Control Evaluation* (CRWMS M&O 1995a) also reported that strength loss of concrete at temperatures below 300°C is only about 10 to 15 percent. This lower strength level is expected for the repository preclosure lifetime if the concrete is shown to be durable during the initial months after exposure to elevated temperatures. The finding that concrete degradation occurs within the first few months following waste disposal (or at least after significant temperature rise) suggests that a testing program to determine concrete performance could be carried out relatively early in the program.

In regard to blast cooling of emplacement drifts, a cycle of heating and cooling (from about 200°C to 50°C in a matter of hours) is expected to result in a maximum strength loss of about 25 percent, indicating that (even though the results are conservative for repository conditions) repeated cycles of cooling and heating should be avoided.

If it is necessary or desirable to increase the strength and durability of concrete beyond the level currently estimated to be acceptable for repository emplacement drifts, the following approaches can be considered:

- Using a low water-to-cement ratio
- Adding reactive silica (for example, silica fume or rice hull ash)
- Using organic water-reducing admixtures
- Using high-alumina cement (for temperatures exceeding 300°C).

A Portland cement/fly ash waste-disposal form has been developed for low-level radioactive materials. This product has mechanical, thermal, and radiation stability and relatively low actinide and fission leachability (CRWMS M&O 1995a, Appendix A, Section 3.6).

C.3.2 Radiation Effects on Concrete

Although the exposure of concrete to elevated gamma and neutron fluxes can lead to measurable deterioration, numerous studies have defined the radiation exposure limits of concrete that do not result in significant loss in, for example, compressive strength. These limits are below the reasonably predicted radiation exposures for concrete within the waste emplacement drifts during the retrieval period.

Nuclear radiation can result in lattice defects within crystalline material, causing an increase in brittleness. Formation of additional cross linking can also lead to embrittlement in polymers. Ionized radiation may cause the loss of free or bonded water decreasing the hydraulic bonding strength. Finally, radiation may lead to the breakdown of atomic bonds. Attenuation of the radiation by the material often causes its internal temperature to increase. As previously discussed and as documented within the studies cited below, elevated temperature caused by radiative heating may be an important mechanism causing a loss in concrete strength, perhaps the predominant strength-loss mechanism.

Granata and Montagnini (1972) showed that Portland cement-based concrete with a limestone aggregate was resistant to integrated neutron fluxes of the order of 10^{19} n * cm^{-2}. These specimens displayed limited loss in compressive strength after exposure and concomitant heating to 125°C. Samples that were exposed to an integrated neutron flux of 10^{20} n * cm^{-2} were essentially destroyed.

Elleuch et al. (1972) also measured the effects of neutron flux on the properties of high-alumina cement-based concretes. They subjected serpentine aggregate-bearing concretes to integrated irradiation fluxes (or fluence) of 2×10^{19} to 20^{20} n * cm^{2} at energies above 1 Mev and at temperatures on the order of 200°C. Compressive strengths were shown to be the same or only slightly diminished relative to those that experienced only thermal cycling in the absence of irradiation. Although not directly a part of their study, these researchers also simultaneously exposed the same concrete specimens to a gamma flux exceeding 1 x 10^{11} rads, resulting in no measured deterioration of compressive strengths.

Hilsdorf et al. (1976) summarized the results of several gamma and neutron irradiation concrete exposure studies and concluded that most concretes are resistant to deterioration by neutron fluxes of less than 10^{19} n * cm^{2}. They report that Houben (1969) recommends the following maximum irradiation fluxes for prestressed-concrete reactor vessels for a 30-year life:

- Thermal neutrons: 6 x 10^{19} n * cm^{-2}
- Fast neutrons: 2 to 3 x 10^{18} n *cm^{-2}
- Gamma radiation: 1 x 10^{11} rads.

Importantly, Hilsdorf et al. (1976) document that various aggregates that enhance the shielding capacity of concrete (to protect workers) also enhance the concrete's resistance to radiation mediated deterioration. Aggregates used in concrete are selected to attenuate either gamma or neutron radiation. Increasing the density of a concrete of a given thickness increases the attenuation of gamma radiation. Consequently, dense (or high specific-gravity) aggregates are selected. High specific-gravity aggregates that may be used include barite, magnetite, ilmenite, hematite, ferrophosphorus, ferrosilicon, and iron or steel shot or punchings. Use of these materials is not without operational considerations. For example, the difference in the density between these materials and the rest of the concrete can lead to segregation upon placement. Ferrophosphorus also tends to generate hydrogen gas upon reaction with the Portland cement, an issue that would have to be addressed during design and operations.

Neutrons are attenuated by hydrogen-bearing compounds. Water is an effective attenuating component of neutrons; however, concrete frequently does not contain sufficient water to result in neutron capture. Consequently, appropriate aggregates are needed. Neutron-attenuating aggregates that contain hydroxyl groups to aid in neutron capture include limonite, goethite, bauxite, and serpentine. When hydrogen absorbs thermal neutrons, high-energy gamma radiation is released, which also must be attenuated. Boron is an effective absorber of neutrons and also results in the production of relatively lower energy gamma rays. Thus, various boron-containing compounds may be used to develop neutron-shielding concrete. These boron-containing forms include boron glass, borocalcite, colemenite, ferroboron, boron carbide, and boron frit. Water-soluble boron compounds can act as a strong set inhibitor to cementitious reactions, a problem that would have to be addressed (for example, by using a set accelerator). Descriptions of radiation-shielding aggregates and their standard specifications are presented in ASTM C638-84 and C637-84, respectively.

Gamma radiation field strength at concrete surfaces within the waste emplacement drifts is conservatively estimated at 10 (R/hr) (rems per hour) from a typical package. Based on an integrated exposure over 144 years (YMP 1994, Section 6.2) and assuming no decay, this results in an integrated exposure of 1.23×10^{7} R at the concrete surface. This exposure is four orders of magnitude below an approximate threshold of 1 x 10^{11} R, above which, the measurable degradation of concrete is predicted.

Radiolysis can occur upon elevated exposure of water to gamma radiation. Elleuch et al. (1972) measured 6,362 cm^3 of gas per kilogram of irradiated concrete. Hilsdorf et al. (1976) report that the gas evolved from irradiated concrete consists of hydrogen, oxygen, nitrogen, carbon monoxide, and carbon dioxide. They report that this gas development has minimal effect on concrete properties.

This discussion has emphasized that sulfate-reducing bacteria are obligate anaerobes and that free oxygen is lethal to their existence. The findings of Cember (1983) document that the production of free radicals and oxygen (and oxygenated) compounds due to gamma radiation may impede this type of bacterial development. This is in addition to the potentially lethal irradiated environment of the waste emplacement.

When pure water is irradiated the following reaction occurs:

$H_2O = H_2O^+ + e^-$, with the positive ion immediately dissociating according to the equation:

$H_2O^+ = H^+ + OH$, while the electron is picked up by a neutral water molecule:

$H_2O + e^- = H_2O^-$, which dissociates immediately by the following reaction:

$H_2O^- = H + OH^-$

The free radicals H and OH may combine with like radicals, or they may react with other molecules in solution. For example, the OH free radicals may combine together to form hydrogen peroxide:

$OH + OH = H_2O_2$

Whereas the above reactions produce free radicals with half lives on the order of a microsecond, hydrogen peroxide, being a relatively stable compound, persists long enough to diffuse to points remote from its point of origin. The hydrogen peroxide, which is a powerful oxidizing agent, can thus affect molecules or cells that did not suffer direct radiation damage. If the irradiated water contains dissolved oxygen, the free hydrogen radical may combine with oxygen to form the hydroperoxyl radical, $H + O_2 = HO_2$, which is not as reactive, and therefore has a longer lifetime, than the free OH radical. This greater stability allows the hydroperoxyl radical to combine with a free hydrogen radical to form hydrogen peroxide, thereby further enhancing the toxicity of the radiation. The dissociation of hydrogen peroxide by the reaction, $2H_2O_2 = 2H_2O + O_2$, results in a strongly oxygenated solution lethal to SRB.

C.3.3 Biological Effects on Concrete

A concern has been expressed regarding the potential for bacterially mediated attack of sulfuric acid on the concrete components used for ground support. The basis for this concern seems to stem from the attack by sulfuric acid on a concrete cooling tower located in a New Zealand geothermal field. Sulfuric acid is generated from the bacterially mediated oxidation of reduced sulfur species, presumably primarily hydrogen sulfide gas. Hydrogen sulfide gas may be derived from the geothermal brines. Sulfuric acid corrosion of concrete components is also well established in the crowns of concrete sewer tile. Bacterially produced hydrogen sulfide gas emanating from the stagnant sewage collects in the moisture along the crown of the tile. There the hydrogen sulfide gas is oxidized to sulfate ion along with the production of acid. Severe corrosion of the concrete can result in this situation.

The predominant dissolved phase of sulfide ion will depend on the pH condition of the aqueous solvent. At pH conditions less than about 7, hydrogen sulfide (H_2S) will be the predominate dissolved form of sulfide ion. At pH conditions from 7 to 14, bisulfide ion (HS^-) will be the predominant dissolved sulfide phase. However, *hydrogen sulfide*, as used in this text, will denote total sulfide concentration (or thermodynamic activity of sulfide ion), partially for readability of this text but also because the specific pH conditions that may exist at any given moment or location are uncertain.

Eglinton (1987) emphasizes that oxygen must be deleted to promote sulfuric acid chemical deterioration of concrete. Loss of oxygen is required for the initiation of bacterial sulfate reduction. Even within the organic-enriched sewer environment, diffusion of atmospheric oxygen can prevent the production of bacterially mediated hydrogen sulfide, preventing potential sulfuric acid damage to the concrete.

Attack of concrete by sulfuric acid is only documented in cases where anaerobic sewer conditions prevail or where concrete is in direct contact with sulfidic soils or rock (Mindess and Young 1980; Eglinton 1987). The literature does not describe any cases where concrete is attacked by oxidized hydrogen sulfide in the absence of organic wastes, extrinsic hydrogen sulfide, or pre-existing sulfide minerals.

Literature describing bacterial degradation beyond that within stagnant sewers is lacking, which suggests that bacterially mediated deterioration of concrete is isolated. Concrete is often exposed to warm, organic-rich conditions. In spite of these favorable conditions, measurable bacterial degradation is not recognized. Under certain inorganic chemical conditions, organic acids can cause concrete deterioration. However, Portland cement-based concrete is also often resistant to attack by various organic acids. For example, Eglinton (1987) reports that Portland-cement concrete tanks have a reasonable life when used to store fermentation products that contain butyric, lactic, and acetic acids (among others). These acids are present in fodder silage, and the precast concrete staves used in the construction of the silos are generally made with ordinary Portland cement. Similarly, tanks made with ordinary Portland- cement concretes are used to distill residues containing lactic, acetic, and other acids. Presumably, bacterial activity should be maximized in these warm, organic-rich conditions, yet no reports of serious bacterially mediated attacks are documented.

Portland-cement concrete is also successfully used in manure trenches, such as those in barns, without bacterially mediated deterioration. The absence of severe bacterial attack under these warm, wet, organic-rich conditions further argues that bacterial deterioration of concrete is not a widespread process nor is it inevitable.

The potential for sulfuric acid attack of concrete can be evaluated by examining plausible sulfur cycles and assessing the applicability to the waste repository. The following analysis will show that sulfuric acid attack is very unlikely to occur because (1) the conditions at the site are not conducive to hydrogen sulfide production and (2) empirical evidence demonstrates that hydrogen sulfide production does not occur within saturated concrete.

The sulfuric acid attack discussed herein is differentiated from the more typical sulfate deterioration that may occur when Portland cement-based products encounter unacceptably elevated sulfate concentrations. The distinguishing factor between these two degradation mechanisms is that sulfuric-acid attack, in addition to potentially resulting in sulfate deterioration of the concrete, is characterized by acid dissolution of the cementitious calcium silicates, aluminate, and ferrite phases. Expansive ettringite attack may also simultaneously occur with the sulfuric acid dissolution of the concrete. Expansive ettringite attack can also occur under neutral or even alkaline conditions. Ettringite attack can be mitigated by using the appropriate type of sulfate-resistant Portland cement and a low water-to-cement ratio in the concrete formulation.

Sulfuric acid attack requires the presence of a reduced sulfur phase (having a valance less than S^{+6}), for example, hydrogen sulfide. Hydrogen sulfide can be abiotically or biotically produced. Abiotic production requires elevated temperatures, such as in geothermal systems. Elevated temperatures are required for abiotic reduction of sulfate ion to the sulfide form, due to the kinetic inhibition of sulfate ion from participating in the oxidation/reduction reaction at temperatures below about 250°C (a temperature above the maximum predicted for the waste emplacement drifts). Production of sulfide ion from a sulfate source requires bacterial production at temperatures less than 250°C due to the kinetic limitation of sulfate ion. Because most bacteria are rendered inactive at temperature above about 80°C and are killed above 121°C, limited sulfide production occurs within the temperature range of about 80°C to 250°C.

Because biotic sulfide production requires anaerobic conditions, oxygen that is present must be eliminated by rapid metabolic activity or limiting its transport or both. Rapid metabolic activity uses substantial amounts of readily metabolizable organic carbon or carbon dioxide and other required nutrients. Transport of oxygen in the subsurface (for example, through sediment or rock) is inhibited by saturated water conditions. Oxygen diffusion is slowed by a factor of 10,000 times by saturated or even near-saturated conditions in the subsurface relative to its diffusion in the atmosphere due to the formation of water-filled pore connections. Consequently, it follows that bacterial sulfide production is maximized in high-organic, saturated environments. A further requirement is a large or renewable sulfate reservoir. Without a large or renewable sulfate reservoir, sulfide production slows and ultimately ceases as the sulfate ion is consumed.

The conditions that promote sulfide-ion production were examined to assess the likelihood that sulfuric acid will be generated in the waste emplacement drifts. The waste emplacement drifts and surrounding area are not saturated. Additionally, organic carbon concentrations are low or nonexistent, depriving SRB of its necessary carbon source. Because the fundamental requirements for bacterially mediated sulfide production do not exist in the host formation, it is extremely unlikely that sulfur-metabolizing bacteria will colonize the area. Consequently, only the potential for sulfide generation within the waste emplacement drifts must be evaluated.

The waste emplacement drifts lack significant metabolizable organic carbon. Organic carbon-based components are specifically limited in use to minimize this potential. Additionally, minimal water is anticipated within the waste emplacement drifts, which will prevent large volumes of saturated material from developing.

Assuming that saturated conditions do develop within a concrete invert, empirical evidence suggests that hydrogen sulfide is still unlikely to form. Portland cement does contain a small amount of sulfate; gypsum is added to the components during the manufacturing process to regulate the cement's setting characteristics. However, despite the presence of sulfate ion and possible saturated conditions in the concrete, intrinsic hydrogen sulfide production is unknown in concrete. This is the case even for submerged concrete. Oxidized conditions are maintained in concrete, even under saturated conditions, because sulfidization or corrosion of reinforcement steel does not occur. This reinforcement steel commonly retains an oxide coating when encased within the concrete, documenting both oxidizing conditions and the absence of hydrogen sulfide (or a dissolved sulfide ion form) which would quickly react with the ferric oxide to form a iron sulfide phase (such as mackinawite or greigite and ultimately transforming into pyrite) (Berner 1972).

An intrinsic sulfide source in the concrete will be prevented by limiting the sulfide content of the aggregate used in the formulation of the concrete, a standard industry practice (Eglinton 1987).

To combat the effect of bacteria on concrete, numerous bacteriocidal admixtures have been developed (Ramachandran 1984). Materials that are the most effective in imparting bacteriocidal properties include polyhalogenated phenols, sodium benzoate, benzalkonium chloride, and copper compounds. Addition rates range from 0.75 to 10 percent, by weight, of cement. An elevated concentration of copper is required to kill SRB because hydrogen sulfide precipitates otherwise toxic soluble copper as insoluble and less-toxic copper sulfides. Ramachandran (1984) reports that these compounds result in the destruction of microorganisms both on the concrete surface and within the matrix. The admixture's effectiveness is dependent on the method of incorporation into the mix. For example, polyhalogenated phenols should be incorporated into the cement prior to blending into the concrete mixture to ensure long-term effectiveness. Use of phenol-based compounds do not adversely impact the strength development of the concrete (Ramachandran 1984).

The primary method of preventing bacterial attack by sulfide oxidation is to prevent the initial bacterial production of hydrogen sulfide, which is best accomplished by continuously maintaining oxidizing conditions within the drift. This process will be facilitated by preventing readily metabolizable organic materials from depositing in the drift and minimizing the development of free-standing water. These preventive activities are planned and will produce reducing conditions. The development of free radicals by radiolysis and the subsequent production of hydrogen peroxide will also limit the development of anaerobic conditions. Bacterial sulfate reduction is not observed to occur in or on concrete in the absence of elevated concentrations of organic matter. Even with elevated organic and carbon concentrations (for example, manure trenches), sulfate reduction may not occur on or within concrete.

If a large amount of Portland cement-based concrete is used in the waste emplacement drifts, the drifts' geochemical and biogeochemical conditions will be impacted. Not only should the potential effect of various bacteria on the concrete be assessed, but also the effect the concrete has on the bacteria that may attempt to inhabit the concrete surface or matrix. Because certain bacteria are sensitive to their environment's pH conditions, the pH-controlling processes that develop within Portland cement-based concrete should be examined.

The hydration of Portland cement results in the sustained production of calcium hydroxide that is available for reaction with pozzolanic materials (Mindess and Young 1980; Popovics 1992). This reaction develops a three-dimensional cementitious framework which gives Portland cement-based concretes their strength. Unreacted calcium hydroxide typically remains in the Portland cement-based concretes. Calcium hydroxide and other alkaline components, including sodium and potassium hydroxides and the aluminosilicates, contribute to Portland cement's residual alkalinity. Portland cement may contain up to 0.5-percent, by weight, free lime in the form of nonchemically combined calcium hydroxide (although this level is not specifically constrained by an ASTM specification) (Mindess and Young 1980). Solutions with weak buffering capacity or that lack extreme acidity and initially come into contact with previously unleached concrete often develop a pH of about 12. High solubility of calcium hydroxide in aqueous solutions also contributes a high ionic strength to the contacting solution. These conditions are not conducive to the growth of certain bacteria.

Although, under certain extreme conditions, bacteria can survive on or perhaps within concrete, a major modification resulting in an acceptable microenvironment is necessary. This modification typically requires the presence of an external source of gaseous hydrogen sulfide or the presence of anomalous amounts of organic carbon, neither of which have been shown to be probable. This fact further argues that deleterious bacterial activity on or within the concrete is unlikely.

Although presently not proposed, various inorganic oxidants are available as admixtures to increase the oxidation capacity of the concrete and to prevent locally reducing conditions from developing. These oxidants would augment the hydrogen peroxide and free radicals produced by radiolysis and the oxidizing capacity of atmospheric oxygen.

The use of strong oxidants or the production of free radicals or hydrogen peroxide would not cause the concrete or reinforcing steel to deteriorate (Elleuch et al. 1972). Concrete is composed of non-electroactive components, with the exception of iron which has a protective oxide coating that is already in its thermodynamically stable oxidized form. The ferric oxide is stable in the presence of hydrogen peroxide and, consequently, would not react with this compound.

As noted earlier, sulfate reduction can develop, under certain conditions, under a ferric hydroxide coating in a water-filled pipe. Using Fick's Law of Diffusion equation-based calculations, boundary conditions for sulfate reduction under a ferric hydroxide mass can be established for a ferric hydroxide coating exposed to the atmosphere under a thin water film. These calculations can quantify the limits of oxygen diffusion and the minimum hydrogen-sulfide production rate. From this information, the bacterial metabolic rate and the associated requirements can be defined.

Because SRB are obligate anaerobes, the complete oxygen consumption by reaction with hydrogen sulfide is required to protect the bacteria. Since oxygen transport is limited by diffusion through a ferric hydroxide layer, a one-dimensional diffusion limited transport model can be used.

From Fick's First Law of Diffusion:

$$J = K\, \partial C/\partial x$$

Where:
- J = Flux Rate of Diffused Oxygen (In terms of unit mass per unit area per unit time)
- K = Effective Diffusion Coefficient (assumed to 1×10^{-6} cm^2/s)
- ∂C = Change in Concentration of Oxygen (Diffusion Gradient, assumed to be 7 ppm, the solubility of O_2 in 25 °C water)
- ∂x = Distance of Diffusion (assumed to be 0.3 cm)

Assuming a 1-cm^2 area of ferric hydroxide:

$$J = 1 \times 10^{-6}\ [7 \mu g/cm^3/0.3\ cm]$$
$$J = 2.33 \times 10^{-5}\ \mu g/cm^2/s \text{ or } 2.33 \times 10^{-11}\ g/cm^2/s$$

which translates into 1.46×10^{-12} moles O_2/cm^2/s. Consequently, bacteria must produce at least this rate of hydrogen sulfide to survive. This oxygen diffusion rate through the ferric hydroxide layer is very high, in fact, it is too high to allow the sustained activity of obligate anaerobes, to whom oxygen is poisonous. The production of hydrogen sulfide in nearshore marine sediments, which represent an ideal environment with very high organic content and an abundant sulfate supply, has been measured at 1.8×10^{-14} moles S/cm^3/s (Berner 1972), or two orders of magnitude below that required in the above scenario (assuming a thin sulfate reduction zone) to sustain anaerobic life. The absence of either sulfate or organic carbon within the ferric hydroxide coating would prevent such an accelerated hydrogen-sulfide production rate (as measured in the nearshore marine sediments) from being established or maintained. Even in the unusual event that such a rate could develop, it would be two orders of magnitude too slow to quantitatively consume the available oxygen, thus killing the anaerobes.

In summary, the waste emplacement drifts will ultimately be a hostile environment for sulfate reducing, anaerobic bacteria. Radiation will develop immediately after waste emplacement, followed by lethal heating of the drift. The combined radiation and heat will pose lethal challenges to all bacteria. The heat will dry the drifts, eliminating a water source for the bacteria. Even the most thermophilic bacteria cannot withstand 160°C temperatures. Temperatures exceeding 80°C will develop in the drifts within nominally 25 years after waste emplacement, preventing any bacterial activity for the remainder of the waste retrieval period. Autoclaving, a method of sterilizing laboratory and hospital equipment by super heating it to 121°C for 15 minutes, eliminates bacteria regardless of their metabolic state (Rechart, R., Ph.D., personal communication with Laura Jantz, Morrison-Knudsen, 9 November 1995). Consequently, even in an improbable worst-case condition, bacterial degradation can only occur for a short time immediately after waste emplacement.

C.3.4 Potential Longevity of Concrete

Past research indicates that the waste emplacement drifts will be very hot and radioactive. Recent research has also demonstrated that the predicted heat and radioactivity will not lead to accelerated deterioration of the concrete. Consequently, concrete should not have a shortened performance lifetime.

Concrete and concrete-like products have been used successfully since antiquity (Mindess and Young 1980; Eglinton 1987). Gypsum and lime were the first calcareous materials to be used as mortar cements. The Egyptians used gypsum mortars (by calcining impure gypsum) in the construction of the Pyramid of Cheops (about 3,000 B.C.). Lime mortars were later used in Egypt during the time of the Romans (about 2,000 years ago). The Romans and the Greeks also produced hydraulic limes by calcining limestone that contained argillaceous (clayey) impurities. They also knew that certain volcanic deposits, when finely ground and mixed with lime and sand, yielded mortars that were not only stronger than ordinary lime mortars but also were water resistant. The Roman-constructed Pantheon, perhaps the best preserved building of the ancient world (dating from the second century A.D.), was built primarily of concrete

The quality of cementing materials gradually declined during the Middle Ages; high-quality cementing materials did not reappear until the after the fourteenth century. In 1756, John Smeaton, who was commissioned to rebuild the Eddystone Lighthouse off the coast of Cornwall, England, determined that the best limestones for mortar contained a large proportion of clayey materials. The mortar developed from these limestone allowed the lighthouse to stand for 126 years before it was replaced with a more modern structure. After this discovery, Portland cement developed rapidly through the nineteenth and twentieth centuries, and many structures completed during the nineteenth century are still standing.

The examples given above document that concrete can successfully perform for extended periods of time under a variety of environmental conditions. Direct extrapolation of concrete under any specific set of conditions to the waste emplacement drift environment must be done with caution. For example, an inappropriate analogy of deterioration would be a concrete cooling tower that conveys hydrogen sulfide-bearing gases. The above examples do show that under certain circumstances and lacking known degradation processes, concrete can last for extended periods of time on the order required for the retrievability period.

C.4 REFERENCES

ACI (American Concrete Institute) 1989. *Building Code Requirements for Reinforced Concrete (ACI 318-89) and Commentary (ACI 318R-89).* Detroit, Michigan: American Concrete Institute.

AISC (American Institute of Steel Construction) 1989. *Manual of Steel Construction Allowable Stress Design.* 9th Edition. Chicago, Illinois: American Institute of Steel Construction, Inc.

ASM (American Society for Metals) 1990. *Metals Handbook.* 10th Edition. Vol. 1, "Properties and Selection: Irons, Steels, and High Performance Alloys." Materials Park, Ohio: American Society for Metals International.

Berner, R. A. 1972. *Chemical Sedimentology.* New York, New York: McGraw-Hill.

Cember, H. 1983. *Introduction to Health Physics.* Pergamon Press.

Cord-Ruwisch and Widdel 1986. "Coording Iron as a Hydrogen Source for Sulfate Reduction in Growing Cultures of Sulfate-Reducing Bacteria." *Applied Microbiology and Biotechnology, 25,* 169-174.

CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) 1993. *Site Characterization Plan Thermal Goals Reevaluation.* B00000000-01717-5705-00005, Rev. 00. Las Vegas, Nevada.

CRWMS M&O 1994. *Initial Summary Report for Repository/Waste Package Advanced Conceptual Design.* B00000000-01717-5705-00015, Rev. 01. Las Vegas, Nevada.

CRWMS M&O 1995a. *Repository Ground Control Evaluation.* BC0000000-01717-5705-00017, Rev. 00. Las Vegas, Nevada.

CRWMS M&O 1995b. Interoffice Correspondence, J.K. McCoy to M. Grigore. "Irradiation Effects on Steels." LV.WP.JKM.08/95. Las Vegas, Nevada.

Eglinton, M. S. 1987. *Concrete and its Chemical Behavior.* London: Thomas Telford, Ltd.

Elleuch L. F.; DuBois, F; and Rappeau, J. 1972. "Effects of Neutron Radiation on Special Concretes and Their Components." *Concrete for Nuclear Reactors.* Volume II. Special Publication SP-34, 1071-1108. Detroit, Michigan: American Concrete Institute.

Granata, S. and Montagnini, A. 1972. "Studies on Behavior of Concretes Under Irradiation." *Concrete for Nuclear Reactors.* Volume II. Special Publication SP-34, 1163-1173. Detroit, Michigan: American Concrete Institute.

Hilsdorf, H. K.; Knopp, J.; and Koch, H.J. 1976. *The Effects of Nuclear Radiation on the Mechanical Properties of Concrete.* Publication SP-55, 223-250. Detroit, Michigan: American Concrete Institute.

Houben J. A. 1969. *DeBestraling van Mortelproefstukken* (Radiation of Mortar Specimens). 170-183. Brussels: Commission of the European Communities.

Kaiser, P.K.; Maloney, S.M.; and Singh, S.P. 1990. "Feasibility of Long-Term Ground Control with Stainless Steel Friction Rock Bolts." *CIM Bulletin, 83,* 55-60.

Karnhak, J. M. 1984. "Corrosion and Wear Problems Associated with the Mining Industry." *Corrosion '84, Proceedings of the International Corrosion Forum,* Paper 230, p. 12.

Kiewit/PB 1995. Letter, J. D. Murphy to R. Dow. "Materials Testing Data."

Merritt, F.S. (Editor) 1983. *Standard Handbook for Civil Engineers.* Third Edition. McGraw-Hill Book Company.

Mindess, S. and Young, J. F. 1980. *Concrete*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

Ramachandran, V. S. 1984. *Concrete Admixtures Handbook.* Park Ridge, New Jersey: Noyes Publications.

Popovics, S. 1992. *Concrete Materials*. Park Ridge, New Jersey: Noyes Publications.

SNL (Sandia National Laboratories) 1995. Lin, M. and Gilbride, L. *Repository Design Data: Update through August 1995*. Sandia Letter Report SLTR95-0009. Albuquerque, New Mexico.

Tilman, M. M.; Jolly, A.F. III; and Neumeier, L.A. 1989. *Corrosion of Friction Rock Stabilizers in Selected Uranium and Copper Mine Waters*. Report of Investigations 8904. U.S. Bureau of Mines.

YMP 1994. *Engineered Barrier Design Requirements Document.* YMP/CM-0024, Rev. 0, ICN 1. Las Vegas, Nevada: Yucca Mountain Site Characterization Project.