3.0 ASSESSMENT OF PROBABLE MAXIMUM MAGNITUDE

3.1 Terminology

- *Moment magnitude is preferred standard*
- *Probable maximum magnitude versus Maximum Credible Earthquake*

It will be useful at the outset in this section to clarify terminology. First, in our consideration of "magnitude," we will ultimately use moment magnitude $\boldsymbol{M}$ (Hanks and Kanamori, 1979), which is preferentially used as the uniform size measure of earthquakes in seismic hazard analysis and associated ground-motion characterization. Second, we discard the term "Maximum Credible Earthquake" in favor of "probable maximum magnitude."

Magnitudes routinely determined by UUSS are either Richter local magnitude M_L or coda magnitude M_C, an empirical estimate of M_L commonly relied on for measuring the size of shocks smaller than magnitude 3. Conveniently, M_L is equivalent to $\boldsymbol{M}$ for M_L less than about 5.5–6.0 (Hanks and Boore, 1984). Further, M_C has been carefully calibrated to M_L by the University of Utah (see *UUSS Report*, p. 3-7), and independent testing by the USGS confirmed that M_C values in the TM earthquake catalog are reasonably good approximations to $\boldsymbol{M}$ (as described above). Thus, for all practical purposes in this report, UUSS magnitude values reported as either M_L or M_C are equivalent to $\boldsymbol{M}$ and will ultimately be considered as such.

Although the term Maximum Credible Earthquake (MCE) was used in describing a key project objective, the term is ill-defined and often contentious. One expert has humorously asked, “When does the Maximum Credible Earthquake become the Minimum Incredible Earthquake?” The lack of a clear definition for the MCE makes it difficult to apply in practice. A concept better suited to meet the needs of this project, particularly in light of agreement to approach the issue of an upper-bound magnitude in a probabilistic way, is that of a probable maximum magnitude. In seismic hazard analysis, the maximum magnitude m_{max} is conventionally understood to be the largest magnitude that a seismic source is capable of generating, where a seismic source is a geometrically defined plane, area, or volume with relatively uniform seismicity characteristics (e.g., Senior Seismic Hazard Analysis Committee, 1997).

It is the consensus of the Joint Working Group that the maximum magnitude is best represented using a distribution (discussed specifically in Section 3.3). However, we acknowledge that for use in conventional engineering assessments, a single value is often required. Thus, we define the probable maximum magnitude (PMM) to be a specified value in a probability distribution of m_{max} for a given seismic source. We propose using the 84th-percentile value of the cumulative distribution function of m_{max} as the PMM.

For the problem at hand, the seismic source region is the Cottonwood Coal Tract, within the areal boundaries of which only shallow MIS will be considered. To make this point clear: we give no consideration to the possible size of naturally occurring tectonic earthquakes beneath the Cottonwood Coal Tract. We assume that such earthquakes are appropriately evaluated as part of existing seismic hazard assessments for Joes Valley Dam.

3.2 Considerations

3.2.1 MIS Worldwide

- *International reviews provide useful perspective*
- *Largest mine tremors ever observed in magnitude 5 range*
- *Largest MIS in coal mines in magnitude 4 range*

Gibowicz and Kijko (1994) and the Department of Energy Working Group (1999) reviewed MIS associated with underground mines on a worldwide basis, including useful documentation of the largest events. The latter report was compiled for the purpose of assessing MIS as a potentially confounding factor in monitoring the Comprehensive Nuclear-Test-Ban Treaty.

The largest mine tremor observed to date had a magnitude (M_L) of 5.6 ($m_b = 5.5$) and was associated with cascading pillar failures in a room-and-pillar potash mine in the former German Democratic Republic in March 1989 (Knoll, 1990); a smaller prior event in this same mining district also reached magnitude 5 (see Gibowicz and Kijko, 1994, p. 2). A notable mine failure in February 1995 in the Solvay Trona Mine, a room-and-pillar mine near Green River Wyoming, produced a seismic event of magnitude (M_L) 5.2 ($m_b = 5.3$, $M_S = 4.6$) (Pechmann et al., 1995; Swanson and Boler, 1995). Mine tremors in the mid-to-upper magnitude (M_L) 3 range are included among other instances of cascading pillar failures in room-and-pillar mines documented by the Department of Energy Working Group (1999)—including two cases in Utah coal mines (Taylor, 1994; Boler et al., 1997).

Mine tremors in hard rock mines have been reported as large as magnitude (M_L) 5.2 in the South African gold mining district, magnitude (M_L) 4.5 in a copper mining district in Poland, and magnitude (M_L) 4.1 in the Couer d'Alene mining district in northern Idaho (Gibowicz and Kijko, 1994; Department of Energy Working Group, 1999).

In terms of larger mine tremors in coal mines, it is apparent from the international review of Gibowicz and Kijko (1994, p. 1-10) that MIS in the mid-to-upper magnitude (M_L) 3 range has been observed in many coal districts around the world, but large MIS in the magnitude (M_L) 4 range has been relatively rare.

The report of the Department of Energy Working Group (1999, p. 28) includes a tabulation of larger mining seismic events in the U.S. for the period 1981–1999 that contains five coal bumps in eastern U.S. coal mines in the magnitude 4 range: M_L 4.0 (1988, Buchanan, VA), M_L 4.0 (1995, Lynch, KY), M_L 4.2 (1995, Lynch, KY), M_L 4.0 (1997, Shoal Creek , AL), and M_L 4.0 (1999, Shoal Creek , AL). Given the relative rarity of MIS in the magnitude (M_L) 4 range in coal mines worldwide, the size of these events may be overestimated, but it is difficult to verify accuracy without scrutiny of the original seismological data.

3.2.2 History of MIS in the WP-BC Coal-Mining Region

- *Uniform catalog of largest MIS in Utah since 1962 available*
- *M_L 4.2 (Willow Creek Mine) largest historical mining-related seismic event since 1962*

- *Larger historical events (except for Willow Creek Mine events) predominantly implosional?*
- *Bimodal distribution of MIS suggests larger shocks form a separate set*

Arabasz et al. (1997) developed a catalog of the larger mining-related seismic events in the Wasatch Plateau (WP)–Book Cliffs (BC) coal mining districts from July 1962 (when systematic instrumental monitoring began) through March 1996. Importantly, careful efforts were made to achieve homogeneous size estimates. The largest event in the catalog had a weighted-average estimate of M_L (termed M_L') of 3.8, associated with inferred cascading pillar failures in a remote part of a room-and-pillar mine in the Gentry Mountain area (about 23 km [14 mi] NNE of the TM area) in May 1981 (Taylor, 1994). The magnitude assigned to an earthquake is intended to be the mean of measurements made at multiple, azimuthally diverse, recording stations, with a typical standard deviation of ±0.3. Accordingly, Arabasz et al. (1997) identified the (then) largest historical MIS in the WP-BC region as M_L 3.8 ± 0.3.

The catalog of the larger MIS in the WP-BC region was slightly refined and updated by Arabasz and Pechmann (2001), who systematically examined all earthquakes of $M_L \geq 3.0$ in the WP-BC region from January 1978 through June 2000. Their listing is reproduced here in Table 3. Since June 2000, no other earthquakes of $M_L \geq 3.0$ have occurred in the WP-BC region through the date of this report. Two important additions to this list of larger MIS in the WP-BC region were two sizable earthquakes near the Willow Creek Mine—one of M_L 3.8 on February 5, 1998, and another of M_L 4.2 on March 7, 2000 (Arabasz and Pechmann, 2001; Ellenberger et al., 2001). The latter earthquake now represents the largest historical MIS in Utah instrumentally recorded since 1962.

Table 3 identifies 18 earthquakes of $M_L \geq 3.0$ in the WP-BC region since 1978. Three of these had unambiguous shear-slip-type source mechanisms (Arabasz and Pechmann, 2001): the M_L 3.8 and M_L 4.2 earthquakes near the Willow Creek Mine in 1998 and 2000, respectively, and an earthquake of M_L 3.0 in June 1996 south of the Skyline Mine, for which there is convincing evidence that the shock was a non-mining-related tectonic earthquake more than several kilometers deep. For 13 of the other 15 events, coincident with sites of both longwall and room-and-pillar mining throughout the WP-BC region, only dilatational P-wave first motions were recorded by the UUSS regional seismic network, and multiple pillar failures are documented for four of these events. According to Arabasz and Pechmann (2001, p. iv; see also Arabasz et al. 2001), "Available evidence favors the working hypothesis that the predominant mechanism of larger (magnitude ≥ 3.0) mining-induced seismic events in the WP-BC region is implosional and caused by sudden roof-floor closure, either partial or total, due to loss of pillar support."

Using data compiled by Arabasz and Pechmann (2001), we constructed plots of frequency of occurrence versus magnitude, shown in Figure 6, for MIS in the WP-BC region for January 1978 through June 2000. The inset shows a standard plot of cumulative number of shocks greater than or equal to a specified magnitude. On the low-magnitude end, the plot flattens as usual due to incomplete sampling below some threshold, here identified as magnitude 1.85. The maximum-likelihood recurrence relation illustrated in Figure 6 was determined using the procedure of Weichert (1980) for a doubly-truncated exponential, assuming $m_{min} = 1.85$ and

m_{max} = 4.6. To calculate *N(M),* the cumulative number of earthquakes per year of magnitude *M* and greater in the sample region, one uses the equation (e.g., Pechmann and Arabasz, 1995):

$$N(M) = A \frac{10^{-b(M-m_{min})} - 10^{-b(m_{max}-m_{min})}}{1 - 10^{-b(m_{max}-m_{min})}}$$

where A = 0.12E+03 and b = 1.91 ± 0.04. The error bars in Figure 6 show the 90-percent confidence intervals for the plotted frequencies. An observation of particular significance for us is the systematic departure from linearity in log–magnitude space shown by the plots in Figure 6 to the right of the upper magnitude 2 range. This feature suggests that the earthquake sample is bimodal (e.g., Gibowicz and Kijko, 1994, p. 22f) with the larger shocks belonging to a set of events separate from the lower-energy events routinely accompanying extraction—and not simply an extrapolation of the lower-energy events following a power-law scaling. From the data of Figure 6 we infer that the boundary between what might be called normal background MIS and infrequent large seismic events in the WP-BC mining region is roughly in the upper magnitude 2 range, perhaps close to magnitude 3.

To guide our evaluation of how the largest MIS in the WP-BC region is distributed in size, we constructed a probability mass distribution for the 17 mining-related events listed in Table 3, excluding the one event (#17) identified as a deeper tectonic earthquake. The results are shown in Figure 7. The distribution has a mode at magnitude 3.1 and an upper bound at magnitude 4.2, the size of the March 2000 Willow Creek Mine earthquake.

3.2.3 History of MIS at the TM Mine

- *Continuous record of MIS available from UUSS regional network for entire period of longwall mining (1995–2001) in the TM Mine*
- *Largest mine tremor in TM Mine during* this *period had magnitude* (M_C) *2.5*
- *5.4-year record of MIS during longwall operations did not include any extreme events*

Thanks to continuous monitoring by the University of Utah's regional seismic network, we have a temporal record of MIS associated with the TM Mine spanning the entire period of longwall mining from October 1995 through March 2001. A magnitude-versus-time plot for the TM local study area, including the time period of special study as part of this project, is shown in Figure 8. For the data sample in Figure 8, M_C values from the regional network catalog were recomputed using the same procedures as for the TM catalog (see sections 3.3.3 and 4.2 of the *UUSS Report*) to ensure uniformity of magnitudes.

An important observation from Figure 8 is that the largest earthquake recorded during 5.4 years of longwall operations in the TM Mine had a magnitude (M_C) of 2.5. As emphasized in the figure caption, the gaps in the seismicity time series are not due to gaps in monitoring. Rather, they are inferred to be associated variously with interruptions in mining, such as during longwall moves, and variations in mine characteristics such as cover depth.

The *UUSS Report* discusses the reduction in size of MIS that was recorded during the period November 2000–March 2001, which is apparent in Figure 8. In order to get a representative sample of energetic MIS associated with the TM Mine, we used Figure 8 as a guide and selected the time period November 1, 1998–September 30, 2000. Using the same procedures described earlier for Figure 6, we constructed frequency-of-occurrence versus magnitude plots for this 23-month sample of MIS, with the results shown in Figure 9. In this case, the cumulative-number plot (inset) indicates a threshold of completeness at magnitude 1.75, above which there is simple linearity. The position of the data point for the largest magnitude class (≥ 2.45) below the extrapolated trend suggests inadequate temporal sampling for this size event. What is apparent from Figure 8 is that the MIS recorded during longwall operations at the TM Mine did not include any extreme events but rather consisted exclusively of lower-energy seismicity accompanying the regular release of mine-induced stresses.

3.2.4 Characteristics of the Cottonwood Coal Tract

- *Subjective comparison of Cottonwood Tract to four other areas of MIS in the region*
- *Inferred geologic conditions of the Hiawatha coal seam in the Cottonwood Tract*
- *In the absence of a proposed mining plan, different scenarios are considered*
- *Both ameliorating and exacerbating factors for MIS are present in the Cottonwood Tract*

A quantitative means for assessing m_{max} for MIS based on site factors is not available at this time. A useful approach is to compare conditions in the Cottonwood Tract with those in mining areas elsewhere in the Wasatch Plateau-Book Cliffs region. In this way, a subjective measure can be made as to whether m_{max} is likely to be larger or smaller than past events in areas where conditions and mining practices can be compared. For this purpose, four relevant case studies were selected and examined by M. K. McCarter in Appendix F of the *UUSS Report*. These include: the Willow Creek event (M_L 4.2 on March 7, 2000); the Cottonwood event (M_L 3.5 on July 5, 1992); the Trail Mountain event (M_L 3.3 on December 16, 1987); and the largest MIS associated with longwall mining in the Trail Mountain Mine (M_C 2.5 on April 7, 2000).

Geologic conditions in the Cottonwood Tract were inferred utilizing publicly available logs for ten drill holes together with information from the Trail Mountain Mine provided by Energy West. These logs along with available topography allowed estimation of the structural contour of the Hiawatha coal seam and interpretation of depth of cover. The orientation of the coal seam and depth of cover are critical factors in assessing m_{max} relative to other mines in the Wasatch Plateau and Book Cliffs. These factors are based on limited data which are not optimally distributed spatially. The actual structure, depth of cover, and geological conditions will undoubtedly be refined in the detailed planning required prior to mining. Some changes in interpretation are expected, but the analyses presented in the *UUSS Report*, Appendix F, provide reasonable estimates and the best information publicly available at this time.

The topography of the Tract is similar to conditions at the Trail Mountain Mine and the Cottonwood Mine. It is dominated by canyons and steep slopes on the north and on the south, highlands with more gradual slopes truncated at the margins by cliffs formed by stream erosion and the Joes Valley escarpment. It is not as steep or varied as that present at the Willow Creek Mine. Sharp transitions in topography seem to induce stress gradients which may exacerbate MIS. On the basis of topographic transitions, conditions for most of the Tract are less likely to produce MIS compared to Willow Creek and would be about the same for the Trail Mountain and Cottonwood areas.

In the central region of the Tract, the cover depth is likely to be 730 m (2,400 ft) or greater (see Figure 10). Consequently, m_{max} is potentially higher than in the TM study area (cover depth up to 670 m or 2,200 ft), the pre-Energy West Trail Mountain workings (cover depth up to 580 m or 1,900 ft), or the Cottonwood Mine (cover depth of 550–610 m or 1,800–2,000 ft). The depth of cover is comparable to the Willow Creek Mine or slightly higher. On the basis of cover depth, m_{max} in the central part of the Tract could be higher than in the Trail Mountain and Cottonwood areas. It could be equal to or even higher than the Willow Creek area. The cover depth for about one-half (~48 percent) of the Tract is in excess of 550 m (1,800 ft) and is expected to be bounce-prone.

The Hiawatha seam ranges in thickness from about 4.4 meters (14 ft) near the center of the Tract to about 1.5 m (5 ft) on the south and 2.6 m (8.5 ft) on the north; therefore, thickness is comparable to the other four areas. The coal strength is similar to the Trail Mountain and Cottonwood areas. Coal in the Willow Creek area (Castlegate D seam) is typically stronger and perhaps more brittle. Consequently, the effect of coal strength on producing MIS in the Tract should be about the same as at the Trail Mountain and Cottonwood mines while the stronger coal at the Willow Creek Mine would likely produce higher magnitudes.

As in the Cottonwood and Trail Mountain areas, the Hiawatha seam occurs near the bottom of the Blackhawk Formation. This formation contains sand channels which have been associated with MIS in the past. It also contains shales, mudstones and siltstones which promote caving. The sand channels exacerbate MIS while the ease of caving ameliorates MIS. The nature of the main roof in the Tract is lithologically similar to Cottonwood and Trail Mountain areas. The thickness of the overlying Castlegate Sandstone for the Tract is about the same as for Cottonwood and Trail Mountain areas, perhaps even less. The thickness over the Willow Creek mine is about twice that for the Wasatch Plateau and may have contributed to the larger events recorded in the Book Cliffs area.

The major structures in the Tract include the Straight Canyon syncline and Joes Valley fault. Several other structures are projected into the area. These include the Mill Fork graben and the Roan's Canyon graben with associated faults. Similar fault structures have been known to increase vertical stresses at the margins of grabens. These structures may complicate mining and exacerbate MIS relative to the Cottonwood and Trail Mountain areas. Unusual stress fields may exist in the Willow Creek area as evidenced by a substantial bounce early in the development stages of the mine. Based on the possible presence of tectonic structures, m_{max} may be greater in the Tract than in the Cottonwood and Trail Mountain areas but probably less than Willow Creek.

In addition to the geological and topographical factors, the details of the mining plan to be used in the Tract will also influence the magnitude of MIS. A mining plan has yet to be proposed and may require access to proprietary information as well as additional drillholes. In the absence of a mining plan, two scenarios can be considered for a preliminary assessment. Scenario 1A would involve developing panels beginning just north and west of the last panel mined in the Trail Mountain Mine. This is identified as Scenario 1A with a possible variant identified as Scenario 1B (see *UUSS Report*, Appendix F for additional details). The other option, identified as Scenario 2, initiates panel development in the southwest corner of the tract.

The most advantageous place to begin longwall mining is at 1A. This is near the thickest portion of the coal seam in the Tract and can be reached with a minimum of development work. Unfortunately, it is also where the depth of cover is greatest and will likely have the highest potential for MIS. Initiation of mining at 1A has the additional advantage that the distance from Joes Valley Dam would begin at approximately 4.0 km (13,000 ft) and would increase as mining progresses northward. Beginning mining operations at this point and working towards the Dam would allow an opportunity to limit how close mining would be allowed based on accumulated operating experience.

The advantage of Scenario 2 would be to maximize recovery of the coal resource. This location must be far enough to the north of the boundary so as not to cause stability problems with the Straight Canyon escarpment. The main advantage of this location is lower cover relative to Scenario 1A (430–610 m or 1,400–2,000 ft). The disadvantages include high development costs, substantial delay and close proximity to the Dam (0.9 km or 3,000 ft).

A comparison of conditions for the two scenarios relative to the case histories is summarized on Table 1(a) and 1(b). As indicated, some factors are ameliorating, some are exacerbating and others have little influence or the influence is unknown. For the low-cover areas in the Tract, m_{max} would probably be less than that historically observed for the Cottonwood or Trail Mountain mines (M_L 3.3 to 3.5). In the high-cover areas (in excess of 550 m or 1,800 ft), m_{max} might exceed 3.3 to 3.5 observed in the case studies. Because the exact cause of the Willow Creek event is not well understood, an event of 4.2 cannot be ruled out entirely, but the probability of an event of this magnitude is considered low for the Tract as a whole.

3.3 Probability Distribution of m_{max}

- *Informed consensus as opposed to independent assessments*
- *Consensus probability distribution has a lower bound of 2.7, a mode of 3.1, and an upper bound of 4.6 (mean = 3.43, median = 3.41)*
- *"Seismically large" events do not necessarily equate with hazardous rockbursts*
- *Probable maximum magnitude (proposed as 84th-percentile value) is 3.9*

Based on all the considerations discussed in the preceding sections, we proceed to assess a probability distribution for m_{max}. Because the problem is not simply amenable to an analytical solution, we use a subjective probability approach for quantifying our expert opinion. In terms of methodology, we made the decision to use a simple triangular distribution to capture our best judgment of the central tendencies and bounding values of m_{max}. Further, we agreed to pursue by iterative interaction an "informed consensus," as opposed to a mathematical aggregation of independent assessments.

Our consensus probability distribution for m_{max} is presented in Figure 11 both as a probability density function (PDF) and a cumulative distribution function (CDF). Values of m_{max} and cumulative probability for the CDF are given in Table 4. The PDF has a lower-bound value of 2.7, a mode of 3.1, and an upper-bound value of 4.6. The mean of the distribution is 3.47 and the median is 3.41.

Our upper-bound value of 4.6 rules out the likelihood of energy release comparable to the magnitude 5 earthquakes produced by cascading pillar failures in room-and-pillar mines or by failures in deep South African gold mines. We do not consider those situations relevant to the Cottonwood Coal Tract. At the same time, we do not believe that we can completely rule out (i.e., assign zero probability) to an event like the magnitude 4.2 Willow Creek Mine earthquake. Simply put, without a clear understanding of what caused that earthquake, we are forced to be reasonably conservative—including some allowance for a typical standard deviation of ± 0.3 in magnitude determinations—in considering what may happen in mining the Cottonwood Coal Tract. We do not know, for example, what the detailed mine plan will be. From Table 4, our implied probability for a magnitude 4.2 or larger earthquake in the Cottonwood Coal Tract is approximately 0.06.

For the mode of our PDF, we are influenced by the historical experience of MIS in the WP-BC mining region, notably by the probability mass function shown in Figure 7, and we adopt the observed mode of 3.1. While this size event may have the greatest relative frequency, our CDF (Table 4) indicates that there is a substantial probability (approximately 0.8) that m_{max} will exceed 3.1.

To explain our choice of 2.7 for a lower bound for m_{max}, recall that what we are assessing is the largest MIS that the Cottonwood Coal Tract is capable of generating. From considerations discussed above in section 3.2.2, we recognize two sets of MIS and place the lower bound of large-class events at 2.7. This makes some allowance, once again, for ± 0.3 uncertainty in magnitude determinations. Because no large-class events occurred during the 5.4 years of longwall mining in the TM Mine (section 3.2.3), the observation of magnitude 2.5 as the largest MIS during that period is not inconsistent with the lower bound of our PDF for m_{max}.

Finally, we emphasize that our considerations of m_{max} relate to earthquake size in terms of radiated seismic energy and its manifestation as surface ground shaking. It is well recognized that "seismically large" events do not necessarily equate with hazardous rockbursts, and vice-versa (e.g., Arabasz et al., 1997; Ellenberger et al., 2001). Thus, the relevant consideration here is not the likelihood of a damaging rockburst, but rather the triggering of seismic energy release large enough to have an adverse vibratory impact on Joes Valley Dam.

Based upon our definition of the probable maximum magnitude (PMM) defined in Section 3.1 and the probability distribution developed for m_{max} (Figure 11 and Table 4), our estimate of the PMM for the Cottonwood Coal Tract is 3.9.