ATTACHMENT B

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Unnumbered. My confidence in the reliability of the modeling results is low. I think the initial and boundary conditions of the model set-up are not fully reflective of physical conditions.

No response is possible without knowing the basis for the low confidence and what initial and boundary conditions are of concern. Presumably they are included in the items of the subsequent numbered comments.

1. The concussive and thermal effects of the nuclear detonation are not fully incorporated into the model. The modeled system is treated isothermally. The convection effects of 40 billion calories of heat are ignored. There is a strong driving force moving contamination up and out. The assumption that advective transport is not active during the modeled time frame is hard to justify. Prompt injection effects are also ignored.

The reviewer is correct that the bulk of the modeling effort was conducted for isothermal conditions. Nonisothermal conditions were addressed as a sensitivity analysis in the report. That analysis found that the tritium field extended approximately 50 m farther in all directions as a result of the pressure gradient induced by the elevated chimney temperature.

Also included in the nonisothermal sensitivity analysis is examination of the possibility of convection, using both Rayleigh number criterion and a separate analysis of the rise of a buoyant plume. Those analyses show that fluid motion by convection is not expected. Including convection in the chimney would have minimal effect because diffusion in the chimney is extremely rapid in the model, such that the tritium concentration throughout the chimney is uniformly high within a month (e.g., see Figure 5-5 a-1 in the report and note the red zone extending throughout the chimney). Thus, thermal convection is not needed to transport tritium upward in the chimney; it gets there quickly by diffusion anyway. Convection would not be a force driving contamination out of the chimney, as the permeability of rocks above the chimney does not support convection (due to the low Rayleigh number) even if convection occurred in the chimney itself.

Note that most of the energy was used to melt the rock. For example, the volume of rock in the cavity is approximately 100,000 m^3. Assuming a rock density of 2500 kg m^{-3}, the mass of rock that melted was approximately 2.5×10^8 kg. For a specific heat of rock of 500 J kg^{-1} K^{-1}, and an increase in temperature of 1000 K needed to melt the rock, then the energy required to melt the rock is on the order of 10^{14} J. Forty billion calories is equal to 1.7×10^{11} J, so we agree that a tremendous amount of energy was released from the explosion.

The point is that most of the energy was used to melt the rock, which acts as a seal to encase most of the radionuclides. The detonation caused a pressure gradient to develop with decreasing pressure away from the cavity. However, as the initial plasma associated with the explosion cooled, the condensation of vapor resulted in a pressure gradient back toward the cavity. This is part of the reason that the initial transient pressure gradient was not included in the model. Further discussion of these effects are found in Borg (1975, "Radioactivity trapped in melt produced by a nuclear explosion," *Nuclear Technology* (26): 88–100); Borg et al. (1976, *Information Pertinent to the Migration of Radionuclides in Groundwater at the Nevada Test Site*, Part 1: review and analysis of existing information, Lawrence Livermore National Laboratory, UCRL-52078 Pt. 1, 216 pp.); and Toman and Tewes (1972, *Project Rio Blanco: Phase I technical studies*, Lawrence Livermore Laboratory Report UCID-15968, 138 pp).

Advective transport is active during the modeled time frame, beginning with the onset of gas production. Prompt injection is a process used to explain the observation of small amounts of radioactive material at distances up to several cavity radii away from a nuclear cavity. That effect can be simulated by assigning the starting location of a portion of the radioactive material outside of the cavity.

There are two reasons it was not explicitly included in the simulations. One is that the gas-phase transport throughout the 3 to 4 cavity radii region around the chimney is rapid in the model (because those cells are assigned higher permeability to simulate nuclear-generated fractures) such that those grid cells do not act as any sort of barrier to movement.

The second reason is that the prolonged production testing from the cavity instilled a gradient toward the cavity in reverse of any prompt injection. By the end of production testing, uncontaminated gas flowed into the chimney from the surrounding formation. Even without the production testing, the pressure situation around nuclear cavities cannot be characterized as a force for contaminant migration. Indeed, pressures in nuclear cavities are invariably lower than that in the surrounding formation (believed to result from the effects of vaporization of material); the cavities act as sinks with flow toward them until pressures recover. The time for that recovery depends on the permeability of the surrounding rock; a recovery time of decades has been observed in some relatively tight aquifers that are considerably more permeable than the Williams Fork. In some tight aquifers, a halo of high pressure can be observed where the nuclear test shock wave pressures are in effect trapped in the low-permeability material, but this halo surrounds a low-pressure, slowly recovering chimney. The recovery period and recovery from the production testing were ignored in the model, but if included, they would reduce transport away from the Rulison cavity in the decades following the test.

2. Outside the zone of crushing, or chimney, the rock formations are considered un-altered from their native conditions. The source of radioactivity is restricted to the chimney zone. I think this is a gross simplification. These assumptions pre-dispose the model results to the minimum transport range.

The reviewer is incorrect that the rock was considered unaltered outside the chimney. The rock was considered fractured by the nuclear test to distances between 3 and 4 cavity radii, as shown on Figures 4-8 and 4-9 and described in the associated text. This distance is based on analysis of the production tests by two independent organizations, and based on the observed fractures in the re-entry drilling. The distances are consistent with the wider nuclear testing experience at the Nevada Test Site. The permeability assigned to the nuclear test fractures was also based on the production tests analyses mentioned above.

The location of the radioactivity is addressed in the previous comments. The reason that radioactivity is assumed to be restricted to the chimney is explained in our response the reviewer's No. 1 comment, that is, that the condensation of melted rock acts as a sort of seal around the wall of the chimney/cavity, as explained in the references associated with our response to comment No. 2.

3. The modeling assumption that rock fractures are 80 meters or less 95% of the time is based on scant data. I have data from EnCana that fracture length from a borehole reaches 250 meters and sometimes 300 meters. This change will greatly impact modeling results.

Please note that these distances refer to hydraulic fractures specifically, not "rock fractures." All sandstone in the model is assumed naturally fractured. The model does not assume that hydraulic fractures are 80 m or less 95 percent of the time. Rather, 95 percent of the lognormal distribution occurs between 40 m and 160 m in length, with a mean of 85 m. The distances reported by EnCana at the COGCC informational hearing were stated as the distances of microseismic responses. The gentleman continued in the presentation to describe that the propped lengths were considerably less. Though microseismic signals record ground motion as a result of hydraulic fracturing, they are generally not considered to represent effective lengths for the operation. Rather, some fractures may be created but then close due to overburden pressure. The hydraulic fractures are a hypothetical part of the model, and we are open to suggestions for improving the distribution. We initiated discussions on this topic with COGCC staff and industry representatives, and the result was that the distribution used has seemed acceptable for current practice. Hydrofracturing is clearly complex, and the initial fracturing operation apparently must be followed up with additional treatments to create conductive pathways by cleaning out or breaking down the fracturing fluids themselves. It is our understanding that those treatment operations are not effective over the lengths suggested by the reviewer. It should also be recognized that at the upper end of the distribution used, hydrofractures can connect directly to the chimney. Extending hydrofractures beyond that distance would be unimportant.

In responding to this comment, we identified an error in the report. The hydrofracture assumptions stated above in our response are correct and reflect the section in the report describing the hydraulic fracture length (Section 4.7.2.1). However, the summary Table 4-1 erroneously reports a minimum hydrofracture length of 36 m, mean of 72 m, and maximum of 133 m. The correct values are a minimum of 35 m, mean of 85 m, and max of 182 m.

4. All the mobile radioactive species are not considered. Tritium is the species modeled. Xenon-137 is also produced in large quantities by the nuclear detonation. It very quickly decays to Cesium-137, which is very radioactive and water mobile. By only modeling tritium other mobile radioactive species are ignored. From a risk evaluation perspective all pathways need to be considered.

Radionuclides in the gas phase travel much faster and farther than those in the liquid phase in this environment. Liquid velocities are extraordinarily small at these permeabilities, and even more so given the tortuous liquid pathways resulting from the partially saturated environment. As noted by the reviewer, the ^{137}Xe half-life is short (3.82 minutes), but it is long enough that a portion of ^{137}Cs is observed to occur higher in nuclear chimneys, in contrast to the majority in the solidified nuclear melt glass puddle at the bottom of the cavity. However, ^{137}Cs itself is not particularly mobile in groundwater. It reacts with rock minerals by sorbing onto their surfaces, retarding its movement relative to nonsorbing radionuclides such as tritium and ^{99}Tc. Nork and Fenske (1970) evaluate retardation at Rulison. Distribution coefficients (K_d) for Cs in contact with shaley siltstone and sandstone from the Gasbuggy site are 309 and 102 mL/g, respectively. Gasbuggy is another gas stimulation test, located in the San Juan Basin in northern New Mexico. Comparing the Gasbuggy rock with that at Rulison led Nork and Fenske to conclude the following in regard to both ^{90}Sr and ^{137}Cs at Rulison: “Significant retardation and sorption are predicted for these radionuclides” (Nork, W.E., and P.R. Fenske, 1970. *Radioactivity in Water—Project Rulison*, Teledyne Isotopes report prepared for the U.S. Atomic Energy Agency, NVO-1229-131.

5. The statement that: “the conceptual site model does not consider tritiated natural gas as a pathway.” Is very bold. What physical data supports this contention?

This statement occurs on page 8 as part of the discussion of constituents of concern and exposure pathways. As described earlier in the paragraph, the flaring operations at Rulison removed most of the tritiated methane gas and tritiated hydrogen gas from the subsurface. As a result, in contrast to the Rio Blanco site, where considerable tritiated methane remained, an exposure pathway involving tritiated natural gas (e.g., via combustion for heating or cooking in a home, as shown on Figure 1-6, which is called out in the commented sentence) is not meaningful for Rulison. Rather, as explained in the paragraph following the commented sentence and shown in Figure 1-6, the conceptual site model for Rulison identifies water vapor migration as the release mechanism, and a pathway of water (vapor and liquid) entrainment with natural gas production.

6. I think the permeability ranges given are too low. They are equivalent to un-fractured metamorphic rocks and basalts.

The permeability ranges are based on extensive data from the Williams Fork Formation in the Piceance Basin and are consistent with site-specific measurements. The low permeabilities are the topic of many professional peer-reviewed papers. The consistency of these formation characteristics is borne out by the widespread operation of the gas fields at close well spacings.

Unnumbered. In computer modeling there are many choices and assumptions made in setting the model parameters. The big choices need to be correct before the little ones matter. In the best case there is physical data from the site. Often, though, there are only analogs, assumptions, distributions, and estimates of approximations to fill in for data. The more the model relies on non-site data, the greater the uncertainty associated with the model results. There is a lot of uncertainty for this model.

We agree that there are significant uncertainties in this problem. Given the inability to ever directly observe more than only a small portion of the subsurface, combined with significant spatial variability in hydrogeologic properties, uncertainty cannot be eliminated from any subsurface problem. We are fortunate in this case to have access to abundant data collected from the same formation and under rigorous scientific investigation. These data are consistent with the more limited data from the immediate location and provide more confidence than analogs and assumptions. The data are also extensive enough to support distributions of key parameters, and distributions provide a rigorous way of addressing the spatial variability noted above.

Unnumbered. My experience has been that the best model results have a reliability of one order of magnitude. This model is filled with estimates, approximation, and guesses, The distance tritium has migrated according to the model is 80 meters (approximately 262 feet) from the blast point. I would put reliability at two orders of magnitude, at best. That means the "true" answer for tritium transport distance is probably in the band between 2.5 and 2500 meters. Because the Department takes the conservative approach to risk evaluation, we would evaluate risk based on the upper limit of this range, if there was no other reliable information.

We are aware of no simple method for assessing reliability of models. Supporting data and rationale were presented and justified for the model parameters, open for independent reader analysis. The Monte Carlo approach allowed combining the best estimate of formation parameters with information on their possible range. The resulting distributions are not guesses but rather are based on available information for the area and include the uncertainty inherent due to spatial variability. The range in transport distance suggested by the reviewer does not correspond to information we can identify from either data or analysis of the governing equations. The model conclusion highlighted here is the distance for diffusion of tritium from the nuclear chimney during the last 38 years. It is not obvious that there are any reasonable parameters to apply that would lead to a diffusion distance of 2500 meters for concentrations above the minimum detectable level.

The focus on diffusion migration distance is probably not in itself useful for evaluating risk. If applying orders of magnitude of conservatism is CDPHE policy, applying it to the predicted concentrations has more relevance for risk. These concentrations similarly only have meaning if there is a pathway to a receptor, so that processes along the exposure pathway should also be taken into account.

CDPHE may also want to consider use of the computed confidence intervals (50th, 95th, 99th) in their conservative approach to risk evaluation.