RESULTS OF GROUND-WATER TRACING EXPERIMENTS IN THE NELSON-WOOSTER-HUMPHREY TUNNEL

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1.0 Introduction

This report describes ground-water tracing investigation done in the Nelson -Wooster - Humphrey Tunnel system during September 2001. A fluorescent dye tracer was injected and recovered at various locations inside and outside the mine system and the results used to infer flow conditions in the tunnel. Tritium data that had been collected were also interpreted. Using these two tracers enables water tracing to be done in mixtures of ground waters that have residence times of hours to decades. Quantitative tracing of ground water enables an estimate to be made of hydraulic and other parameters along pathways where parts of subterranean pathways are not accessible for physical examination.

2.0 Ground Water Tracing Using Fluorescent Dyes

Fluorescent dyes are the most analytically sensitive, most versatile, non–toxic, and least expensive water tracers currently available (Käss, 1998). Fluorescent dyes have been successfully used as ground water tracers since 1877 (Bögli, 1980, p. 113; Käss, 1998, p. 125), when a major tracing experiment using, among other tracers, a dye (uranine) was conducted in southern Germany. The results of this experiment showed that an upper section of the River Danube actually flowed to the North Sea (east) rather than into the Black Sea (west) after most of its flow disappeared into its bed near the town of Tüttlingen. The flow from the river bed at Tüttlingen appeared to go east but actually went south and emerged at the Aäch Spring. The discharge from this spring flows into Lake Constanz in northern Switzerland and that lake is the source of the River Rhine, which flows northwestward into the North Sea. This experiment showed that, at the European continental divide, when discharge is low, flow may be reversed, and one of the biggest rivers in Europe crosses the divide in the opposite direction to the evidence of all surface hydrology. All maps show the Danube to enter the Black Sea hundreds of kilometers southeast of the source; there is rarely reference to the tracing. This complete reversal of flow was only determined from the results of tracing experiments, and is a classic example of the value of performing ground water tracing experiments in any setting.

3.0 Ground Water Tracing Using Natural Isotopes - Tritium

Tritium is a man made isotope of hydrogen (^{3}H) formed as a result of atmospheric testing of nuclear weapons. The unit used is the tritium unit (TU) which is one tritium atom to every 10^{18} hydrogen atoms. Tritium is a useful tracer for residence times of water of decades or more. The largest amounts of tritium (^{3}H) were released to the atmosphere during nuclear weapons testing several decades ago. The peak of atmospheric testing and tritium activity occurred in the late 1950's and early 60's. This peak in testing and subsequent peak in tritium activity is known as the bomb spike. This isotope of hydrogen has a half-life of 12.43 years, so unsupported it could provide useful tracing data for about 60 years.

Tritium-charged precipitation recharged ground-water during the testing period. Prior to atmospheric testing only minute amounts of natural tritium existed in ground water. After bomb testing ceased, tritium in ground water remained in the atmosphere and subsequently ground water but then decayed without being replenished. Mixtures of ground water in fractured rocks can be relatively dated in terms of the timing of the bomb spike. The easiest results to interpret are pre-bomb waters that have no detectable tritium (or below the detection limit for enriched tritium analysis of 0.8 TU).

However, all ground waters are mixtures and these mixtures can contain various combinations of pre-bomb, bomb spike and recent waters. Waters that have relatively high tritium values are interpreted as being those waters that recharged near the time of maximum testing (1963 - 1964). Tritium is still produced in nuclear reactions but not to the extent that was present at the peak of atmospheric testing.

During the last decade , because of the unsupported decay of tritium, activity is generally quite low. This has resulted in using a method so the activity of the daughter isotope of tritium ^{3}He, is also measured. It has become conventional when using this method that an “age” is calculated and the piston-flow model is assumed. This may not be appropriate because when using this model it is implicitly assumed that the packet of water that has been sampled for dating was isolated from any other water throughout the time it has been in the system and there is no mixing with any other waters. In reality this is almost never likely to be the case, even when old or young waters are involved.

An example of severe problems with using the “absolute ages “ is cited in work that Cambrian Ground Water Co. completed in Florida where injected tracers, TU (tritium units) and $^{3}H/^{3}He$ (and CFC) “dates” were obtained for a variety of ground and surface waters. Waters that are flowing in large subterranean tunnels (see http://www.wkpp.org) were traced using fluorescent dyes and shown to be moving at velocities of kilometers per day (i.e., implying transit times through the entire aquifer of weeks or months). The same water was “dated” as apparently being over 45 years old using the $^{3}H/ {}^{3}He$ dating technique, even though the mixture of water currently contains only small amounts of tritium (if really 60 years old it should reflect the bomb spike).

Also, CFC’s were used to “date” these waters. The CFC dates were about 16 years before present and obviously highly discordant with the $^{3}H/ {}^{3}He$ dates. Both these dates are apparently far too old for waters that move several kilometers per day. The problem is obviously the piston flow model, and the stringent assumption that there can be no mixing when using this model.

Cambrian Ground Water Co believes that it is far more sensible to assume there is mixing (it can be proved there is) and assume that the tritium number represents the average age for the whole mixture. For example, if water that is 10,000 years old from the rock matrix is mixed in the correct proportions with water that is a few hours or days old, an average age of 40 years (or 16 years) could easily result, but it is an average age and not as sometimes implied an absolute age.

4.0 Injected Tracer Experiment at Creede

It was necessary to study the hydraulics along the Nelson Tunnel. An injected tracer (4.5 kg of the dye sulphorhodamine B [C.I. Acid Red 52]) was added to the water at the Berkshire Shaft about noon on September 17, 2001. An automatic sampling machine was used collect samples at a regular frequency at the portal.

4.1 Injected Tracing Results

As expected the majority of the tracer discharged from the Nelson Portal, but there were other locations where it leaked out. Table 1a lists all the locations where this tracer was recovered. A listing of the recovery parameters is included for the Nelson Portal discharge (Table 1b) and a graph of the time-concentration curve is provided (Figure 1) which was the basis for calculation of the data in Table 1b.

5.0 Tritium Data from Creede

Selected sites in the mine and on the surface were used to collect tritium data. Tritium data are useful when used in combination with injected dyes as they both cover a time span of decades to hours and better describe the nature of waters. In this system the largest amount of water is the main discharge from the Nelson Tunnel, but there are other waters that are tributary flows that mix with that water. It is useful to interpret the tritium results along with the injected tracing results.

5.1 Tritium Data Interpretation

In discussing tritium data we should remind ourselves that ground waters are a mixture of waters of different residence times, and that it is impossible to obtain "absolute ages" of ground water without violating basic assumptions that must be made.

To avoid this problem a conventional interpretation method for these values is suggested by Clark and Fritz (1998, p. 185) and is used here. The tritium data from Creede (Table 2, Figure 2) show that a component (of the mixture) of the water in the mine pool (where it is accessible, the Berkshire Shaft) is decades old (pre-1952), and other components could be hundreds of thousands or even millions of years old. There could of course also be a recent component in the mixture.

Water in Windy Gulch could be mostly be a mixture with a significant proportion of relatively recent water; mean Colorado precipitation was 7 TU in 1999. In some cases such recent water and could be rapidly recharging the mine workings and could account for some mixtures with low but measurable tritium, or a two component mixture of recent water and pre-bomb water. A conceptual model of waters along the tunnel, based upon two end members of pre-bomb (1950's and early 60's) water and recent water (< 5 years old) could be developed thus:

Water in the Berkshire shaft is probably a mixture of pre-bomb and small amounts of recent water, the latter component assumed to be originating as inputs from the Happy Thought and Park Regent shafts from the surface (these waters not individually sampled but we can reasonably assume they are recent waters). In addition there are likely to be other recent inputs from the surface that are unknown or undocumented.

Water discharging from the Nelson portal is the “oldest” water - or has the largest pre-bomb component. This is water that is related to the Amethyst Vein and is a mixture of Berkshire water and Amethyst water. Even though this water mixes with other waters along the path to the portal it has the lowest tritium number and this suggests that it contains a large component of pre-bomb water. It is noted that when the Nelson -Wooster-Humphrey tunnel was driven the largest quantity of water was encountered east of the Berkshire Shaft. This volume change east of the Berkshire shaft add large amounts of “old” water and lowers the TU value and this mixture discharges from the portal.

The water from the Peak Drift Borehole has a slightly higher tritium number than the main flow or water in the Berkshire Shaft because it could be relatively old water (say decades old) that is mixed with a significant component of more recent water.

6.0 Other Observations

The water at the Berkshire Shaft and that discharging from the Nelson Tunnel portal is relatively warm so it can be inferred that it is related to a source relatively deep within the mountain, and this supports a source that may predate the accumulation of significant atmospheric tritium. The results show that even though the water at the Berkshire Shaft may have recharged prior to the 1960’s bomb spike (the maximum tritium activity recorded in the atmosphere), thereafter it is rapidly discharged to the Nelson Tunnel Portal along the mine workings. The fact that this water is relatively old means that a remedial solution to the discharge of this water into Willow Creek may not be feasible from the perspective of shutting off the source. Passive or active techniques will have to be used on the water after it has discharged from the mine workings.

There has been speculation that in recent years the discharge from the Nelson Tunnel Portal has increased. Other water could be from other workings higher up south and southwest of the Commodore/Nelson Tunnels.

A possibly significant “other source” of water sampled in the Commodore #5 level is part of the mixture sampled at the Peak Drift Borehole. This could be relatively recent water mixed with decades old (pre-bomb) water. The source of this recent water is undetermined, but could originate south and west of the Peak Drift Borehole. If this component is significant it does not appear to be easily identifiable in the Nelson Portal discharge.

7.0 Recommendations

It may be useful to collect samples from inputs on the west side of the Commodore #5 level to check for tracer that was used by Homestake Mining Company - tracer that has never been recovered anywhere. If a large amount was used it may be flushed through with melt events for several years.   Determining the fate of that tracer, possibly by additional tracing , may help reveal the source of mixture of water in the Peak Drift Borehole.

Alternatively it may be as interesting to see if the Peak Drift Borehole (or other sites) water has active ^{35}S - which would be water that is younger than a few years old. ^{35}S is a natural tracer formed by spallation of ^{40}Ar in the atmosphere and is contained in precipitation, its 90 day half-life means that unsupported it should not be present in waters that recharged more than a year or so ago.

Analysis of stable isotopes of oxygen and deuterium could also help shed light on recharge mechanisms with regards to snow melt events and how they change water chemistry and relative proportions of mixtures of water.

8.0 References

Bögli, A., 1980, Karst Hydrogeology and Physical Speleology, Springer-Verlag, New York, 284 p.

Käss, W., 1998, Tracer Technique in Geohydrology, Balkema, 581 p.

Clark, I.D., and Fritz, P., 1997, Environmental Isotopes in Hydrogeology, Lewis, New York, 328 p.

Tables And Figures

Table 1a. Summary of injected tracing results

Location	Tracer Recovery /Comments
Nelson Tunnel (discharge)	Majority of tracer recovered (see Figure 1, Table 1b)
Commodore Shaft	ND
Daylight Winze	ND
Javelin Winze	ND
WW Seep	Detection in seep/spring in west bank of Willow Creek
WWE	Detection in Willow Creek downstream of NT discharge
Bachelor Shaft (puddle) see note below	ND
Willow Creek upstream of NT discharge	ND
Spring below Sorting House	ND

Note:
Bachelor Shaft (the original location was an isolated puddle of perched water seen from the Commodore #5 Level); the flowing water in the vicinity of the Bachelor Shaft has since been physically accessed and is obviously the same water as the Nelson discharge; that flowing water was not sampled during this test. The puddle should not be expected to have tracer.

Table 2. Summary of tritium results

Location	TU +/- counting uncertainty	Description of water
Nelson Discharge	1.9 +/- 0.6	significant component of pre-1952 water?
Berkshire Shaft	3.3 +/- 0.6	significant component of pre-1952 water mixed with recent water from Park Regent, Happy Thought + other unknown inputs?
Peak Drift Borehole	4.5 +/- 0.6	mixture of pre-1952 water and recent water from unknown source?
Windy Gulch (stream)	9.7 +/- 1.0	component of recent water mixed with some bomb spike water?

Table 1b. Tracer Recovery Parameters (from Figure 1)

Lower integration limit	.00000 hrs
Upper integration limit	1242.0 hrs
The quantity of tracer recovered	2.1215 kg
Distance from input to outflow point	4.8300 km
Time to leading edge (first arrival)	108.00 hrs
Time to peak tracer concentration	204.00 hrs
For a peak tracer concentration	84.450 ug/L
The mean tracer transit time	444.2317 hrs
Standard deviation for tracer time	267.16 hrs
The mean tracer velocity	260.9448000 m/d
	10.87270 m/hr
	.30202E-02 m/s
Standard deviation for tracer velocity	3.7547 m/d
	.15645 m/hr
	.43457E-04 m/s
Dispersion coefficient	1.4503 m^2/s
Longitudinal dispersivity	480.19 m
Peclet number	10.059
	Advection > Diffusion
The maximum tracer velocity	1073.333000 m/d
	44.72222 m/hr
	.12423E-01 m/s
Pathway volume estimate	35183. m^3
Pathway cross-sectional area	7.2843 m^2
Pathway surface area	1771195.0 m^2
Tracer sorption coefficient (conduit)	.22270E-01 m
Hydraulic head loss along conduit	.16609E-03 m
Based on a friction factor	.22519
Laminar flow sublayer along walls	26.090 mm
Estimated Reynolds number	8068.058000
Based on an estimated tube diameter	3.0454 m
Estimated Froude number	.62359E-03
Based on an estimated hydraulic depth	2.3919 m
Shear velocity	.89813E-03 m/s
Total quantity of tracer recovered	2.1215 kg
Total water volume estimate	35183. m^3
Total aquifer surface area estimate	1771195.0 m
Final tracer sorption coefficient	.22270E-01 m
Percent recovery of tracer injected	47.14 %
Accuracy index (0.0 = Perfect Recov.)	.5286

Executive Summary

Ground water tracing was done in the Nelson-Wooster-Humphrey system using quantitative recovery and analysis of an injected tracer. The data obtained from the test reveal hydraulic parameters along the pathway and show that there is rapid discharge of water from the mine. Tritium data show that the majority of this discharging water is relatively old - almost certainly predating the early 1960's bomb spike caused by atmospheric testing. In a few places this relatively old water is diluted with what is thought to be more recent water, probably snowmelt from open shafts connecting the drainage tunnel system with the surface.

Figure 1. Tracer Recovery Curve, Nelson Portal Discharge

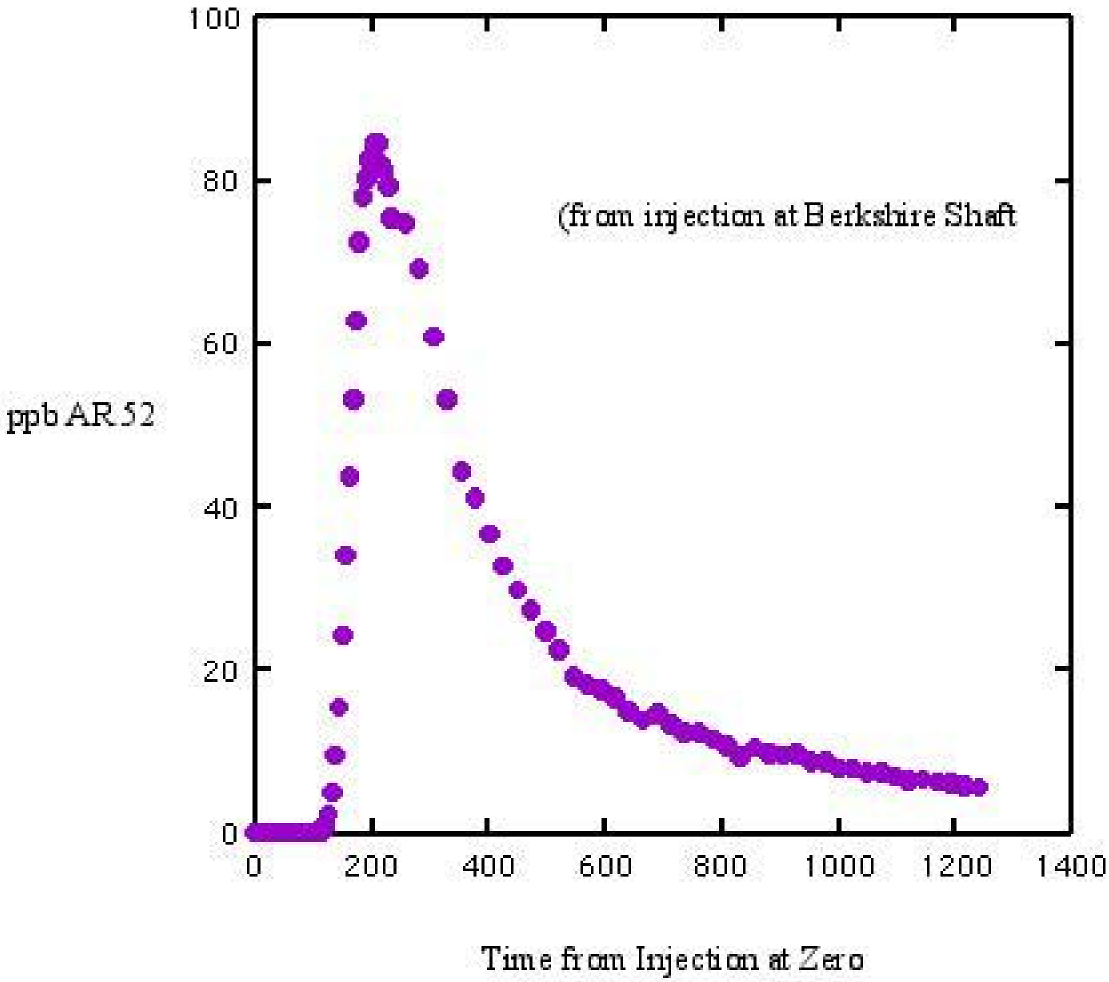
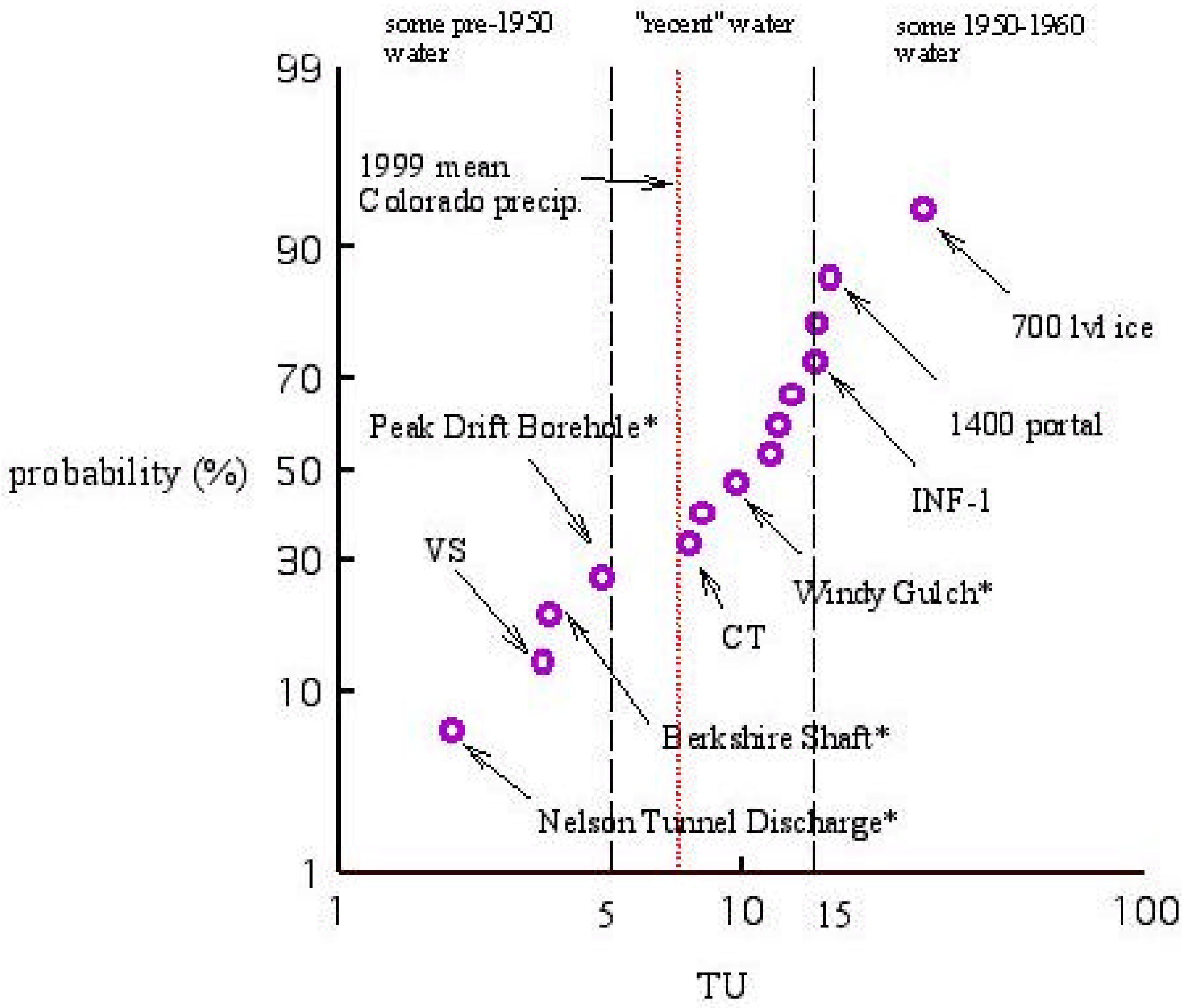


Figure 2. Tritium data, Creede (*); Leadville, Mary Murphy (for comparison)



Note:atmospheric testing peaked in the late 1950's and 1960's