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Evaluation of the Colloidal Borescope as a Monitoring Tool at the Waste Isolation Pilot Plant Site

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Evaluation of the Colloidal Borescope as a Monitoring Tool at the Waste Isolation Pilot Plant Site

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ABSTRACT

This report presents an evaluation of the utility of the colloidal borescope as a monitoring tool at the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The colloidal borescope measures the velocity and direction of horizontal groundwater flow by imaging and tracking natural colloidal-size (1-100 μm) particles flowing through monitoring wells. The colloidal borescope was deployed in ten WIPP wells to evaluate its effectiveness in defining the direction and velocity of groundwater flow under ambient and stressed conditions in wells completed in different fashions. The seven wells at the H-19 hydropad and well H-9b are completed open-hole to the fractured Culebra Dolomite Member of the Rustler Formation, well H-2b2 is screened to unfractured Culebra, and well H-6c is perforated to the unfractured Magenta Member. If effective, the colloidal borescope could provide objective validation of the flow directions and velocities predicted by the groundwater-flow models of the Culebra used for WIPP performance assessment, and help meet regulatory requirements to determine those parameters on an annual basis. The colloidal borescope proved capable of determining flow directions and velocities in open-hole intervals of fiberglass-cased wells in which the water column could be kept clean of suspended particles, but could not be used successfully in steel-cased wells in which the interval of interest was behind a well screen or in a perforated section of casing, primarily because the water in those wells could not be cleaned sufficiently to allow the camera to resolve an image. Interpretable data were obtained from only 20 percent of the stations logged in the fiberglass-cased wells at the H-19 hydropad because positioning of the tool precisely at the position of a flowing fracture is critical and difficult. Flow velocities were consistent with independently calculated pore-water velocities. Flow directions were consistent within individual wells, but variable between wells spaced 11 to 25 m apart. This variability probably reflects the small-scale variability in flow directions inherent in fractured systems. Point measurements made with a colloidal borescope in a fractured system should not be expected to agree in every instance with flow directions predicted by continuum models on a larger scale. Flow directions in four of the seven H-19 wells were consistent with model predictions. We were unable to evaluate the performance of the colloidal borescope in screened or perforated wells or in unfractured rock.

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1. INTRODUCTION

This report presents an evaluation of the utility of the colloidal borescope as a monitoring tool at the Waste Isolation Pilot Plant (WIPP) site. The colloidal borescope measures velocity and direction of horizontal groundwater flow through a well. As described by Kearn et al. (1999), the colloidal borescope consists of a set of lenses and miniature CCD (charged-couple device) video camera capable of imaging natural colloidal-size (1-100 μm) particles flowing through monitoring wells. Pattern-recognition software identifies the same particles from one video frame to the next, allowing the velocity and direction of particle movement to be calculated. Directional orientation is provided by a flux-gate magnetometer incorporated within the tool. A schematic diagram of the colloidal borescope in operation is shown in Figure 1. The colloidal borescope is 61.1 cm long and 4.32 cm in diameter (Figure 2), and images a 1.6 x 2.2-mm field of view within a focal plane 0.1-mm thick.

Figure 1. Conceptual diagram of the colloidal borescope.

Figure 2. Colloidal borescope (courtesy of AquaVISION).

The colloidal borescope can measure velocities from $<10 \mu\text{m/s}$ to 3 cm/s (<0.9 to 2600 m/day) and directions within 1° . Velocities are best considered in a relative (qualitative) sense to compare flow at different depths than as an absolute (quantitative) measure of groundwater velocity. This is because flow fields are often distorted in the immediate vicinity of wells so that more water passes through the well than passes through an equivalent cross section of aquifer (Drost et al., 1968). Kearl (1997) estimates that water velocity through a well may be as much as four times greater than the seepage velocity (the average velocity per cross-sectional area) in the surrounding formation.

The colloidal borescope was deployed in ten WIPP wells by RAS, Inc., in cooperation with Sandia National Laboratories to evaluate its effectiveness in defining the direction and velocity of groundwater flow under ambient and stressed conditions in wells completed in different fashions. Nine of the wells are completed to the Culebra Dolomite Member of the Rustler Formation, the most significant water-bearing horizon above the WIPP repository, and one well is completed to the Magenta Member of the Rustler Formation. If effective, the colloidal borescope could provide objective validation of the flow directions and velocities predicted by the groundwater-flow models of the Culebra used for WIPP performance assessment (PA) as well as help satisfy regulatory requirements to determine Culebra groundwater flow rates and directions on an annual basis (NMED, 1999).

2. WELLS LOGGED

The colloidal borescope was used in all seven wells on the H-19 hydropad, well H-9b, well H-6c, and well H-2b2 (Figure 3). The H-19 wells are cased with fiberglass to near the top of the Culebra, and then open holes through the Culebra (Figure 4), which was the interval of interest and is known to be fractured at this location (Beauheim and Ruskauff, 1998). H-9b is similarly completed through fractured Culebra, except that it contains steel casing rather than fiberglass. H-6c is cased with steel, and perforated across the unfractured Magenta, which was the interval of interest in that well. H-2b2 is cased with steel, and contains a stainless steel well screen across the unfractured Culebra interval.

Figure 3. Wells involved in colloidal-borescope logging.

Notes:
All depths in feet below ground surface
Drawing not to scale

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Figure 4a. As-built configurations of wells H-19b0, H-19b3, H-19b5, and H-19b7.

Figure 4b. As-built configurations of wells H-19b2, H-19b4, and H-19b6.

Colloidal-borescope logging was performed at H-19 from August 14 to 16, 1999, October 8 to 12, 1999, and March 9 to 11, 2000. The logging on October 11 and 12, 1999 was performed while nearby well WQSP-4 was being pumped for water-quality sampling. Figure 5 shows the relative positions of the wells on the H-19 hydropad and WQSP-4. Colloidal-borescope logging was performed in well H-9b on August 13, 16, and 17, 1999, in well H-6c on March 7, 2000, and in well H-2b2 on March 8, 2000. No

Figure 5. Relative locations of the wells on the H-19 hydropad and WQSP-4.

valid logs were obtained from either H-6c or H-2b2 because suspended casing-scale particles in the water prevented the camera from obtaining an image.

3. LIMITATIONS OF THE COLLOIDAL BORESCOPE

The colloidal borescope has limitations that restrict its application and usefulness. The tool is run in and out of wells by hand on a cable lacking reliable, permanent depth markers. Temporary tape markers are placed on the cable at 100-ft increments every time the tool is deployed using a 100-ft engineer's tape as the calibration standard. At the last 100-ft marker before the interval to be logged is reached, the engineer's tape is itself taped to the cable and thereafter read directly to provide information on tool depth below top of casing (btc). The engineer's tape is detached and reattached each time the colloidal borescope is removed from one well and placed in another. This entire procedure is unlikely to be repeatable with a precision of less than one or two inches. Considering that the focal plane of the tool is only 0.1 mm thick, repeating a measurement precisely at any given depth is virtually impossible. In general, depth measurements made during the same deployment of the tool (i.e., August 1999, October 1999, or March 2000), and especially while the tool remains in a single well, should be more directly comparable than measurements made during different deployments because they will be referenced to the same 100-ft depth markers.

Because of the limitations associated with positioning the colloidal borescope, the only way to determine the effect that pumping has on flow at any particular horizon is to make a measurement before pumping begins and then leave the tool at that horizon until pumping begins and another measurement can be made. This obviously precludes making directly comparable measurements at multiple horizons before and during a single pumping episode. The best that can be done to evaluate the effects of pumping at multiple horizons is to make measurements at approximately the same positions. Given the similarities in flow directions but differences in velocities that we have observed at different depths within individual wells, comparison of flow directions is likely to be more meaningful than comparison of velocities when making before- and during-pumping measurements.

The colloidal borescope requires clean water to function. Excessive suspended material in the water, such as was encountered in H-2b2 and H-6c, renders the tool useless. The act of inserting the tool into a well dislodges loose material on the casing wall, which then interferes with operation of the tool. In H-2b2 and H-6c, we scraped the casing and allowed several weeks for particulate matter to settle out of the water column before running the colloidal borescope, but enough residual material was either dislodged from the casing during tool emplacement or was still suspended in the water to prevent the tool from obtaining images.

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4. DATA COLLECTION, REDUCTION, AND INTERPRETATION

When first using the colloidal borescope, we observed that the presence of good directional flow was usually evident within 20 minutes. Kearn and Roemer (1998) recommend that once a flowing zone is identified, data be collected for at least two hours to determine flow direction and velocity. We found that, in most cases, once directional flow was established, 20 minutes of additional data collection were adequate to provide direction and velocity data sufficient for our purposes. Thus, we established criteria of 20 minutes to establish the existence of flow and 20 minutes of good flow data to define flow direction and velocity to guide our investigation. These general criteria were modified as felt appropriate at individual stations. Later, more-detailed examination of the data revealed a few instances where longer monitoring periods might have been fruitful.

The act of positioning the colloidal borescope at each measurement station caused localized turbulence and swirling of the water. This was typically reflected in initially high and variable velocities and variable flow directions in the early-time data. For calculation of mean flow directions and velocities, the data subjectively determined to have been affected by the tool movement were eliminated. This resulted in the first five to 52 minutes of data being excluded from each data set.

Visual observation of the colloidal-borescope data-acquisition system in operation during logging revealed that the pattern-recognition software would occasionally incorrectly identify different particles in two video frames as being the same particle, providing erroneous readings of particle velocity and flow direction. These erroneous readings are easily identified on plots of the data as outliers from the main data trends (see Figure 6). Erroneous readings were filtered from the data used to calculate mean flow directions and velocities by subjectively defining "acceptable" flow direction and velocity ranges for each data set, and excluding all data outside those ranges. In those cases where flow had a strong northerly component such that the "acceptable" range of flow directions encompassed both flow to the northeast (e.g., 20°) and flow to the northwest (e.g., 330°), 360° were added to the northeastern azimuths (e.g., $20^\circ + 360^\circ = 380^\circ$) so that the correct average azimuth would be calculated (e.g., $(380^\circ + 330^\circ)/2 = 355^\circ$). The resulting ranges encompassed 50 to 180 degrees for flow direction (with one exception), and 150 to 400 $\mu\text{m/s}$ (13 to 35 m/day) for velocity (with two exceptions). In almost all cases, the selected ranges proved to be broader than the mean $\pm$ two standard deviations of the remaining data. Results are presented below for the mean flow direction and velocity at each measurement station providing interpretable data. Directions are given in terms of degrees clockwise from true north. Uncertainties are given as $\pm$ two standard deviations of the filtered data.

The responses observed at the different measurement stations can be grouped into three categories: 1) directional flow; 2) nondirectional swirling flow; and 3) decaying or stagnant flow. Examples of these three types of responses are shown in Figures 6 through 8. Responses such as that presented in Figure 6 show that water is passing through the well at that horizon. Responses such as that presented in Figure 7 are

Figure 6. Example of directional flow from 752.0 ft btc in H-19b4.

Figure 7. Example of nondirectional swirling flow at 744.0 ft btc in H-19b5.

Figure 8. Example of decaying to stagnant flow at 764.0 ft btc in H-19b2.

thought to represent horizons not directly in a flowing zone, but close to one because continued swirling requires an input of energy. Responses such as that presented in Figure 8 reflect horizons where water is not moving. These three types of responses are not completely distinct, but grade into one another.

Metric units are used for all measurements in this report with the exception of depths. As discussed in Chapter 3, depths were measured in the field using a 100-ft engineer's tape and recorded in the field logbooks in units of feet. The footage depth was also used in labeling the computer data file for each logging run. For ease of referencing, the footage depths are also used in this report. Equivalent depths in meters are given in the summary tables for each well.

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5. RESULTS FROM H-19

Colloidal-borescope logging was performed at H-19 under both ambient (undisturbed) conditions and while pumping well WQSP-4, which is located approximately 220 m eastnortheast of H-19b0 (Figure 5). All seven of the wells on the H-19 hydropad were logged under ambient conditions, but only H-19b0, H-19b2, H-19b3, and H-19b4 were logged while pumping WQSP-4. As-built configurations of the H-19 wells are shown in Figure 4.

5.1 Logging Under Ambient Conditions

5.1.1 H-19b0

Colloidal-borescope logging was performed under ambient conditions at 14 stations in H-19b0 on October 9, 1999 (Table 1). Only two of the stations, 763.0 and 765.0 ft btc, provided clear indications of flow direction and velocity (Figures 9 and 10). Flow directions were consistent, 160° and 161°, and flow velocities were 220 and 180 $\mu\text{m/s}$ (19 and 16 m/day) at 763.0 and 765.0 ft btc, respectively (Table 1). Variable, swirling flow was observed at the other measurement stations. No stagnant zones were detected.

Table 1. Summary of Colloidal-Borescope Logging in H-19b0

Depth (ft btc)	Depth (m btc)	Date	Duration (min.)	Start time ¹ (min.)	Azimuth range ² (°)	Velocity range ² ($\mu\text{m/s}$)	Mean azimuth ± 2 std. dev. (°)	Mean velocity ± 2 std. dev. ($\mu\text{m/s}$)	Flow Type ³
742.00	226.16	10/9/99	23	NA					2
744.00	226.77	10/9/99	20	NA					2
746.00	227.38	10/9/99	19	NA					2
748.00	227.99	10/9/99	16	NA					2
750.00	228.60	10/9/99	19	NA					2
752.00	229.21	10/9/99	21	NA					2
754.00	229.82	10/9/99	21	NA					2
756.00	230.43	10/9/99	19	NA					2
758.00	231.04	10/9/99	21	NA					2
760.00	231.65	10/9/99	20	NA					2
762.00	232.26	10/9/99	23	NA					2
763.00	232.56	10/9/99	30	10	120-200	120-300	160 $\pm$ 22	222 $\pm$ 67	1
764.00	232.87	10/9/99	51	NA					2
765.00	233.17	10/9/99	31	10	120-200	95-280	161 $\pm$ 35	184 $\pm$ 73	1
10/12/99 logging was performed while WQSP-4 was being pumped at 0.16 to 0.20 L/s									
756.00	230.43	10/12/99	17	NA					2
763.00	232.56	10/12/99	56	10	320-420	all	347 $\pm$ 30	1410 $\pm$ 900	1
765.00	233.17	10/12/99	55	NA					3

¹ Starting time of data used to calculate mean direction and velocity

² Range used to filter data for calculations

³ 1 = directional; 2 = nondirectional swirling; 3 = decaying or stagnant

NA: not applicable; data not suitable for determination of direction and velocity

Figure 9. Colloidal-borescope logging results at 763.0 ft btc in H-19b0.

Figure 10. Colloidal-borescope logging results at 765.0 ft btc in H-19b0.

5.1.2 H-19b2

Colloidal-borescope logging was performed under ambient conditions in H-19b2 at 13 stations on August 15, 1999, 14 stations on August 16, 1999, and seven stations on October 10, 1999 (Table 2). Clear indications of flow direction and velocity were obtained from eight of these 34 stations (Figures 11 through 18). Flow directions at these stations ranged from 175° to 184° with uncertainties of $\pm 16^\circ$ to 33° , with the exception of the station at 752.9 ft btc, where the flow direction was $161^\circ \pm 27^\circ$ (Figure 13). Flow velocities ranged from 120 to 280 $\mu\text{m/s}$ (11 to 24 m/day) with uncertainties ranging from ± 67 to 120 $\mu\text{m/s}$ (± 5.8 to 10 m/day) (Table 2). Variable, swirling flow was observed at half of the other measurement stations, while flow decaying toward stagnation was observed at the other half.

Figure 11. Colloidal-borescope logging results at 748.0 ft btc in H-19b2.

Table 2. Summary of Colloidal-Borescope Logging in H-19b2

Depth (ft btc)	Depth (m btc)	Date	Duration (min.)	Start time ¹ (min.)	Azimuth range ² (°)	Velocity range ² (µm/s)	Mean azimuth ± 2 std. dev. (°)	Mean velocity ± 2 std. dev. (µm/s)	Flow type ³
744.00	226.77	8/15/99	32	NA					2
746.00	227.38	8/15/99	25	NA					2
748.00	227.99	8/15/99	30	14	120-240	150-350	179 ± 20	244 ± 78	1
750.00	228.60	8/15/99	29	NA					2
751.00	228.90	8/16/99	21	NA					2
752.00	229.21	8/15/99	44	20	135-225	150-400	175 ± 16	281 ± 98	1
752.33	229.31	10/10/99	21	NA					2
752.58	229.39	10/10/99	30	NA					2
752.90	229.48	10/10/99	32	14	120-210	100-350	161 ± 27	220 ± 99	1
753.00	229.51	8/16/99	19	NA					2
754.00	229.82	8/15/99	35	21	90-210	0-320	178 ± 19	216 ± 81	1
755.00	230.12	8/16/99	11	NA					2
756.00	230.43	8/15/99	20	NA					3
756.50	230.58	8/16/99	17	NA					2
757.00	230.73	8/15/99	20	NA					3
757.50	230.89	8/16/99	11	NA					3
758.00	231.04	8/15/99	23	NA					3
758.50	231.19	8/16/99	14	NA					3
759.00	231.34	8/15/99	20	NA					3
759.50	231.50	8/16/99	20	NA					3
760.00	231.65	8/15/99	22	NA					3
761.00	231.95	8/15/99	23	NA					3
761.75	232.18	8/16/99	30	NA					2
762.00	232.26	8/15/99	48	20	120-240	0-350	176 ± 32	131 ± 116	1
762.25	232.33	8/16/99	20	NA					3
762.50	232.41	8/16/99	21	NA					3
763.00	232.56	8/16/99	14	NA					2-3
764.00	232.87	8/16/99	38	NA					3
765.00	233.17	8/16/99	37	10	140-220	60-250	184 ± 25	146 ± 69	1
765.50	233.32	10/10/99	10	NA					2
765.80	233.42	10/10/99	17	NA					2
766.00	233.48	8/16/99	38	10	140-220	100-350	182 ± 29	202 ± 104	1
766.05	233.49	10/10/99	31	NA					2
766.50	233.63	10/10/99	22	10	140-220	50-200	184 ± 33	123 ± 67	1

10/11/99 logging was performed while WQSP-4 was being pumped at 0.18 to 0.24 L/s

752.80	229.45	10/11/99	60	26	135-210	100-300	170 ± 21	184 ± 72	1
752.90	229.48	10/11/99	95	52	120-240	0-300	167 ± 48	171 ± 92	1
766.50	233.63	10/11/99	30	16	90-240	0-200	173 ± 57	98 ± 63	1
766.80	233.72	10/11/99	61	30	135-210	0-200	171 ± 29	104 ± 60	1

¹ Starting time of data used to calculate mean direction and velocity

² Range used to filter data for calculations

³ 1 = directional; 2 = nondirectional swirling; 3 = decaying or stagnant

NA: not applicable; data not suitable for determination of direction and velocity

Figure 12. Colloidal-borescope logging results at 752.0 ft btc in H-19b2.

Figure 13. Colloidal-borescope logging results at 752.9 ft btc in H-19b2.

Figure 14. Colloidal-borescope logging results at 754.0 ft btc in H-19b2.

Figure 15. Colloidal-borescope logging results at 762.0 ft btc in H-19b2.

Figure 16. Colloidal-borescope logging results at 765.0 ft btc in H-19b2.

Figure 17. Colloidal-borescope logging results at 766.0 ft btc in H-19b2.

Figure 18. Colloidal-borescope logging results at 766.5 ft btc in H-19b2.

5.1.3 H-19b3

Colloidal-borescope logging was performed under ambient conditions at 11 stations in H-19b3 on October 9, 1999 (Table 3). Only the station at 757.0 ft btc provided any indication of flow direction and velocity (Figure 19), and even the data from this station were not as clear as the data from the good flowing zones found in H-19b2 or H-19b4. The indicated flow direction was 214° and the flow velocity was $180 \mu\text{m/s}$ (15 m/day) (Table 3). Swirling flow was observed at 752.0, 754.0, 756.0, and 758.0 ft btc, whereas flow appeared to be dying away to stagnation from 759.0 through 764.0 ft btc.

Table 3. Summary of Colloidal-Borescope Logging in H-19b3

Depth (ft btc)	Depth (m btc)	Date	Duration (min.)	Start time ¹ (min.)	Azimuth range ² (°)	Velocity range ² ($\mu\text{m/s}$)	Mean azimuth ± 2 std. dev. (°)	Mean velocity ± 2 std. dev. ($\mu\text{m/s}$)	Flow type ³
752.00	229.21	10/9/99	25	NA					2
754.00	229.82	10/9/99	24	NA					2
756.00	230.43	10/9/99	22	NA					2
757.00	230.73	10/9/99	30	15	150-275	0-300	214 ± 44	176 ± 85	1
758.00	231.04	10/9/99	15	NA					2
759.00	231.34	10/9/99	11	NA					3
760.00	231.65	10/9/99	15	NA					3
761.00	231.95	10/9/99	10	NA					3
762.00	232.26	10/9/99	10	NA					3
763.00	232.56	10/9/99	10	NA					3
764.00	232.87	10/9/99	9	NA					3

WQSP-4 pumping rate during 10/11/99 logging was 0.02 L/s, except at 757.00 ft btc when it decreased from 0.18 to 0.02 L/s; WQSP-4 pumping rate during 10/12/99 logging increased from 0.03 to 0.20 L/s

754.00	229.82	10/11/99	43	20	180-240	100-250	214 ± 18	169 ± 51	1
754.00	229.82	10/12/99	52	16	150-225	80-250	190 ± 25	166 ± 67	1
755.00	230.12	10/11/99	35	16	135-300	0-250	217 ± 76	126 ± 69	1
756.80	230.67	10/11/99	60	36	170-270	0-250	223 ± 42	131 ± 78	1
757.00	230.73	10/11/99	63	24	120-300	50-400	225 ± 60	214 ± 152	1
765.00	233.17	10/11/99	30	NA					2

¹ Starting time of data used to calculate mean direction and velocity

² Range used to filter data for calculations

³ 1 = directional; 2 = nondirectional swirling; 3 = decaying or stagnant

NA: not applicable; data not suitable for determination of direction and velocity

Figure 19. Colloidal-borescope logging results at 757.0 ft btc in H-19b3.

5.1.4 H-19b4

Colloidal-borescope logging was performed under ambient conditions in H-19b4 at 13 stations on August 14, 1999, five stations on August 15, 1999, and four stations on October 10, 1999 (Table 4). Two of the stations logged on October 10, 1999 had been logged previously: 753.0 ft btc on August 14, 1999, and 764.0 ft btc on August 15, 1999. Good flow direction and velocity data were collected from the stations at 750.0, 752.0, 753.0 (both dates), 753.52, 754.0, 755.0, 761.0, 762.0, 763.0, 763.5, and 764.0 (both dates) ft btc (Figures 20 through 32). With two exceptions, flow directions were all in the range from 282° to 296° with uncertainties ranging from $\pm 11^\circ$ to 37° . The flow direction at 761.0 ft btc was $261^\circ \pm 29^\circ$ and at 763.5 ft btc was $311^\circ \pm 49^\circ$ (see Figures 27 and 30), so all of the direction measurements have overlapping ranges of uncertainty. The flow data collected on October 10, 1999 at 753.0 and 764.0 ft btc were not as clear as the data collected previously (compare Figure 22 to Figure 23 and Figure 31 to Figure 32), but provided consistent information. The differences observed in the data from the two dates may be due to the colloidal borescope not really being at exactly the same depths for the different sets of measurements. Measured velocities ranged from 96 to $290 \mu\text{m/s}$ (8.3 to 25 m/day) with uncertainties of 43 to $140 \mu\text{m/s}$ (± 3.7 to 12 m/day) (Table 4). Flow was decaying to stagnation from 757.0 to 760.0 ft btc, and swirling at the remaining stations.

Figure 20. Colloidal-borescope logging results at 750.0 ft btc in H-19b4.

Table 4. Summary of Colloidal-Borescope Logging in H-19b4

Depth (ft btc)	Depth (m btc)	Date	Duration (min.)	Start time ¹ (min.)	Azimuth range ² (°)	Velocity range ² (µm/s)	Mean azimuth ± 2 std. dev. (°)	Mean velocity ± 2 std. dev. (µm/s)	Flow type ³
744.00	226.77	8/14/99	28	NA					2
746.00	227.38	8/14/99	25	NA					2
748.00	227.99	8/14/99	24	NA					2
750.00	228.60	8/14/99	48	25.5	260-330	100-300	293 ± 17	205 ± 92	1
752.00	229.21	8/14/99	43	20	255-315	150-300	287 ± 14	231 ± 58	1
753.00	229.51	8/14/99	50	40	240-330	150-300	291 ± 11	231 ± 43	1
753.00	229.51	10/10/99	36	16	240-330	150-400	282 ± 37	261 ± 111	1
753.52	229.67	10/10/99	34	14	270-320	200-400	296 ± 15	292 ± 76	1
754.00	229.82	8/14/99	43	20	270-320	100-250	296 ± 18	150 ± 54	1
755.00	230.12	8/14/99	74	20	260-330	80-250	295 ± 20	145 ± 58	1
756.00	230.43	8/14/99	25	NA					2
757.00	230.73	8/14/99	23	NA					3
758.00	231.04	8/14/99	21	NA					3
758.50	231.19	8/15/99	24	NA					3
759.00	231.34	8/14/99	21	NA					3
760.00	231.65	8/14/99	21	NA					3
761.00	231.95	8/15/99	30	0	225-300	0-200	261 ± 29	96 ± 66	1
762.00	232.26	8/15/99	41	12	260-330	100-300	289 ± 18	199 ± 70	1
763.00	232.56	8/15/99	41	10	260-320	100-300	292 ± 14	196 ± 59	1
763.50	232.71	10/10/99	20	6	250-360	100-400	311 ± 49	206 ± 142	1
764.00	232.87	8/15/99	36	10	260-320	100-300	292 ± 17	189 ± 73	1
764.00	232.87	10/10/99	24	10	250-330	80-350	293 ± 34	176 ± 132	1

10/12/99 logging was performed while WQSP-4 was being pumped at 0.02 to 0.03 L/s, except at 753.52 ft btc, when the rate was 0.16 L/s

752.00	229.21	10/12/99	36	NA					2
753.00	229.51	10/12/99	29	NA					2
753.52	229.67	10/12/99	27	NA					2
754.00	229.82	10/12/99	21	NA					2
754.50	229.97	10/12/99	21	8	240-480	0-200	1 ± 125	89 ± 61	1
755.00	230.12	10/12/99	17	NA					2
764.00	232.87	10/12/99	61	30	240-330	0-300	291 ± 28	144 ± 79	1

¹ Starting time of data used to calculate mean direction and velocity

² Range used to filter data for calculations

³ 1 = directional; 2 = nondirectional swirling; 3 = decaying or stagnant

NA: not applicable; data not suitable for determination of direction and velocity

Figure 21. Colloidal-borescope logging results at 752.0 ft btc in H-19b4.

Figure 22. Colloidal-borescope logging results at 753.0 ft btc in H-19b4, first run.

Figure 23. Colloidal-borescope logging results at 753.0 ft btc in H-19b4, second run.

Figure 24. Colloidal-borescope logging results at 753.52 ft btc in H-19b4.

Figure 25. Colloidal-borescope logging results at 754.0 ft btc in H-19b4.

Figure 26. Colloidal-borescope logging results at 755.0 ft btc in H-19b4.

Figure 29. Colloidal-borescope logging results at 763.0 ft btc in H-19b4.

Figure 30. Colloidal-borescope logging results at 763.5 ft btc in H-19b4.

Figure 31. Colloidal-borescope logging results at 764.0 ft btc in H-19b4, first run.

Figure 32. Colloidal-borescope logging results at 764.0 ft btc in H-19b4, second run.

5.1.5 H-19b5

Colloidal-borescope logging in H-19b5 was performed at ten stations on October 10, 1999, four stations on March 10, 2000, and eight stations on March 11, 2000 (Table 5). The results were ambiguous at best. Flow directions and velocities were inferred for four stations, but uncertainties are high in all cases (Figures 33 through 36). The four stations were selected because neither flow direction nor velocity showed the periodic sweeping changes associated with nondirectional, swirling flow but instead seemed to be focused within distinct, although in some instances broad, ranges. The four stations can be divided into two groups based on overlapping ranges of uncertainty for flow direction. The inferred flow directions for the stations at 743.00 and 753.00 ft btc were $358^{\circ} \pm 58^{\circ}$ and $305^{\circ} \pm 56^{\circ}$, respectively, and those for the stations at 750.02 and 752.00 ft btc were $146^{\circ} \pm 69^{\circ}$ and $183^{\circ} \pm 62^{\circ}$, respectively. In each pair, one of the measurements was performed in October 1999 and the other was performed in March 2000, so the difference between pairs does not represent a change over time. Because of the inconsistency in inferred flow directions at the four stations, we question whether any of the measurements are providing reliable data. Velocities ranged from 53 $\mu\text{m/s}$ (4.6 m/day) to 190 $\mu\text{m/s}$ (16 m/day) (Table 5). Flow at half of the other stations monitored in H-19b5 was variable and swirling, while flow at the other half showed declining velocities indicative of stagnant zones (Table 5).

Table 5. Summary of Colloidal-Borescope Logging in H-19b5

Depth (ft btc)	Depth (m btc)	Date	Duration (min.)	Start time ¹ (min.)	Azimuth Range ² (°)	Velocity range ² ($\mu\text{m/s}$)	Mean azimuth ± 2 std. dev. (°)	Mean velocity ± 2 std. dev. ($\mu\text{m/s}$)	Flow type ³
742.00	226.16	3/10/00	34	NA					2
743.00	226.47	3/10/00	42	10	300-420	0-300	358 ± 58	139 ± 103	1
744.00	226.77	3/10/00	38	NA					2
745.00	227.08	3/10/00	35	NA					2
746.00	227.38	3/11/00	35	NA					2-3
747.00	227.69	3/11/00	44	NA					2-3
748.00	227.99	3/11/00	49	NA					2-3
749.00	228.30	3/11/00	51	NA					2
750.00	228.60	10/10/99	43	NA					2
750.02	228.61	3/11/00	60	30	60-240	0-100	146 ± 69	53 ± 29	1
751.00	228.90	10/10/99	24	NA					2
752.00	229.21	10/10/99	23	14	130-260	0-300	183 ± 62	141 ± 115	1
753.00	229.51	10/10/99	27	10	210-360	50-350	305 ± 56	186 ± 133	1
753.02	229.52	3/11/00	49	NA					2-3
754.00	229.82	10/10/99	20	NA					2
755.00	230.12	10/10/99	20	NA					2
756.00	230.43	10/10/99	13	NA					3
757.00	230.73	10/10/99	8	NA					3
758.00	231.04	3/11/00	51	NA					3
759.00	231.34	10/10/99	15	NA					3
760.00	231.65	3/11/00	32	NA					3
761.00	231.95	10/10/99	10	NA					2

¹ Starting time of data used to calculate mean direction and velocity

² Range used to filter data for calculations

³ 1 = directional; 2 = nondirectional swirling; 3 = decaying or stagnant

NA: not applicable; data not suitable for determination of direction and velocity

Figure 33. Colloidal-borescope logging results at 743.0 ft btc in H-19b5.

Figure 34. Colloidal-borescope logging results at 750.02 ft btc in H-19b5.

Figure 35. Colloidal-borescope logging results at 752.0 ft btc in H-19b5.

Figure 36. Colloidal-borescope logging results at 753.0 ft btc in H-19b5.

5.1.6 H-19b6

Colloidal-borescope logging was performed at 22 stations in H-19b6 on October 8, 1999 (Table 6). Flow direction and velocity could be inferred for only one station, 752.0 ft btc (Figure 37). At this station, the flow direction was 299° and the velocity was 270 $\mu\text{m/s}$ (23 m/day) (Table 6). Swirling flow was observed at most of the other stations. Flow rates were low and declining in the intervals from 742.0 to 744.0 ft btc and 757.0 to 761.0 ft btc, indicating stagnant conditions.

Table 6. Summary of Colloidal-Borescope Logging in H-19b6

Depth (ft btc)	Depth (m btc)	Date	Duration (min.)	Start time ¹ (min.)	Azimuth range ² (°)	Velocity range ² ($\mu\text{m/s}$)	Mean azimuth $\pm$ 2 std. dev. (°)	Mean velocity $\pm$ 2 std. dev. ($\mu\text{m/s}$)	Flow type ³
742.00	226.16	10/8/99	29	NA					3
744.00	226.77	10/8/99	18	NA					3
746.00	227.38	10/8/99	21	NA					2
748.00	227.99	10/8/99	25	NA					2
749.00	228.30	10/8/99	20	NA					2
750.00	228.60	10/8/99	20	NA					2
751.00	228.90	10/8/99	21	NA					2
751.50	229.06	10/8/99	21	NA					2
751.90	229.18	10/8/99	28	NA					2
752.00	229.21	10/8/99	25	10	250-350	100-500	299 $\pm$ 38	267 $\pm$ 192	1
752.10	229.24	10/8/99	16	NA					2
753.00	229.51	10/8/99	24	NA					2
754.00	229.82	10/8/99	20	NA					2
755.00	230.12	10/8/99	22	NA					2
756.00	230.43	10/8/99	20	NA					2
757.00	230.73	10/8/99	23	NA					3
758.00	231.04	10/8/99	21	NA					3
759.00	231.34	10/8/99	33	NA					3
760.00	231.65	10/8/99	14	NA					3
761.00	231.95	10/8/99	12	NA					3
762.00	232.26	10/8/99	12	NA					2
764.00	232.87	10/8/99	12	NA					2

¹ Starting time of data used to calculate mean direction and velocity

² Range used to filter data for calculations

³ 1 = directional; 2 = nondirectional swirling; 3 = decaying or stagnant

NA: not applicable; data not suitable for determination of direction and velocity

Figure 37. Colloidal-borescope logging results at 752.0 ft btc in H-19b6.

5.1.7 H-19b7

Colloidal-borescope logging was performed in H-19b7 at 20 stations on March 9, 2000 and 11 stations on March 10, 2000 (Table 7). Flow direction and velocity could be determined only for the stations at 743.10 and 763.05 ft btc (Figures 38 and 39). At 743.10 ft btc, the flow direction was 188° and the velocity was $220 \mu\text{m/s}$ (19 m/day), while at 763.05 ft btc, the flow direction was 164° and the velocity was $74 \mu\text{m/s}$ (6.4 m/day) (Table 7). At neither of these stations was flow direction as well defined as in the good flowing zones in H-19b2 and H-19b4. In hindsight, longer monitoring periods would have been useful at these stations, but we were unaware at the time of logging that these would be the best (or only) flowing zones found. Flow was either decaying or stagnant in the intervals from 751.08 to 752.60 ft btc and 755.09 to 762.08 ft btc. Swirling flow was observed at most other locations.

Table 7. Summary of Colloidal-Borescope Logging in H-19b7

Depth (ft btc)	Depth (m btc)	Date	Duration (min)	Start time ¹ (min.)	Azimuth range ² (°)	Velocity range ² (µm/s)	Mean azimuth ± 2 std. dev. (°)	Mean velocity ± 2 std. dev. (µm/s)	Flow type ³
743.10	226.50	3/9/00	21	5	140-300	0-400	188 ± 57	216 ± 154	1
745.20	227.14	3/9/00	22	NA					2
747.13	227.73	3/9/00	19	NA					2
747.98	227.98	3/10/00	31	NA					2
749.07	228.32	3/9/00	21	NA					2
750.00	228.60	3/10/00	32	NA					2
751.08	228.93	3/9/00	21	NA					3
752.04	229.22	3/9/00	51	NA					3
752.60	229.39	3/10/00	26	NA					3
753.10	229.54	3/9/00	28	NA					2
753.43	229.65	3/9/00	22	NA					2
754.01	229.82	3/9/00	27	NA					2
754.50	229.97	3/10/00	29	NA					2
755.09	230.15	3/9/00	19	NA					3
755.53	230.29	3/10/00	25	NA					3
756.02	230.43	3/9/00	25	NA					3
756.49	230.58	3/10/00	29	NA					3
757.04	230.75	3/9/00	26	NA					3
757.70	230.95	3/10/00	20	NA					3
758.10	231.07	3/9/00	13	NA					3
758.51	231.19	3/10/00	9	NA					3
759.12	231.38	3/9/00	5	NA					3
759.54	231.51	3/10/00	26	NA					3
760.11	231.68	3/9/00	6	NA					3
760.50	231.80	3/10/00	19	NA					3
761.07	231.97	3/9/00	7	NA					3
761.51	232.11	3/10/00	6	NA					3
762.08	232.28	3/9/00	11	NA					3
763.05	232.58	3/9/00	24	11	120-220	20-150	164 ± 42	74 ± 50	1
764.13	232.91	3/9/00	16	NA					2
765.01	233.18	3/9/00	18	NA					2

¹ Starting time of data used to calculate mean direction and velocity

² Range used to filter data for calculations

³ 1 = directional; 2 = nondirectional swirling; 3 = decaying or stagnant

NA: not applicable; data not suitable for determination of direction and velocity

Figure 38. Colloidal-borescope logging results at 743.1 ft btc in H-19b7.

Figure 39. Colloidal-borescope logging results at 763.05 ft btc in H-19b7.

5.1.8 Summary of Logging Performed Under Ambient Conditions at H-19

Based on the modeling of Culebra transmissivity fields for PA calculations (e.g., WIPP PA Department, 1993), flow in the Culebra at the H-19 hydropad was expected to be to the south or southeast. Flow in the Culebra at H-19 is also thought to be concentrated primarily in fractures (Beauheim and Ruskauff, 1998). Flow directions and velocities could be determined for only 31 of the 156 stations logged in the wells on the H-19 hydropad, which may represent the frequency with which we positioned the colloidal borescope adjacent to a flowing fracture. The clearest flow directions were obtained in H-19b0, H-19b2, and H-19b4. The data from H-19b3, H-19b6, H-19b7, and especially H-19b5 are more ambiguous.

The mean flow directions determined at each well are shown in Figure 40. Two directions are shown for H-19b5 corresponding to the two pairs of measurements with overlapping uncertainty bounds. Flow in H-19b0, H-19b2, H-19b3, and H-19b7 is generally to the south, as expected, whereas flow in H-19b4 and H-19b6 appears to be slightly north of west. Flow in H-19b5 could be in either (or both?) direction(s). Interestingly, H-19b4, H-19b5, and H-19b6 were found to be more poorly connected to H-19b0 than H-19b2, H-19b3, and H-19b7 during sinusoidal pumping tests conducted in 1995. Flow in fracture systems is not necessarily perpendicular to regional potentiometric contours, but is controlled in part by the orientations of the fractures themselves. Perhaps the small fractures intersected by each well feed into some larger fracture features (through which flow trends predominantly to the south), and H-19b4, H-19b5, and H-19b6 feed into a feature located to the northwest while the other four H-19 wells feed into a feature to the south.

Beauheim (2000) reports multiple lines of evidence indicating that the permeability of the upper 3 m of Culebra is much lower than that of the lower 4 m at H-19. Likewise, convergent-flow, tracer tests showed that most solute transport occurs in the lower Culebra (Meigs et al., 2000). Thus, we expected that the colloidal borescope would reveal more flowing zones in the lower Culebra than in the upper Culebra and, in fact, concentrated our efforts in the lower Culebra in the initial stages of this investigation. However, good flowing zones were found in the upper Culebra in both H-19b2 and H-19b4, the wells with the most flowing zones. In addition, velocities were as high or higher in the upper Culebra than in the rest of the Culebra.

The mean velocities observed in the H-19 wells ranged from 53 to 290 $\mu\text{m/s}$ (4.6 to 25 m/day), with an average of 190 $\mu\text{m/s}$ (16 m/day). Kearl (1997) states that compression of flow lines leading toward a well may cause velocities to increase by as much as a factor of four, so the actual velocities at H-19 may range from only 13 to 73 $\mu\text{m/s}$ (1.1 to 6.3 m/day). In a medium in which flow enters and exits a well under laminar conditions only through fractures, the flow velocity through the well should be related to the flow velocity in the fractures in the surrounding formation, increased by the compression factor discussed above. We can calculate expected velocities in fractures, commonly called pore-water velocities (v_p), based on the available data on the hydraulic conductivity (K), hydraulic gradient (I), and advective porosity (ϕ_a) of the Culebra using the equation:

Figure 40. Mean flow directions in H-19 wells under ambient conditions.

$$v_p = \frac{KI}{\phi_a}$$

Beauheim and Ruskauff (1998) give the transmissivity of the Culebra at H-19 as $6.8 \times 10^{-6} \text{ m}^2/\text{s}$. If this transmissivity were uniformly distributed over the 4.4-m-thickness of the lower Culebra, the average hydraulic conductivity would be $1.5 \times 10^{-6} \text{ m/s}$. Altman et al. (2000) estimate the hydraulic gradient at H-19 as approximately 0.01. Kelley et al. (2000) estimated advective porosities ranging from 1×10^{-4} to 7×10^{-2} from simulation of the H-19 convergent-flow tracer tests using a multirate-diffusion model. These values give mean pore-water velocities ranging from 0.2 to 150 $\mu\text{m/s}$ (0.02 to 13 m/day). Thus, the velocities shown by the colloidal borescope are consistent with pore-water velocities estimated independently within the factor of four uncertainty proposed by Kearn (1997).

While flow in the Culebra may be concentrated in fractures, no part of the Culebra matrix is impermeable, so we would expect to see some flow, albeit at a low velocity, at every measurement station. Instead, we saw directional flow at only 20 percent of the stations, nondirectional swirling flow at approximately 45 percent of the stations, and no mean velocity lower than 53 $\mu\text{m/s}$ (4.6 m/day) at a station showing directional flow. We characterized flow at approximately 35 percent of the H-19 measurement stations as decaying or stagnant. To be characterized in this way, the flow velocity had to be below 100 $\mu\text{m/s}$ and steadily declining with no clear flow direction being established. Flow was actually stagnant at only a few stations (e.g., Figure 8). Perhaps a flow direction and stable low velocity would have been established at most of the stations showing decaying flow after a prolonged monitoring period, or perhaps the velocity would have been below the resolution limit of the colloidal borescope ($< 10 \mu\text{m/s}$).

5.2 Logging While Pumping WQSP-4

Colloidal-borescope logging was performed in H-19b0 (three stations), H-19b2 (four stations), H-19b3 (six stations), and H-19b4 (seven stations) on October 11 and 12, 1999, while well WQSP-4 (see Figures 3 and 5) was being pumped for water-quality sampling. The well was pumped at a relatively high rate ranging from approximately 0.16 to 0.24 L/s (2.5 to 3.7 gpm) during primary daytime working hours, and was lowered to a rate ranging from approximately 0.019 to 0.027 L/s (0.3 to 0.4 gpm) the rest of the time. The logging in H-19b0 and H-19b2 was performed while WQSP-4 was being pumped at the higher rate. The logging in H-19b3 and H-19b4 was performed while WQSP-4 was being pumped at the lower rate, except for the logging at 754.0 and 757.0 ft btc in H-19b3 and at 753.52 ft btc in H-19b4, which were performed at the higher pumping rate. Flow direction and velocity information could be derived for 12 of the 20 stations logged.

5.2.1 H-19b0

Of the three stations logged in H-19b0 while pumping WQSP-4 at 0.16 to 0.20 L/s, flow direction and velocity could be determined only at 763.0 ft btc (Table 1). The flow direction was primarily northnorthwest, but would periodically shift rapidly to the northeast and then shift back to the northwest more gradually (Figure 41). The average

Figure 41. Colloidal-borescope logging results at 763.0 ft btc in H-19b0 while pumping WQSP-4.

flow direction was 347° (Table 1). Velocity measurements were cyclic, with higher amplitudes and magnitudes than had been observed at any measurement station under ambient conditions. The average velocity was approximately 1400 $\mu\text{m/s}$ (120 m/day), but had a wide variation and appeared to be decreasing with time.

5.2.2 H-19b2

Flow directions and velocities could be determined for all four stations where the colloidal borescope was set in H-19b2 while pumping WQSP-4 at 0.18 to 0.24 L/s (Table 2). The data from 752.8, 752.9, 766.5, and 766.8 ft btc are shown in Figures 42 through 45. The mean flow directions were all very similar, ranging only from 167° to 173°, with uncertainties ranging from $\pm 21^\circ$ to 57° . Velocities ranged from 98 to 180 $\mu\text{m/s}$ (8 to 16 m/day) with uncertainties ranging from ± 60 to 92 $\mu\text{m/s}$ (± 5 to 8 m/day) (Table 2).

Figure 42. Colloidal-borescope logging results at 752.8 ft btc in H-19b2 while pumping WQSP-4.

Figure 43. Colloidal-borescope logging results at 752.9 ft btc in H-19b2 while pumping WQSP-4.

Figure 44. Colloidal-borescope logging results at 766.5 ft btc in H-19b2 while pumping WQSP-4.

Figure 45. Colloidal-borescope logging results at 766.8 ft btc in H-19b2 while pumping WQSP-4.

5.2.3 H-19b3

Colloidal-borescope logging was performed at five stations in H-19b3 on October 11, 1999 and was repeated at one station (754.0 ft btc) on October 12, 1999 (Table 3). All of the logging on October 11, 1999 was performed while WQSP-4 was being pumped at 0.02 L/s, except for the logging at 757.0 ft btc which spanned the time when the rate was decreased from 0.18 to 0.02 L/s. The logging on October 12, 1999 spanned the time in the morning when the rate was increased from 0.03 to 0.20 L/s. Flow direction and velocity information could be determined from all of the logs except for the one from 765.0 ft btc (Figures 46 through 50).

Figure 46. Colloidal-borescope logging results at 754.0 ft btc in H-19b3 while pumping WQSP-4, first run.

The four logs collected on October 11, 1999 showed flow directions ranging from 214° to 225° (Table 3). Although the differences are slight compared to the uncertainties ($\pm 18^\circ$ to 76°), we note that the mean flow direction at each successive station was slightly to the east of that at the previous station on October 11. At the station with the highest mean velocity, 757.0 ft btc, the flow direction appeared to be shifting to the east (from the southwest to the south) with time during the logging run (Figure 50). The colloidal borescope was left in place at 754.0 ft btc overnight and, when logging resumed on October 12, 1999, the mean flow direction at that depth had shifted from 214° to 190° (compare Figures 46 and 47). The data from 754.0 ft btc on October 12 also had a more oscillatory appearance than the data from October 11, perhaps because of the increase in pumping rate that occurred approximately 20 minutes after the logging run began. Mean velocities in H-19b3 ranged from 130 to 210 $\mu\text{m/s}$ (11 to 18 m/day), with uncertainties of ± 51 to 150 $\mu\text{m/s}$ (± 4 to 13 m/day) (Table 3).

Figure 47. Colloidal-borescope logging results at 754.0 ft btc in H-19b3 while pumping WQSP-4, second run.

Figure 48. Colloidal-borescope logging results at 755.0 ft btc in H-19b3 while pumping WQSP-4.

Figure 49. Colloidal-borescope logging results at 756.8 ft btc in H-19b3 while pumping WQSP-4.

Figure 50. Colloidal-borescope logging results at 757.0 ft btc in H-19b3 while pumping WQSP-4.

5.2.4 H-19b4

Six stations were logged with the colloidal borescope in H-19b4 while WQSP-4 was pumped at 0.02 to 0.03 L/s, and one station was logged while pumping at 0.16 L/s, all on October 12, 1999 (Table 4). Flow direction and velocity could be inferred for two of the stations logged at the lower rate: 754.5 ft btc (Figure 51) and 764.0 ft btc (Figure 52). The direction data from 754.5 ft btc oscillated with an amplitude of approximately 180° and a mean of 1° . The velocity data also oscillated, but within a narrow band of approximately $150 \mu\text{m/s}$ (13 m/day) and a mean of $89 \mu\text{m/s}$ (8 m/day). The data from 764.0 ft btc were more consistent (Figure 52). The flow direction at this depth was 291° and the velocity was $140 \mu\text{m/s}$ (12 m/day) (Table 4).

Figure 51. Colloidal-borescope logging results at 754.5 ft btc in H-19b4 while pumping WQSP-4.

Figure 52. Colloidal-borescope logging results at 764.0 ft btc in H-19b4 while pumping WQSP-4.

5.3 Comparison of Logs Collected Under Ambient Conditions to Logs Collected While Pumping WQSP-4

We expected flow directions at H-19 to shift toward WQSP-4 to the east when that well was pumped because water-level measurements in each of the H-19 wells showed more than 0.7 m of drawdown, but this was not reflected in the data. Except at H-19b0, flow directions at those stations logged under both ambient conditions and while pumping WQSP-4 were generally more variable (i.e., had higher uncertainties) but not significantly different during pumping than under ambient conditions (compare Figures 13 and 43 and see Table 8). In many instances, the pumping at WQSP-4 appeared to create an oscillatory pattern in both the velocity and flow direction in the H-19 wells (e.g., Figures 41, 42, 47, and 52). Perhaps the distribution and orientation of fractures between WQSP-4 and H-19 are not conducive to a strongly oriented east-west response. Logging during a longer period of pumping at a consistently higher rate might provide more definitive results.

Table 8. Comparison of H-19 Colloidal-Borescope Logging Under Ambient Conditions and While Pumping WQSP-4

Well	Depth (ft btc) (m btc)		Logging Under Ambient Conditions			Logging While Pumping WQSP-4		
			Date	Mean azimuth ± 2 std. dev. (°)	Mean velocity ± 2 std. dev. ($\mu\text{m/s}$)	Date	Mean azimuth ± 2 std. dev. (°)	Mean velocity ± 2 std. dev. ($\mu\text{m/s}$)
H-19b0	763.0	232.56	10/9/99	160 $\pm$ 22	222 $\pm$ 67	10/12/99	347 $\pm$ 30	1410 $\pm$ 900
H-19b2	752.8	229.45	NL			10/11/99	170 $\pm$ 21	184 $\pm$ 72
	752.9	229.48	10/10/99	161 $\pm$ 27	220 $\pm$ 99	10/11/99	167 $\pm$ 48	171 $\pm$ 92
	766.5	233.63	10/10/99	184 $\pm$ 33	123 $\pm$ 67	10/11/99	173 $\pm$ 57	98 $\pm$ 63
	766.8	233.72	NL			10/11/99	171 $\pm$ 29	104 $\pm$ 60
H-19b3	754.0	229.82	10/9/99	ND	ND	10/11/99	214 $\pm$ 18	169 $\pm$ 51
	754.0	229.82	10/9/99	ND	ND	10/12/99	190 $\pm$ 25	166 $\pm$ 67
	755.0	230.12	NL			10/11/99	217 $\pm$ 76	126 $\pm$ 69
	756.8	230.67	NL			10/11/99	223 $\pm$ 42	131 $\pm$ 78
	757.0	230.73	10/9/99	214 $\pm$ 44	176 $\pm$ 85	10/11/99	225 $\pm$ 60	214 $\pm$ 152
H-19b4	754.5	229.97	NL			10/12/99	1 $\pm$ 125	89 $\pm$ 61
	764.0	232.87	10/10/99	293 $\pm$ 34	176 $\pm$ 132	10/12/99	291 $\pm$ 28	144 $\pm$ 79

NL: not logged

ND: not determinable

The only pronounced change noted was at 763.0 ft btc in H-19b0, where the southsoutheast flow (160°) observed under ambient conditions (Figure 9) shifted to the northnorthwest (347°; Figure 41). In addition, the mean velocity increased from 220 to 1400 $\mu\text{m/s}$ (19 to 120 m/day). This may indicate the presence of a feature (fractures?) lying to the north of H-19b0 that provides a higher transmissivity connection to WQSP-4 than the shortest, direct pathway. No significant differences were seen at H-19b2 or H-19b4 between the logs collected under ambient conditions and those collected while pumping WQSP-4. While the flow direction at H-19b3 appeared to be shifting eastward as pumping continued (see Section 5.2.3), only the final log during pumping showed a direction eastward of that found under ambient conditions. Figure 53 shows the mean flow directions observed in H-19b0, H-19b2, H-19b3, and H-19b4 while pumping WQSP-4.

Figure 53. Mean flow directions in H-19 wells while pumping WQSP-4.

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6. RESULTS FROM H-9b

Colloidal-borescope measurements were taken at 22 different stations in the Culebra interval of well H-9b (642.7 to 671.7 ft btc) on August 13, 16, and 17, 1999 (Table 9). The flow at 666.0 ft btc appeared to be decaying toward stagnation, while variable, swirling flow was observed at the other 21 stations. No clear flow direction or velocity was indicated by any of the measurements. Three sets of measurements were taken at 660.0 ft btc and two sets were taken at both 662.5 and 663.0 ft btc. Between the first and second set of measurements at 662.5 ft btc, well H-9c was pumped dry in 24 minutes by pumping at a rate of approximately 0.8 L/s. H-9c is located 30.9 m from H-9b along an azimuth of 209°. The logging in H-9b began approximately 42 minutes after H-9c had been pumped dry. We expected that the flow direction in H-9b might be toward H-9c at this time, but Figure 54 shows only swirling flow.

Table 9. Summary of Colloidal-Borescope Logging in H-9b

Depth (ft btc)	Depth (m btc)	Date	Duration (min.)	Flow type ¹
645.00	196.60	8/13/99	27	2
646.00	196.90	8/13/99	30	2
647.00	197.21	8/13/99	29	2
648.00	197.51	8/13/99	30	2
649.00	197.82	8/13/99	29	2
654.00	199.34	8/13/99	20	2
655.00	199.64	8/13/99	20	2
658.00	200.56	8/13/99	30	2
659.00	200.86	8/13/99	43	2
660.00	201.17	8/13/99	18	2
660.00	201.17	8/13/99	25	2
660.00	201.17	8/16/99	45	2
660.50	201.32	8/17/99	26	2
661.50	201.63	8/17/99	16	2
662.00	201.78	8/16/99	31	2
662.50	201.93	8/17/99	7	2
662.50 ²	201.93	8/17/99	52	2
663.00	202.08	8/13/99	27	2
663.00	202.08	8/13/99	8	2
664.00	202.39	8/16/99	27	2
666.00	203.00	8/16/99	22	3
668.00	203.61	8/16/99	31	2
670.00	204.22	8/16/99	26	2
672.00	204.83	8/16/99	23	2
673.50	205.28	8/17/99	7	2
674.00	205.44	8/16/99	25	2

¹ 2 = nondirectional swirling; 3 = decaying or stagnant

² Logging performed after pumping H-9c

Figure 54. Colloidal-borescope logging results at 662.5 ft btc in H-9b after pumping H-9c.

7. EVALUATION OF THE COLLOIDAL BORESCOPE

The colloidal borescope appears to be a useful and informative instrument. It provides downhole measurements of flow direction and velocity that no other technology can provide. The factors that differentiate a colloidal-borescope measurement from a true *in situ* measurement are the distortions introduced into the flow field by the well. These distortions take two forms. The first type of distortion is the convergence of flow lines approaching the well caused by the higher permeability of the wellbore compared to the surrounding formation. As shown by Drost et al. (1968), this causes more water to pass through the well than passes through an equivalent cross section of aquifer. The second source of distortion is the physical difference between the wellbore column containing only water and the surrounding solid aquifer containing water only in pore spaces. In the well, momentum can be transferred to water that is not flowing, causing swirling that does not occur in the aquifer. Thus, the colloidal borescope may observe higher velocities than occur in the aquifer and swirling that is confined to the wellbore.

The Culebra presents a challenging environment both for use of the colloidal borescope and for interpretation of its results. Because flow in the Culebra is concentrated in fractures, the colloidal borescope must be positioned precisely adjacent to a flowing fracture to provide directional information. In addition, fractures in the Culebra are generally not planar features that intersect a wellbore around its entire circumference. Holt (1997) reports that the most common fractures in the Culebra are randomly oriented, less than 5 cm in length, and have highly variable apertures. With these types of fractures, water would not flow through a well in a continuous "sheet", but might enter at a point where a fracture aperture was large and exit at a similar point somewhere on the other side of the borehole, not necessarily 180° away or at exactly the same elevation. Thus, the colloidal borescope might not show directional flow even at a flowing horizon if it was not positioned directly between the points of water entry and exit. It might instead show the swirling nondirectional flow that we saw at the majority of measurement stations. Point entry and exit of water might also create a degree of variability in the flow directions observed within a well. Controlled experiments performed in a laboratory are recommended to gain a better understanding of possible flow patterns in wells completed in media with different types of fractures.

Some of the factors that make the colloidal borescope difficult to use in the open-hole wells at H-19 might be mitigated by placement of screens and gravel packs through the Culebra. A gravel pack and screen might act to diffuse the tightly focused fracture flow into a slower but more pervasive, and hence easier to find, flow. Evaluating this possibility was the purpose of our attempted logging in H-2b2, but the deteriorated condition of the steel casing and screen in that well prevented successful logging. We recommend that colloidal-borescope logging be attempted in a newer well cased and screened with fiberglass when such a well becomes available.

As discussed in Chapter 3, colloidal-borescope measurements are not repeatable because the tool cannot be repositioned at a given depth with the necessary precision. We did not find this limitation to be a serious problem, because we were primarily

concerned with determining flow directions, which proved to be remarkably consistent regardless of depth in an individual well. Velocity measurements show much more variability with depth, and a change in velocity over time would be difficult to demonstrate.

The colloidal borescope is an operator-intensive tool. The entire logging procedure is performed manually instead of using a geophysical-type logging truck with a mechanical winch and encoded depth counter. At least in a fractured medium such as the Culebra, the operator must be continually reviewing the data in real time to distinguish flowing zones from nonflowing zones and collect the appropriate amount of data based on that determination. Finding flowing zones can be difficult. We were able to obtain directional data at only 31 of the 156 stations we investigated at H-19 under ambient conditions, with success rates (stations showing flow/total stations logged) at the individual wells ranging from five to 59 percent. We obtained no directional data at 22 stations logged in H-9b.

The colloidal borescope is not a characterization tool in the sense of being able to characterize heterogeneity as a function of depth. Flowing zones are easy to miss when logging at decimeter intervals. With a 0.1-mm-thick focal plane, continuously logging over a one-meter section would require 10,000 stations and far more depth control than the current system allows. Even sampling a statistically significant number of stations would be difficult without a more automated system.

Thus, the colloidal borescope is a useful tool so long as its capabilities and limitations are understood. It provides good information on flow directions in wells and some information on the variability that exists in flow velocities. The total flux passing through an aquifer over its total thickness might be estimable within an order of magnitude if the velocity distribution is well characterized and the advective porosity is known. The colloidal borescope is not well suited for profiling the vertical variability in a formation, or for identifying the relative flow capacities of different intervals within a well. The tool is operator-intensive and measurements made with the tool cannot be directly repeated.

8. SUMMARY AND CONCLUSIONS

The colloidal borescope was deployed in ten wells at the WIPP site to evaluate its capabilities and determine its usefulness as a monitoring tool. If effective in determining the direction and velocity of groundwater flow, it might help meet regulatory requirements to acquire that information on an annual basis (NMED, 1999) as well as provide objective validation of the groundwater-flow models used for PA.

We deployed the colloidal borescope in wells completed in four different fashions: wells that are open holes through the Culebra with fiberglass casing through the overlying units (H-19); wells that are open holes through the Culebra with steel casing through the overlying units (H-9b); wells that are screened through the Culebra with stainless steel screen and steel casing (H-2b2); and wells with perforations through steel casing (H-6c). The best results were obtained from the wells with fiberglass casing. Even though all the steel-cased wells had been scraped and cleaned prior to logging with the colloidal borescope, residual rust and/or casing scale was dislodged by the borescope and its cable. The resulting particulate matter in the water made obtaining images with the colloidal borescope difficult (H-9b) to impossible (H-2b2 and H-6c).

Directional and velocity data were obtained from 31 of the 156 measurement stations logged in the wells on the H-19 hydropad under ambient conditions. The inferred flow directions were very consistent within individual wells, but variable between wells (Figure 40). The mean flow directions in H-19b0, H-19b2, H-19b3, and H-19b7 ranged from 161° to 214°, which are generally consistent with the southerly flow directions predicted by Culebra flow models. The mean flow directions in H-19b4 and H-19b6 were 291° and 299°, respectively. The flow directions in H-19b5 were not clear, and could have been to the south and/or northwest.

The change from southerly flow on the central and southeastern part of the H-19 hydropad to northwesterly flow at H-19b4 and H-19b6 may reflect variability in fracture patterns and/or density on the dekameter scale. Culebra flow modeling (e.g., LaVenue and RamaRao, 1992) has always been performed using continuum models in which flow is perpendicular to the potentiometric contours, perhaps refracted slightly by anisotropy in permeability. In a fractured system, however, flow directions on a local scale may be controlled more by the orientations of the fractures and by the locations of high-permeability features than by larger scale potentiometric contours. Thus, highly localized measurements of flow direction in a fractured medium may not be representative of the regional flow direction. In fractured regions of the Culebra, therefore, colloidal-borescope measurements at single wells may not be effective in confirming the flow directions predicted by continuum models with hectometer-scale grid blocks. Colloidal-borescope measurements in wells in unfractured portions of the Culebra might be more typically consistent with model predictions. Flow velocities in such regions, however, might be below the resolution limit of the borescope ($< 10 \mu\text{m/s}$).

The mean flow velocities shown by the colloidal borescope at H-19 ranged from 53 to 290 $\mu\text{m/s}$ (4.6 to 25 m/day). Because of the compression of flow lines that occurs as flow approaches a well, these velocities may be as much as a factor of four higher than the actual velocities in the Culebra. Subject to this uncertainty, the measured velocities are consistent with pore-water velocities calculated from independent sources of data (Section 5.1.8).

The colloidal borescope was deployed in four of the H-19 wells while pumping WQSP-4, located approximately 220 m eastnortheast of H-19b0 (Figure 53). Flow directions in H-19b2, H-19b3, and H-19b4 were not significantly different from flow directions under ambient conditions (Figure 40), although flow in H-19b3 appeared to be shifting progressively eastward as pumping continued. Flow in H-19b0 changed significantly, however, as the flow direction shifted from the south to the north and the velocity increased to 1400 $\mu\text{m/s}$ (120 m/day). We speculate that this shift may indicate the presence of a fracture feature lying to the north of H-19b0 that provides a higher permeability connection to WQSP-4 than the shortest, direct pathway.

The colloidal borescope was also deployed at 22 stations in well H-9b, but only nondirectional swirling or stagnating flow was detected. This highlights the primary difficulty we encountered in using the colloidal borescope: the borescope needs to be positioned directly adjacent to a flowing fracture to provide interpretable data. With a focal-plane thickness of only 0.1 mm, proper positioning of the tool is both critical and difficult. This thin focal-plane thickness combined with the manual method of tool installation (Chapter 3) make repeating a measurement at a specific station impossible.

To gain a better understanding of the flow patterns we observed, controlled experiments performed in a laboratory using a synthetic well penetrated by different types of fractures are advisable. The colloidal borescope might also be deployed in a gravel-packed well with a fiberglass screen and casing to determine if the gravel pack and screen act to diffuse tightly focused fracture flow into a more pervasive, easier to find, flow. The colloidal borescope could also be used to determine how flow in unfractured Culebra differs from flow in fractured Culebra in terms of velocity, pervasiveness, and agreement with model predictions.

In summary, the colloidal borescope proved capable of determining flow directions and velocities in open-hole intervals of fiberglass-cased wells in which the water column could be kept clean of suspended particles. Interpretable data were obtained from only 20 percent of the stations logged in such wells, because positioning of the tool precisely at the position of a flowing fracture is critical and difficult. Flow velocities were consistent with independently calculated pore-water velocities. Flow directions were consistent within individual wells, but variable between wells spaced 11 to 25 m apart. This variability probably reflects the small-scale variability in flow directions inherent in fractured systems. Point measurements made with a colloidal borescope in a fractured system should not be expected to agree in every instance with flow directions predicted by continuum models on a larger scale. We were unable to evaluate the performance of the colloidal borescope in screened or perforated wells or in unfractured rock.

9. REFERENCES

Altman, S.J., T.L. Jones, and L.C. Meigs. 2000. "Chapter 4: Controls on Mass Recovery for Single-Well Injection-Withdrawal Tracer Tests," *Interpretations of Tracer Tests Performed in the Culebra Dolomite at the Waste Isolation Pilot Plant Site*. Eds. L.C. Meigs, R.L. Beauheim, and T.L. Jones. SAND97-3109. Albuquerque, NM: Sandia National Laboratories. 37-68.

Beauheim, R.L. 2000. "Appendix E: Summary of Hydraulic Tests Performed at Tracer-Test Sites," *Interpretations of Tracer Tests Performed in the Culebra Dolomite at the Waste Isolation Pilot Plant Site*. Eds. L.C. Meigs, R.L. Beauheim, and T.L. Jones. SAND97-3109. Albuquerque, NM: Sandia National Laboratories. 253-257.

Beauheim, R.L., and G.J. Ruskau. 1998. *Analysis of Hydraulic Tests of the Culebra and Magenta Dolomites and Dewey Lake Redbeds Conducted at the Waste Isolation Pilot Plant Site*. SAND98-0049. Albuquerque, NM: Sandia National Laboratories.

Drost, W., D. Klotz, A. Koch, H. Moser, F. Neumaier, and W. Rauert. 1968. "Point Dilution Methods of Investigating Ground Water Flow by Means of Radioisotopes," *Water Resources Research*. Vol. 4, no. 1, 125-146.

Holt, R.M. 1997. *Conceptual Model for Transport Processes in the Culebra Dolomite Member, Rustler Formation*. SAND97-0194. Albuquerque, NM: Sandia National Laboratories.

Kearl, P.M. 1997. "Observations of Particle Movement in a Monitoring Well Using the Colloidal Borescope," *Journal of Hydrology*. Vol. 200, no. 1-4, 323-344.

Kearl, P.M., and E.K. Roemer. 1998. "Evaluation of Groundwater Flow Directions in a Heterogeneous Aquifer Using the Colloidal Borescope," *Advances in Environmental Research*. Vol. 2, no. 1, 12-23.

Kearl, P.M., K. Roemer, E.B. Rogoff, and R.M. Renn. 1999. "Characterization of a Fractured Aquifer Using the Colloidal Borescope," *Advances in Environmental Research*. Vol. 3, no. 1, 49-57.

Kelley, M.J., L.C. Meigs, R.L. Beauheim, S.A. McKenna, and R. Haggerty. 2000. "Appendix S: Double-Porosity Single-Rate and Multirate Interpretations of Multiwell Convergent-Flow Tracer-Test Data," *Interpretations of Tracer Tests Performed in the Culebra Dolomite at the Waste Isolation Pilot Plant Site*. Eds. L.C. Meigs, R.L. Beauheim, and T.L. Jones. SAND97-3109. Albuquerque, NM: Sandia National Laboratories. 363-407.

LaVenue, A.M., and B.S. RamaRao. 1992. *A Modeling Approach to Address Spatial Variability within the Culebra Dolomite Transmissivity Field*. SAND92-7306. Albuquerque, NM: Sandia National Laboratories.

Meigs, L.C., R.L. Beauheim, and T.L. Jones. 2000. "Chapter 3: Experimental Design and Observed Tracer Recoveries for the 1995-96 Tracer Tests," *Interpretations of Tracer Tests Performed in the Culebra Dolomite at the Waste Isolation Pilot Plant Site*. Eds. L.C. Meigs, R.L. Beauheim, and T.L. Jones. SAND97-3109. Albuquerque, NM: Sandia National Laboratories. 17-35.

New Mexico Environment Department (NMED). 1999. *Hazardous Waste Facility Permit Issued to Waste Isolation Pilot Plant: EPA No. NM4890139088*. Santa Fe, NM: New Mexico Environment Department. Vols. 1-4.

WIPP Performance Assessment Department. 1993. *Preliminary Performance Assessment for the Waste Isolation Pilot Plant, December 1992, Volume 4: Uncertainty and Sensitivity Analyses for 40 CFR 191, Subpart B*. SAND92-0700/4. Albuquerque, NM: Sandia National Laboratories.

**WASTE ISOLATION PILOT PLANT (WIPP)
SAND2000-2162 Distribution List**

Federal Agencies

US Department of Energy (1)
Office of Civilian Radioactive Waste Mgmt.
Attn: Deputy Director, RW-2
Forrestal Building
Washington, DC 20585

US Department of Energy (6)
Carlsbad Area Office
Attn: I. Triay
R. A. Nelson
G. T. Basabilvazo
R. Patterson
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Office of Environmental Restoration and
Waste Management
Attn: D. Huizenga, EM-20
Forrestal Building
Washington, DC 20585-0002

US Department of Energy
Office of Environmental Restoration and
Waste Management
Attn: Lynne Wade, EM-23, Trevion II
Washington, DC 20585-0002

US Department of Energy (1)
Office of Environment, Safety & Health
Attn: C. Borgstrom, EH-25
Washington, DC 20585

US Environmental Protection Agency (1)
Radiation Protection Programs
Attn: M. Kruger
ANR-460
Washington, DC 20460

US Army Environmental Center
Environmental Restoration Division
Attn: W.A. Mandell
SFIM-AEC-ERA
5179 Hoadley Rd.
APG-EA, MD 21010

Boards

Defense Nuclear Facilities Safety Board
Attn: D. Winters
625 Indiana Ave. NW, Suite 700
Washington, DC 20004

State Agencies

Attorney General of New Mexico
P.O. Drawer 1508
Santa Fe, NM 87504-1508

Environmental Evaluation Group (3)
Attn: Library
7007 Wyoming NE
Suite F-2
Albuquerque, NM 87109

NM Environment Department (1)
Secretary of the Environment
1190 St. Francis Drive
Santa Fe, NM 87503-0968

NM Bureau of Mines & Mineral Resources
Socorro, NM 87801

Laboratories/Corporations

Battelle Pacific Northwest Laboratories
Battelle Blvd.
Richland, WA 99352

Los Alamos National Laboratory
Attn: B. Erdal, INC-12
P.O. Box 1663
Los Alamos, NM 87544

Westinghouse Electric Corporation (4)
Attn: R. G. Richardson
W.A. Stensrud
S.J. Patchett
Library
P.O. Box 2078
Carlsbad, NM 88221

Golder Associates
Attn: T. W. Doe
18300 NE Union Hill Rd. #200
Redmond, WA 98052-3391

AquaVISION (2)
Attn: P. M. Kearl
375 33 1/2 Road
Palisade, CO 81526

RAS Inc.
311 Rock Ave.
Golden, CO 80401

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Barbara Pastina (15)
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2101 Constitution Ave.
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Universities

University of Arizona
Department of Hydrology and Water Resources
Attn: S. P. Neuman
Tucson, AZ 85721

University of New Mexico
Geology Department
Attn: Library
141 Northrop Hall
Albuquerque, NM 87131

University of Wisconsin-Madison (3)
Department of Geology and Geophysics
Attn: M. P. Anderson
H. F. Wang
J. M. Bahr
1215 W. Dayton St.
Madison, WI 53706-1692

Kansas Geological Survey
University of Kansas
Attn: J. J. Butler, Jr.
1930 Constant Ave., Campus West
Lawrence, KS 66047

New Mexico Institute of Mining and Technology
Department of Geoscience
Attn: J. Wilson
Socorro, NM 87801

Oregon State University
Department of Geosciences
Attn: R. Haggerty
104 Wilkinson Hall
Corvallis, OR 97331-5506

Libraries

Thomas Brannigan Library
Attn: D. Dresp
106 W. Hadley St.
Las Cruces, NM 88001

Government Publications Department
Zimmerman Library
University of New Mexico
Albuquerque, NM 87131

New Mexico Junior College
Pannell Library
Attn: R. Hill
Lovington Highway
Hobbs, NM 88240

New Mexico State Library
Attn: N. McCallan
325 Don Gaspar
Santa Fe, NM 87503

New Mexico Tech
Martin Speere Memorial Library
Campus Street
Socorro, NM 87810

WIPP Information Center
Attn: J. Mireles
4021 National Parks Highway
Carlsbad, NM 88220

Foreign Addresses

Atomic Energy of Canada, Ltd.
Whiteshell Laboratories
Attn: C. C. Davison
Pinawa, Manitoba
CANADA R0E 1L0

Posiva Oy
Attn: A. Hautajarvi
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Bundesanstalt fur Geowissenschaften und
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Universidad Politecnica de Catalunya
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