

APPENDIX B1 RAFT RIVER INJECTION TESTING RECOVERY CURVES

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INTRODUCTION

A total of nine injection-backflow tests were conducted on well RRG5 at the Raft River geothermal site. Several variables can be altered during huff puff testing to aid in characterization of the reservoir. These variables include: 1) flow rate, during both injection and backflow; 2) quiescence time between injection and backflow; 3) chemical character of the tracer solution; 4) temperature of the tracer solution; and 5) volume of tracer solution injected.

Three test series were run. The purpose of each series was to examine the effect of a given variable on the character of the recovery curves. In the "2 series" the volume of solution injected was varied. In the "4 series" the quiescence time was varied and in the "5 series" both the volume of solution and quiescence time, were varied. A summary of each test is listed in Table 1. For each test the chemical character of the tracer solution was changed, whereas the flow rates and injection temperatures were maintained at approximately 150 gal/min and 122°C (± 2), respectively.

The purpose of the "2 series" tests, in which injection volume was varied, was to determine if the reservoir characteristics changed with increasing distance from the test well. It was anticipated that substantial changes in the permeability of the reservoir being tested would lead to variations in the degree of mixing between the injected solution and the reservoir water. These differences would then be reflected in the

characteristics of the recovery curve. This series includes tests 2A-1, 2A-2, 2C and 2D, with the volume of solution injected into the formation ranging from 0 liters (well bore test only) to 3.3×10^6 liters. The quiescence time for each of these tests was 0 hrs.

Four tests were run in the "4 series", 4A, 4B, 4C and 4D. The purpose of this series was to examine the effect of local groundwater movement on the injected solution in the near well bore environment. The volume of solution injected into the formation during these tests was relatively small, varying from 0.61×10^4 to 1.1×10^4 liters.

The "5 series" consists of a single test (5). Test 5 was to be a breakthrough test. Fluid was injected into RRGP5, while a nearby well, RRGE1, was backflowed at 200 gal/min. Pressure decreases in RRGE1, in response to production of RRGP5, suggested a reservoir connection between the two wells (EG&G, in press). After 376 hrs. breakthrough of tracer from RRGP5 to RRGE1 had not yet been achieved. At that time both wells were shut in for 80 hours to conduct a geophysical survey (Sill, 1983), then RRGP5 was backflowed at 150 gal/min. This sequence of testing with an injection volume of 1.3×10^7 liters and 80 hrs. of quiescence allows comparison with the "2 series" and "4 series" of tests all having lesser injection volumes and quiescence times.

CHEMICAL DATA COLLECTION

During both the injection and backflow portions of injection testing, surface water samples were collected at intervals ranging from 10 minutes to 4 hours. These samples were analyzed for the artificial tracers used in testing and for all other major and minor elements including: Na, K, Ca, Mg, Fe, B, SiO_2 , Cl, F, HCO_3 , CO_3 , SO_4 , pH, and total dissolved solids. Methods of sample preservation and analysis are compiled in Table 2. The results of

these analyses are provided in a report by EG&G (Large, 1983).

TRACER RECOVERY

Mixing Curves

The fraction of injectate mixed with reservoir water in the backflow solution can be calculated from the relationship:

$$X = \frac{C - C_R}{C_I - C_R} \quad (1)$$

where X = fraction of injectate in the backflow solution

C = concentration of tracer in the backflow solution

C_R = concentration of tracer in the reservoir water

C_I = average concentration of tracer in injection solution

Other processes, besides mixing, can affect tracer concentrations in the backflow solution. These include tracer gains or losses as a result of adsorption or desorption, ion exchange, mineral dissolution or precipitation and in the case of the organic dyes, Na₂Fluorescein and Rhodamine-B, thermal instability. Because these processes can have a substantial effect on tracer recovery, it is important to account for the resulting gains or losses in preparation of recovery curves for each test. One means of doing this is to use a "conservative" tracer which is relatively unaffected by these processes. Ultimately the extent of these various effects can be estimated by comparing the recovery curves of conservative and nonconservative tracers.

An ideal conservative tracer is one which is unreactive with the geologic formations present in the study area, is not present in the rocks in a form that is readily released into the tracer solution, and whose concentration in the tracer solution can be well documented. The natural tracer Cl appears to best fit this description. It is highly soluble in natural waters, well above

the maximum concentration of 3000 ppm injected during testing. Because Cl is not greatly affected by adsorption, desorption and ion exchange, minor gains and losses resulting from these processes would be relatively small compared to the high Cl concentrations in the injectate. In addition, no Cl minerals were identified in the reservoir rocks in the vicinity of RRG5 (Blackett and Kolesar, 1983) and therefore Cl gains resulting from mineral dissolution are not a concern.

Comparison of Cl recovery curves from each test with all other natural and artificial tracers used suggests that two other natural tracers, K and Na, also acted conservatively in RRG5 testing. The comparison of the recovery curves for Cl, K and in some cases Na are shown in Figures 1 through 7. Differences in the geochemical behavior of the elements make it unlikely that gains or losses resulting from water-rock reactions would affect all three of these elements equally.

The artificial tracers, NaI, NaBr, NaSCN and $\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$ (Borax), all contain Na. In some cases the concentration of these tracers in the injected fluid was not maintained at a constant level throughout injection. The Na recovery curve from tests in which one of these tracers was used may therefore reflect this discontinuous injection. Na recovery curves were therefore only compared to K and Cl recovery curves for those tests in which Na was not added as a component of the artificial tracer.

A generalized mixing curve for the "2" and "5 series" tests was then taken from a visual estimation of a best fit curve from the Cl, K and, when applicable, Na recovery curves. These generalized mixing curves are presented in Figure 8. For the "4 series" of tests the Cl recovery curve was taken as the mixing curve for each test. K was not included in selecting these mixing curves because the spacing between analyses was too large. Mixing curves for

the "4 series" tests are compiled in Figure 9.

A recovery curve for the first test, 2A-1, is not included in this report because an unknown quantity of RRGP5 water remained in the surface pipe at the start of injection. In addition, the sample spacing was too far apart to adequately document tracer returns. Both of these conditions make evaluation of mixing in the backflow solution from test 2A-1 ambiguous. Revisions in the injection test program to correct for these problems resulted in greatly improved data sets for subsequent tests.

Calculation of the recovery curves required estimation of the average injection concentration, C_I , and average reservoir concentration, C_R , for each element. The average injection concentration for continuous tracers was obtained from the weighted average of all analyses from samples of injected solution. For tracer slugs the maximum concentration in the injected solution was used as the average injection concentration.

The average reservoir concentration, C_R , for the initial test is the background concentration found in water flowing from RRGP5. Extended testing of RRGP5 shows the composition of fluid in the reservoir was relatively uniform (Dolenc et al., 1981). Interpretation of huff puff tests beyond the first test, however, was affected by small amounts of tracer solution which remained in the formation from previous tests. Therefore, in calculating a mixing curve for each successive test, an elevated reservoir concentration was used. The elevated reservoir composition was obtained from chemical analyses of the final backflow sample from the previous test. The reservoir compositions, C_R , used for Cl, K and Na are listed in Table 2.

The artificial tracer injection schedule allowed for rotation of tracers so that the same artificial tracer was generally not used in two consecutive tests. Because of this, the average reservoir concentration for artificial

tracers for all tests was taken as the original reservoir background concentration for well RRG5. For all of the artificial tracers used (Mg, B, Br, I, SCN, Na₂Fluorescein and Rhodamine-B) the original background concentration in the reservoir water is less than the detection limits of the methods of analysis (Table 2). C_R was, therefore, taken as zero for these tracers.

Calculation of Mass Recovered

The total mass, M, of each element injected and recovered is calculated using the equation

$$M = \sum_{i=0}^n \frac{1}{2} (T_{i+1} - T_i) (C_{I i} X_i + C_{I i+1} X_{i+1}) R_i \quad (2)$$

where,

T_i = relative collection time for the ith sample

R_i = average flow rate during time interval T_i + T_{i+1}

n = number of samples

When using Equation 2 there are two special cases in which C_IX_i or C_IX_{i+1} should be replaced with the actual analytic value of tracer in the sample, C_i or C_{i+1}, respectively. These include, 1) when calculating the mass of tracer injected and 2) when X is greater than or less than zero.

Well Bore Recovery

The effects of water-rock reactions and mixing are minimal in solution confined to the well bore. Therefore the tracer content of the final solution injected in the well bore (7.1 x 10⁴ liters) should equal the tracer content of the initial solution removed from the well bore. This comparison provides a unique opportunity to evaluate the overall quality of data collected for each test. For example, errors in chemical analyses or in estimation of flow rates, mixing in the well bore and accidental flow during quiescence periods

are all potential sources of error that can be evaluated.

During injection testing downhole conductivity surveys were conducted to follow the tracer front into and out of the well bore (EG&G, in press). The results showed that during injection little or no mixing occurred between the tracer solution and the reservoir water within the confines of the well bore. Thus errors caused by mixing in the well bore as a result of injection will not be significant.

The fractions of well bore recovery for the conservative tracers Na, K and Cl and all the continuously injected artificial tracers are listed in Table 4. For the "2 series" tests, which involved no quiescence, the conservative tracers, Na, K, and Cl showed less than 5% difference in recovery. Considering the analytic precision for these elements, which ranges from 3 to 5% (Table 2), and the probable 5% or greater error on the flow rate determinations, these comparisons are surprisingly close.

An exception to the above generalization is Cl from test 2D. Eighteen percent more Cl was recovered from the well bore during test 2D than injected. During the final 6 hours of test 2D injection, $MgCl_2$ tracer was added to the injectate. Industrial grade $MgCl_2$ was used and solid impurities constricted flow and at times clogged the filters leading from the tracer tanks into the main flow stream. This resulted in erratic injection of this tracer. The sample spacing during this period of injection was not close enough to adequately document variations in concentration and therefore the exact amount of Mg and Cl injected into the well bore. These problems also account for the poor agreement between Mg tracer injected into and backflowed from the well bore during tests 2C and 2D.

The remaining tests from the "4 and 5 series" all involve a quiescence period. Cl alone was used to judge recovery for the "4 series" tests because

the spacing between Na and K analyses is too wide to allow for an accurate estimation of recovery. Recoveries for test 4B and 4C were relatively good at 95% and 92% respectively. For test 4A, 4D and 5 the recoveries were poor, ranging from 76 to 58%.

Poor recoveries for tests 4A and 5 are the result of backflow that occurred accidentally during the quiescence period. The exact volume of solution backflowed during quiescence is unknown. Solution lost from the wellbore during quiescence is replaced with mixed water from the reservoir, thereby accounting for the low wellbore recoveries. The 58% recovery from test 4D suggests that accidental backflow also occurred during the 50 hr. quiescence period for this test. A component of the poor recoveries for tests 4A, 4D and 5 and then 8% error in wellbore recovery from test 4B may be the result of mixing in the well bore during quiescence.

The artificial tracers generally have poor well bore recoveries, (Table 4) with the exception of I from test 2A-2 and Na₂Fluorescein from test 2C. The poor agreement in comparison with conservative tracer recoveries suggests errors in the determination of variables other than mixing in the well bore, flow rate and accidental flow during quiescence. Possible problems that could account for these poor well bore recoveries include irregular tracer injection rates, early shutdown of artificial tracer injection, analytic errors and too wide a spacing between analyses.

TOTAL MASS RECOVERED

The mass of conservative tracer recovered during backflow is proportional to the mass of injectate recovered. Therefore the fraction of the conservative tracers, Na, K and Cl, recovered during the backflow portion of each test will reflect the fraction of injectate recovered. These recovery

fractions were calculated by ratioing the total mass recovered against the total mass injected, and are listed in Table 5. The average recovery fraction for each test is taken as the average of the Na, K and Cl recoveries.

An average reservoir concentration, C_R , must be estimated to calculate the total mass of tracer recovered during the "2" and "5 series" of tests, using equations 1 and 2. The background reservoir concentration of these elements was used for C_R , despite contamination by previous testing, because the volume of contamination is relatively small compared to the total volume of reservoir mixing.

Reservoir contamination during the "4 series" tests is relatively important because only a small volume of solution was injected into the formation. However, it is not possible to discern the exact ratio of mixing that occurred with contaminated and uncontaminated reservoir water. Therefore the fractions of recovery for the "4 series" tests must lie somewhere between the fractions calculated using background and elevated reservoir concentrations.

Recovery for the "2 series" tests ranged from 99% for test 2A-2, to 63% and 66% for tests 2C and 2D, respectively. The quiescence test series, 4, has recoveries ranging from 112% to 121% calculated with background reservoir concentrations, and from 77% to 104% calculated with elevated reservoir concentrations. The greater than 100% recovery calculated for the "4 series" tests using the background reservoir calculations reflects increased recovery resulting from contamination. Test 5 had 18% recovery.

These percentages of recovery are proportional to the total amounts of solution backflowed for each test (Table 6). If less than 100% recovery was achieved, then extrapolation of the recovery curves allows prediction of the total volume of backflow necessary to recover 100% of the injectate. The

estimated backflow volume necessary for 100% recovery for test 2C and 2D are listed in Table 6, along with recovery results from test 2A-2 (already 100% recovered). Comparison of these 100% recovery volumes to injection volumes indicates that approximately 8 injection volumes must be backflowed to recover 100% of the injectate from test 2C and 2D. This volume is independent of the volume of solution injected. In contrast approximately 11 injection volumes are needed to recover 100% injectate from the shorter term test 2A-2.

This extrapolation procedure was not used on the "4 series" tests. Calculation of the volumes necessary for 100% recovery for the "4 series" tests will have large errors because of contamination. In addition, recovery curves calculated with elevated reservoir concentrations have a slope of zero before 100% recovery is achieved. Therefore, instead of 100% recovery volumes, the volume of solution backflowed required to reach a concentration equal to that of the elevated background concentration (zero mixing) has been used to compare the "4 series" tests. Comparison of these volumes to the injection volumes indicates that recovery to zero mixing (at the elevated background concentrations) requires backflow of approximately 6 to 8 injection volumes for tests 4A, 4B and 4D (Table 6), whereas test 4C requires backflow of 17 injection volumes (Table 6).

Test 5 had insufficient backflow relative to the amount of injection to allow estimation of the amount of backflow needed to achieve 100% recovery.

Artificial tracer recoveries can be compared with conservative tracer recoveries and thereby gains and losses of the artificial tracer resulting from processes other than mixing can be determined. Fractions of recovery for artificial tracers injected continuously during the "2 series" tests are listed in Table 5. It appears that I from test 2A-2 and Mg from test 2C were depleted relative to the conservative tracers by 13% and 46%, respectively.

For the remaining tests, artificial tracers were injected discontinuously or as slugs. Relative gains and losses of tracers injected in this manner must be determined through comparison of individual samples, rather than bulk recoveries. This detailed evaluation is planned for a later study.

CONCLUSIONS

A total of nine injection backflow tests were conducted on well RRG5 at the Raft River geothermal site. Three test series were run to examine the effects of changing volume and quiescence time on tracer recovery and to test for breakthrough into nearby well RRGE1. The fraction of injectate mixed with reservoir water in the backflow solution from each test was calculated and recovery curves presented. The following points summarize the results of these calculations.

1. The natural tracers Na, K and chloride acted conservatively under the conditions encountered at Raft River.
2. In calculation of the recovery curves for the "4 series" tests, in which the injection volume was relatively small, it is necessary to correct for tracer contamination from previous tests. This correction was made by using an elevated background concentration in the mixing equation.
3. Comparison of the amounts of conservative tracers injected into and recovered from the well bore shows better than 95% recovery for the "2 series" tests. On the other hand, recovery was not as good for tests involving a quiescence period of 12 hrs. or greater. Losses up to 42% occurred during the "4 and 5 series" tests. These errors are the result of accidental backflow during quiescence and mixing of reservoir water with the well bore solution during quiescence.
4. Ninety-nine percent recovery was achieved during backflow of 11 injection volumes during test 2A-2. Over 55% of the injectate went unrecovered during the backflow portions of the intermediate and long term injection backflow tests 2C and 2D, respectively. Extrapolation of these recovery curves indicates that approximately 8 injection

volumes must be backflowed to achieve 100% recovery. This suggests that for the volumes of solution involved in tests 2C and 2D, that mixing increases proportional to the volume of injection.

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TABLE 1. RAFT RIVER INJECTION TESTS

TEST NO.	VOLUME INJECTED ^a (liters)	QUIESCENCE TIME (hours)	NATURAL TRACER (from well)	ARTIFICIAL TRACERS		SOLUTION INJECTED BEHIND SLUG (liters)
				CONTINUOUS	SLUG ^e	
<u>2 SERIES</u>						
A-1	0 ^b	0	RRGE3	NaI, NaBr, MgCl ₂ , Borax ^f		
A-2	6.3 x 10 ⁴	0	RRGE3	NaI		
C	1.5 x 10 ⁶	0	RRGE3	MgCl ₂ , Fluor. ^{f,9}		
D	3.3 x 10 ⁶	0	RRGE3	MgCl ₂ ^c , Rhod. ^{d,f}		3.3 x 10 ⁶ 2.5 x 10 ⁶
<u>4 SERIES</u>						
A	1.1 x 10 ⁴	28	RRGE3	NaI		
B	0.72 x 10 ⁴	2	RRGE3	NaSCN, Fluor.		
C	0.61 x 10 ⁴	12	RRGE3	NaI		
D	0.99 x 10 ⁴	50	RRGE3	NaBr, Fluor.		
<u>5 SERIES</u>						
5	1.3 x 10 ⁷	80	RRGE3	NaI, NaBr, Fluor., Rhod.		1.3 x 10 ⁷

^a This is only the volume that entered the formation. It does not include the 7.1 x 10⁴ liters injected into the well bore.

^b This was a well bore test only. The 3.3 x 10⁶ liters injected into the 7.1 x 10⁴ liter well bore did not enter the formation.

^c Injected continuously during final 6 hrs. of injection.

^d Injected continuously during final 2 hrs. of injection.

^e Slug injected during 10 minute period, approximately 5700 liters.

^f Borax = Na₂B₄O₇·5H₂O, Fluor. = Na₂-Fluorescein, Rhod. = Rhodamine-B.

^g Injected continuously for 3 hrs., starting at 3.5 hrs. before the end of injection.

TABLE 2. METHODS OF WATER ANALYSIS

ELEMENT	PRESERVATION		ANALYTIC TECHNIQUES	DETECTION LIMITS (mg/l)	PRECISION (%)
	FILTERED ^{a, f}	ACIDIFIED ^a			
Na	Yes	20% HNO ₃	ICP ^b	3	4 ^d
K	Yes	20% HNO ₃	ICP	3	5 ^d
Ca	Yes	20% HNO ₃	ICP	2	2.5 ^d
Mg	Yes	20% HNO ₃	ICP	2	4.5 ^d
Fe	Yes	20% HNO ₃	ICP	0.02	-- ^d
B	Yes	20% HNO ₃	ICP	0.1	-- ^d
Si	Yes	20% HNO ₃	ICP	1	-- ^d
Cl	No	None	AgNO ₃ Titration	1	3
F	Yes	None	Specific Ion Electrode	0.2	1
SO ₄ ⁼	Yes	1% HCl	Gravimetric	2	1
HCO ₃ ⁼ , CO ₃ ⁼	No	None	H ₂ SO ₄ Titration ^a	-- ^e	-- ^e
I	No	None	Specific Ion Electrode ^c	0.20	10
Br	No	None	Ion Chromatography	1	3
SCN	No	None	Ion Chromatography	1	3
pH	No	None	pH electrode ^a	±1	-- ^e
T.D.S. ^g	Yes	None	Gravimetric	5	1
Na ₂ Fluorescein	No	None	UV-Visible	0.02	-- ^e
Rhodamine-B	No	None	UV-Visible	1	-- ^e

^a Preservation or analysis completed immediately after sample collection.

^b Inductively Coupled Argon Plasma Spectrophotometry.

^c Used methods of additions to allow for chloride interference.

^d Precision at the detection limit is approximately ± 100% of the given value with a confidence level of 95%. At ten times the detection limit the precision is ± 10%. Detection limits and precision taken from Christensen et al. (1980).

^e Not determined.

^f 0.45 μ membrane filter.

^g Total dissolved solids.

TABLE 3. Reservoir Composition, C_R

ELEMENT	BACKGROUND RRGP5	ELEVATED ^a								
		2A-1	2A-2	2C	4A	4B	4C	4D	2D ^b	5
Na	414	414	414	417	469	466	445	443	414	452
K	27	27	27	28	34	33	31	30	27	31
Cl	659	659	659	674	793	772	756	756	659	799

^a Listed in sequence in which testing took place.

^b RRG5 was backflowed an extended period of time to return the reservoir to background levels before the start of test 2D.

TABLE 4. Ratio of the Mass of Tracer Recovered vs. Mass Injected into the Well Bore^a.

TRACER ^b	TESTS							
	2A-2	2C	2D	4A ^c	4B	4C	4D	5 ^c
Na	0.96	1.01	0.96	0.73	0.78	0.70	0.61	0.70
K	0.98	1.02	0.97	0.72	0.78	0.71	0.62	0.70
Cl	1.03	0.95	1.18	0.76	0.95	0.92	0.58	0.71
Mg		0.73	13.04					
I	0.94			0.81		1.22		
Br							0.91	
SCN					0.72			
Na ₂ Fluorescein		0.96			0.85		0.87	
Rhodamine-B			0.55					

^a Well bore volume is 7.1×10^4 liters.

^b Tracer slugs not included unless injected during the last 7.1×10^4 liters of injection.

^c Operators log indicates that during the quiescence portion of this test an unknown volume of solution backflowed from the well.

TABLE 5. FRACTION OF TRACER RECOVERED

TEST	C _R ^a	Conservative Tracers				Artificial Tracers	
		Na	K	Cl	Average ^b	I	Mg
2A-2	BG	.93	1.06	.99	.99	.86	
2C	BG	.63	.67	.60	.63		.34
2D	BG	.64	.65	.70	.66		
4A	BG	1.16	1.29	1.12	1.19		
	ELEV	.81	.79	.70	.77		
4B	BG	1.14	1.33	1.17	1.21		
	ELEV	.88	.88	.84	.87		
4C	BG	1.09	1.15	1.17	1.14		
	ELEV	1.02	1.04	1.06	1.04		
4D	BG	1.04	1.29	1.02	1.12		
	ELEV	.80	.92	.65	.79		
5	BG	.19	.18	.18	.18		

^a BG = Background reservoir concentration, ELEV = elevated reservoir concentration.

^b Average of Na, K and Cl fractions

TABLE 6. Volume of Solution Backflow to 100% Recovery
Or "Elevated" Reservoir Concentration.

TEST	VOLUME OF SOLUTION (liters) ^a			
	INJECTED ($\times 10^6$)	BACKFLOWED ($\times 10^6$)	TO: 100% RECOVERY ^b ($\times 10^6$)	(100% RECOVERY) (Injected Volume)
2A-2	0.063	0.66	.68	10.8
2C	1.5	3.2	12.5	8.3
2D	3.3	8.0	26.3	8.0
5	13	3.41	--	--
	INJECTED ($\times 10^6$)	BACKFLOWED ($\times 10^6$)	TO: ELEV. RES. CONC. ^b ($\times 10^6$)	(ELEV. RES. CONC.) (Injected Volume)
4A	.011	.48	.066	6.0
4B	.0072	.38	.049	6.8
4C	.0061	.16	.106	17.4
4D	.0099	.65	.078	7.9

^a The well bore volume is subtracted from these totals.

^b See text for explanation. ELEV RES. CONC. = elevated reservoir concentration.

RAFT RIVER TEST 2A-2

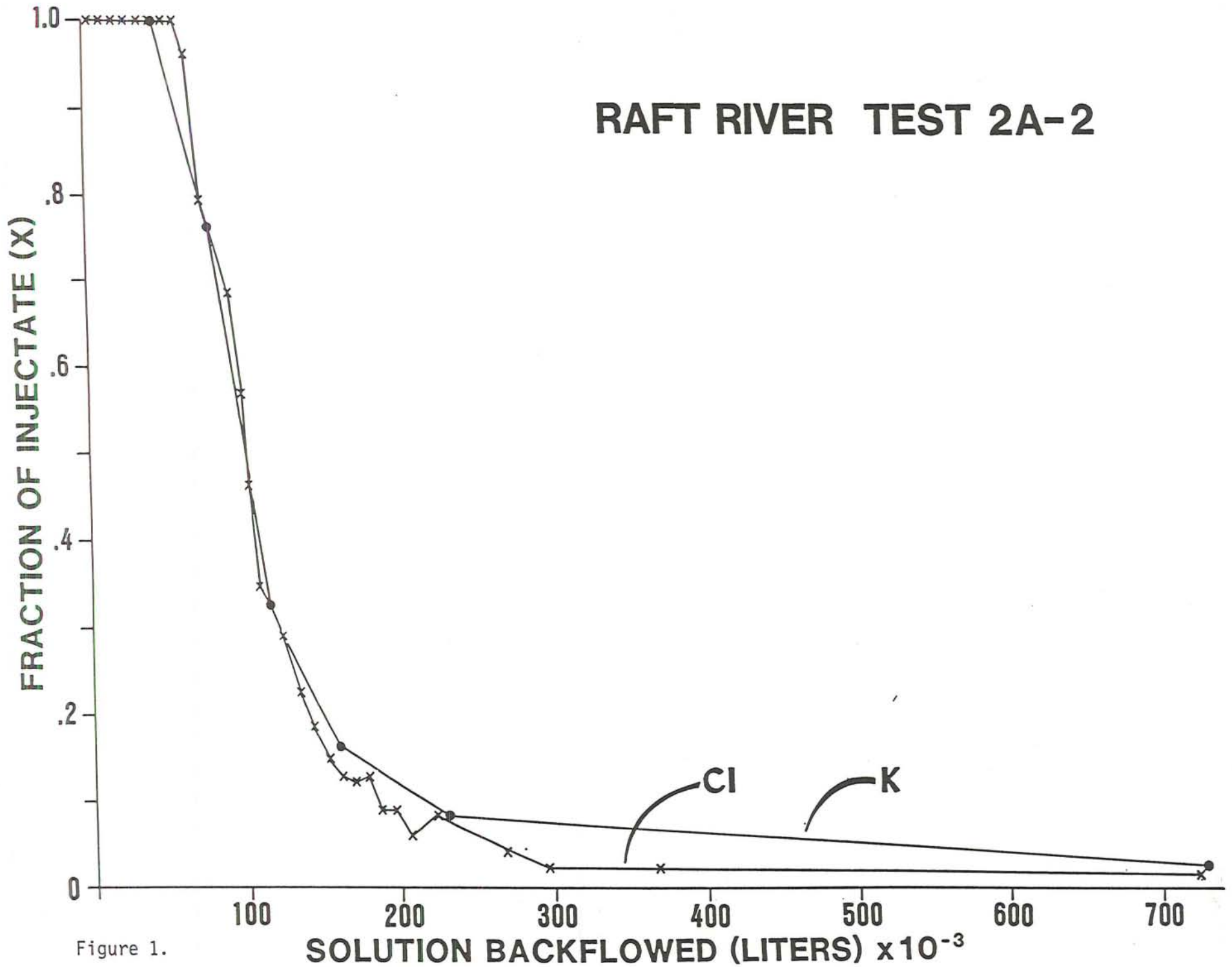


Figure 1.

RAFT RIVER TEST 2C

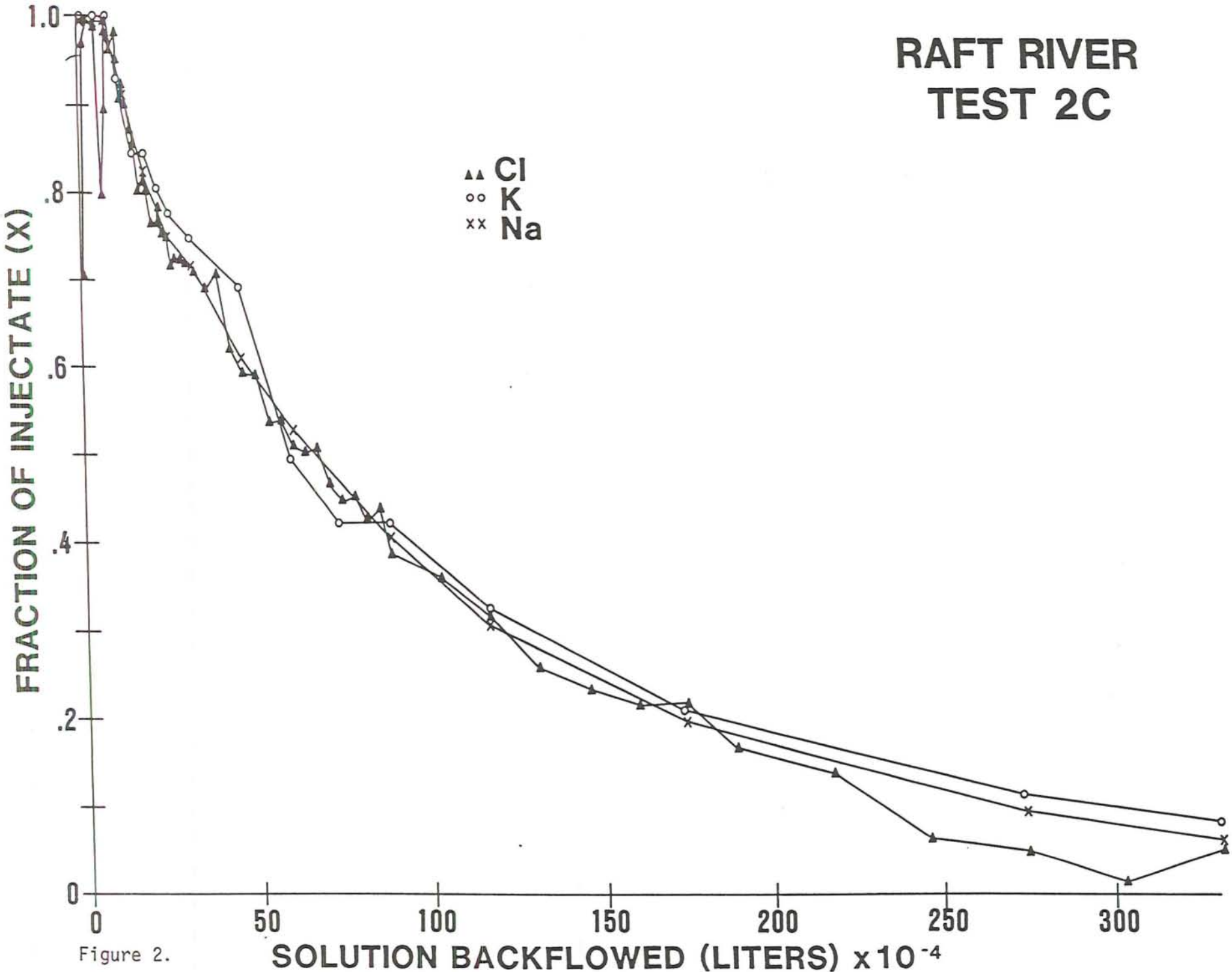


Figure 2.

RAFT RIVER TEST 2D

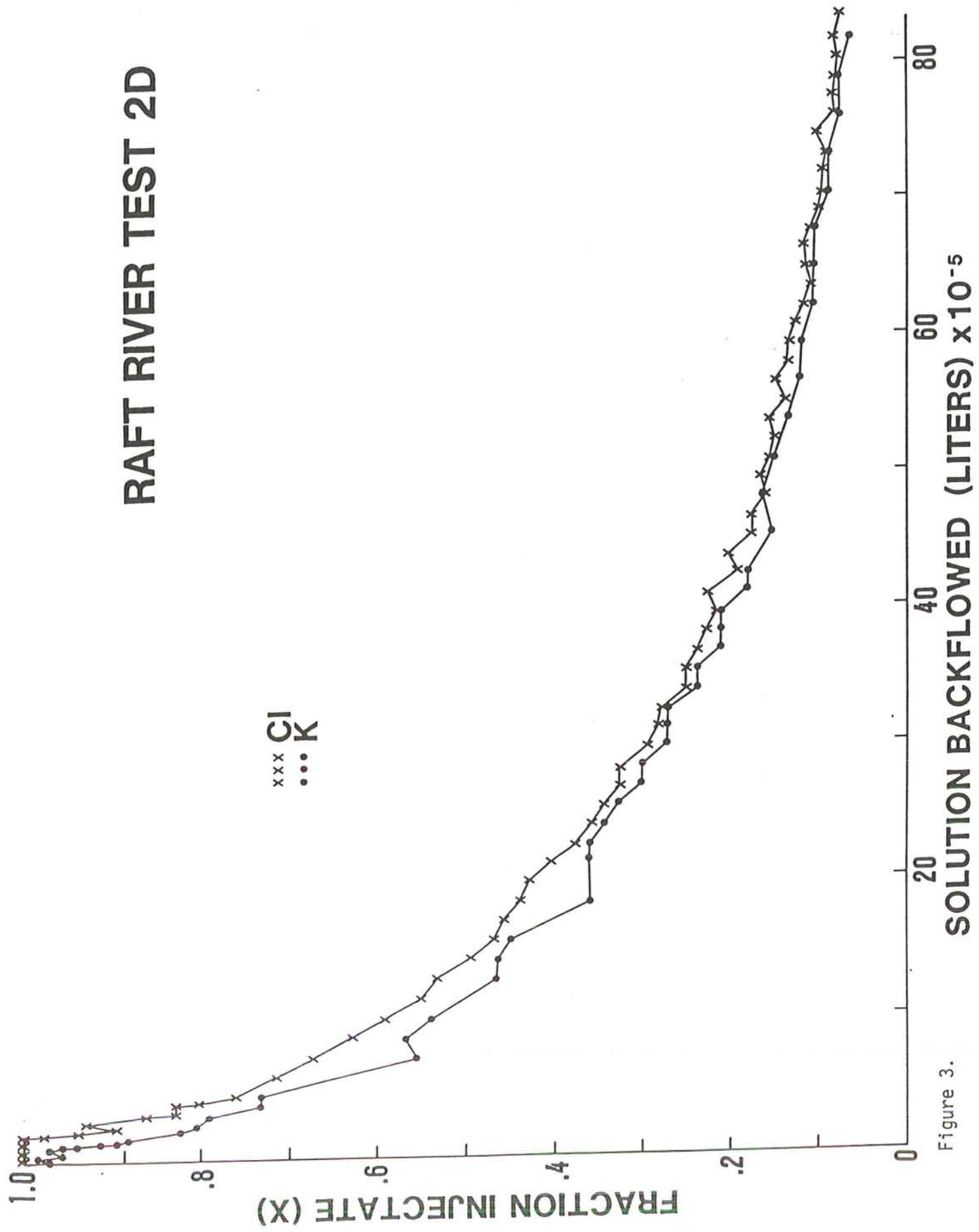


Figure 3.

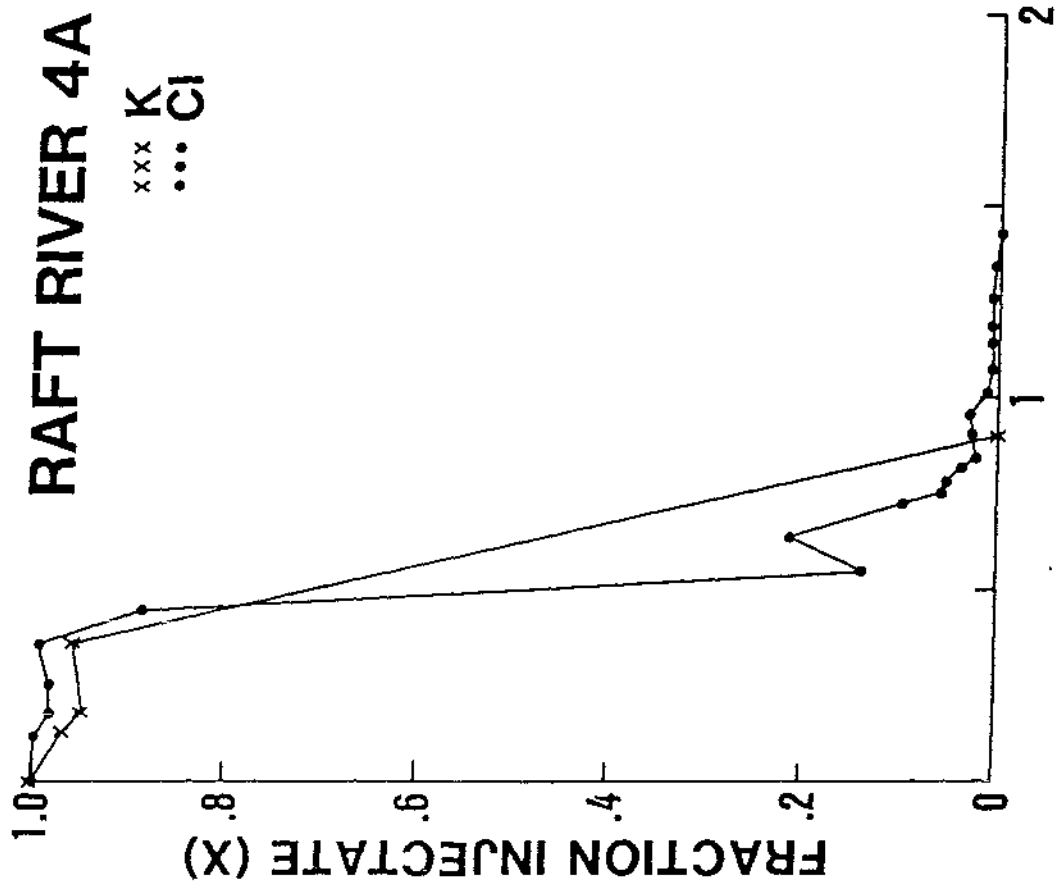
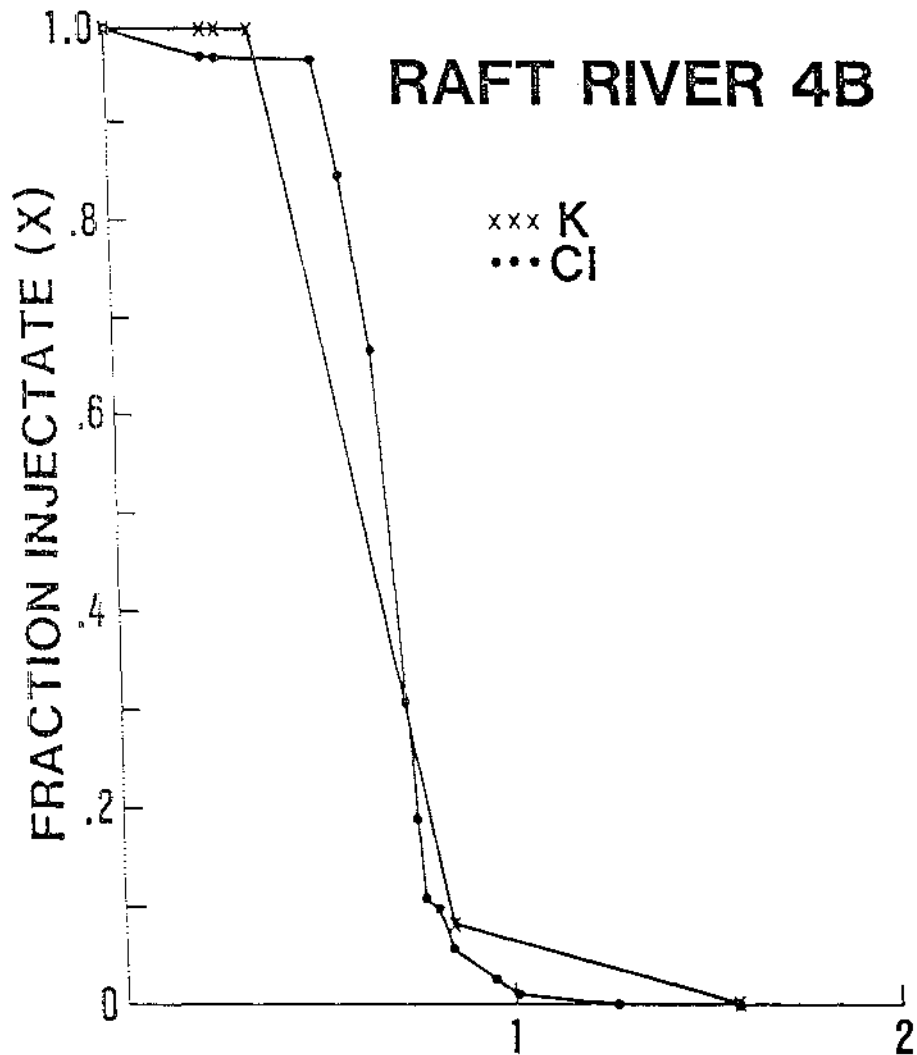


Figure 4. SOLUTION BACKFLOWED (LITERS) $\times 10^{-5}$

RAFT RIVER 4B



RAFT RIVER 4C

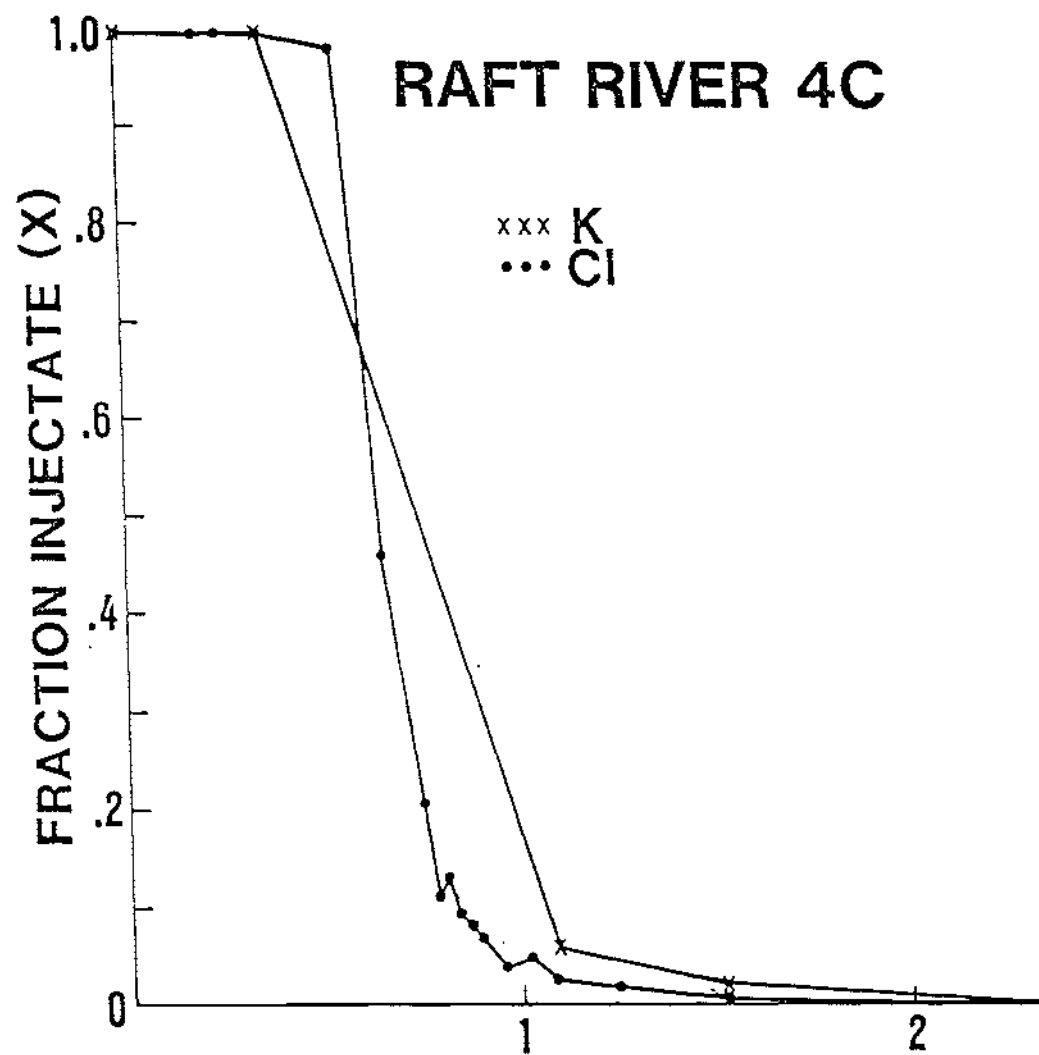


Figure 5.

SOLUTION BACKFLOWED (LITERS) $\times 10^{-5}$

RAFT RIVER 4D

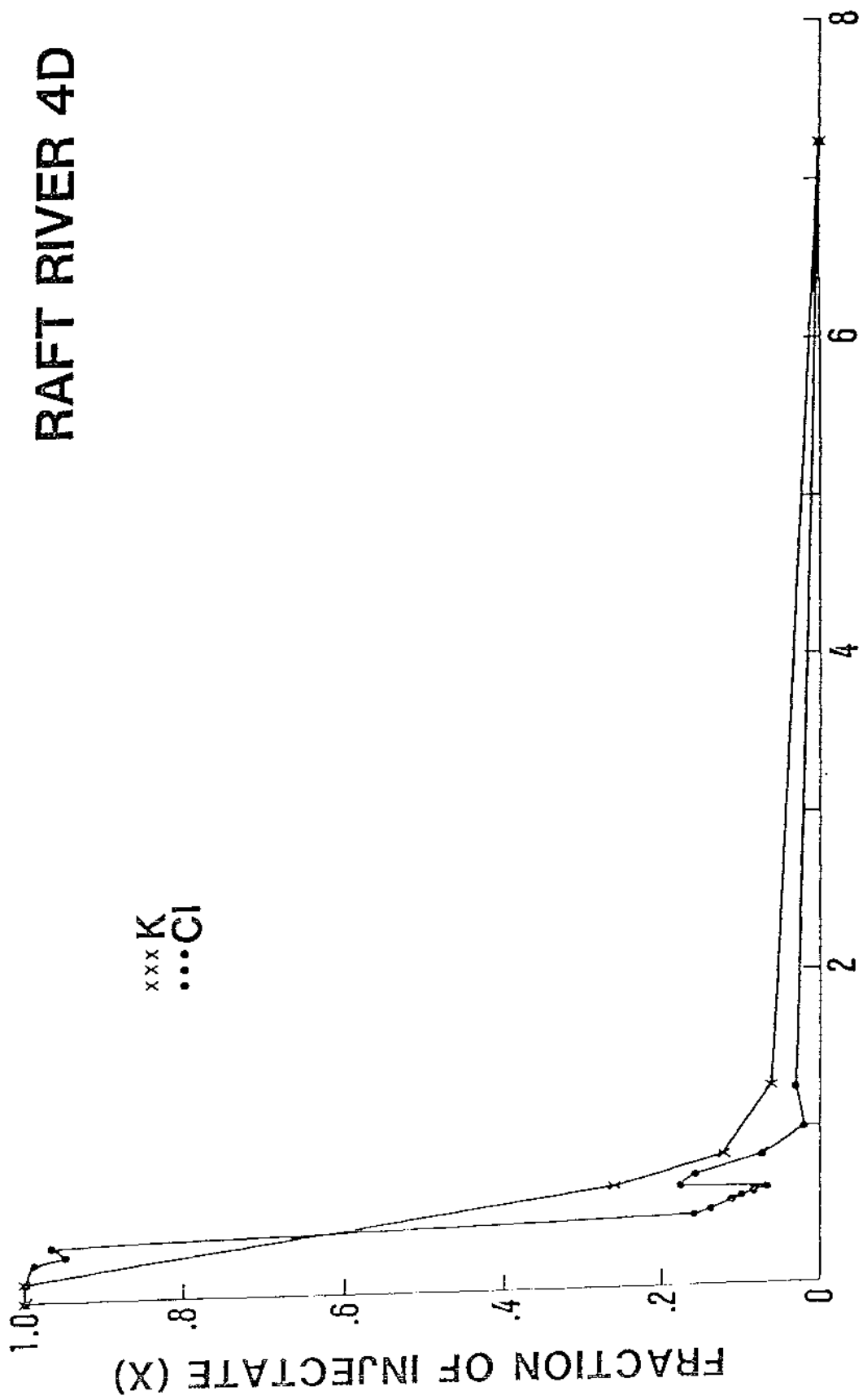


Figure 6. SOLUTION BACKFLOWED (LITERS) $\times 10^{-5}$

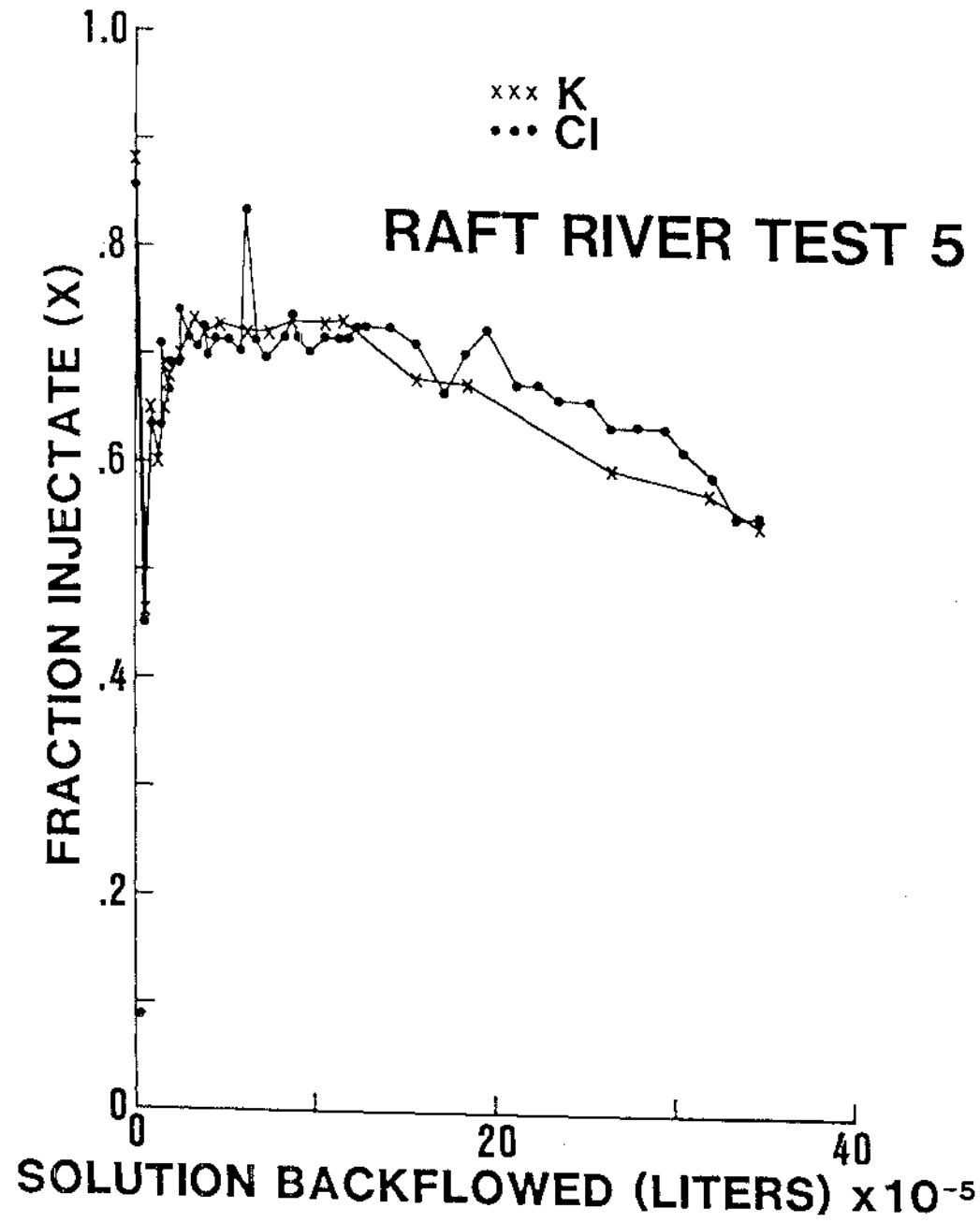


Figure 7.

GENERALIZED MIXING CURVES RAFT RIVER

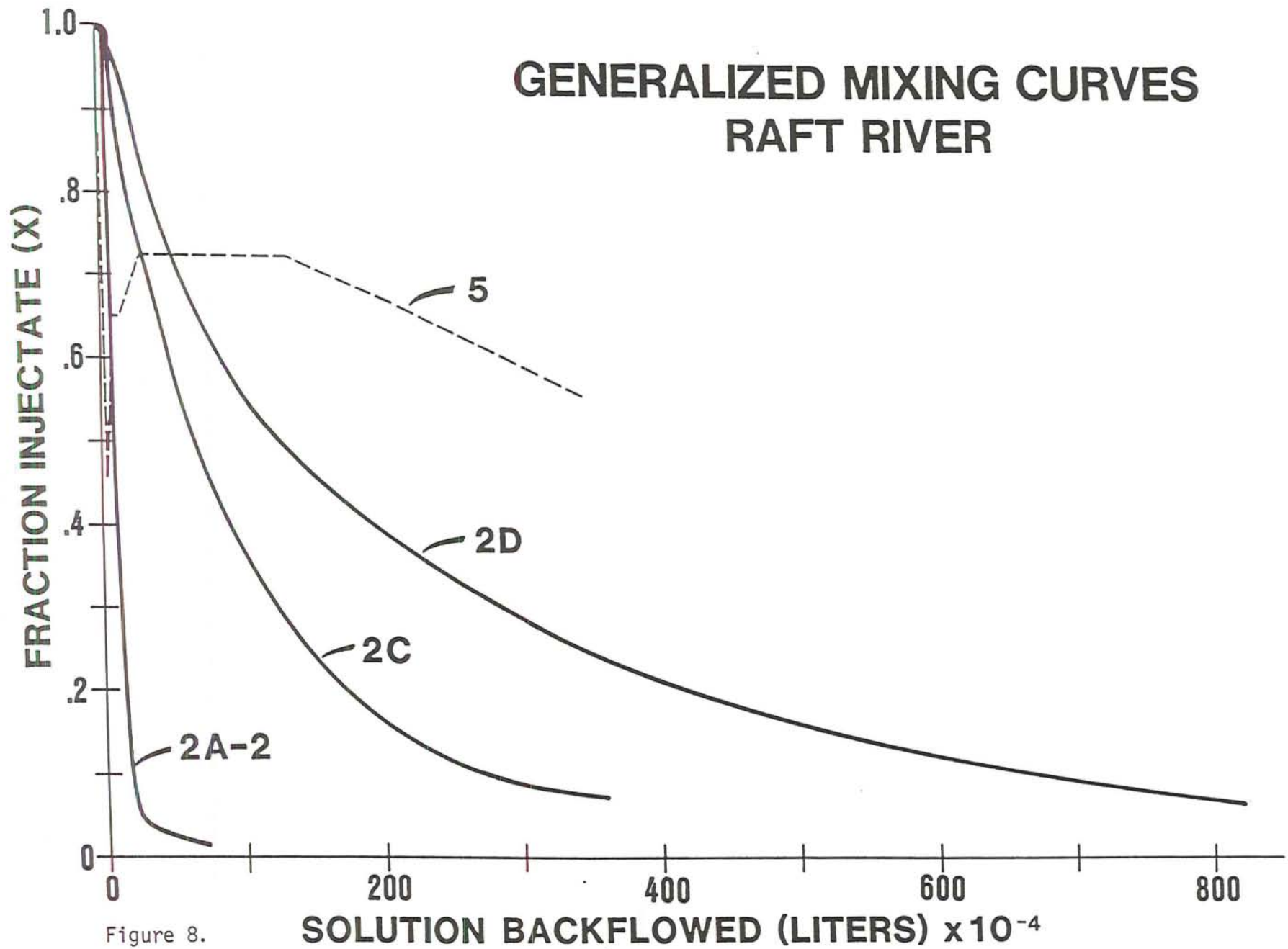


Figure 8.

RAFT RIVER 4 SERIES

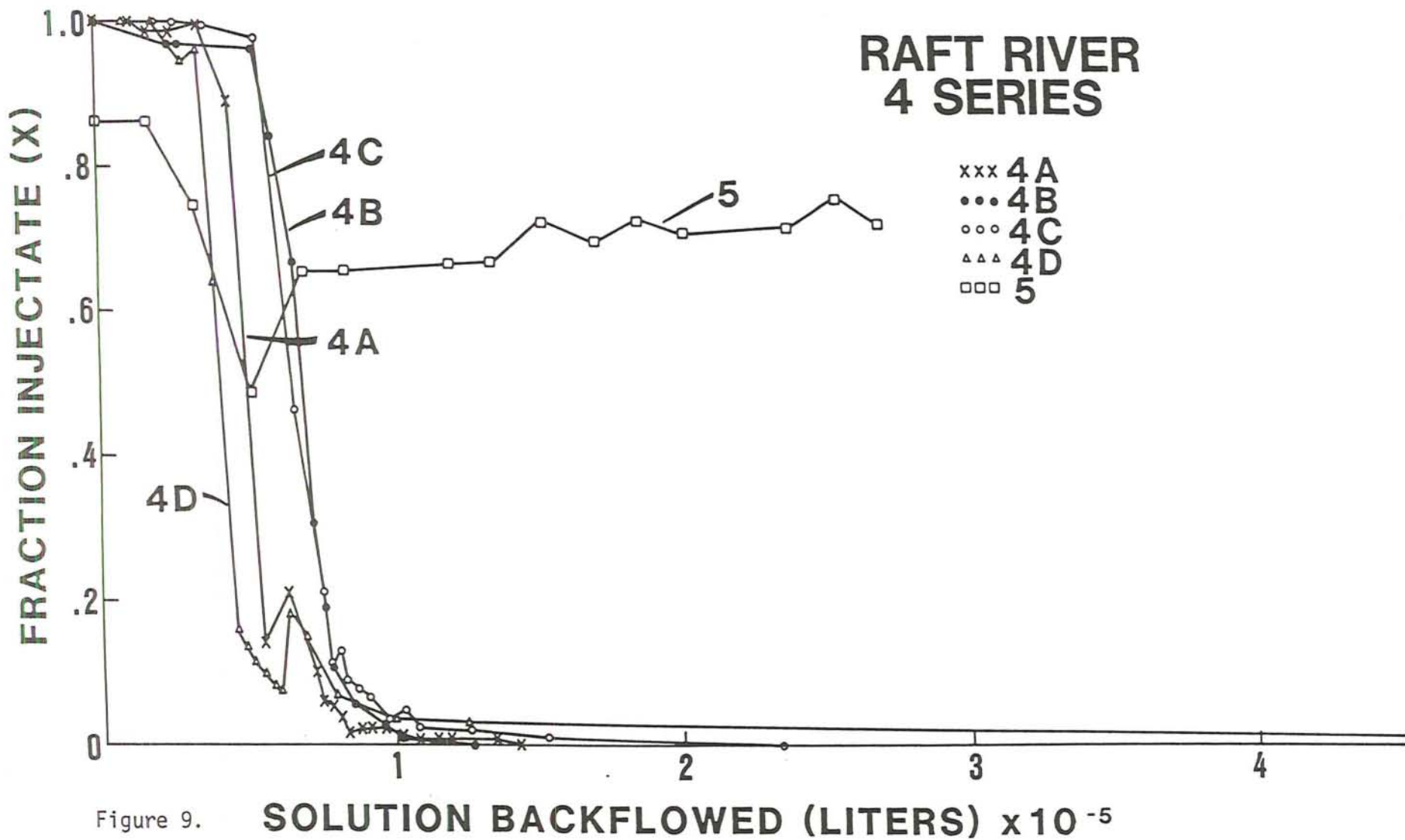


Figure 9.

SOLUTION BACKFLOWED (LITERS) x 10⁻⁵