Use of Fluoride as a Tracer in Distribution System Studies

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A paper presented on Oct. 30, 1952, at the Chesapeake Section Meeting, Washington, D.C., by Gilbert V. Levin, Public Health Engr., Bureau of Public Health Eng., Dist. of Columbia Health Dept., Washington, D.C., and Norman E. Jackson, Chief, Dalecarlia Section, Washington Aqüeduct, Water Supply Div., Washington Dist. Office, U.S. Army Corps of Engrs., Washington, D.C.

WHEN fluoridation of the District of Columbia water supply was begun in 1952, the agencies concerned took the opportunity to determine some important hydraulic characteristics of the headworks and 1,200 miles of distribution system. No other city is known to have used this method, which may prove to have many applications.

When the fluoride was first introduced into the water supply system, a simple chemical test showed the time of arrival of fluoride-bearing water at each of a number of selected points. From these data, information concerning velocities, direction of flow, detention periods, system balance, and other related factors was deduced.

Using as much manpower as the Washington Aqueduct, the water division, the U.S. Public Health Service, and the health department could spare, the participants balanced the number of sampling stations and the frequency of sampling to get the data that would be most useful. Forty-eight stations were picked (Fig. 1–4), at each of which samples were collected at least once during every 4-hour period (called "shift") of the test. Except for the treatment plants and reservoirs, all stations selected were fire hydrants. They afforded 24-hour accessibility, ready parking, sizable flow, and proximity to mains.

To reduce analysis time, a 5-min qualitative test was developed, employing a modification of the zirconium-alizarin method described by Megregian and Maier (*1*). A 5-ml portion of the reagent was mixed rapidly with both the control and test samples of water. After standing 5 min, the test sample would bleach detectably if 0.2 ppm or more fluoride was present. Quantitative determinations of all samples indicating fluorides were made during slack periods.

District of Columbia System

Water for the District of Columbia is diverted from the Potomac River to the Dalecarlia Plant. Approximately one-third of the water is treated completely at that plant. The other two-thirds is treated there with alum and then flows by gravity through the Georgetown Reservoir and across town to the McMillan Plant for final treatment. The various service zones are:

Service Zone	Supplied by
Low	McMillan (by gravity)
1st High	McMillan and Dalecarlia jointly
1st High (Anacostia)	McMillan via booster station on low service
2nd High	McMillan and Dalecarlia jointly
2nd High (Anacostia)	McMillan via booster station on low service
3rd High	Dalecarlia
4th High	Dalecarlia via booster station on 3rd high service

All fluoridation equipment is at the Dalecarlia Plant, and the chemical is added, by separate machines, to the finished water produced there and to the partially treated water being shunted to McMillan. The average water consumption during the test period was 211 mgd.

Procedure

Sampling was begun shortly after the fluoride was injected into the supply at 9:30 AM on June 23, 1952. As soon as fluoride was positively detected in a sample, that station was eliminated from further sampling. Initial fluoride content at the various stations varied from 0.06 to 1.0 ppm. Five stations indicated positive on the qualitative test at fluoride concentrations below 0.2 ppm, which was thought to be the minimum detectable by the test. These stations were resampled on the subsequent sampling round, with the exception of one (No. 31) due to oversight, and the presence of fluoride was verified. Within two weeks all pressure zones showed fluoride in the neighborhood of 1.0 ppm in the regular control samples.

Handling of the data was simplified by consecutively numbering the 4-hour sampling periods, beginning with 8 AM–12 noon of June 23, and using those numbers for plotting and reference (Table 1). The time of the arrival of fluoride at each sampling station was recorded on a large map of the distribution system. After this information had been accumulated, clear-plastic overlays were placed over the map, and the appropriate shift numbers were marked on the overlays at the locations of the stations. These points were then connected on the overlays in chronological order by way of the transmission mains that were thus indicated. Arrows were placed on the routes indicating the direction of flow, except in several small loops where insufficient sampling stations made this deduction unreliable.

Data indicating the time of initial detection of fluoride at the sampling stations are presented in Table 2. This material is chronologically arranged for each of the pressure zones. It should be emphasized that the interpretation of the data obtained is based on the specific pumpages and reservoir levels prevailing during the period of the test, as shown in Table 3. Further attention is directed to the fact that the accuracy of the times of fluoride appearance may be off as much as 4 hours—one sampling shift—except for the intraplant data, for which samples were collected every 2 hours and sometimes hourly. The data, therefore, are not acceptable for any precise mathematical treatment. Certain useful, generally applicable conclusions can, however, be deduced, as will be shown. The value of any increase in precision

TABLE 1—*Sampling Periods and Shift Numbers*

Date	Time	Shift No.
June 23	8–12 AM	1
	12–4 PM	2
	4–8 PM	3
	8–12 PM	4
24	12–4 AM	5
	4–8 AM	6
	8–12 AM	7
	12–4 PM	8
	4–8 PM	9
	8–12 PM	10
25	12–4 AM	11
	4–8 AM	12
	8–12 AM	13
	12–4 PM	14
	4–8 PM	15
	8–12 PM	16
26	12–4 AM	17
	4–8 AM	18
	8–12 AM	19
	12–4 PM	20
	4–8 PM	21
	8–12 PM	22
27	12–4 AM	23
	4–8 AM	24
	8–12 AM	25
	12–4 PM	26
	4–8 PM	27
	8–12 PM	28
28	12–4 AM	29
	4–8 AM	30
	8–12 AM	31
	12–4 PM	32
	4–8 PM	33
	8–12 PM	34
29	12–4 AM	35
	4–8 AM	36
	8–12 AM	37
	12–4 PM	38
	4–8 PM	39
	8–12 PM	40
30	12–4 AM	41
	4–8 AM	42
	8–12 AM	43
	12–4 PM	44
	4–8 PM	45
	8–12 PM	46
July 1	12–4 AM	47
	4–8 AM	48
	8–12 AM	49
	12–4 PM	50
	4–8 PM	51
	8–12 PM	52

of the data is questionable, because any practical application of the results would probably take more than 4 hours (one shift) to apply in the field.

The results for the intraplant system and the various pressure zones are discussed below.

Intraplant System

The intraplant system (Fig. 1) consists of the reservoirs, conduits, and treatment works supplying the distribution system. Using the capacities of the Georgetown and McMillan reservoirs and the flow records through these basins, the theoretical detention times are easily calculated. The ratio of the actual to the theoretical detention time, which might be called the "detention ratio," is a useful index of short-circuiting in a reservoir. Under ideal conditions, not obtainable in practice, the detention ratio for a perfect reservoir would be unity. The determination of the actual detention times by use of the fluoride tracer makes this comparison possible.

There may be some argument on whether the first appearance of a portion of water is truly indicative of the detention time of the slug from which it came. Perhaps an average detention time would be more correct. This could be measured by waiting for the fluoride content of the water to build up to a precalculated level representing the concentration at the average detention time. Use of the first fluoride-positive sample, however, greatly simplifies the field work and in no way hampers the comparability of the detention ratios if this method is employed throughout.

Fluoride ion traversed the Georgetown Reservoir on June 23. On that day approximately 114 mil gal flowed through the reservoir. The capacity of the reservoir at the elevation maintained on that day is approximately 160 mil gal. The theoretical detention time is, therefore, approximately $24 \times 160 \div 114 = 33.7$ hours (say 34). The actual detention time, as measured between Stations *A* and *C*, was two shifts, or approximately 8 hours. The detention ratio is 8:34, or approximately 0.24, indicating considerable short-circuiting through the reservoir.

At McMillan, the fluoride ion crossed the reservoir on June 24 and 25. On those days the total flow to McMillan was 260 mil gal and the reservoir elevation dropped an amount equivalent to 6.6 mil gal, making the total flow out of the reservoir approximately 267 mil gal. The capacity of the reservoir at the average elevation maintained on those two days is 265 mil gal. One-third of this, however, is at an elevation below the outlet. Owing to stratification, it is believed that this portion constitutes dead stor-

TABLE 2

Initial Appearance of Fluoride

Pressure Zone	Station	Date (June 1952)	Shift No.	Initial F^- Concentration *ppm*
Intra-plant	A	23	1	1.0
	B	23	3	0.36
	C	23	3	0.20
	D	24	5	0.20
	E	25	12	0.26
	F	26	17	0.28
	G	26	21	0.22
Low Service	1	26	21	0.22
	2	26	22	0.30
	10	26	22	0.24
	6	27	23	0.29
	3	27	23	0.30
	7	27	23	0.36
	9	27	23	0.20
	8	27	23	0.24
	4	27	24	0.28
	5	27	24	0.29
	10a	27	27	0.30
1st High Service	12	23	1	0.78
	13	24	6	0.46
	14	24	7	0.68
	19a	24	7	0.60
	11a	26	19	0.31
	11	27	23	0.30
1st High Service Anacostia	17	27	23	0.24
	18a	27	24	0.24
	18	27	25	0.22
	19	27	27	0.28
	17a	28	31	0.42
	15	28	32	0.30

Pressure Zone	Station	Date (June 1952)	Shift No.	Initial F^- Concentration *ppm*
2nd High Service	24	23	4	0.72
	25	23	4	0.48
	22	23	4	0.84
	26	24	5	0.90
	21	24	6	0.24
	23	24	8	0.30
	27	27	24	0.30
	20	28	31	0.32
	28	1*	49	0.50
2nd High Service Anacostia	29	27	23	0.60
	30	27	24	0.16
3rd High Service	37	23	3	0.54
	33	23	4	0.41
	32	24	7	0.28
	36	24	10	0.46
	35	24	10	0.58
	34	24	10	0.29
	38	25	11	0.14
	31	25	12	0.06
	39	28	29	0.22
4th High Service	42	24	5	0.20
	41	24	7	0.28
	43	24	7	0.44
	44	24	7	0.60
	40	25	11	0.35

* July.

age. The theoretical detention time based on total capacity is $48 \times 265 \div 267$, or approximately 48 hours. The actual detention time (Station *D–E*) is seven shifts, or approximately 28 hours. The detention ratio is approximately 28:48, or 0.58. This figure indicates that the detention characteristics of the McMillan Reservoir are considerably better than those of the Georgetown Reservoir. Whether the 0.58 ratio for McMillan should be higher the authors cannot tell, as they have no data to indicate what ratios can actually be obtained in reservoirs.

Low Service

Fluoridated water was first detected in the low service (Fig. 1) during Shift 22, one shift after it was found in the McMillan clear well outlet. During Shift 28, fluoride was established as passing the furthest station in the system, completing its detection at all sampling stations in the system. This had happened in the surprisingly short time of six shifts, approximately 24 hours. The rapid progression of fluoridated water through the system was highlighted by the appearance of fluoride at Station 10, across the Anacostia River, within 4 hours after it had first entered a 4½-mile transmission main at McMillan. Stations 2 and 10 presented an apparent incongruity in the chronology of the test because they both showed fluoride during Shift 22 although all the sampled mains feeding them did not give evidence of fluoride until later shifts. A check of the distribution system map showed a large main having no sampling stations on it. The timing proved that this main was the only one through which the fluoride could have arrived at stations 2 and 10. It was possible to show how water from this main had divided between the two mains sampled by stations 2 and 10. Another division of this type was detected between stations 3, 9, and 7.

TABLE 3

Water Demand

Date (June 1952)	Low Service	1st High Service				2nd High Service				3rd & 4th High Services			
		Dalecarlia	McMillan	Reservoir Fluctuation	Total	Dalecarlia	McMillan	Reservoir Fluctuation	Total	Dalecarlia	McMillan	Reservoir Fluctuation	Total
Water Demand—*mil gal*													
23	66.4	24.6	25.0	−0.4	50.0	10.2	10.9	−1.1	22.2	25.3	11.5	+0.3	36.5
24	70.6	28.2	25.1	0.0	53.3	5.3	20.0	+2.1	23.2	34.5	5.4	−0.2	40.1
25	81.6	28.7	27.6	−6.6	62.9	7.9	19.8	−0.9	28.6	37.3	9.6	+0.2	46.7
26	84.6	43.8	29.2	+7.0	66.0	10.4	20.5	−0.6	31.5	40.4	10.7	−0.5	51.6
27	83.4	36.0	28.4	+0.1	64.3	13.6	16.6	−2.6	32.8	40.4	14.1	+0.6	53.9
28	77.8	29.2	29.2	−0.4	58.8	13.9	18.0	+3.6	28.3	39.2	12.6	+0.6	51.2
Avg	77.4				59.2				27.8				46.7

1st High Service

A major break in a 36-in. main feeding the 1st High Service (Fig. 2) put that service out of operation for 6 hours, beginning at 3:15 PM on June 25. A total of 25 mil gal of unfluoridated water drained through the break. This water was replaced with fluoridated water, which may have advanced the arrival of fluoride in the 1st High Service by half a day.

dated water came from the McMillan Plant until Shift 21. It would thus appear that the pressure of 1st High Service water pumped from McMillan was not sufficient to balance that from Dalecarlia in the principal service area of the former. Had it not been for the break in the line, with the subsequent

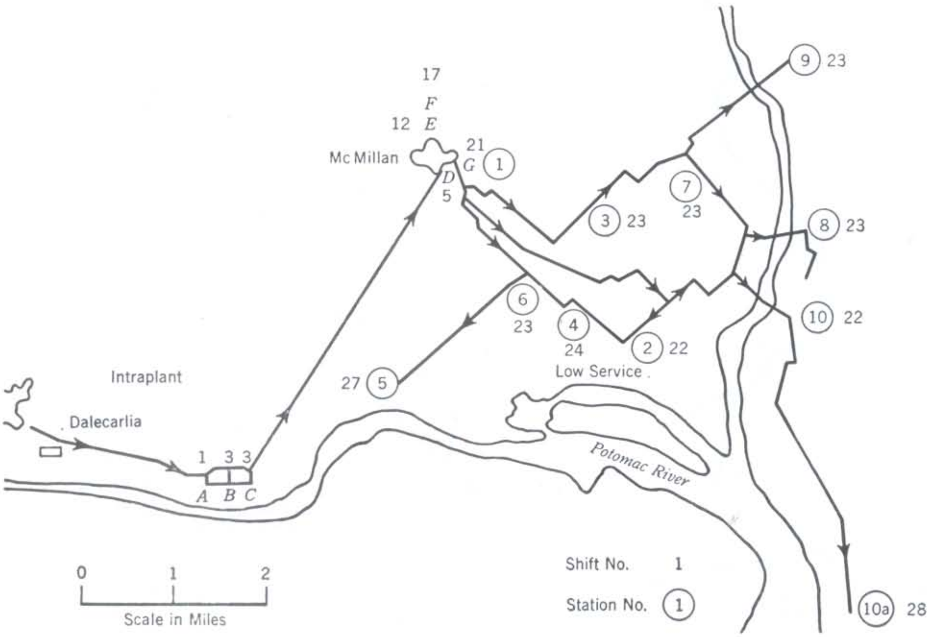

Fig. 1. Intraplant and Low-Service Sampling Stations

Intraplant: A—*Georgetown Reservoir inlet;* B—*midpoint in Georgetown Reservoir;* C—*Georgetown Reservoir outlet;* D—*McMillan Reservoir inlet;* E—*McMillan Reservoir outlet;* F—*McMillan clear well inlet;* G—*McMillan clear well outlet. Low service (circled numbers): 1—McMillan clear well; other stations are hydrants at various points on distribution system. Uncircled numbers represent shifts (see Table 1).*

All the fluoridated water detected in this service came from the Dalecarlia Plant, although the McMillan Plant also pumps to this service. This statement is borne out by the fact that fluorides were detected at all sampling stations on the distribution system itself by Shift 7 even though no fluoridated water from Dalecarlia, these data would have led to the conclusion that Dalecarlia was doing the lion's share of work in the 1st High Service. Whether or not this tendency would have prevailed under normal operation is not known.

Fluoridated water passed the 1st High-Service Reservoir, which floats on the system, sometime before Shift 4. Not until Shift 19, however, was fluoride detected at the inlet, and fluoridated water was not returned to the system from the reservoir until Shift 23. (Flap gates and a baffle wall provide a separate inlet and outlet although the reservoir floats.) It can thus be seen that water entering the reservoir was detained nineteen shifts, or approximately 76 hours. This reservoir has had an occasional history of poor bacteriological samples due to seepage through the slab roof during periods of heavy rain. It is doubtful whether any chlorine residual would be retained after 76 hours, which may account for the sporadic coliform-positive samples.

1st High Anacostia Service

During the test period water flowed from the pumps through the 1st High Anacostia Service (Fig. 3) to all sampling stations in an orderly fashion within eight shifts.

2nd High Service

In the 2nd High Service (Fig. 3), examination of the data reveals that by

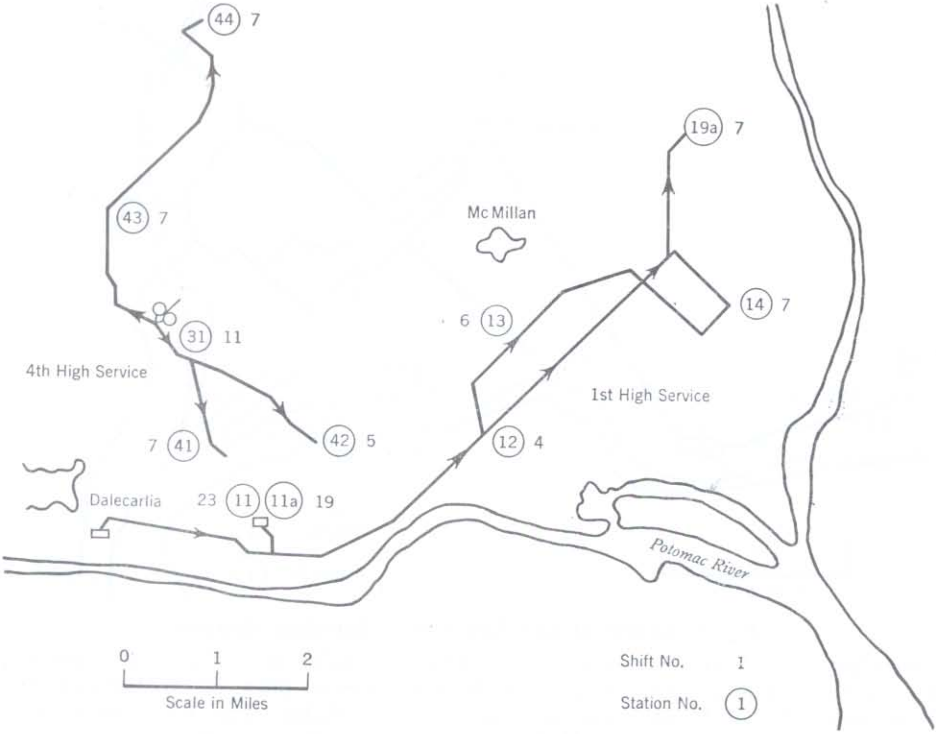

Fig. 2. 1st and 4th High-Service Sampling Stations

Circled numbers: 11—1st High-Service Reservoir outlet; 11a—1st High-Service Reservoir inlet; other stations are hydrants at various points on distribution system. Uncircled numbers represent shifts (see Table 1).

Shift 8 fluoridated water had progressed through all the distribution mains sampled west of McMillan, the Dalecarlia side. This water must have come from Dalecarlia as McMillan produced no fluoridated water until Shift 21. No fluorides were detected in water from stations east of McMillan until Shift 24. It may be safely concluded that a pressure balance existed in the system just east of McMillan, and Dalecarlia water did not flow past this balancing line. This condition divides about equally the service area supplied by each plant. Records show that McMillan pumped considerably more water during the test period than did Dalecarlia, indicating a difference in consumption characteristics in the two areas.

Fluoride was not detected in the 2nd High-Service Reservoir, which floats on the system, until Shift 31, although it was found in the main floating the reservoir at a considerable distance past it during Shift 4. It can readily be deduced that new water did not enter the reservoir for a minimum of 27 shifts, approximately 4½ days. This information should be considered in connection with the fact that poor bacteriological samples have been obtained

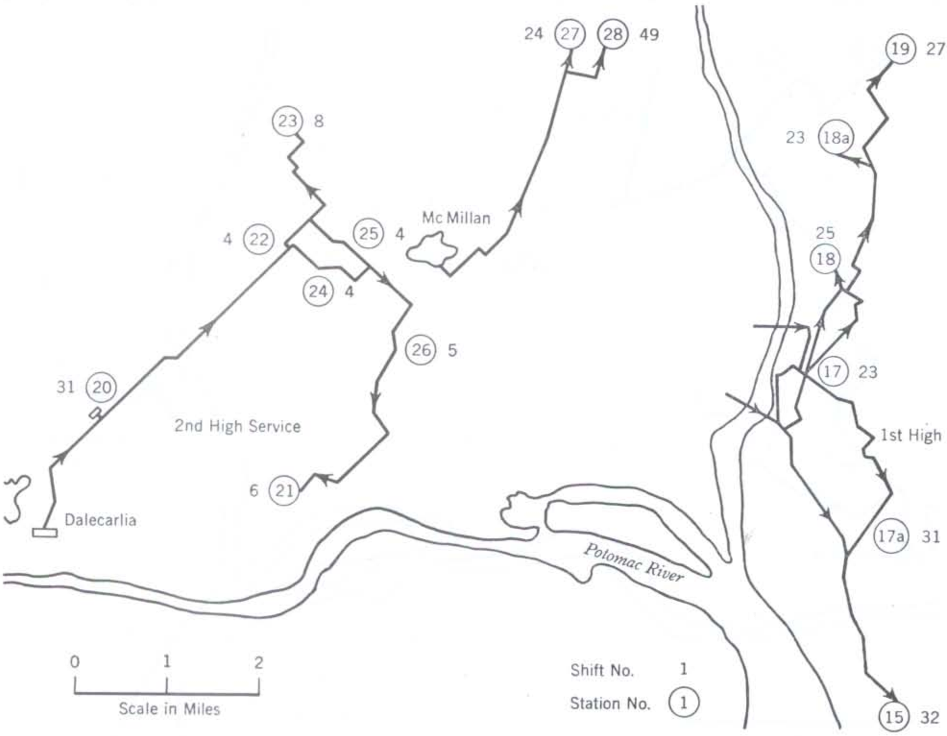

Fig. 3. 2nd High-Service and 1st High Anacostia Service Sampling Stations
Circled numbers: 20—2nd High-Service Reservoir (instrument house); other stations are hydrants at various points on distribution system. Uncircled numbers represent shifts (see Table 1).

from this reservoir (more frequently than from the 1st High-Service Reservoir).

An interesting sidelight for investigation is the fact that, although fluoridated water reached Station 27 during Shift 24, it did not reach nearby Station 28 until Shift 49. Station 27 is on a large main which also supplies a smaller main to Station 28. A very light demand in the main sampled by Station 28 or a partially blocked line might account for the large difference in time.

2nd High Anacostia Service

Only two sampling stations were selected in the relatively small 2nd High Anacostia Service area (Fig. 4). Fluoridated water reached the first station during Shift 23 and proceeded to the second station, where it arrived during Shift 24.

3rd High Service

Stations 32 and 37 on the 3rd High Service (Fig. 4) are connected by a fairly new 36-in. main, which was the expected route of flow. The test showed, however, that a longer, older, and more circuitous route (as shown on map) was actually pursued. The data were carefully examined and found to be reliable. A water department employee familiar with that section of the distribution system sug-

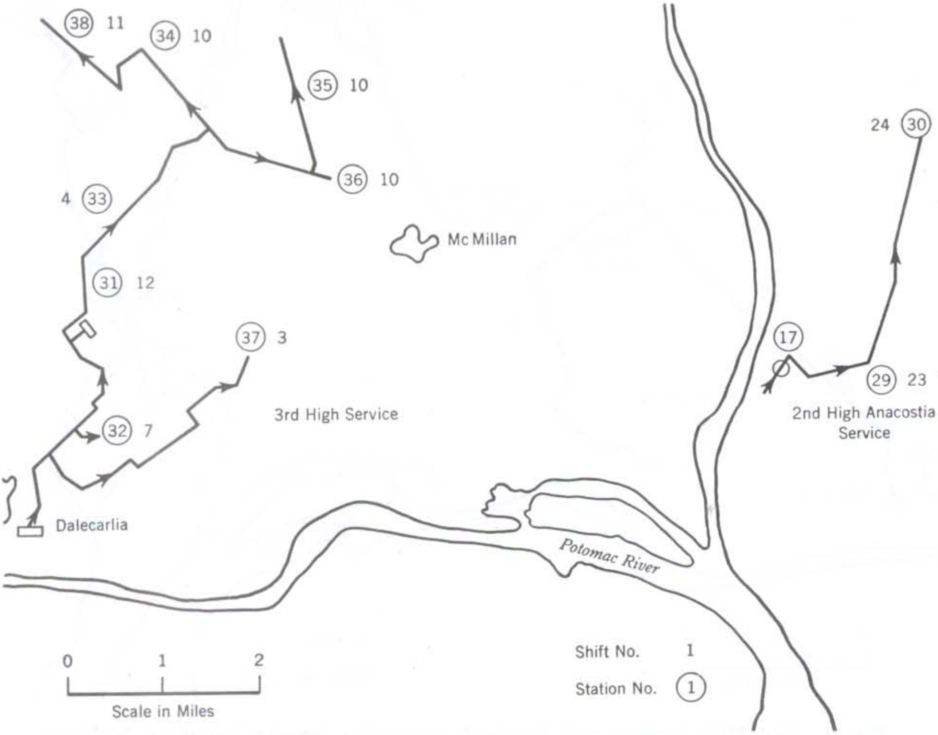

Fig. 4. 3rd High-Service and 2nd High Anacostia Service Sampling Stations
Circled numbers: 31—3rd High-Service Reservoir; other stations are hydrants at various points on distribution system. Uncircled numbers represent shifts (see Table 1).

gested that the 36-in. main might be partially obstructed, but as of October 1952 no field investigation had been made because of the heavy schedule of the work crews.

It was found that the 3rd High-Service Reservoir received fluoridated water during Shift 12. Station 33, on the main supplying the reservoir, and a considerable distance past it, showed fluoride during Shift 4. It is thus indicated that fluoridated water bypassed the reservoir for more than seven shifts.

4th High Service

The 4th High Service (Fig. 2) is pumped directly from the 3rd High Service, although storage is also provided in towers. Thus, fluoride did not reach this system until Shift 5, one shift after fluoridated 3rd High Service water had passed the pumping station. The 4th High Service water progressed both north and south from the pumping station in an orderly fashion, making its appearance at the final distribution system station during Shift 7. Fluoride was detected in the towers during Shift 11.

General Applications

The most important result of the tests was the establishment of reasonably well-defined times of travel in the system. Although the data presented pertain to specific demand conditions in the system, a simple application of the law of continuous flow makes possible the determination of approximate arrival times or velocities for, or between, any points originally trace-sampled in a distribution system.

In the equation:

$$Q = AV = \frac{Ad}{t}$$

Q is the average water demand on the pressure zone during the time of test; A is the equivalent cross-section area of the pipes from the plant to the point under study; V is the average velocity of the water flowing from the plant to the point under study, as determined by the trace test; and d is the distance traveled by the water in time t, as determined by the trace test. If A and d are constant $(Ad = k)$, then:

$$Q = \frac{k}{t}$$

or:

$$t \sim \frac{1}{Q}$$

Then to find t_1 for any Q_1:

$$t_1 = \frac{tQ}{Q_1}$$

Time of travel may also be calculated between any two points by finding the difference between the respective t values.

Factors which may render this analysis invalid, by varying A and d, are: [1] any major physical change in the distribution system which will either provide a new route to the point under study or will replace pipe in the route with pipe of a diameter different from the original; [2] a major change in the operating level of the reservoir; or [3] a major change in demand characteristics of the system. None of these factors is likely to invalidate the original data for some time, as such changes do not occur rapidly in a system.

By use of the tracer method, a chart showing water travel times to all critical points for varying demands can be prepared. In the event of a major break, sabotage by poisoning, or bombing at any point in the system, the chart would readily indicate the areas that would be affected at any time.

Estimating the time required to get to the valve locations, the operator could determine which valves should be closed to limit the effects of the incident.

The determination of actual detention times in reservoirs and settling basins by the tracer method provides easily obtained, useful information. In addition to detention time, the actual velocity of the water may be established by cross-section sampling at various points in the basin. This information can be applied to the design of new basins or improvements in existing ones not functioning properly.

Areas of influence and the effects on a system of its various pumping stations can also be deduced from the tracer data. As has been shown in this paper, the actual balancing condition between pumping stations can be found. Such information can be used to increase the operating efficiency of a water supply system by obtaining optimum pumping schedules for the various stations.

Used simultaneously with flowmeter tests, the tracer test can establish actual times of travel for measured flows in any given main or mains. Accurate information on pipeline characteristics, including roughness coefficients, can thus be obtained.

A program to trace the progress of fluoride ion through a water treatment plant and distribution network offers many real advantages. The results of such a practical, empirical study can be applied to the design, construction, and operation of the system. Although the beginning of fluoridation in a water supply system is an excellent time to make such a study, it may be possible to use other harmless, odorless, and tasteless elements easily detectable in trace quantities, such as chlorides, nitrates, or minute concentrations of short half-life radioisotopes. The method may be made as precise as desired or as time and personnel permit.

Acknowledgment

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