MONITORING AND REMEDIATION OF RESERVOIR RIM LEAKAGE AT TVA's TIMS FORD DAM

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ABSTRACT

TVA has monitored leakage from the reservoir right rim at its Tims Ford Dam since 1973. In 1995, a significant increase in discharge prompted TVA to initiate a remedial program. This program included investigative drilling, cementitious and polyurethane grouting, and extensive environmental monitoring and increased discharge observations during the grouting.

This paper describes the history of the monitoring of reservoir rim leakage; the investigation that was conducted prior to the design and specification of the grouting; and the selection and properties of the cementitious grouts and properties of the polyurethane mixes that were used. Details are provided for the drilling, permeability testing, grouting operations, and verification of the effectiveness of grouting. Monitoring data during the grouting include seepage flow with time and reservoir level, and piezometric records. Current piezometric and discharge data are included to demonstrate the effectiveness of the grouting, which was completed in February of 1998.

INTRODUCTION

A basic principle of dam design is to provide as impervious a water barrier as feasible, satisfying safety and economic, as well as technical requirements. Rims of reservoirs are integral parts of the water barrier and as such may be the sites of saddle dams, and subject to grouting programs or other types of treatment.

Inspections of rims before and after impoundment provide information on their performance by noting and measuring the discharge of leakage or the change in discharge of existing

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springs. Maintenance of reservoirs often involves grouting to reduce leakage.

TIMS FORD INSPECTION AND MAINTENANCE

The Tennessee Valley Authority's (TVA) Tims Ford Dam (Figure 1) is a 175-foot high compacted rock-fill dam with a sloping rolled earth fill core. It is located on the Elk River about 9 miles west of Winchester, Tennessee. The embankment is 1,500 feet long and has a crest elevation of 910 feet. At its normal maximum pool elevation of 888 feet, the reservoir comprises an area of 10,600 acres and a total storage volume of about 608,000 acre-feet.

Figure 1. Tims Ford Dam and Reservoir

The rock at the Tims Ford site consists of thinly bedded, nearly horizontal layers of limestone and shale. The right rim near the abutment of the rock-filled dam is comprised of:

- Overburden of red clay and chert mostly residuum from the Fort Payne Formation;
- Brassfield limestone, a coarse-grained, gray limestone, cherty, shaley, and glauconitic, containing numerous

solution cavities along bedding planes and near-vertical joints;

- Fernvale limestone, a coarse-grained, gray to red crystalline limestone, also containing solution cavities along bedding planes and joints; and
- Catheys-Liepers limestone, a fine- to coarse-grained limestone containing shale lenses and fossiiferous layers and displaying a prominence of clay seams.

These Paleozoic formations as present along the right rim are shown schematically in Figure 2.

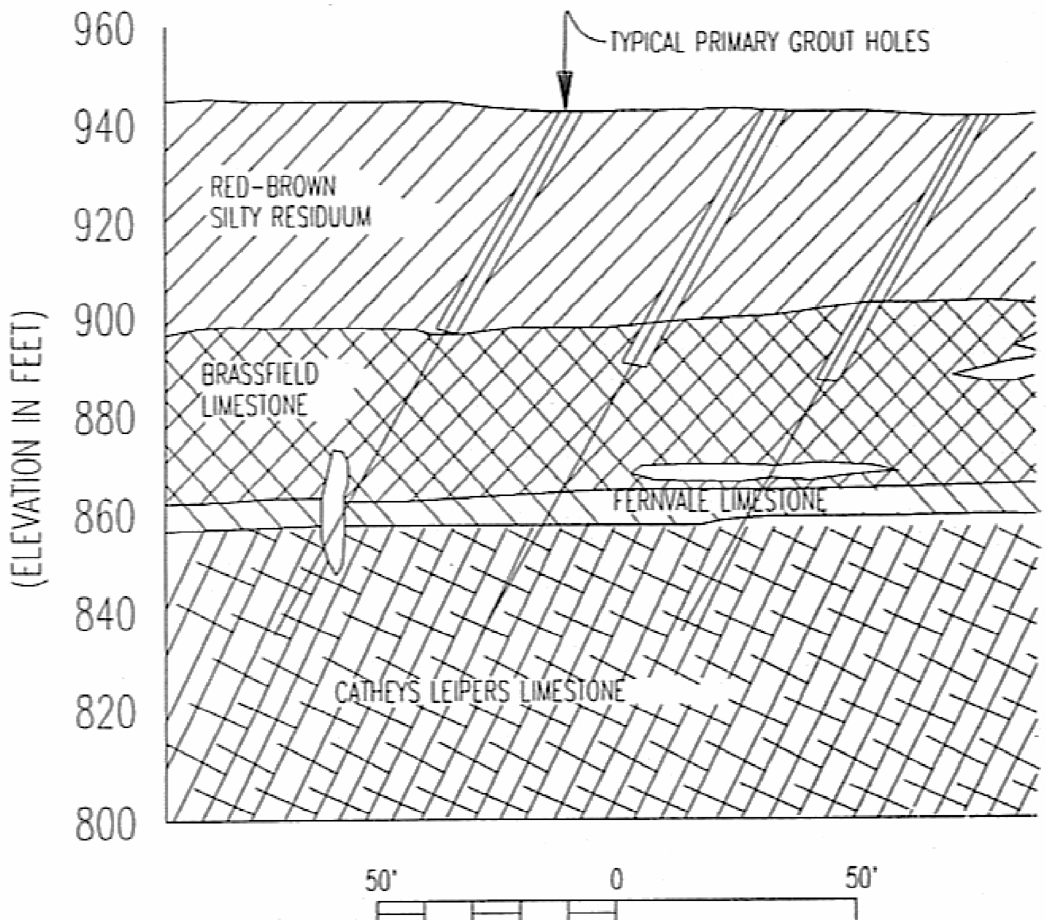


Figure 2. Tims Ford Reservoir Right Rim simplified geological elevation

During early planning of the project, two schemes for rim treatment were considered: (1) a complete grouting program along both rims prior to impoundment, or (2) treating only those portions of the rims that showed leakage after impoundment. The second scheme, considered more practical and economical, was adopted. Construction began in December 1966 and dam closure was on December 1, 1970. In March 1971, when the pool reached approximately 865 feet in elevation, leakage developed at several areas on both left and right rims, as well as the left abutment.

Leakage developed in two areas along the west side of the right rim (Figure 3) designated Leaks 6 and 8. Leak 6 was approximately 1,000 feet upstream from the axis of the dam, while Leak 8 was approximately 150 feet upstream from the axis of the dam. Flowing springs were found adjacent to Leak 6 at elevation 852 feet and included a spring at about elevation 790 feet that was active before reservoir filling. Another minor wet area was located 2800 feet upstream of the dam baseline. Rectangular weirs were established on an unnamed tributary of the Elk River to monitor the rim leaks.

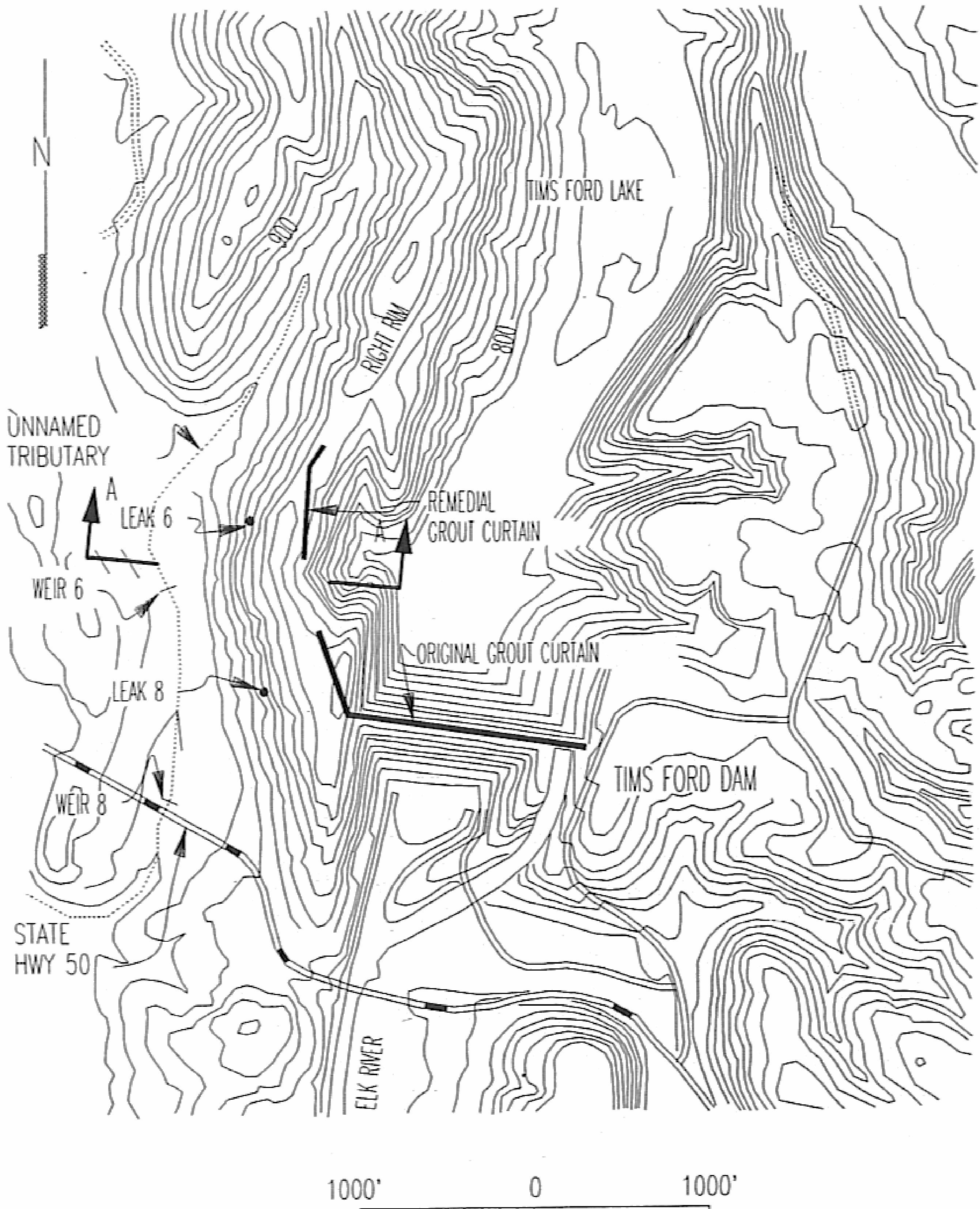


Figure 3. Plan of Tims Ford Dam and Reservoir

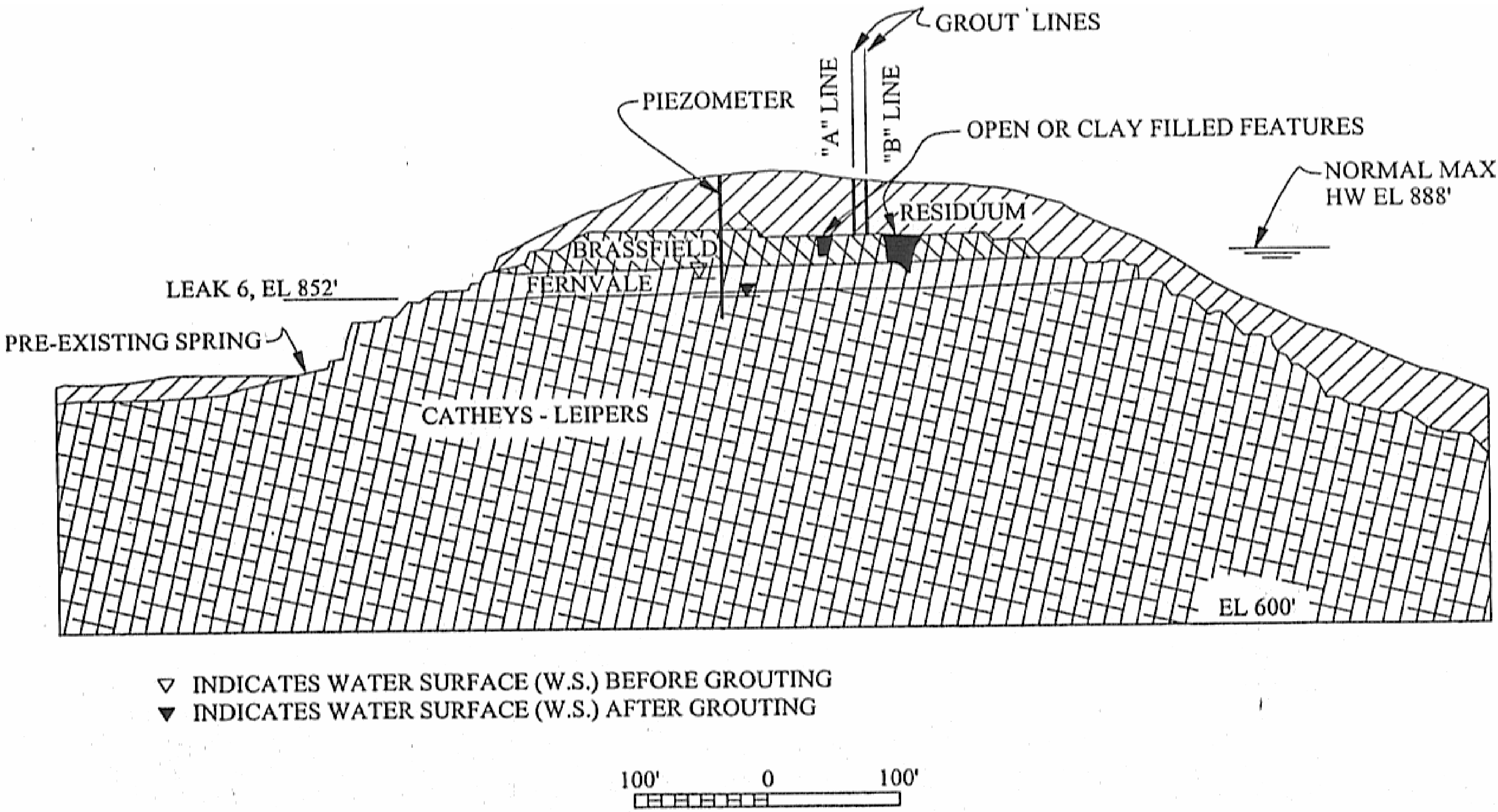


FIGURE 4. SECTION A-A OF RIGHT RIM AT LEAK AREA 6

A program of investigation was initiated at the right rim during the winter season of 1971-1972. The main program consisted of drilling holes along the crest of the rim, upstream of the leakage areas. When leakage paths were established by dye tests, grouting was done using a limited amount of cement grout (200 bags per hole per day) with 4% Calcium Chloride as an accelerator. When refusal at 20 pounds per square inch (psi) of pump pressure was obtained, the hole was re-drilled and re-grouted. Also, the grout curtain for the dam was extended from the baseline NNW along the crest of the right rim approximately 600 feet; this resulted in significantly reduced flow from Leak 8. However, because of long dye travel times from drill holes to Leak 6, no grouting was attempted for this area.

TVA then began a program of yearly rim inspections from the reservoir by boat, and monitoring the discharge of the leakage. Leakage increased steadily at Leak 6, reaching about 4,000 gallons per minute (gpm) at maximum pool in 1995. Later that year the rate of flow increased dramatically to just under 8,000 gpm at the same pool elevation, Figure 5. This was followed by a large washout of overburden on the hillside around Leak 6, resulting in heavy discharge of sediment from the leakage area into the unnamed tributary, and ultimately the Elk River. Inspection revealed the overburden at the elevation of discharge was saturated over a 200-foot width of the ridge.

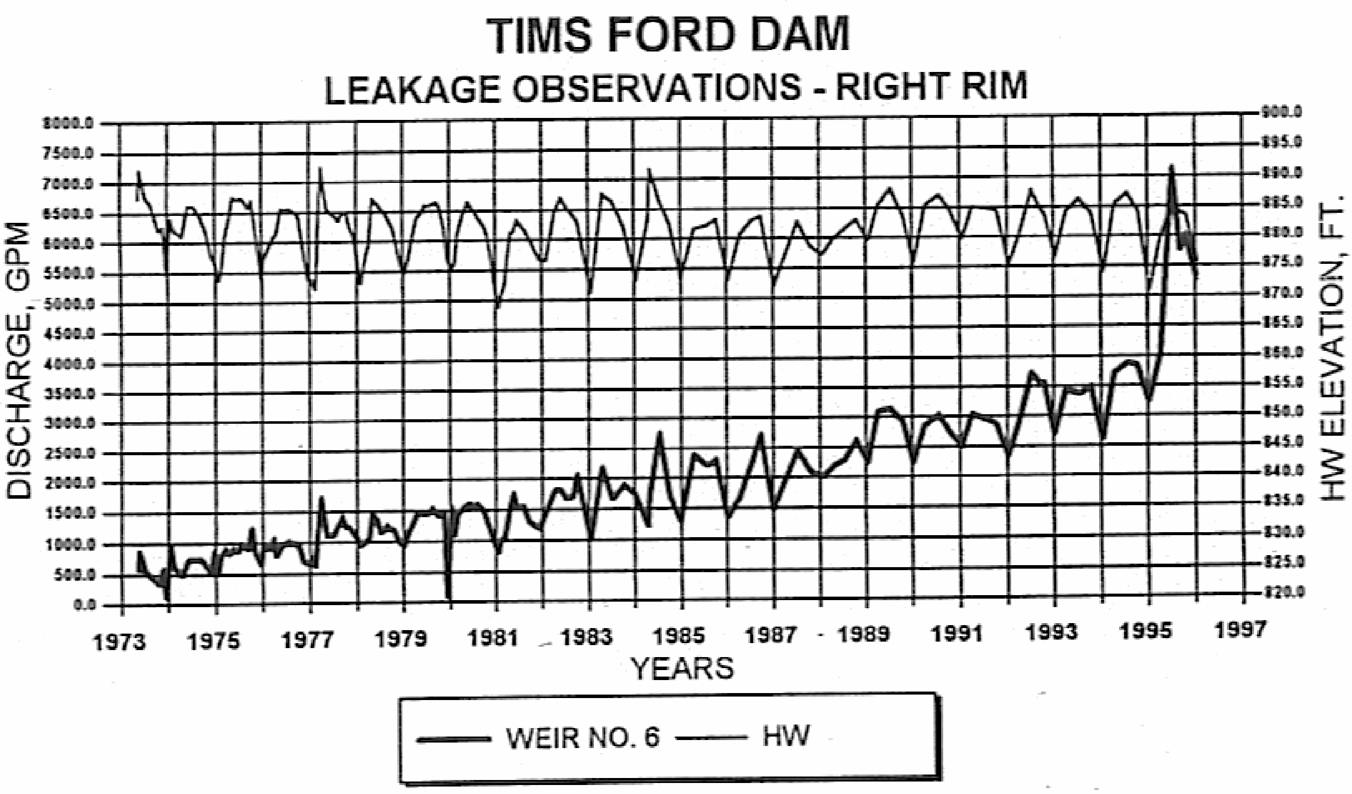


Figure 5. Discharge at Leak 6 through 1995

TREATMENT OF THE RIGHT RIM, 1997-1998

The dramatic increase of discharge at Leak 6 prompted TVA to evaluate the need for remedial action at the right rim of the reservoir. Criteria considered were:

- Proximity of the leakage to the dam
- Damage to the downstream environment from sediment discharges of washouts
- Potential for breach of the rim and loss of pool
- Public concern for safety of the reservoir
- Potential for successful remediation if postponed until its need was readily evident
- Strong increasing trend of leakage
- Reservoir draw-down requirements for remediation

After due consideration of these factors, TVA decided to proceed with planning of remedial actions. Also, TVA contracted with Dr. Donald Bruce to provide specialty advice on the capability of grouting to reduce the leakage.

A site investigation was initiated in the spring of 1997 to define the top of rock more accurately, define the extent of the rim to be treated, locate voids, perform permeability testing, perform dye testing, and assist in fine-tuning a remediation plan. The remediation project was scheduled to begin in the fall to coincide with TVA's usual winter draw-down of the reservoir.

Several alternatives for stopping the leakage were evaluated. The preferred alternative was to drill and grout from the top of the rim (Figure 6). The advantages of this scheme were: the area to be treated could be fairly well defined; the likelihood of success was good; the work could be done with the reservoir a few feet below normal minimum pool elevation; standard drilling and grouting equipment could be used; and the effectiveness of the grouting could be monitored by observing the leakage.

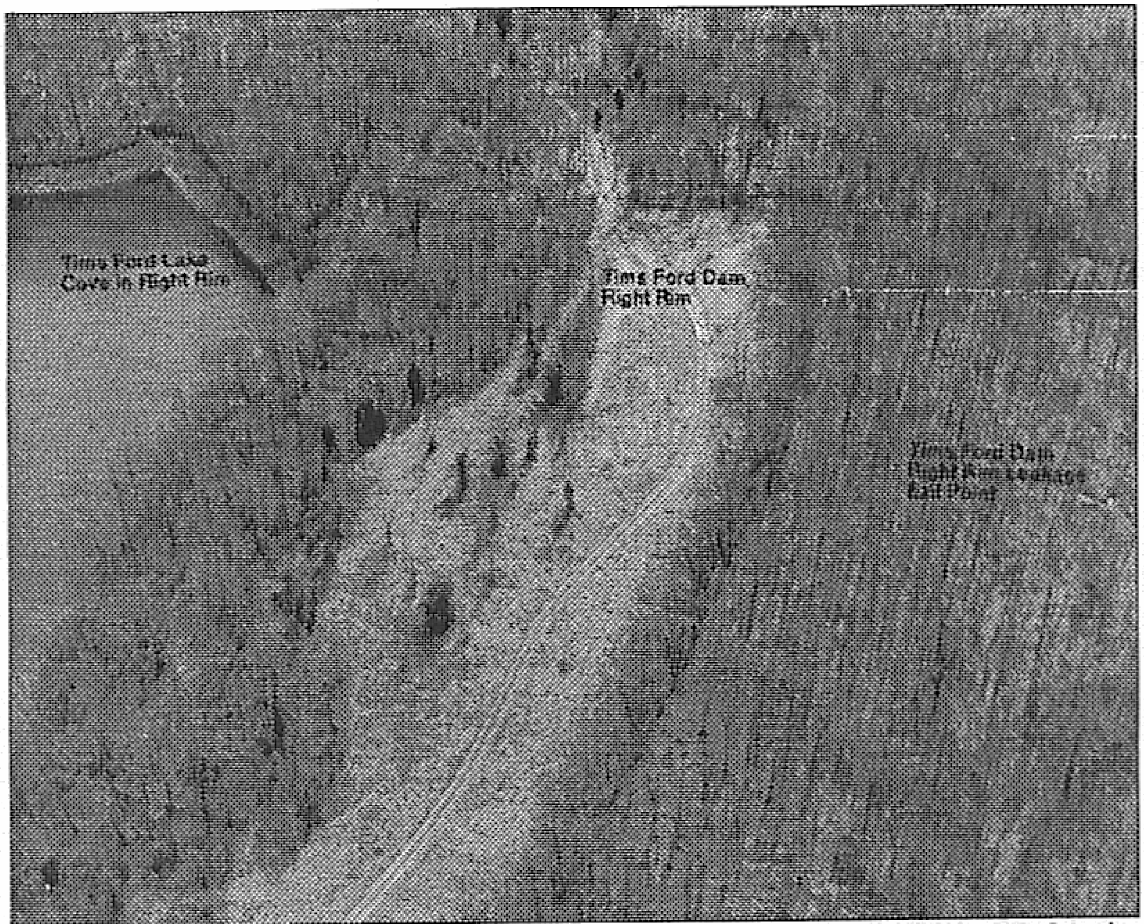


Figure 6. Tims Ford Reservoir Rim - Photograph of Rim at Grout Curtain

Other alternatives were estimated and their advantages and disadvantages evaluated. One alternative was to cover the rim from the reservoir side with concrete or shotcrete; this would require a draw-down of the reservoir 25 feet below the normal minimum elevation. Another alternative was to treat the rim from the side of the leakage,but this had the potential to force the spread of the leakage to other areas. Grouting was selected based on cost estimates and likelihood of success. TVA established 3 goals for the project:

1) Health and safety of workers during construction
2) Protection of the environment
3) Permanent reduction of rim leakage

DESIGN OF THE GROUT CURTAIN

On the basis of the site investigation, a multirow, remedial grout curtain was designed, approximately 800 feet long (Figure 3). The holes were inclined at 30 degrees to the vertical to encourage intersection of (sub)vertical features and were oriented in opposite directions in the two outside rows. Primary holes in each row were foreseen at 40-foot centers, with conventional split spacing methods to be employed (to reduce interhole spacings to 10-foot centers). The central tightening row was vertical. The grouting was to be executed between Elevations 888 and 840 feet and locally deeper if dictated by the stage of permeability tests conducted prior to the grouting of each stage (Figure 2).

Because of the suspected high-flow conditions, the holes of the downstream row that encountered voids and active-flow conditions were designated to be grouted with fast-setting (1 to 3 minute set time) hydrophillic polyurethane resin to provide an initial semi-permanent flow barrier. Holes that did not encounter voids or active flow were to be grouted with fluid, cementitious grouts. Upon completion of the downstream row, it was anticipated that the active-flow conditions would be mitigated, thus, allowing the entire upstream row, followed by the third, central closure row to be grouted with fluid cementitious grouts to form a permanent and durable grout curtain. The grouting was designed to be performed using upstage methods, although it was anticipated that poor foundation conditions could locally require utilization of downstage methods in conjunction with the polyurethane resin. The grout holes were to be cased through the overburden from the surface to the top of the curtain. The Owner's goals were to reduce the peak seepage to about 1,000 gpm and to focus only on the major features (i.e. not to specifically or systematically treat the smaller fissures and so eliminate totally all flow).

The Specifications contained provisions that required monitoring and limitations to outflow pH and turbidity to protect the downstream environment. As noted above, TVA agreed to draw down the reservoir to Elevation 855 (10 feet below minimum normal pool) to minimize hydraulic gradient and flow through the rim. The curtain was to be constructed by first grouting the far ends, so conceptually channeling the flow through a middle zone, which would then be grouted.

HIGHLIGHTS OF CONSTRUCTION OF GROUT CURTAIN

As is usually the case in such projects, actual field conditions vary in detail from what were generally foreseen, and this project proved no exception to this rule. The work generally progressed as anticipated, but the following major differences and modifications were made, the latter in full cooperation with the contractor.

- This project had to observe a very intense schedule due to reservoir drawdown restraints. The schedule required multiple shifts and the ability to drill, at times, with two rigs and to be able to grout with various mixes simultaneously. Drilling of overburden and rock was accomplished with track-mounted diesel hydraulic drill rigs. The overburden casing was installed using rotary drilling techniques, and rock drilling was performed with 3-1/2 inch down-the-hole hammers. The cement grout plant also consisted of two helical screw Moyno pumps so grout holes could be pumped simultaneously. Polyurethane grouts were pumped using a high-pressure piston pump (B-10 Rocker Multi-Component). Compaction grout was batched onsite, using a two-conveyor, three-component, trailer-mounted batch plant, with hydraulic-driven mixer/conveyor auger. This system of providing the compaction grout mix was supplemented by ready mix trucks dispatched from local ready-mix plants. Specially configured, high-pressure, double-piston pumps were used to pump the compaction grout.
- When drawdown of the reservoir reached Elevation 859 feet, the outflow from Leak 6 completely and naturally stopped. As a consequence, much of the grouting work could be done in "no flow" conditions, therefore, largely eliminating the need for the polyurethane grouts and extending the applicability of cement-based formulations (including low-mobility "compaction" grouts).
- Larger-than-anticipated open or clay-filled features were encountered, especially in the upper 20 feet or so of the curtain. For technical, commercial, environmental, and scheduling reasons, such features were treated with a low-mobility "compaction grout" (slump of 2 to 6 inches and containing water-reducing and antiwashout agents).
- A suite of cement-based grouts were developed to permit the appropriate match of mix design and "thickening sequence" to the particular stage conditions as revealed by drilling and permeability testing (both multi- and single-pressure tests). Details of the initial mixes and their application are provided in Tables 1 and 2.
- In response to conditions revealed during the treatment, observations of the seepage and further dye testing, extra groups of holes were added at the north end of the curtain, including 11 orthogonal to the original curtain, to allow specific treatment of key features.
- About 2,000 cy of compaction grout, 400 gallons of polyurethane, and 790 cy cement-based grouts were

injected into a total of 250 holes (comprising 11,000 linear feet of rock drilling).

Ingredient	Unit	Mix A	Mix B	Mix C	Mix D
Water	lb	141	141	94	94
Bentonite	lb	4.7	4.7	4.7	4.7
Cement	lb	94	94	94	94
Rheobuild 2000 (water reducing agent)	oz	15	30	20	30
Rheomac UW450 (anitwashout agent)	oz	0	0	0	5
Volume of batch	Gal	20.8	21.0	15.1	15.1
Specific gravity		1.39	1.4	1.53	1.53
Bleed	%	<5	<1	<1	0
Kpf	$min^{-1/2}$	<0.104	<0.042	<0.042	<0.042
28-Day Compress	psi	500	500	800	800
Marsh time	sec	35	50	60+	100+
Stiffening time	hh:mm	4:30	4:30	4:00	4:00
Hardening time	hh:mm	10:30	8:30	8:00	8:00
Water and slurry volumes					
Bentonite slurry volume	gal	8.0	16.1	8.0	8.0
Additional water volume	gal	9.9	2.8	4.2	4.2

Table 1. Compositions and properties of cement grout mixes, Tims Ford Dam, Tennessee

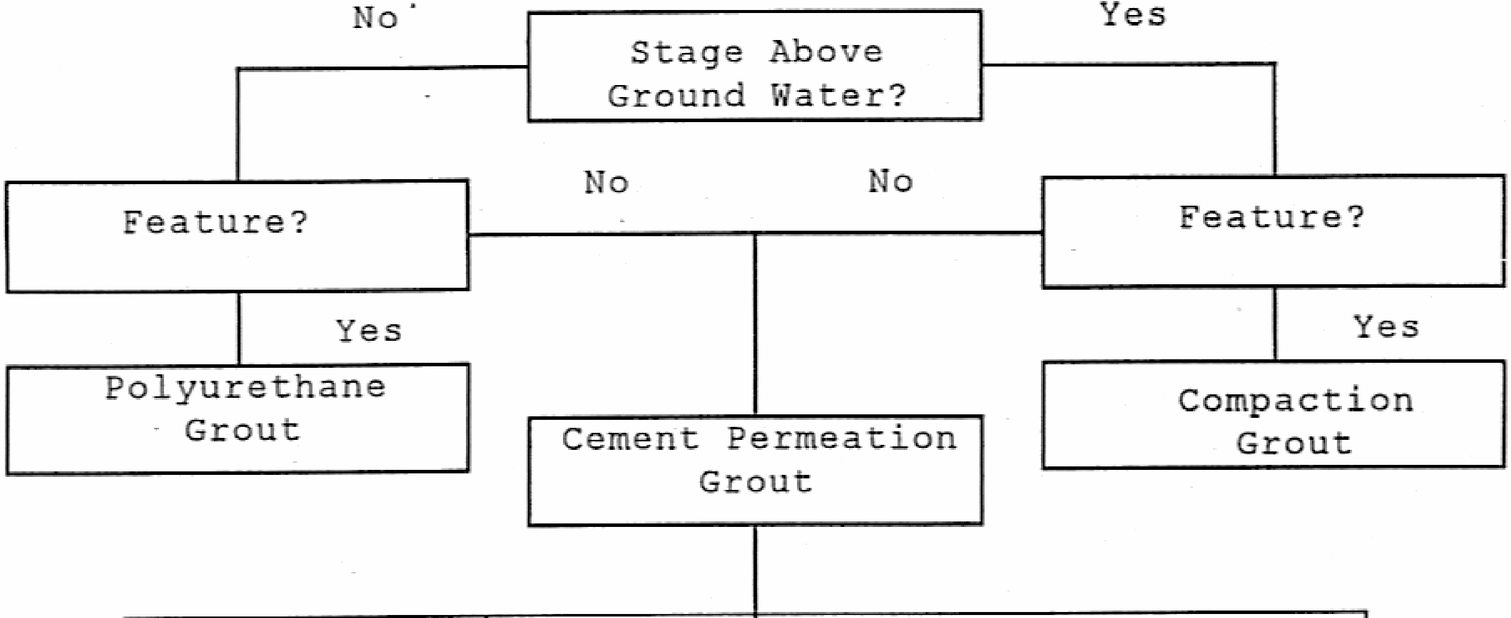
VERIFICATION OF EFFECTIVENESS OF THE TREATMENT

Real-time performance monitoring used during grouting included results from drilling, water tests, calculation of grout hole reduction ratios, and dye testing. This monitoring allowed onsite engineers to track the development of the integrity of the grout curtain and focus grouting efforts on specific zones along the grout rows. Also, the results of the grouting were demonstrated from data monitored for 1) discharge from the rim leak; 2) groundwater elevations down-gradient from the grout curtain; and 3) headwater elevations.

Engineers used results from water tests to evaluate permeability of the rock in Lugeon values (Lu). The water tests (and drilling) confirmed more open void stages in two certain areas, and higher order holes were added to these zones.

Grout takes closely followed trends observed in the water test data. To evaluate grouting progress, reduction ratios were calculated by dividing the average take of one order of holes by the average take of the previous order of holes. Using this evaluation, grout takes were reduced by 64 percent from primary/secondary holes to tertiary holes (upstream row); by 51 percent from primary/secondary to tertiary holes (downstream row); and by 63 percent from quarternary to quinary holes (central row).

As the contractor began the final stages of the grouting, quaternary and quinary holes were required to fully treat certain problem zones, dye tests were performed to identify connections to the leak and confirm the extent of the curtain,(Figure 7). By this time, it was apparent that flow was no longer spread out across the rim, but channeled by the grouting process to the north end of the grout curtain. The evaluation of connections, not only by dye tests, but also by observing washout of grout and turbidity in the leak, were instrumental in achieving the success that was attained under flowing conditions in the features of the karstic limestone. (The reservoir by this time was at elevations above 859 feet.)



Stage Permeability	Activity
0-1 Lu	Backfill hole with any stable mix
1.1-5 Lu	4 Batches of A Mix 4 Batches of B Mix Begin reducing content of Rheobuild 2000B by 5 oz per mix in 2 bag steps for Mix B until refusal or until mix is too thick to mix easily
5.1-15 Lu	4 Batches of A Mix 4 Batches of B Mix 6 Batches of C Mix Begin reducing content of Rheobuild 2000B by 3 oz per mix in 4 bag steps for Mix C until refusal or until mix is too thick to mix easily
15 Lu +	4 Batches of B Mix 6 Batches of C Mix 10 Batches of D Mix Begin reducing content of Rheobuild 2000B by 3 oz per mix in 4 bag steps for Mix D until refusal or until mix is too thick to mix easily Note: Engineer must be notified when stage approaches refusal or when reduction of Rheobuild 2000B anticipated.

1. Refusal will be defined as a flow of 1 gpm measured over a 10-minute period at the target pressure of 1 psi per foot of depth.
2. No more than 60 batches of cement grout will be injected into a given stage on one 12-hour shift.
3. Compaction grout may be used for filling features below the water table.

Table 2. Flow chart providing guide to mix selection and variation, Tims Ford Dam, Tennessee

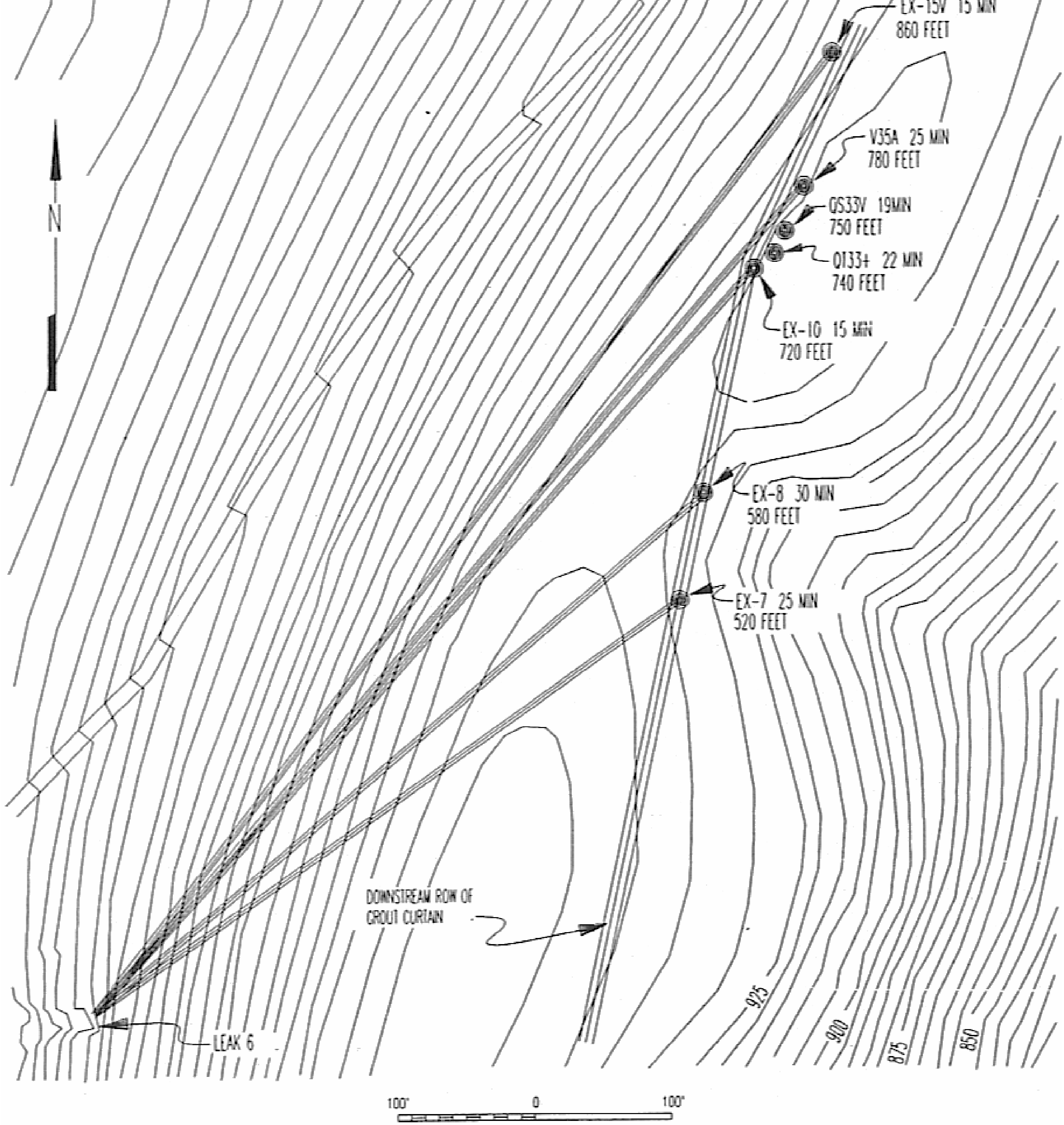


Figure 7. Tims Ford Reservoir - Plan of Flow Paths, Connection Times and Distances (Minutes and Feet)

Three piezometers installed during the 1997 investigation program were monitored before, during, and after construction of the grout curtain. The piezometers were installed down-gradient of the proposed grout curtain to monitor the effectiveness of grouting. At all three piezometers, fluctuations of groundwater levels were influenced by reservoir headwater levels prior to grouting. Of the three piezometers originally installed, one was grouted up early during construction of the grout curtain; another collapsed soon after construction was completed; and only Piezometer PZ-10 continues to provide data.

On February 16, 1998, while injecting compaction grout into a quinary hole that had a strong dye connection to the leak, leakage at the elevation 852' spring decreased from 1,075 gpm to less than 60 gpm. Groundwater at Piezometer PZ-10 dropped about 2 feet and ceased to be influenced by reservoir levels.

Monitoring during grouting included daily measurements at Weirs 6 and 8 (Figure 8) and observation of all known leaks. Also, engineers observed water surface elevations daily at piezometers installed prior to grouting (Figure 9). Groundwater measured at the piezometers was reduced about 10 feet after completion of grouting.

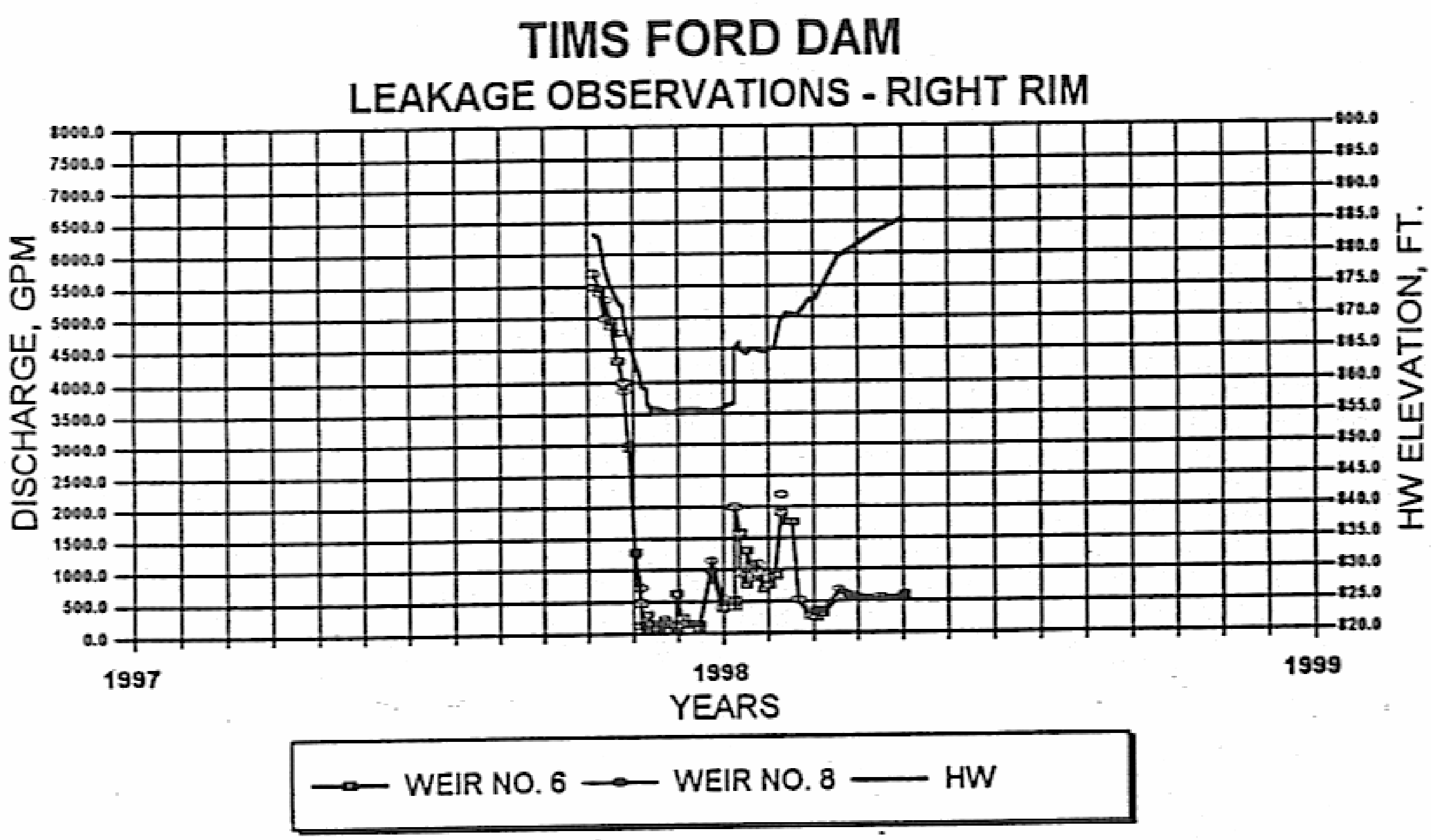


Figure 8. Discharge at Weirs 6 & 8 - October '97 through April '98

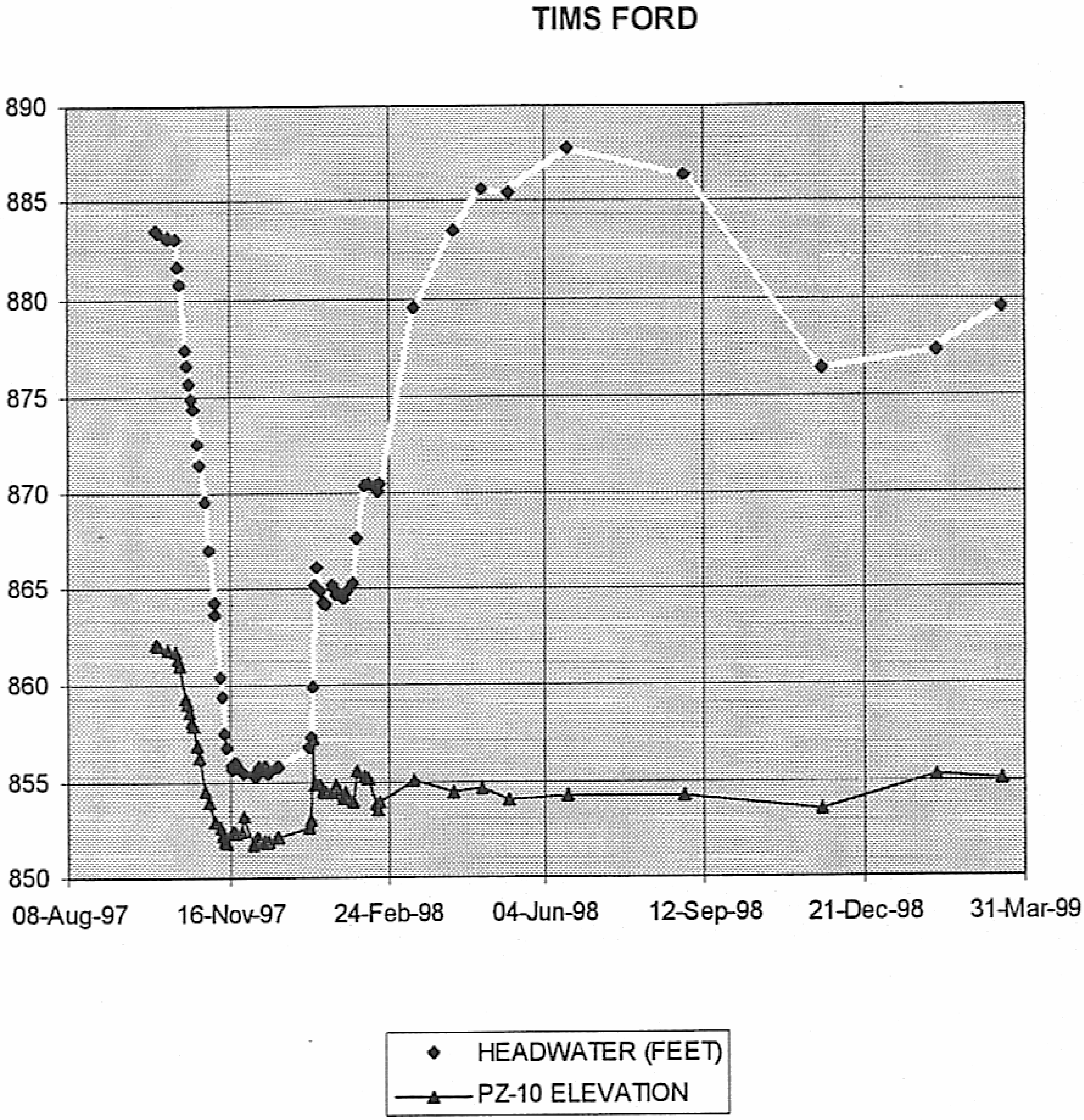


Figure 9. Tims Ford Reservoir Piezometer Observations.

Observations of the weirs and leakage are now scheduled monthly, while observations of the piezometers were discontinued, except for special observations. Overall rim leakage has been reduced from its pre-grouting maximum of 7,772 gpm to about 500 gpm at maximum normal pool levels

(Figure 10), well within the goal set for permanent reduction. Recent inspections of the rim have revealed no breakouts of new leaks, and the saturated overburden in the leak area 6 has dried completely.

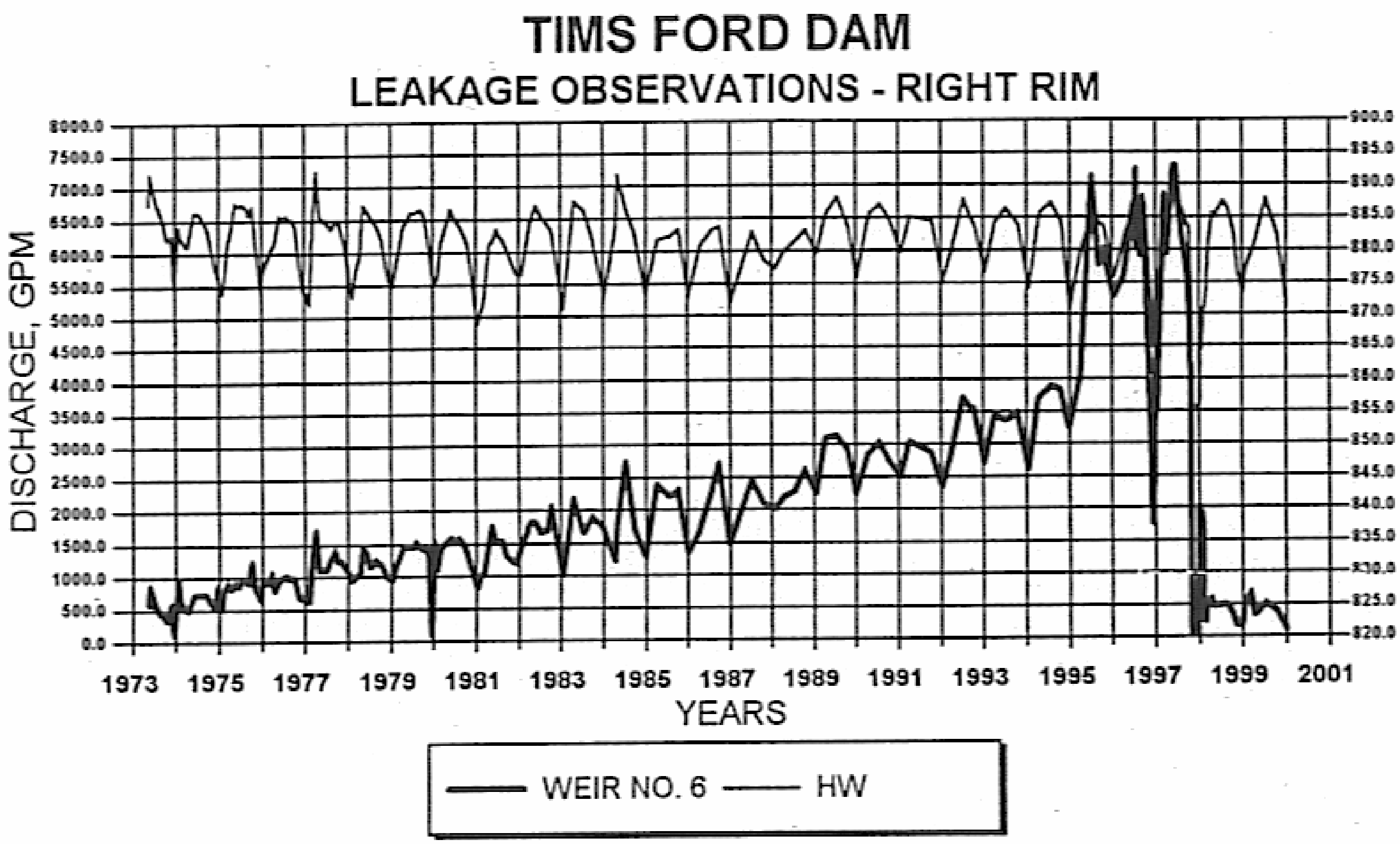


Figure 10. Tims Ford Right Rim-Current Discharge at Weir 6

ACKNOWLEDGEMENTS

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