Remedial Grouting using "Responsive Integration^{sm}"

at

Jocassee Dam
Oconee County, South Carolina

by D.A. Bruce*, E.C. Luttrell†, and
L.J. Starnes†

1. INTRODUCTION

Duke Power Company's Jocassee Dam impounds the 7500-acre Lake Jocassee in the northwest corner of South Carolina on the Keowee River, 7 miles north of Salem. The 408-foot high structure is composed of an earth core with rockfill shells, and can sustain a 30-foot drawdown when utilized in the pumped-storage scheme for power generation. The crest length is 1787 feet, and normal pool elevation is about 1105 feet.

Following first reservoir filling in late 1973, a number of springs and seeps were observed on both downstream abutments. The first evidence of substantial seepage occurred in May, 1976 at spring C-3 located about one-third of the way down the left abutment. (Figure 1) A small subsidence was noted and repaired by station personnel by replacing the disturbed material with gravel ballasted by surge stone. A perforated pipe was embedded in the gravel to collect the flow and route it to a collection and measurement weir. Small quantities of silt and sand were periodically observed in the C-3 weir, with occasionally larger amounts of material movement occurring at sporadic intervals. The flow from C3 (at El 986 feet) was directly dependent on the reservoir level in the range of El 1080 to 1110 feet and varied from 0 to 50 gpm.

The third Independent Consultant Inspection (Part 12) report of October, 1988 recommended repairs to the spring by wrapping the perforated pipe with a geotextile. After a short time, seepage began bypassing the pipe and the geotextile was removed. Although no increases in flow occurred, additional deposits of silt and sand did occur into 1991. In October of that same year, Duke undertook the first of a 3 phase remedial program of action to concentrate on Spring C-3 in particular.

This phase 1 included a subsurface investigation to collect data for incorporation into the grouting plan, along with a records review and geologic study. The investigation included soil and rock borings, and a dye testing program wherein angled holes were drilled just upstream of the centerline and dye was injected at various elevations as much as 106 feet below ground surface. Several East Abutment springs indicated a positive dye response. Phase 2 (the subject of this paper) consisted of grouting for about 200 feet eastward from the embankment. Phase 3 involved the rebuilding of the filter/collection system at the spring (not discussed further.)

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*Nicholson Construction Company, P.O. Box 98, Bridgeville, PA 15017
† Duke Power Co., Geotechnical Center, Box 219, Seneca, SC 29679

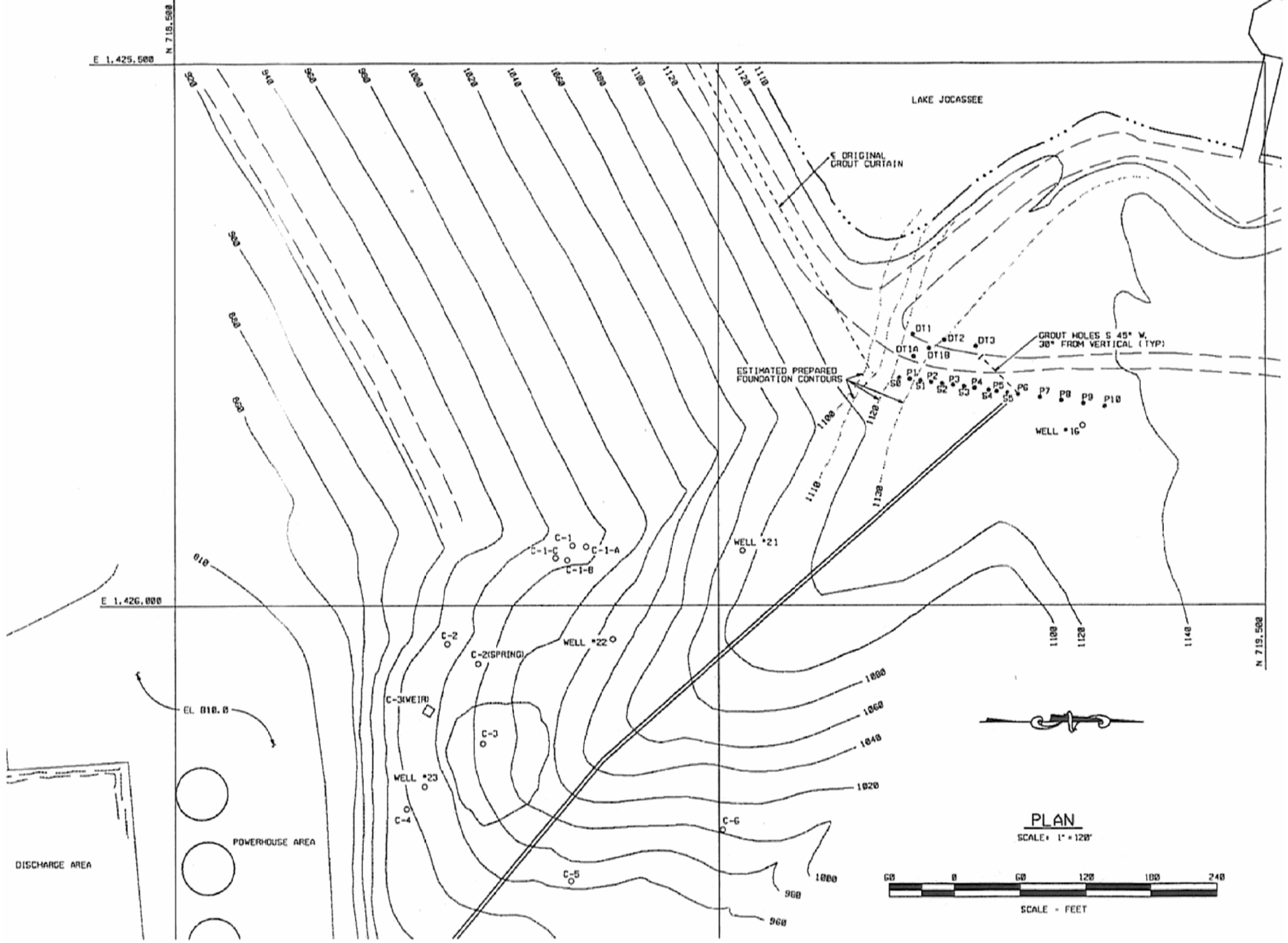

Figure 1. Location of grout holes, Dye Test holes, and springs.

2. PHASE 1 - EXPLORATION

2.1 Site Geology

Jocassee Hydro Station is located in the Brevard/Chauga geologic belt between the Blue Ridge and Piedmont physiographic provinces. The site is underlain by the Henderson Gneiss, a coarse to very coarse grained augen gneiss with microcline augen up to 1 inch diameter. Interlayered with the gneiss are hornblende-biotite gneiss and fine to medium grained augen gneiss. Pegmatites are generally parallel to the dominant foliation. Review of available data indicated that the seepage exiting at spring C-3 was most likely moving along the predominant N45W:85NE joint set, the best developed based on visual observation of the powerhouse rock cut and dam foundation geology. Less important were the N20E joint set and quartz-feldspar pegmatites parallel to foliation in the Henderson Gneiss. A straight line projection from C-3 toward the dam crest was used to locate the most likely area to be grouted. Study of the joint orientation yielded a most effective orientation for the grout holes of S45W, inclined 30 degrees from vertical.

2.2 Records Review

Original dam foundation grouting records included grout hole locations, orientations, depths, and takes. The new single-row curtain was designed to intersect the original 3-row curtain, but not to intrude into core material. The depth of the new curtain was determined as Elevation 1050, given the relationship between reservoir level and seepage volume.

2.3 Additional Exploration Drilling

Using the projection of the N45W joints from C-3, locations were established for three primary and two alternate drill holes along the upstream left abutment adjacent to the dam. (Figure 1) Holes were oriented S45W and inclined 30 degrees from vertical. These holes provided additional geologic and other subsurface information useful in designing the planned grout curtain.

2.4 Additional Dye Testing

Fluorescent Rhodamine WT red dye was injected in these boreholes at selected depths. Water samples were collected manually at various spring locations at regular specified time intervals and tested for the presence of dye by use of a Fluorometer. An automated sampler was used at C-3 to provide unattended 24-hour sample collection. Conclusions from this work were as follows:

1. Flow paths suggested by the geologic review were confirmed by the dye test study.

2. Apparent velocities varied, to a maximum of 1 cm/sec. (Apparent velocity equals straight line flow path distance divided by time from dye injection to first show.) This demanded that grout mix design and placement had to accommodate the danger of dilution or washout prior to stiffening in situ.

3. The planned location and lateral extent of the grout curtain would be adequate to intercept most flows to C-3. Other springflows would probably be affected and reduced as well.

As a result of this Exploratory Phase, the orientation, depth and length of the new curtain were initially determined (as shown in Figure 1), and important information was made available for the design of the grout mix.

3. BIDDING METHODOLOGY FOR PHASE 2

Duke Power wished to allow bidders maximum flexibility in proposing and utilizing processes they felt most effective and economical, while still meeting the owner's criteria for stage grouting, controlled grout travel, stability and penetrability. The owner did not therefore specify the drilling technique, drilling equipment, grout, grout equipment or injection method. The award was determined by the owner's evaluation with respect to anticipated effectiveness and economy, and with regard to employees' health and safety.

A variable "menu type" bid form was accompanied by a detailed questionnaire regarding the bidders' method statement, program, experience, workforce references, and environmental protection plan.

Afterward, and prior to commencement of work, the owner and contractor met to discuss specific details of the contractor's processes, equipment schedule, contract administration, facilities, requirements and so on, and to make final revisions to the specification and procedure, based upon the selected drilling and grouting process. The completed specification and procedure was then "Released for Construction."

As a basis for financially comparing the different bids, the following major quantities of work items were listed:

- 14 holes, each inclined 30° off vertical
- 6" drilling through overburden (Av. 32 ft/hole)
- 4" p.v.c. through overburden (Av. 32 ft/hole)
- 2 or 3" drilling through rock (Av. 64 ft/hole)
- Set down the hole packers
  - - - Stage I at base of casing
  - - - Stage II at base of casing or bottom of Stage I

  (Total - 2 stages/hole)
- Grout (Av. 1000 gallons/hole)

4. CONCEPT OF "RESPONSIVE INTEGRATION"sm

The use of grouting techniques for existing dam remediation has not always met with the expected degree of success (Weaver, 1991; Bruce, 1992.) Reasons have included:

- Unsuitability of Methods: including drilling technique, type of grout staging, grout injection method, geometry of holes, grout pressures, and use, location and types of packers.
- Unsuitability of Materials: physical and chemical properties of components (principally water, cement, fillers, additives and bentonite for cement based grouts, and water, base, reagent and accelerator for chemical grouts),

proportioning, rheology, stability, and resistance to physical and chemical attack.

- Lack of Critical Expertise from the Contractor: such as adaptability/flexibility to changing conditions, prior experience, local knowledge, ability to partner with the owner, technical competence, quality of documentation, and understanding of requirements necessary for administering the work.
- Lack of Quality Control and Progressive Monitoring Ability: methods, means and resources to monitor, correct documentation, and timeliness and quality of result evaluation.
- Overly restrictive, outmoded specifications: which give no room for modifying methods or materials during the course of the work, in response to what is progressively revealed.
- Procurement practices which foster contractual disagreements and which incite claims and litigation: a clear understanding of both the owner's and the contractor's needs is essential, but rare, whereas it is most common to find a) unit pricing based on estimated quantities which may not be accurate, and b) factors which force the contractor to build in large overhead charges or to inflate unit prices for unrealistic "what if" circumstances feared by the owner.

As outlined in the previous sections, this project was not extensive in scope, but was technically challenging. It was perfectly suited to the concept of "Responsive Integration"^{sm} recently crystallized by Nicholson Construction. The essence of the concept is for all parties, in active partnership, to evaluate data from all relevant sources, both historical and contemporary. The conclusions of this repetitive integration are then used to direct the progress of the work in the field, in the way which is most responsive to the actual conditions, to secure the most cost effective technical benefit.

Now, whereas this may seem a logical, simple and wholly desirable process, many of the negative factors listed above have usually acted to frustrate the efficacy of process and have therefore adversely impacted the quality of the resulting work.

In order to effect this success, several conditions within the owner-contractor relationship must exist:

- There must be mutual respect for each other's abilities, and the attributes which each party brings to the job.
- Specifications should be structured so as to be non-adversarial.
- There must be mutual desire for success, in terms of objectives, cost, environment, and so on.
- The parties must have the ability to respond quickly to changes in conditions or directions.
- There must be harmonious coordination of each process towards attaining a quality product.

The contractor should know and understand the owner's objectives, know the owner's abilities, understand the owner's share and limits of risk, and understand the owner's desire to control costs. Likewise, the owner should understand the contractor's abilities, expertise, and degree of flexibility, know the contractor's share of the risk, and should appreciate the contractor's desire to make a reasonable profit.

The fact that the benefits of "Responsive Integration" could be used at Jocassee was initially promoted by the owner's attitude towards the method of bid solicitation and contract award, as detailed in Section 3.

5. PHASE 2 - DRILLING AND GROUTING

The preliminary scope called for 10 Primary holes spaced at 20 feet centers, with 4 Secondary holes split-spacing those Primary holes closest to the dam. Daily monitoring of reservoir level, abutment springs and open stand pipe, piezometers, as well as conducting dye testing was agreed as very useful in progressively assessing the effectiveness of the work.

Nicholson Construction was awarded the contract largely on the basis of their technical expertise and especially their proposal to use relatively inexpensive cement-bentonite grouts. The advantages of using these mixes were that they were easy to mix and pumpable at low water-cement ratios, they comprised readily available materials, were controllable, could penetrate finer cracks, possessed moderate strength, and were relatively stable and dilution resistant (De Paoli et al, 1992). Provision was made for the addition of sodium-silicate, if required for flowing water or for ultra fast set times, and for the use of Type III and microfine cements, to encourage penetration of finer fissures.

5.1 Drilling

Since upstage grouting was initially foreseen, and the seepage appeared to be restricted mainly to well defined open channels, holes were advanced to their full depth using a down-the-hole hammer. A track-mounted diesel hydraulic drill with a rotary head was utilized. A six-inch PVC casing was installed through soil overburden, before the 4 1/2 inch grout hole was drilled. The order of drilling and grouting the holes was sequenced to minimize potential difficulties such as interconnection, and the drilling was commenced at the eastern end, in supposedly the tighter rock. Each hole was washed for about 10 minutes prior to water testing.

5.2 Water Testing

Water tests were typically performed in each stage of each hole, as shown in Table 1. Actual stage lengths ranged from 27 to 33 feet. A down-hole packer was set at the lower stage first, and the Houlsby multi pressure method was utilized. (Houlsby, 1976) A maximum excess water head of 38 PSI was applied.

The variation of the resultant Lugeon values over the course of each stage test provided insight into the nature of the fissure geometries and characteristics, and the initial grout mix for each stage was selected on the basis of this information. Certain stages could not be water tested due to the difficulty of packer seating in very soft/weathered horizons.

5.3 Grouting

A suite of grout mixes was derived from an on-site test program which assessed stability, flowability, specific gravity, and set time (Table 2). The Type I cement grouts were judged most appropriate for the Primaries, while the finer grained Type III, and microfine grouts were used in the Secondaries. Applied grouting pressures were typically limited to 1 psi/ft of depth for the Primaries, and 1 1/2 psi/ft for Secondaries.

	Drilling Record				Lugeon Value and Type of Stage Flow*			
HOLE #	CASING LENGTH	UPPER STAGE	LOWER STAGE	TOTAL DEPTH	UPPER	LOWER	GROUT SEQUENCE	REDRILL
P-10	36 FT.	33 FT.	33 FT.	102 FT.	16 TURBULENT	4 WASHIN	UPSTAGE	NO
P-9	36	33	33	102	NO TAKE	25 TURBULENT	UPSTAGE	NO
P-8	36	33	32	101	NO WATER TESTING OR GROUTING CONDUCTED		CONNECTED/ BACKFILLED FROM #8	YES
P-7	32	33	33	98	a) NO TAKE 29 b) TURBULENT 19 c) TURBULENT	29 TURBULENT	UPSTAGE	NO
P-6	30	33	33	96	7 LAMINAR	22 TURBULENT	UPSTAGE	NO
P-5	29	33	33	95	>100 TURBULENT	>100 TURBULENT	DOWNSTAGE	YES
P-4	27	33	33	93	24 TURBULENT (STAGE GROUTED THROUGH THE RODS)	28 TURBULENT	DOWNSTAGE	YES
P-3	36	28	29	93	34 TURBULENT	>100 TURBULENT	DOWNSTAGE	YES
P-2	32	30	28	90	>100 TURBULENT (STAGE GROUTED THROUGH THE RODS)	>100 TURBULENT	DOWNSTAGE	NO
P-1	33	27	27	87	>100 TURBULENT (STAGE GROUTED THROUGH THE RODS)	32 TURBULENT	DOWNSTAGE	YES
S-5	29	33	33	95	28 TURBULENT (STAGE GROUTED THROUGH THE RODS)	26 TURBULENT	DOWNSTAGE	YES
S-4	32	31	30	93	31 TURBULENT	24 LAMINAR	DOWNSTAGE	YES
S-3	24	32	33	89	18 WASHOUT	8 LAMINAR	DOWNSTAGE	NO
S-2	37	27	28	92	18 LAMINAR	28 TURBULENT	DOWNSTAGE	NO
S-1	33	28	27	88	11 HYDROFRACTURE	1 LAMINAR	UPSTAGE	NO
S-0	29	11		40	STAGE GROUTED THROUGH THE RODS (Concern for penetrating the dam core)		N/A	N/A

TABLE 1. Summary of Drilling and Water Testing Data.

* From Houlsby (1976).

Mix #	Water (Gallons)	Bentonite (Pounds)	Cement (Pounds)	Stiffening (Hours)	Hardening (Hours)	S.g (Meas.)	Marsh Cone (Secs)	Final Bleed (%)
B	20	2 1/2	94	6	8+	1.31	40	23
C	20	4	94	5 1/2	7 1/2+	1.34	43	17
D	20	8	94	5	7+	1.35	49	6
H	20	10	94	5	7+	1.36	54	4
E	20	4	188	3-4	4-5	1.56	50	3
F	20	8	188			1.57	65	2
G	20	4	282	3	4	1.73	75+	1

Table 2. Summary of Type I Cement Grout Mixes.

Note:
(1) Water and bentonite mixed for 30 seconds prior to adding cement; samples taken 60 seconds later.
(2) For microfine grout, the mix design was 26 gallons/44 lb bag (W/C = 5.0 by weight), + 7 oz. dispesant
(3) Air temp 55°F.

5.4 Analysis of Water Testing, and Grouting Data

Tables 1 and 3 summarize the results of the water testing and grouting respectively. The decision to terminate the work after treating six Secondary holes in the most critical area (i.e. adjacent to the dam) was made with respect to grout take characteristics (and Reduction Ratio comparisons), and the effect on the spring flows, as discussed in Section 6 below. Table 1 shows that the water test values in the Primaries were uniformly high, especially so in Holes P1-P5. The tests confirmed Turbulent Flow conditions, indicative of the presence of larger, more open flow paths. (During drilling, the rock mass appeared to be typically competent and tight, except for discrete very soft/weathered zones, usually between 30 - 40 feet, and around 60 feet down. In such holes, downstaging was necessary, while grouting through the drill rods had to be occasionally conducted to combat especially unstable conditions which would not allow packers to be set properly for pressure grouting. Lugeon values were smaller, further from the dam, and were reduced in the Secondary holes, the latter highlighting the efficacy of the Primary grouting. In addition, the identification of "Laminar" flow stages in the Secondaries was indicative of the absence of large untreated flow paths, and the presence of finer fissures only.

The magnitude of grout takes generally matched this pattern, as shown in Table 3. The grout thickening sequence appeared to prove successful, with each stage, eventually achieving the pressure criterion for refusal. These figures exclude just over 7000 gallons of grout (mainly Mixes E, F and G) for pressure grouting in the five former dye test holes, and 3100 gallons of Mix E for gravity backfilling all the holes after completion of all other activities.

6. HYDRAULIC EFFECTIVENESS OF THE GROUTING

There were three main independent measures of the impact of the grouting, namely piezometers, seepage flows, and dye tests. Duke personnel performed the monitoring functions for continuous feedback in support of Nicholson's construction activities.

HOLE AND STAGE		BAGS USED	LB. BENTONITE USED	GAL. H2O USED	TOTAL GALS. INJECTED	COMPOSITION OF TOTAL (GALLONS)					
						MICRO-FINE	MIX C	MIX D	MIX E	MIX F	MIX G
P-1	UPPER	108	432	1280	1690	0	238	239	274	938	0
	LOWER	28	136	480	587	0	238	239	111	0	0
	TOTAL	136	568	1760	2277	0	476	478	385	938	0
P-2	UPPER	114	312	1160	1586	0	238	239	273	278	558
	LOWER	49	182	660	846	0	238	239	138	138	93
	TOTAL	163	494	1820	2432	0	476	478	411	416	651
P-3	UPPER (DAY 1)	85	340	1100	1458	0	238	239	274	552	155
	UPPER (DAY 2)	84	288	860	1143	0	119	120	411	276	217
	LOWER	11	48	220	262	0	238	24	0	0	0
	TOTAL	180	676	2180	2863	0	595	383	685	828	372
P-4	UPPER	60	240	800	1027	0	238	239	274	276	0
	LOWER	60	240	800	1027	0	238	239	274	276	0
	TOTAL	120	480	1600	2054	0	476	478	548	552	0
P-5	UPPER	48	192	680	861	0	238	239	238	146	0
	LOWER	22	124	420	505	0	238	239	28	0	0
	TOTAL	70	316	1100	1366	0	476	478	266	146	0
P-6	UPPER	100	320	1100	1476	0	238	239	274	414	311
	LOWER	60	240	800	1027	0	238	239	274	276	0
	TOTAL	160	560	1900	2503	0	476	478	548	690	311
P-7	UPPER (DAY 1)	92	308	1040	1393	0	238	239	274	414	218
	UPPER (DAY 2)	54	216	740	944	0	238	239	274	193	0
	LOWER	72	288	920	1183	0	238	239	274	442	0
	TOTAL	218	812	2700	3520	0	714	717	822	1049	218
P-9	UPPER	0	0	0	0	0	0	0	0	0	0
	LOWER	102	312	1100	1483	0	238	239	274	369	373
	TOTAL	102	312	1100	1483	0	238	239	274	369	373
P-10	UPPER (DAY 1)	72	328	1020	1294	0	238	478	274	304	0
	UPPER (DAY 2)	48	96	480	657	0	0	0	657	0	0
	TOTAL	120	424	1500	1951	0	238	478	931	304	0
OVERALL		1271 bags	4652 lb.	15660 gallons	20,449 gallons	0	4165 gallons	4207 gallons	4860 gallons	5292 gallons	1925 gallons

Average consumption of solids =

$$\frac{1271 \times 94 + 4652}{633} = 196 \text{ lb/ft}$$

$$= \underline{292 \text{kg/m}}$$

TABLE 3A. Summary of Grouting Data - Primary Holes
(Excludes Dye Test Holes and Backfilling)

HOLE AND STAGE		BAGS USED	LB. BENTONITE USED	GAL. H2O USED	TOTAL GALS. INJECTED	COMPOSITION OF TOTAL (GALLONS)					
						MICRO-FINE	MIX C	MIX D	MIX E	MIX F	MIX G
S-0	UPPER	24 Type III	0	160	248	0	0	0	0	0	248
	LOWER	0 Type III	0	0	0	0	0	0	0	0	0
	TOTAL	24 TYPE III	0	160	248	0	0	0	0	0	248
S-1	UPPER	3 MICROFINE	0	78	84	84	0	0	0	0	0
	LOWER	7 MICROFINE	0	182	196	196	0	0	0	0	0
	TOTAL	10 MICROFINE	0	260	280	280	0	0	0	0	0
S-2	UPPER	7 TYPE III	28	140	167	0	167	0	0	0	0
	LOWER	10 TYPE III	40	200	238	0	238	0	0	0	0
	TOTAL	17 TYPE III	68	340	405	0	405	0	0	0	0
S-3	UPPER	10 MICRO + 7 TYPE III	56	600	447	280	167	0	0	0	0
	LOWER	9 MICROFINE	0	234	252	252	0	0	0	0	0
	TOTAL	19 MICRO + 7 TYPE III	56	834	699	532	167	0	0	0	0
S-4	UPPER	11 TYPE III	48	220	262	0	238	24	0	0	0
	LOWER	20 TYPE III	120	400	477	0	238	239	0	0	0
	TOTAL	31 TYPE III	168	620	739	0	476	263	0	0	0
S-5	UPPER	10 MICRO + 36 TYPE III	152	820	976	280	238	239	219	0	0
	LOWER	68 TYPE III	272	880	1138	0	238	239	274	387	0
	TOTAL	10 MICRO +104 TYPE III	424	1700	2114	280	476	478	493	387	0
OVERALL		39 MICROFINE + 183 TYPE III	716 lb	3914 gallons	4485 gallons	1092 gallons	1524 gallons	741 gallons	493 gallons	387 gallons	248 gallons

$$\text{Average consumption of solids} = \frac{39 \times 44 + 183 \times 94 + 716}{313} = \frac{19634}{313}$$

$$= 63 \ \text{lb/ft}$$

$$= \underline{\underline{94 \ \text{kg/m}}}$$

TABLE 3B. Summary of Grouting Data - Secondary Holes
(Excludes Dye Test Holes and Backfilling)

6.1 Piezometers

Most of the piezometers on this abutment were too far from the grouting to be directly influenced by it. However, in one, (No. 16), there was an increase of about 3 feet, suggesting the presence of a seepage barrier in place.

6.2 Spring Flows

As shown in Figure 2, all spring flows, and especially those in C-3 were reduced by the grouting. During the grouting, the lake level was relatively constant, from El 1107·4 to 1109 feet. The change in C-3 , when monitored against the progress of the work is most interesting: the greatest rate of flow reduction was accomplished by the grouting of holes P6 to P3, highlighting the location of the most significant flow paths. Thereafter, the other holes, including the Secondaries did have high permeability values and did have appreciable grout takes, without, however, causing much further reduction in flow, except at point D. This indicates that these remnant flows were not occurring through this new curtain, but either around or below it. Overall, though, the total flows had been reduced from 107 gallons per minute to just over 30 gallons per minute, and the owner judged this an acceptable, cost-effective result.

6.3 Dye Testing

After grouting was completed, the Phase 1 test holes DTI-3 were cleaned out and dye testing repeated. Typical data (from the DT3 test) are shown in Figure 3. Now, while it is not feasible to control exactly the injection concentrations themselves, the key feature is the time of maximum response. Prior to grouting, the peak retrieval period at Spring C3 occurred within 9 hours of dye injection. After grouting, this peak, much less marked, was noted 14 - 15 hours after dye injection. This is a clear indication of the reduction in seepage velocities across the line of the new curtain, and so confirmation that the pre existing open paths had been sealed. The straight line slope distance from DT3 to C3 is 596 feet.

6.4 Subsequent Monitoring

Piezometers have been read monthly and have exhibited no further changes: the level in No. 16 has stabilized. Flow quantities are recorded every two weeks and have remained constant. No sediment accumulation has been observed in the C-3 weir. This monitoring will continue.

7. FINAL REMARKS

The scope of the work conducted at Lake Jocassee Dam was not large, but was technically very challenging: it was the type of repair that has been attempted with disappointingly little success in the past, prompting disillusionment with the grouting industry at large, and the actual participants in particular. However, this project proved to be a considerable technical success, providing the owner with an excellent result within the ceiling of his budget. The key to this was the application of the principles of "Responsive Integration." In particular, the owner and contractor partnered effectively before and during the work - an opportunity initially created by the attitude displayed by the owner from the first stages of prebid planning.

Technically, the work featured innovative drilling and grouting concepts and practices which proved extremely effective. It must be noted, however, that such technical innovation would have been impossible to introduce and apply without an equal degree of innovation in the methods of bid procurement and contract administration.

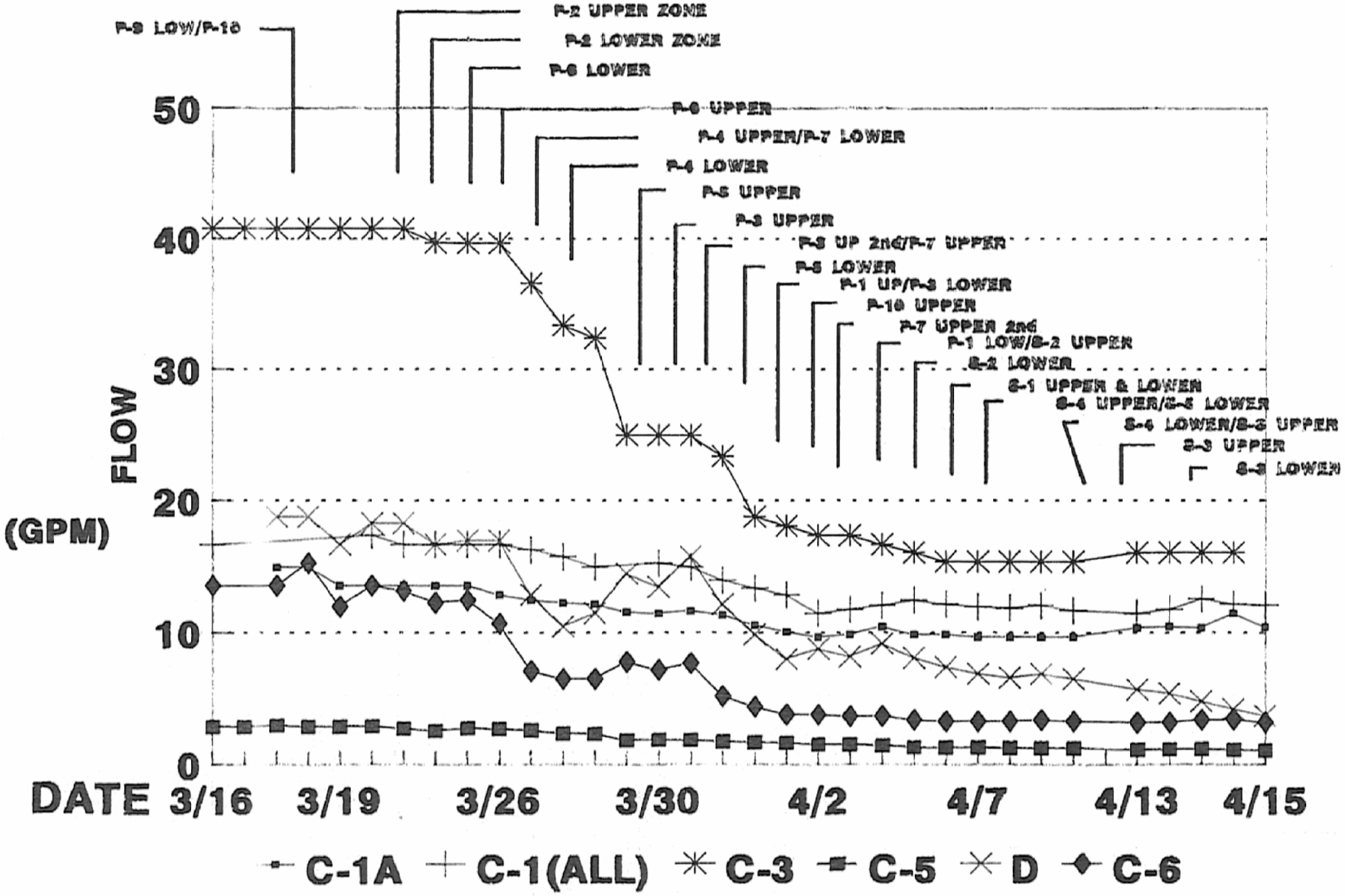

Figure 2. Spring flows measured during grouting (Reservoir level relatively constant 1107.4 to 1109.0 feet. Elevations of flow points: C1 = 980'; C3 = 986'; C5 = 956'; C6 = 1000'; D = 1000').

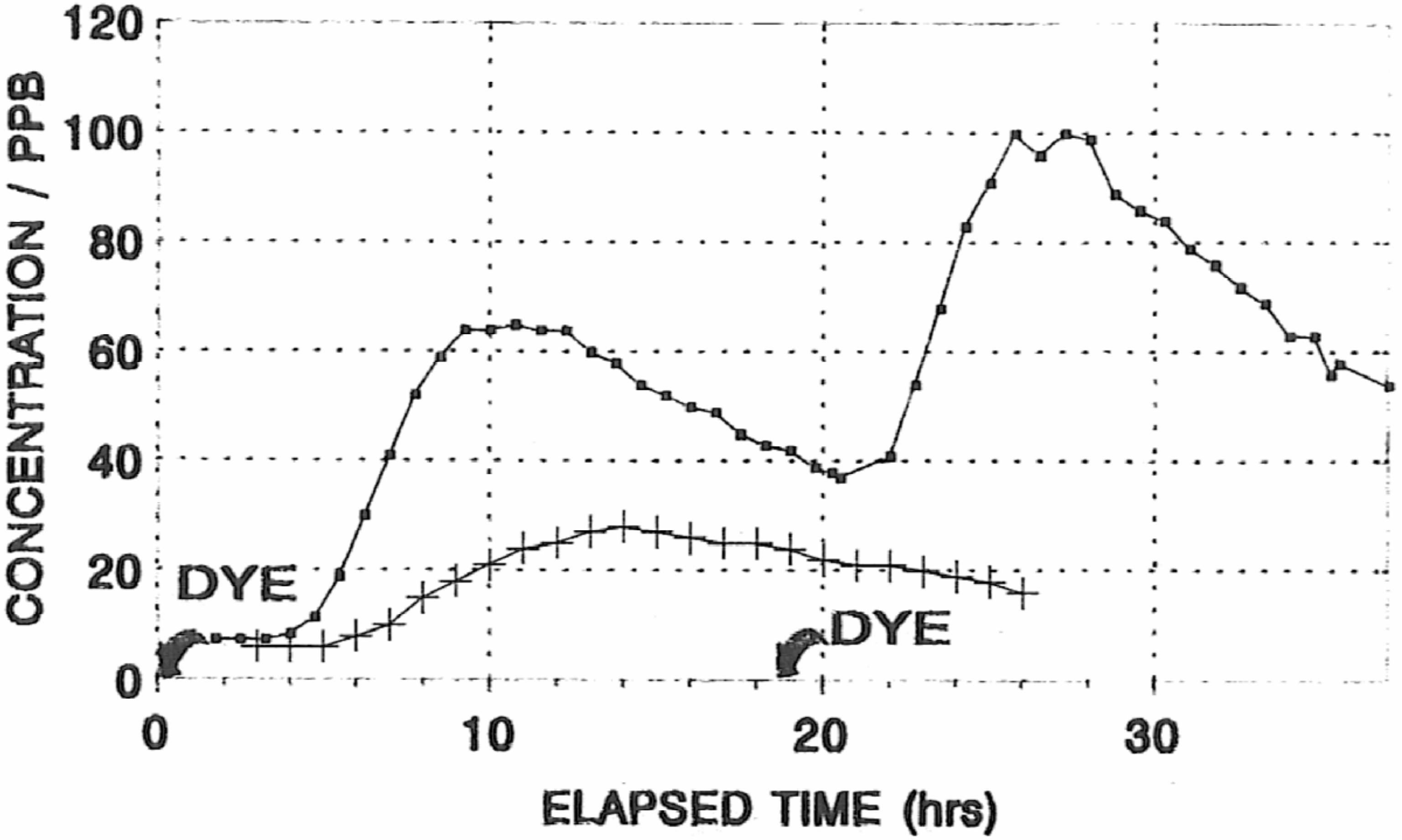

Figure 3. Dye concentrations measured at Spring C-3, following injection at DT3. Upper curve is prior to grouting (10/14-15/91); Lower curve is after grouting (4/13/92).

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