b) **<u>Foundation</u>.** There were no borings or sampling of the foundation during the design phase, and the following assessment resulted from a site visit after the fuse plug activation.

The foundation observed in the side walls of the breach includes a stratum of tan loose to medium dense sand from the ground surface to an approximate depth of 8-10 feet. This stratum contains some outwash material, but is primarily weathered till. The repeated freezing and thawing, with the resultant volume increase of in-situ water, is primarily responsible for creating the loose structure from the original dense till. Beneath the surface layer is a zone of tan very dense weathered till approximately 10 feet thick, followed by dark gray very dense unweathered till to great depth. Both of these stratum appeared cemented. The grain size distribution of all till layers appeared to be a slightly silty coarse to fine sand with some gravel, with the most noticeable difference in stratums being the tan coloration of the upper two weathered zones, and the looser density of the uppermost zone. The till was in general void of clayey or plastic fines. When samples of either the dense tan weathered or gray unweathered till were placed in water, they quickly “melted” into a cohesionless mass. During construction, one grain size analysis was performed on material identified as "foundation soil," sample S-10 in the MWH final construction report. This gradation curve is shown on Figure 1.

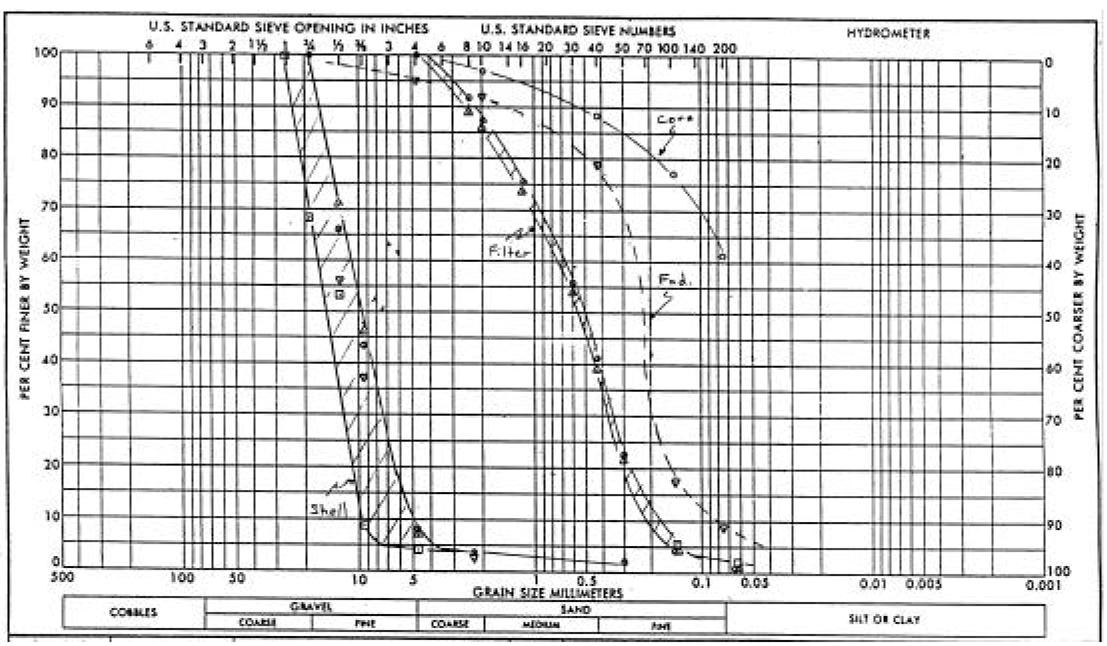

Figure 1, Gradation Curves

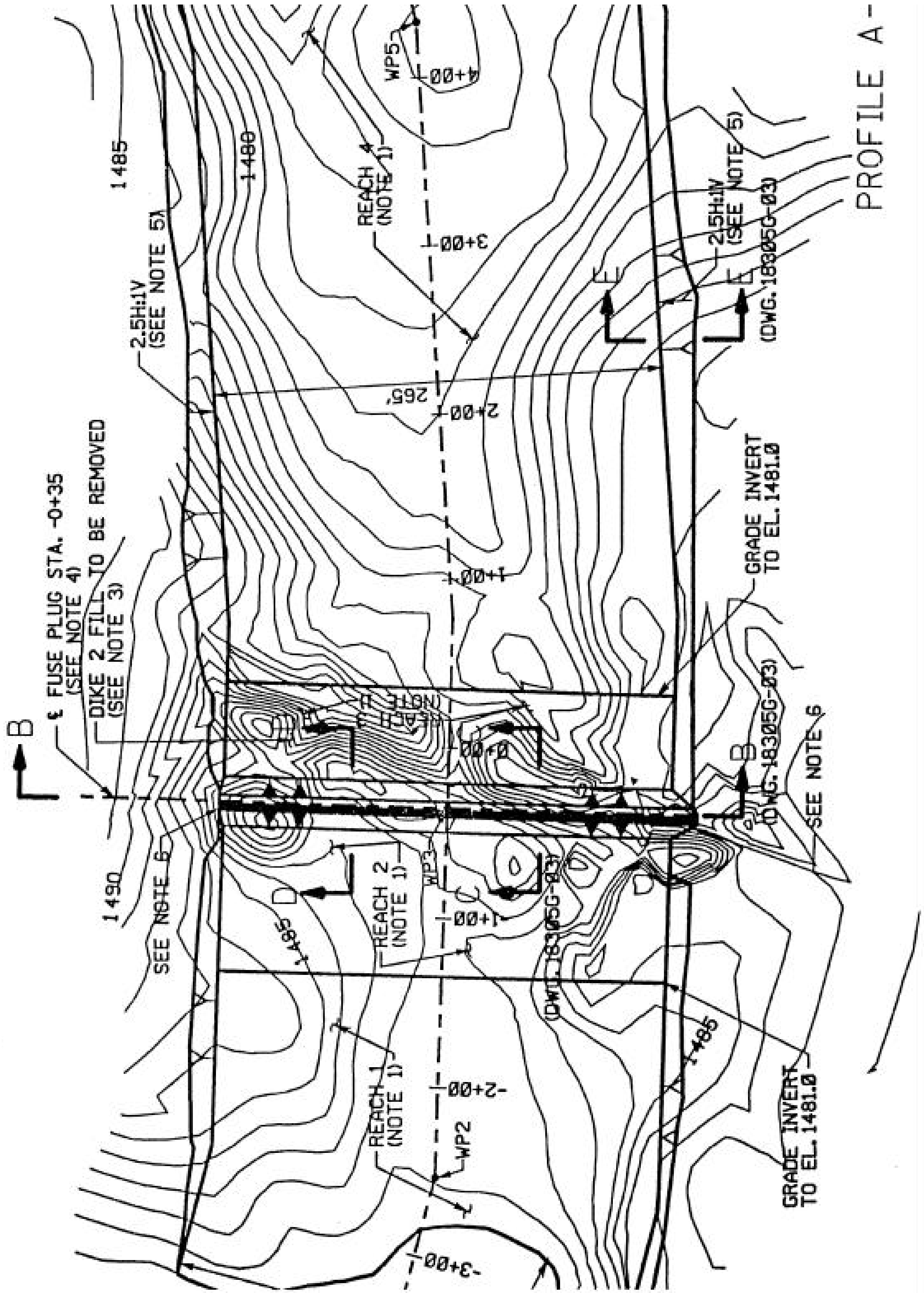

Figure 2, Preconstruction Topography

The original topography shown on the MWH 20895-C5 drawing includes several interesting dike and foundation features, as shown in enlargement on Figure 2. The original dike 2 crest was skewed compared to the constructed fuse plug, and appears to contain two low points in the crest; one at elevation 1484 near the dike centerline, and one at elevation 1486 near the western abutment. These features, if real, would have allowed minor overtopping flows during high water periods in previous years. The topography downstream of dike 2 also suggests small flows and erosion could have been occurring in the past.

Of greater interest to the fuse plug construction are the pits shown upstream of dike 2, in particular the pit near the east abutment. These are drag-line pits and were the borrow source for the original dike construction during the 8-foot-high dam rising in the 1940's. These drag-line pits are shown in photos from operation reports prior to fuse plug construction, and remain visible today at the other dike locations. The large drag-line pit, with bottom elevation 1478, was subsequently overlain by the new fuse plug alignment. It is likely that the 1478 elevation shown includes several feet of muck or washed in soil, and the original pit would have been deeper. The implications of performing muck removal and compaction with backfill having a permeability comparable to the remainder of the foundation are significant, and could represent a foundation weakness for seepage and piping if not properly addressed. Interviews with construction personnel, which have not occurred to date, should address this issue.

c) <u>Fuse Plug</u>. The gradation of four zone 2 filter samples, four zone 3 shell samples, and one core sample are also shown on Figure 1. Being processed materials, the filter and shells have relatively narrow gradation bounds, and filter D15/D85 criteria are met as long as segregation does not occur. These criteria are also satisfied between the core/foundation and placed filter. The forthcoming investigation report by STS should include additional gradation curves for the foundation samples, taken from the small island (original graded channel) that remained after the breach.

Filter criteria are not satisfied between the zone 2 filter and zone 4 surface riprap along the downstream slope. Most earth and rockfill dam gradations require a continuous increase in permeability of zones downstream of the core, to allow easy drainage of seepage past the core. The presence of the zone 2 material along the downstream slope blocks seepage flow from the interior shell, and would increase the pore pressure head within the fuse plug. If increased sufficiently, the head in the zone 3 shell will pipe the zone 2 material into the riprap, effectively dissipating the excess head.

The construction photos reviewed to date from the MWH final construction report, and those provided by Ben Trotter of UPPCO, show considerable attention was being paid to lay out and placement of the various zones. Compaction criteria of 90% standard proctor is indicated as being met for the filter, although the filter appears sufficiently coarse as to suggest relative density as a more meaningful compaction control criteria. The core, on the other hand, compacted by light hand-propelled vibrating sleds, failed to meet the required 90% standard proctor criteria in four of the seven record tests, with values as low as 84% standard proctor. Core material failing these density criteria was not recompacted. This low compaction would likely produce a relatively soft and weak core, possibly susceptible to ice lens formation and frost heaving.

d) <u>Fuse Plug Activation</u>.

<u>Mechanisms</u>. Based on the high water mark and the as-built survey of the constructed fuse plug, only 1 to 3 inches of flow entered the 3-foot-wide pilot channel. It cannot be concluded with certainty that the fuse plug was activated by overtopping.

Hydraulic failures involving earth structures typically remove the forensic evidence needed to reconstruct the failure. One aspect is known, i.e., it is conclusive that the final phase of the breach involved channel floor cutting on the right side of the channel, due either to the shorter hydraulic distance of the curving channel or slightly more erodible soils. However, the Silver Lake breach channel may provide other evidence to allow speculation on the sequence of events. The modest left bank erosion along the original channel slope, shown in Photograph 1, indicates moderate flow in this area prior to the major breach and erosion along the right side of the channel. This may indicate that the problem originated near the left abutment. If this interpretation is correct, the previous discussion regarding construction over the left abutment drag-line pit has added credence.

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Photo 1. Left bank erosion with remnants of original slope. Upper bench and slope erosion indicates level of initial flow

Another possible breach scenario is that the fuse plug breach was initiated on the right side of the fuse plug. The as-built surveys indicate that the pilot channel near the right abutment was at an elevation slightly lower than the left pilot channel. With the lower pilot channel elevation, erosion of the fuse plug could have been initiated on the right side of the fuse plug. Evidence of this is the significantly greater erosion on the right side of the channel than on the left side of the stream channel.

With regard to other potential failure mechanisms, slope stability and potential piping cannot be positively eliminated. Neither should have been a problem, as long as the foundation was homogenous and less pervious than the overlying filter, as would be the case for the gradation shown on Figure 1. Distinct and drastic gradation changes in the foundation were not observed in the walls of the breach. The potential for non-homogenous conditions in the drag-line pit backfill have already been discussed.

The surface compaction of the channel floor could have produced a layered foundation, with the denser upper several feet having a lower permeability than the underlying looser soil, even with identical grain size distribution. Cedergren reports tests by Strohm et al where a well graded sand and gravel containing 5% fines had permeabilities reduced by two orders of magnitude by high compactive effort compared to moderate densities. The comparative effect of compaction on the foundation soils beneath the fuse plug would likely have a less drastic, but significant, effect on permeability. Surface compaction of the channel floor was reported to 95% standard proctor. If conducted both upstream and downstream of the fuse plug, such a layered system should not materially affect the foundation pore pressures at the downstream toe. If poor compaction of the foundation upstream of the fuse plug is combined with good compaction downstream, high foundation pore pressures at the downstream toe could be generated. This was a potential at the drag-line pit, where the fuse plug upstream toe overlies the deepest part of the pit and the downstream toe is beyond the pit limits.

The core and foundation soils may have been susceptible to ice lens formation, in particular with the very low compaction of the core. Subsequent ice lens melting could provide a void and a direct seepage path across the core, with resulting high pore pressures in the downstream shell. Piping of the zone 2 filter on the downstream slope into the riprap would occur

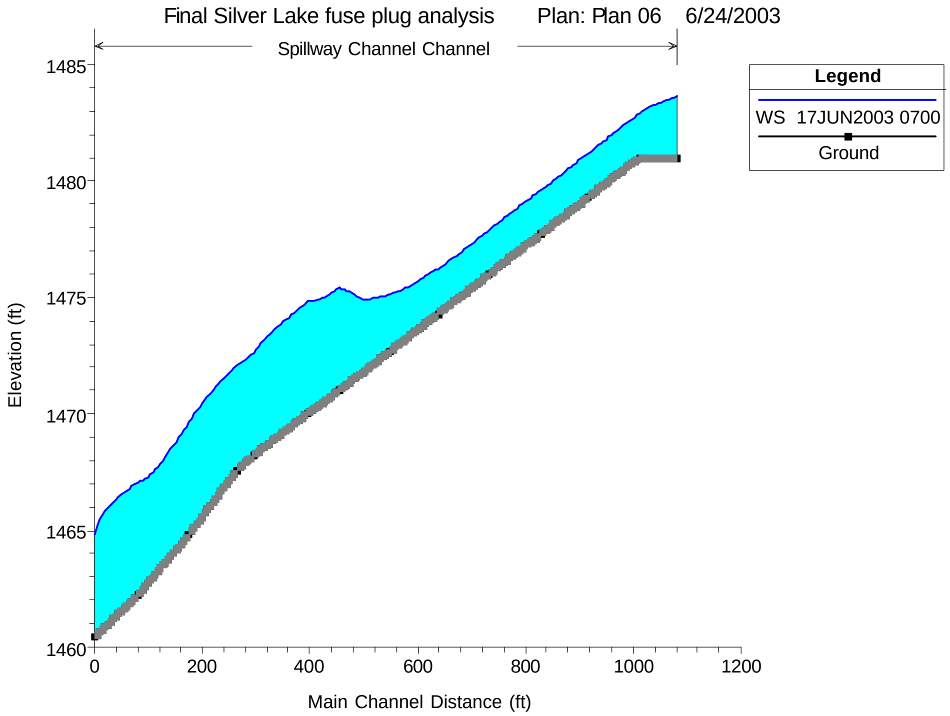
The foundation soil beneath the center of the dike may not have thawed, allowing a roof to form and sustain potential foundation piping.

e) <u>Channel Erosion</u>. Regardless of what mechanism initiated the fuse plug dike breach, the downstream consequences would have been minor if the channel floor had remained in place with a sill elevation of 1481 msl. Channel erosion allowed the entire reservoir to empty in a relatively short time period.

The information presented earlier from the designer, MWH, states that a grass-lined channel is capable of protecting erodible soils to a velocity of 6 fps, with some consideration to increasing the value to 7.5 fps for infrequent floods. A PMF entrance velocity of 9.1 fps is cited in the March 2002 design report, along with acknowledgement that the fuse plug channel floor will be damaged and require repair. A more appropriate design consideration would be velocity in the exit channel. Velocities of 13.8 fps for the PMF flow in the exit channel were presented in an earlier section, for a 1.69% slope. These would increase to 14.5 fps for the design 1.8% exit channel slope. Compared to an allowable value of either 6.0 or 7.5 fps for a grassed channel, significant erosion should have been expected for the PMF condition.

Similar analyses were conducted for peak flows during the breach at the reservoir high water mark of 1485.6, assuming the channel floor did not erode, as shown in Figures 3 and 4. Figure 3 models the earth channel without grass, which was the existing condition during the breach. Calculated velocities over 15 fps occur for much of the exit channel. If the grass had been established, the calculated velocities would have been around 10 fps, as shown in Figure 4. With or without grass, it appears the channel floor was susceptible to erosion.

MAX. WATER SURFACE ELEVATION – Flow: 7,750 cfs
Uniform channel section n=0.02



MAX. CHANNEL VELOCITIES – Flow: 7,750 cfs
Uniform channel section n=0.02

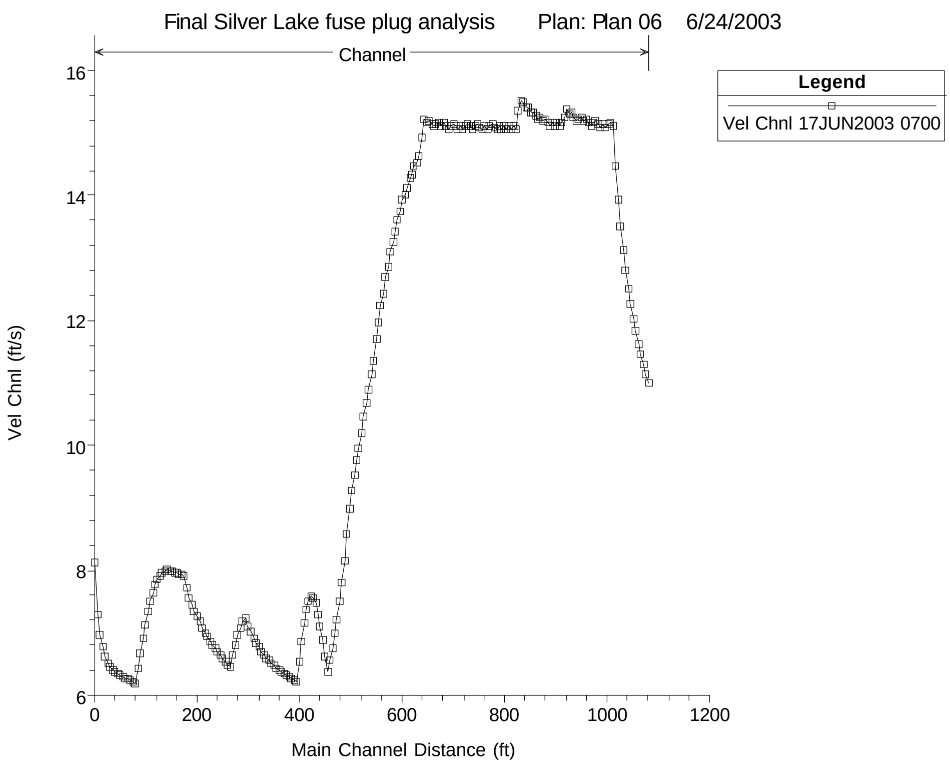
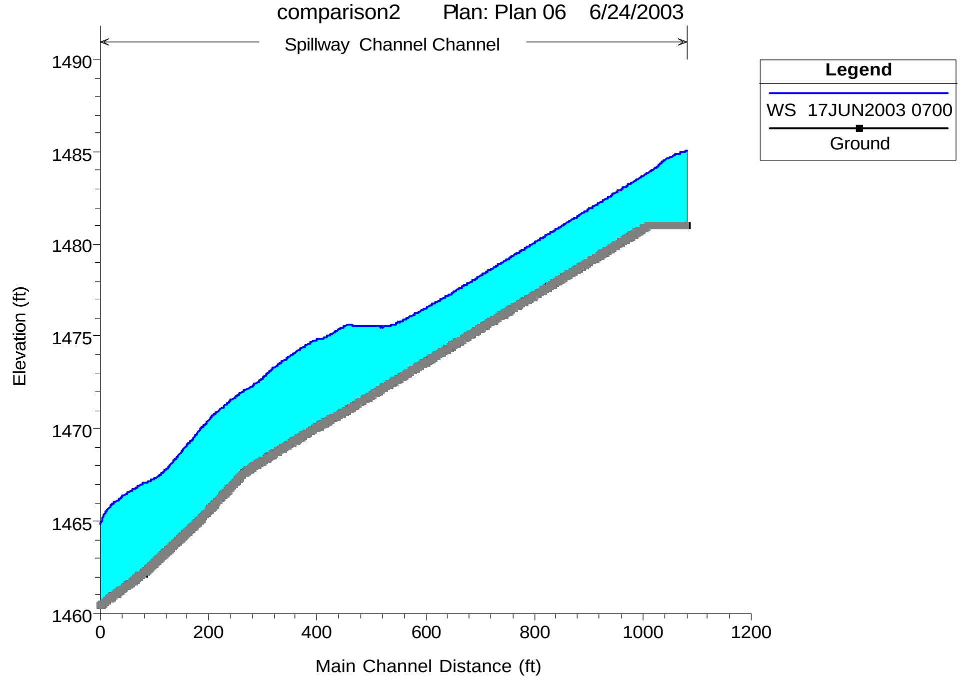


Figure 3

MAX. WATER SURFACE ELEVATION – Flow: 7,750 cfs
Revised model with uniform channel section n=0.04



MAX. CHANNEL VELOCITIES – Flow: 7,750 cfs
Revised model with uniform channel section n=0.04

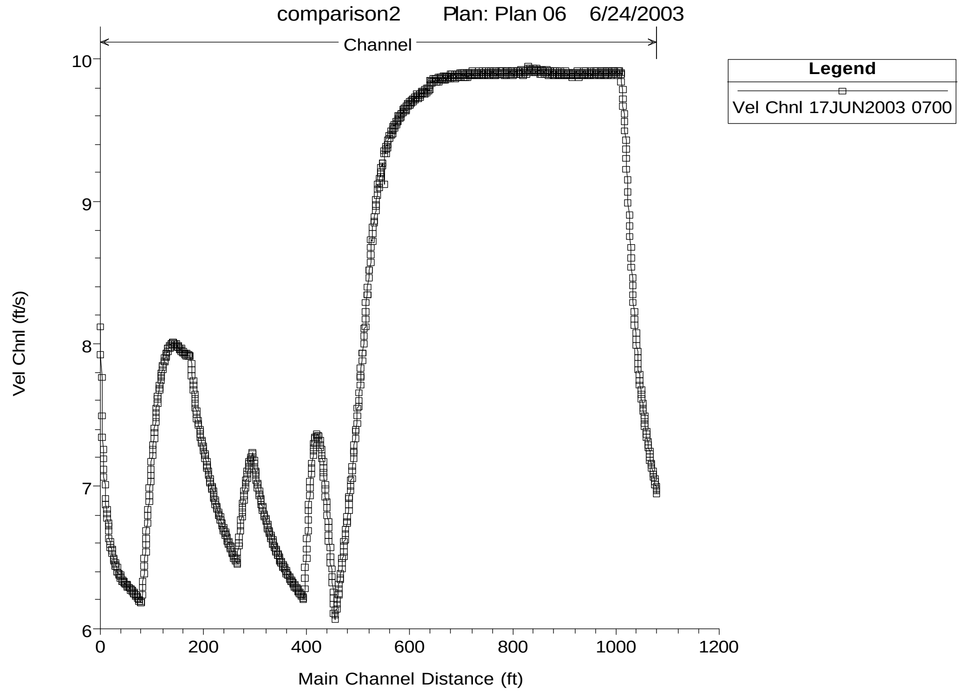


Figure 4

The completed fuse plug viewed from the left end toward the right end.

View looking toward the reservoir from the crest of the fuse plug.