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Geotechnical Investigations and Ground Characterization—The New Irvington Tunnel Project

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1. Introduction and Background

The Existing Irvington Tunnel (EIT) was constructed between 1928 and 1931 as part of San Francisco's Hetch Hetchy Water System. The EIT extends approximately 5.6 km (3.5 miles) from the Sunol Valley to Fremont in Alameda County, California (Figure 1). The 3.2 m (10.5 ft) diameter tunnel and its adjacent connecting pipelines currently deliver water to about 2.5 million customers in San Francisco and 26 other nearby municipalities and water districts. Because of the need to maintain continuous operation, the EIT is considered a critical regional lifeline facility.

Because of high usage demands spurred in part by the rapid growth and development in the Silicon Valley area, and the need for continuous water system deliveries, the San Francisco Public Utilities Commission (SFPUC) has not been able to take the EIT out of service for inspection or repair since 1966. Although built using good practices for the time and believed to still be in relatively sound condition, the existing tunnel was not designed to withstand strong ground shaking and potential fault offset, which are now known to represent substantial hazards. The tunnel alignment is located between two major active tectonic features—the Hayward fault on the west and the Calaveras fault on the east. Surface rupture on either of these faults during a major earthquake would severely impact the adjacent pipelines. Secondary effects including strong ground shaking and sympathetic fault offsets present a major threat of serious damage to the EIT and its portal pipeline connections. Such damage would disrupt flow to SFPUC's customers for many months while repairs were undertaken. This and similar conditions present elsewhere in the system led San Francisco to initiate a $4.5 billion Water System Improvement Program (WSIP) in 2002.

The New Irvington Tunnel (NIT) project is one of approximately 80 WSIP projects underway system wide, including water treatment plant upgrades, strengthening existing pipeline fault crossings, the addition of new pipelines designed to survive anticipated fault offsets, and construction of three new tunnels, all intended to improve system reliability and help SFPUC meet post-earthquake water demands. The primary design objective for the NIT project is to maintain water delivery service at normal levels immediately following the design-level earthquake. The new tunnel facilities will also provide redundancy so either tunnel can be inspected or repaired during normal operations without interrupting water deliveries.

2. Project Description

To provide the needed strength and resilience to survive the design-level earthquake, the NIT will include a much stronger lining system than the EIT. Most of the NIT will be lined with high-quality reinforced concrete, whereas the EIT liner is largely unreinforced. In zones where small secondary fault offsets are considered a threat, steel-lined sections will be installed in the NIT. Steel liner will also be installed at the portals and in other critical areas. For comparison, the EIT has no steel lined sections. The steel-lined sections near the NIT portals will connect directly with new steel pipeline manifolds to resist seismically induced separation. In order for the hydraulic demands to be met, the finished internal diameter of the new tunnel must be at least 2.6 m (8.5 ft). Diameters up to 3.2 m (10.5 ft) are acceptable for the project construction and may be proposed by the contractor based on constructability considerations. The tunnel will have a new overflow shaft at its east (upstream) end to control the maximum hydraulic grade line and guard against development of negative pressures during dewatering. The tunnel will extend from the Alameda West Portal (on the east end) to the Irvington Portal (on the west end). At the Alameda West Portal, the new tunnel will connect to a new distribution manifold leading from one new and three existing Alameda Siphon pipelines crossing underneath Alameda Creek. At the Irvington Portal, the new tunnel will also connect to a new distribution manifold, feeding into one new and four existing Bay Division pipelines heading to service areas in the south bay area and terminal reservoirs on the peninsula south of San Francisco. The approximate alignments of the new and existing tunnels are shown in Figure 1.

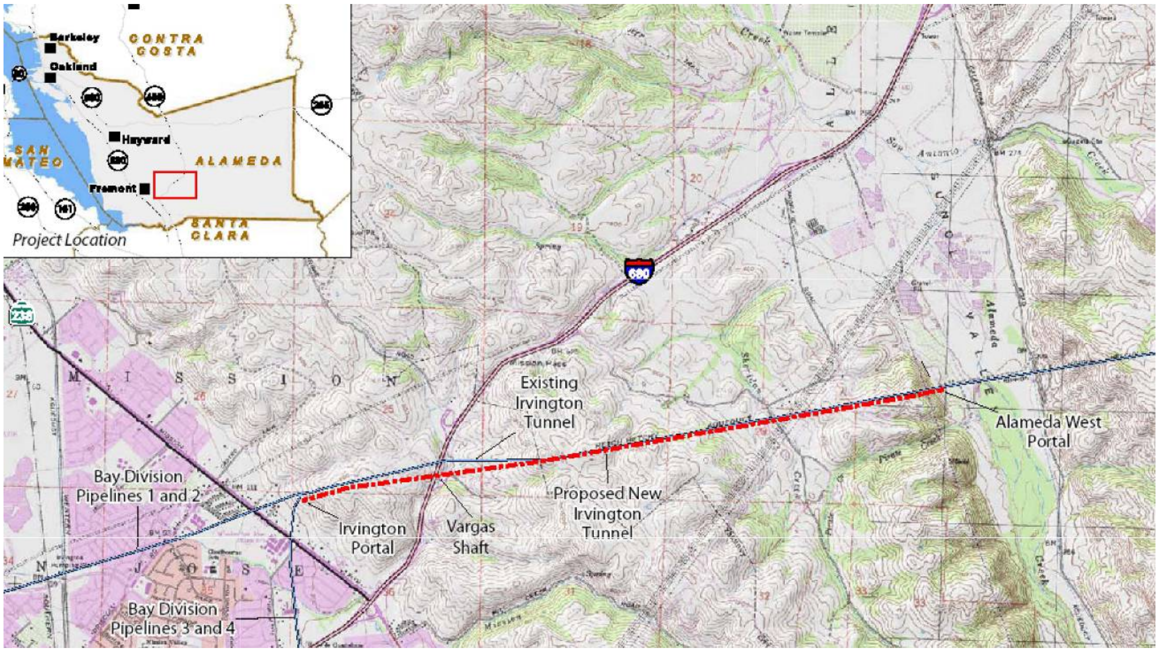

Figure 1. Project Vicinity and Location Map

The ground cover above the NIT varies along the alignment, ranging from about 6 m to 230 m (20 to 750 ft). Ground elevations along the tunnel alignment vary from about El. 72 m (235 ft) at the Irvington Portal to about El. 320 m (1,050 ft) over the central portion of the alignment. About 3,432 m (11,260 ft) of the NIT alignment is located 58 m (190 ft) south of the EIT alignment. This segment extends from the Alameda West Portal (Sta.41+40) to Sta. 154+00. From Sta. 154+00 to the center of Vargas Shaft (Sta. 183+50), the horizontal separation between the NIT and the EIT alignments increases to a maximum distance of about 204 m (670 ft). To the west of the Vargas Shaft, the separation between the NIT and EIT gradually decreases to zero at Sta. 224+00, where the NIT alignment crosses about 30 m below the EIT. At the lower elevation, the NIT extends about 122 m (400 ft) further west than the EIT. The lower elevation for the NIT allows for much easier construction access and logistics at the very tight Irvington Portal site.

Like the EIT, the NIT will be constructed with a relatively flat invert slope, just sufficient to allow the tunnel to drain to the west. The design slope is 0.00125 from the Alameda West Portal (Sta. 41+40) to Sta. 200+00. West from this point, the design slope increases to 0.029 to achieve the lower Irvington Portal elevation noted above. The NIT design invert is El. +93 m (305 ft) at the new Alameda West Portal and El. 62 m (202 ft) at the new Irvington Portal. The NIT will be lower than the EIT for its entire length. The vertical separation between the EIT and NIT alignments ranges from about 9 m (30 ft) at the Alameda West Portal to 37 m (120 ft) at the Irvington Portal.

The NIT construction is planned to occur from three main construction staging areas, located at the Alameda West Portal, Vargas Shaft, and Irvington Portal sites (Figure 1). The eastern portal of the NIT will be located at Alameda West, the largest of these three sites. The connection from this portal to the Alameda Siphon pipelines will be constructed in this area, along with a new overflow shaft on the hillside above the new Alameda West portal. At the Vargas site, tunnel construction will be accessed through a temporary construction shaft, referred to as the Vargas Shaft. This 37 m (120 ft) deep shaft will be located on the east side of Highway I-680, adjacent to Vargas Road. Two tunnel headings are expected to be excavated from this shaft. One heading will be mined downgradient to the west towards the Irvington Portal. The other heading will be mined to the east towards the heading coming from the Alameda West Portal. The temporary shaft size will be determined by the contractor based on construction considerations. The anticipated size is about 10.7 to 12.2 m (35 to 40 ft) in diameter. At the Irvington Portal site, the presence of nearby private residences restricts the available work hours and activities. Therefore, the eastward tunnel heading length allowed from this site is limited to about 170 m (550 ft), to reduce truck traffic and related construction impacts. The other work at the Irvington Portal site includes construction of complex piping connections to the Bay Division Pipelines. Very limited time windows are available when these pipelines can be shut down, so the connection work will be performed over two separate winter seasons, during separate two-month shutdown periods for each of the existing pipelines.

3. Geologic Conditions

The NIT alignment crosses beneath the westernmost ridges of the Diablo Range. This range has been subjected to significant faulting and folding, which has fractured and sheared the rock units. Regional tectonic compression has uplifted the range to form substantial topographic relief. The geologic formations include Cretaceous and Tertiary sedimentary units, which have been folded and faulted into broad, northwest trending synclines and anticlines. Figure 2 shows a geologic profile along the NIT alignment (at a 2:1 vertical exaggeration) [4].

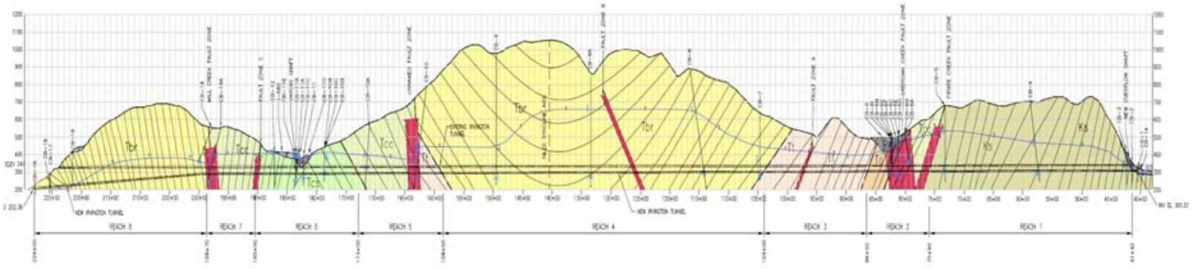

Figure 2. Geologic Profile

The bedrock along the NIT alignment consists of marine sandstone, shale, siltstone, and chert ranging in age from Miocene to Cretaceous (5 to 144 million years old). Younger Quaternary-period deposits include alluvium and colluvium, which are present at the Alameda West Portal, Sheridan Valley, in the vicinity of I-680, and at the Irvington Portal. Geologic units crossed by the tunnel alignment include (in order of increasing age) unconsolidated Quaternary-period deposits and artificial fill (Qoa, Qc, af), Briones Formation (Tbr), Tice Shale Formation (Tt), Oursan Sandstone Formation (To), Claremont Formation (Claremont Formation Chert and Shale Member [Tcc] and Sandstone Member [Tcs]), and Cretaceous Sandstone and Shale (Ks) [4].

The ground surface above the alignment generally consists of steep and rolling hills covered with grass, brush, and trees. Based on surface geologic mapping, four inactive secondary faults are present along the tunnel alignment at boundaries between geologic units. At least three other faults (or major shear zones) have also been identified based on reports from the EIT construction.

The four mapped faults that cross the tunnel alignment are the Pirate Creek, Sheridan Creek, Unnamed, and Mill Creek faults. These are shown in red in Figure 2, along with the three additional fault and shear zones reported in the EIT construction records. As indicated schematically in Figure 2, the bedding dips tend to be steep within the fault-bounded blocks, with dip directions ranging from southwest to northeast. Bedding dip inclinations range from moderate to vertical within the various fold features and are commonly steepest in the vicinity of faults. The largest fold feature is the Niles Syncline, with a near vertical axial plane mapped at approximately Sta. 140+50. The Claremont, Tice, and Briones formations will be encountered two to three times along the alignment because of the folding involved with the regional structure.

Based on the surface mapped geologic conditions and on reports from the EIT construction, the NIT construction is expected to encounter highly variable and difficult ground conditions including very weak to strong rock, sheared and shattered to massive rock, squeezing ground, and high groundwater inflows. To obtain geotechnical data on specific conditions present along the alignment, a program of subsurface investigations was carried out prior to design.

4. Geotechnical Investigations Program

A comprehensive program of geotechnical and geophysical investigations was carried out to characterize the conditions along the tunnel alignment. The overall objective of the geotechnical investigations was to characterize the soil, rock, and groundwater conditions along the tunnel alignment. The investigations started with surface geologic mapping of the project study area to document geologic units, rock outcrops, landslides, fault zones, and other features such as existing wells and springs. The results were documented in a Geotechnical Data Report [4].

A key objective of the investigations was to evaluate and characterize the fault zones and other poor ground conditions present along the tunnel alignment. A number of the exploratory borings were laid out to investigate postulated fault zones at or near tunnel depth. These zones were targeted based on a combination of the surface geologic mapping and existing tunnel construction records. A 66 m (217 ft) long by 5.5 m (18 ft) deep exploratory trench was also excavated at the Alameda West Portal area to evaluate the presence and activity of the mapped Sinbad fault trace. The trench also provided an excellent opportunity to characterize soil conditions in the planned tunnel portal excavation area.

The subsurface investigations included 38 vertical and inclined exploratory borings, ranging up to 232 m (760 ft) deep, totaling over 2,651 m (8,700 ft) in length. Many of the holes were drilled in difficult to access areas located on private property above the tunnel alignment (e.g., Figure 3). The drilling was primarily performed using rotary wash methods with HQ-3 wireline core barrels. Most of the holes were accessed with skid rigs transported to the sites by small trucks. A helicopter was used to transport the drilling equipment to several borings on located on the steep hillslope above the Alameda West Portal. Sonic drilling equipment was also used for several holes in the Sheridan Valley fault zone area, in an effort to obtain better sample recovery in an area experiencing caving/squeezing borehole conditions.

The core samples retrieved from each boring were logged, photographed, and point-load tested in the field. Selected samples were retained for laboratory strength and index testing. In situ testing included water pressure (packer) tests and downhole geophysical surveys. The downhole surveys included caliper logging, televiewer logging, and seismic velocity surveys (P- and S-wave, using OYO suspension equipment).

Pressuremeter tests were performed in one boring at the Sheridan Creek fault zone to obtain data on the deformation properties of the rock mass and fault gouge materials. The results were used as inputs to the final lining design. Seismic refraction surveys were completed at each portal area, to assist in characterizing the overburden depths and bedrock properties. Surface wave (MASW) geophysical surveys were performed in the Vargas Shaft area, where the adjacent highway noise interfered with normal refraction surveys. Aquifer pump testing was also carried out in the Vargas Road and the Sheridan Valley areas, to investigate the hydrogeologic formation properties. These data were used to assist in evaluating dewatering alternatives for the tunnel in the Sheridan area and the temporary construction shaft in the Vargas area.

Figure 3. Drill Rig at Boring CB-8

5. Ground Characterization

The first step in the ground characterization process was an in-depth review of the EIT construction records. Unfortunately, the 1920s-era records contain only very limited descriptions of the ground conditions and lithology encountered in the tunnel, and generally lack definitions of the descriptive and geologic terms used (for example, no distinction was made between running and flowing ground behavior). As a result, the records had to be interpreted based on a current understanding of the site geology and the construction methods that were employed at the time. Along with the current geotechnical investigation results described above, the EIT interpretation was a critical input into the ground characterization process.

The tunnel alignment was divided into eight reaches, with boundaries at geologic contacts. To assist in the selection of tunnel excavation and support methods, the range of ground conditions expected was divided into four ground classes. The ground classes were defined based on the physical characteristics of the ground and its anticipated behavior during the tunnel excavation. Each specific ground class is expected to perform similarly in the tunnel excavation, and to require similar support methods. The ground class definitions, predominant ground behaviors, and key characteristics associated with each ground class are described in Table 1. The anticipated distribution of each ground class along the tunnel alignment was estimated based on evaluation of the geologic and geotechnical data, along with review and correlation of the available EIT construction records. As part of the evaluation, rock mass quality evaluations were performed for each boring utilizing the Rock Quality Designation (RQD) [2] and the Rock Mass Rating (RMR) system [1]. The results are presented in a Geotechnical Baseline Report [5].

Table 1. Anticipated Ground Classes

Ground Class and Definitions	Typical Rock Characteristics	Typical Discontinuity Characteristics	Ground Behavior
I: Massive to Moderately Fractured Rock	Sandstone, siltstone, and interbedded siltstone/sandstone; weak to strong rock; slightly weathered to fresh	Very rough to rough; fresh to slightly weathered surfaces	Structurally controlled block instability; spalling
II: Highly Fractured Rock	Sandstone, siltstone, interbedded siltstone/ sandstone, and shale; weak to moderately strong rock; highly to slightly weathered	Rough, smooth, or slickensided surfaces or bedding planes; moderately to highly weathered/altered surfaces with thin infillings of clay and/or sand (< 5 cm [2 in.] thick)	Slow raveling; fast raveling where flowing groundwater is encountered
III: Intensely Fractured Rock	Sandstone, siltstone, interbedded siltstone/sandstone, and shale; thinly bedded to laminated rock structure; very weak to moderately strong rock, may be friable, poorly cemented; highly to slightly weathered/altered	Smooth, slickensided surfaces; highly weathered/altered with occasional moderately wide clay/sand-filled joints, shears, and shear zones (5 to 15 cm [2 to 6 in.] thick)	Fast raveling/ caving; potentially flowing ground, if groundwater inflows are not controlled
IV: Heavily Sheared/ Faulted Rock with Clay Gouge/Infilling Materials	Heavily sheared rock including fault gouge, shattered rock, poorly laminated rock, all with abundant clay; extremely weak to very weak rock; moderately to completely weathered/altered	Slickensided surfaces; highly weathered/altered with wide clay-filled joints, shears, and fault/shear zones (15 cm [> 6 in.] thick)	Squeezing; swelling; caving; fast raveling

As indicated, potentially unstable ground conditions are expected throughout the tunnel, including but not limited to raveling/caving, squeezing, swelling, running, and flowing conditions. The sheared nature of the rock mass, weak rocks, abundant clay infilling materials, intensely fractured rock mass, and high groundwater heads all will contribute to the instability of the tunnel excavation. Control of groundwater inflows into the tunnel by pre-drainage and/or pre-excavation grouting will be necessary in many areas to minimize and manage the expected adverse effects of groundwater on ground stability and excavation progress. Significant shearing and many shear zones were observed in the borings completed for the NIT. Similar conditions are reported in the EIT construction records.

6. Tunnel Excavation and Support

As indicated in Table 1, the NIT will be constructed in variable ground conditions, ranging from strong, massive rock to very weak and intensely fractured sheared rock including fault gouge. The tunnel will encounter high groundwater inflows and difficult ground conditions including raveling, running, flowing, caving, and squeezing ground. Presupport using spiling and/or forepoling will be required to control raveling, caving, and crown instability, primarily in tunnel reaches with Ground Class III and IV conditions. Presupport may also be required to prevent structurally controlled block instability, expected primarily in Ground Classes I and II. Face support in conjunction with presupport is expected to be required to control block instability, overbreak, raveling, running/flowing, slaking and caving behaviors at the tunnel face in Ground Classes II, III, and IV [5].

Conventional tunneling methods, including the use of roadheaders, drill-and-blast techniques, and hydraulic excavators, are anticipated, given the wide range of ground conditions. Because of the greater risks related to high groundwater and extremely variable ground conditions, TBM excavation was concluded to present excessive cost and schedule risks to the project and so was contractually disallowed. The contractor will be required to select conventional tunnel excavation methods, initial support systems, and groundwater control measures compatible with the anticipated ground conditions [5]. Factors determining the preferred approach will include economic considerations, equipment availability (for a tunnel of this size), and the skills and experience of the contractor's crew and available labor. Where blasting is used, appropriate blast designs and vibration and noise monitoring will be required to control and minimize potential impacts of blasting on the existing tunnel, existing pipeline facilities, and residences adjacent to the portals and above the tunnel alignment.

7. Groundwater Control

The anticipated groundwater levels above the tunnel crown range from zero to 113 m (370 ft). Groundwater inflows are anticipated throughout a significant portion of the tunnel. The heaviest flows will occur where the ground is highly fractured and where fault and shear zones are encountered. The potential groundwater inflows were estimated for each tunnel reach based on 3-D transient groundwater modeling and on interpretation of the EIT construction records. The presence of high groundwater levels, numerous water supply wells, and natural springs indicates a local abundance of groundwater along portions of the tunnel alignment. This is consistent with conditions encountered during construction of the EIT, which included very heavy inflows. Flush flows exceeding 60 L/sec (1,000 gpm) occurred in several locations. At least one inflow event reportedly flooded the tunnel heading completely.

Implementation of effective groundwater control measures will be required to limit uncontrolled inflows into the tunnel, reduce the impact of inflows on tunnel construction, and protect groundwater wells and resources. Surface mitigation via supplemental water is also expected. In addition to pre-excavation grouting, the anticipated groundwater control measures include predrainage of the rock mass ahead of the face, by probe holes drilled from within the tunnel. At selected locations, predrainage from the ground surface is also anticipated. The contractor will generally be responsible for implementation of pre-excavation grouting, predrainage, and/or a combination of both, to reduce sustained groundwater inflows to within workable limits. Drain holes drilled ahead of the tunnel face will reduce the groundwater head and aid in control of heading inflows. Depending on the fracture openings, fracture spacings, permeability, and storativity of the rock mass, the effectiveness of drainage will vary. Typically, drainage should be done ahead of the advancing face to improve the ground behavior at the tunnel walls, roof, and face. Predrainage from the ground surface using dewatering wells is expected to be viable at the Sheridan Valley and the Vargas shaft areas. At these sites, an effective dewatering system will be needed to lower the groundwater table in advance of tunnel excavation [5].

The contractor's drilling, casing, and grouting equipment and methods must be capable of staged grouting in unstable rock formations. The probe and grout holes are expected to encounter hole stability problems in weak rock that includes highly to intensely fractured rock and clayey shear and fault zones. Because of uncertainties associated with the characteristics of groundwater flows in a fractured rock mass, the required probe and verification holes are not expected to detect all potential inflows. The contractor must be prepared to adjust pre-excavation grouting and drainage techniques, criteria, and procedures during construction to accommodate the expected rapidly varying ground conditions.

8. Seismic Design

The NIT is located in a seismically active region of California, dominated by the San Andreas fault system. As noted, the tunnel alignment is located between the Hayward fault on the west and the Calaveras fault on the east. These highly active faults are capable of generating large magnitude (M7.0) earthquakes [3]. However, the tunnel alignment does not cross any faults that are considered Holocene active [4]. In addition to very strong shaking from the nearby active faults, secondary offset on any or all of the four minor inactive faults along the alignment was considered as a design hazard. The NIT final lining design considered up to 150 mm (6 in.) of sympathetic displacement over a width of 1.5 m (5 ft), on the Pirate Creek, Sheridan Creek, Unnamed, and Mill Creek faults. This sympathetic displacement could occur in response to a significant earthquake event on either the Hayward or Calaveras fault [4].

According to the SFPUC's General Seismic Design Requirements [6], the tunnel and portal pipelines are considered Seismic Performance Class III facilities. The design earthquake for Seismic Performance Class III facilities has a 5 percent probability of exceedance in 50 years (975-year approximate return period). The SFPUC's objective for seismic performance of the overall system is to deliver a flow equal to an average winter day demand (~10 m^3/sec [230 MGD]) within 24 hours of a major earthquake. In order for this objective to be achieved, catastrophic damage to the NIT facilities during the design earthquake must be avoided.

The seismic design parameters for the NIT project were developed based on a seismic hazard and ground response analysis [3]. Depending on distance from the active faults, the estimated peak ground accelerations (PGA) for the design earthquake vary from 0.85 g to 1.02 g at the ground surface level, and from 0.45 g to 0.58 g at the tunnel level. The peak ground velocities (PGV) range from 148 to 160 cm/sec (58 to 63 in./sec) at the ground surface level, and from 47 to 58 cm/sec (18 to 23 in./sec) at the tunnel level.

9. Project Schedule

The project design was completed in December 2009, and the advertisement inviting bids was published in January 2010. The scheduled bid opening date is March 2010, and Notice to proceed is anticipated in June 2010. With a 45.5-month construction schedule, project completion is currently scheduled for March 2014.

10. References

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