CALUMET WATER RECLAMATION PLANT
Investigation of Explosion and Structural Collapse in Gravity Belt Thickener Room

Chicago, Illinois

Final Report
November 16, 2018
WJE No. 2018.5953

Prepared for:
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WJE

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WJE | ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

TABLE OF CONTENTS

WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

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INTRODUCTION

At the request of the Metropolitan Water Reclamation District of Greater Chicago (MWRD), Wiss, Janney, Elstner Associates, Inc. (WJE) has performed an investigation of the explosion and subsequent collapse of the floor and roof structures of the Gravity Belt Thickener (GBT) Room, which is located in the Sludge Concentration Building at the MWRD Calumet Water Reclamation Plant (CWRP). The purpose of our investigation was to develop an opinion of the cause of the explosion and structural collapse. WJE was also asked to develop recommendations to prevent an event similar to this from occurring in the future. Procedures involved in the subject investigation have been guided by the National Fire Protection Association's NFPA 921: "Guide for Fire and Explosion Investigation".

BACKGROUND

On August 30, 2018, at approximately 11:00 a.m., an explosion occurred in the GBT Room. The explosion severely damaged the floor structure and the roof structure in the GBT Room. Figure 1 shows an overall view of the collapsed structure. MWRD reported that ten workers were injured during the event. The details and the extent of the injuries were not reported to us.

Description of Construction for the Sludge Concentration Building

An aerial view of the Sludge Concentration Building, identifying the different functional areas, is shown in Figure 2. The Sludge Concentration Building is divided into three functional sections: 1) the Sludge Screen and Polymer Rooms at the north end of the building, 2) the GBT Room located directly south of the Sludge Screen and Polymer Rooms, and 3) three clusters of Gravity Concentration Tanks separated by interior walls at the south portion of the building. The Operating Gallery is located between the Sludge Screen/Polymer Rooms and the GBT Room.

Based on observations of historic photos made available to us at the CWRP offices, the rectangular concrete tanks below the Sludge Screen/Polymer Rooms and GBT Room were constructed first, followed by the northernmost cluster of gravity concentration tanks (a cluster of four cylindrical concrete tanks located immediately south of the GBT Room). The rectangular concrete tanks and the northernmost cluster of gravity concentration tanks were originally constructed as open top tanks without a building enclosure sometime prior to 1975.

We understand that due to odor issues, the building enclosures were constructed over the existing tanks and two additional Gravity Concentration Tank clusters were constructed south of the existing Gravity Concentration Tank clusters in 1986 (Contract 75-215-2P). In 1992, as part of the digester capacity expansion contract (Contract 90-214-2P), the existing northernmost Sludge Flotation tanks (currently below the Sludge Screens and Polymer Rooms) were modified.

In 2009, as part of Contract 96-251-2P, the northernmost rectangular concrete tanks were modified to become the existing Sludge Screen and Polymer Rooms, and the southern rectangular concrete tanks were modified to become the GBT Room. In the GBT Room, the modifications included removing some internal tank walls, installing new internal tank walls, and installing a new cast-in-place reinforced concrete beam-supported slab over the top of the tanks. In addition to serving as a cover over the existing below-grade tanks, this reinforced concrete slab also served as the floor of the new GBT Room and supported the gravity belt thickener equipment. Figure 3 reproduces the structural drawing (S-109) from Contract 96-251-2P showing the new floor structure in the GBT Room. Figure 4 reproduces Drawing S-114 (Contract 96-251-2P) showing a section view through the GBT Room looking north, and Figure 5 reproduces Drawing S-113 (Contract 96-251-2P) showing a section view through the GBT Room looking east.

Description of Gravity Belt Thickener Room Structure

Roof Structure

The roof structure over the GBT Room was separated from the adjacent areas (Operating Gallery roof and Gravity Concentration roof) by expansion joints. The GBT Room roof structure consisted of precast prestressed concrete single tee beams spanning 110 feet between the east and west exterior walls of the building. The single tee beams consisted of a 4 foot deep by 8 inch wide stem with a 10 foot wide flange. The flange thickness varied from 5 1/2 inches at the stem to 1 1/2 inches at the outer tip. Figure 6 shows an end view of one single tee beam. The stems of the single tee roof beams were supported on a cast-in-place reinforced concrete frame at the east wall and at the west wall. At the west wall, the stem of each single tee roof beam was attached with a single 1 inch diameter bolt to double angles welded to an embedded steel plate in the west girder (Figure 7). At the east wall, the single tee roof beams were set between but not bolted to the double angles (Figure 8). The roof structure of the GBT Room consisted of a total of eight single tee beams. The beams were connected to each other with flange connectors consisting of steel plates welded to plates embedded in the beam flanges.

Wall Structure

The east and west walls of the GBT Room each consist of a cast-in-place reinforced concrete frame with brick masonry and concrete masonry infill walls. Windows in the masonry walls were constructed with glass block. The foundations for the east and west walls are separate from and located outside of the below grade tank walls and foundations. The south wall of the GBT Room, which separated the GBT Room from the Gravity Concentration Tanks, consisted of a cast-in-place concrete frame with unreinforced hollow concrete masonry infill walls.

The GBT Room north wall, which separated the GBT Room from the Operating Gallery, was constructed with unreinforced brick masonry and concrete masonry. The roof of the Operating Gallery was constructed with prestressed precast hollow core planks supported on the unreinforced masonry walls. The elevation of the Operating Gallery roof was approximately 4 feet below the elevation of the GBT Room roof. An unreinforced brick masonry and concrete masonry wall extended from the top of the Operating Gallery roof to the tip of the northernmost single tee roof beam for the GBT Room. The north wall of the Operating Gallery, which separated it from the Sludge Screen/Polymer Rooms, was constructed in the same manner as the south wall of the Operating Gallery.

Floor Slab on Top of Tanks

The GBT Room floor structure served as the roof over the three below-grade tanks. This floor structure consisted of cast-in-place reinforced concrete beams with integral 12 inch thick slab sections. In six areas over the east and center tanks, depressed slabs with a tapered cross-section and sloped top surface were separately cast between reinforced concrete beams located at the perimeter of the area. Each of these depressed areas was approximately 16 feet by 16 feet and sloped to drain with a varying design thickness ranging from 8 to 14 inches. The reinforcement for these sloped slab areas was connected to the previously cast perimeter beams with mechanical splices. The four existing GBT machines were supported on the four southernmost depressed slab areas (see Drawing S-109 included in Figure 3).

The concrete beams of the floor structure in the area over the westernmost (largest) tank are supported by six reinforced concrete columns that were constructed in conjunction with the floor structure. Drawing S-109 from Contract 96-251-2P is a plan view of the GBT room floor slab showing the floor beams and the slab reinforcement. This report will reference the beam designations shown on this drawing, which is reproduced in Figure 3.

Below Grade Tanks

The three below-grade concrete tanks which are independent of the building structure's roof and walls consist of reinforced cast-in-place concrete perimeter walls. The walls surrounding these tanks are highlighted in light blue in Figure 3. The three tanks are separated by two reinforced concrete walls oriented in the north-south direction. The reinforced concrete wall that separated the west tank from the center tank was part of the original tank construction sometime prior to 1975. The wall that separated the east tank from center tank was constructed and cast at the same time as the GBT Room floor slab structure.

INVESTIGATION

Document Review

To assist WJE with our investigation, MWRD personnel provided WJE with the following documents.

Construction Documents

Contract 75-215-2P Title: Additional Gravity Concentration Tanks – Full set of contract drawings dated October 1986 for the construction of southern two Gravity Concentration Tank clusters and construction of the building (roof and walls) over the three Gravity Concentration Tank clusters and the two rectangular reinforced concrete below grade tanks. This set of drawings includes design information for the roof structure and walls at the GBT Room. Shop drawings for the precast single tee roof beams were not available.

These drawings also indicate that the walls and roof for the Operating Gallery were constructed sometime prior to this contract. Drawings for the Operating Gallery walls and roof have not been provided.

Contract 90-214-2P Title: 80 DT/D Digester Capacity Expansion – Full set of contract drawings dated August 1992 for the construction of additional Sludge Digestion Tanks and new Sludge Holding Tank attached to the existing Sludge Flotation Tank (currently the Sludge Screen/Polymer Rooms).

Contract 96-251-2P Title: Sludge Thickening Facilities – Full set of contract drawings dated August 2009 for the modification of the rectangular tanks north of the Operating Gallery to create the Sludge Screen/Polymer Rooms, and the modification of the rectangular tanks south of the Operating Gallery to create the GBT Room. Structural drawings in this contract show the configuration and reinforcement of the GBT Room floor structure, a new wall separating the east tank from the center tank, and the columns and footings supporting the floor slab over the west tank. These drawings also show details for the connection of the new floor structure to the previously existing tank walls, including the wall separating the center tank from the west tank.

Plant Operating Information Provided by MWRD Personnel

Plant operational documents provided to WJE mainly included drawings of process piping, and process and instrumentation diagrams[1]. Additional operational information was obtained during several meetings with MWRD staff, tours through the facility and in answers to our requests for operational information. Key information provided included the following:

- Routing of process flows
- Process flowrates
- Operational parameters
- GBT history and circumstances leading to the need to restart the GBT process
- GBT restart planning, maintenance and repair activities. Maintenance work orders were provided for the following activities
  - Removing manhole covers in the GBT room
  - PM (preventative maintenance) of fan equipment in that area
  - Repair of VFD (Variable Frequency Drive) for Concentration Tank Feed Pump No. 1
  - Replacing damaged check valves on effluent flushing water system for GBTs

These are discussed throughout the report.

Observations

In the days immediately following the August 30, 2018 explosion event, an investigation was conducted by the Occupational Safety and Health Administration (OSHA). OSHA did not permit access to the site for a period of several weeks. Prior to OSHA allowing access to the building interior, WJE performed an initial inspection from the exterior of the GBT Room and the roof (south) over the Gravity Concentration Tanks.

After OSHA allowed access to the site, WJE personnel performed an initial site visit on September 10, 2018, prior to the start of demolition. WJE also developed a protocol[2] for inspection and preservation of evidence, and distributed it to the various parties involved. MWRD retained IHC Construction Companies LLC (IHC) to demolish the structure. WJE's site work during demolition included documentation of the structure and direction to the demolition contractor. The demolition was performed in a step-by-step process to permit review and documentation of the roof tee beams, mechanical equipment, floor structure, and below-grade tanks.

The following lists the tasks performed during the demolition.

1. Removal and documentation of roof assembly sections
2. Documentation of floor area
3. Removal of evidence items from floor area and preservation/storage by MWRD personal
4. Removal of floor slabs to expose tanks areas
5. Removal of material from tanks
6. Documentation of tank areas
7. Removal of evidence items from tank areas and preservation/storage by MWRD personal
8. Documentation of remaining wall sections in tank areas

[1] Contract Plans for Sludge Thickening Facilities, Calumet Water Reclamation Plant, Contract 96-251-2P, 2009, particularly drawings P-103, 129-132

[2] WJE, Protocol for MWRD GBT Room Explosion Site Examination

The following is a summary of our observations before, during and after removal of the collapsed GBT Room roof structure and mechanical equipment in the GBT Room by IHC. For the purposes of our investigation, the single tee prestressed roof beams were numbered from 1 at the north end of the GBT Room to 8 at the south end of the GBT Room.

Roof Structure

The collapsed roof structure was inspected and documented before demolition began. The condition of the roof structure was also observed and documented during the demolition process. Some measurements of the roof beams that were not possible prior to demolition were made after roof members were removed. The following lists our observations of the collapsed roof structure.

1. Each of the eight precast prestressed single tee roof beams over the GBT Room had collapsed.

2. Portions of the collapsed single tee roof beam flanges had broken off at all of the roof beams.

3. Each of the collapsed single tee roof beams broke into three sections; 1) a continuous section of the beam stem at the east end with lengths ranging from approximately 32 to 48 feet (see Figure 9); 2) a continuous section of the beam stem at the west end with lengths ranging from approximately 45 to 53 feet (see Figure 10); 3) and a center section where the beam stem was broken into numerous pieces that were mostly separated from the prestressing tendons (see Figure 11).

4. The east end of each of the eight single tee roof beams had moved off their support at the east wall and fallen to the floor slab (see Figure 12). In general, the interior end of these roof beam sections landed on the top of the concrete wall separating the east tank from the center tank or on top of the GBT equipment, which was still supported at the top of this wall (see Figures 9 and 11b).

5. At the west exterior wall of the building, the six single tee beams at the north end of the GBT Room (Roof Beams 1 through 6) had come off of their support at the west wall. Since the stem of each roof beam was bolted to the double angle at the west wall support, this resulted in the bottom portion of the beam stems breaking at the support connection. The west end of Roof Beams 1 through 4 had fallen onto the GBT Room floor slab. Roof Beams 5 and 6 landed on the rolling overhead door, which had been in the open condition at the time of the explosion (see Figure 13). The southern two roof beams were still attached to their bolted connection at the west wall support. The interior end of the west roof beams had landed on the collapsed floor slab, which was then at a significantly lower elevation than the top of the wall separating the east tank from the center tank.

6. The cross-section of the single tee beams measured approximately 4 feet tall with an 8 inch wide vertical stem. The flanges of the single tee beams were 10 feet wide ranging in thickness from 5 1/2 inches adjacent to the vertical stem, tapering to 1 1/2 inches at the tip of the flange (see Figure 12). There were a total of 46 ~ 1/2 inch diameter prestressing strands located in the stem of the single tee beam. Two of these prestressing strands located at the top of the section were not draped. The remaining 44 prestressing strands were uniformly distributed (22 equally spaced rows of tendons) at the ends of the beam stem. These 44 equally spaced tendons were draped into one group near the bottom of the beam stem at the mid-span area of the beam. Welded wire fabric was also used to reinforce the beam flange and stem.

7. Small (maximum dimension of approximately 3 to 6 inches) pieces of crushed concrete was observed on the roof of the Sludge Screen/Polymer roof to the north of the GBT Room roof (see Figure 14). Based on the observed aggregates in this concrete debris, it appeared that the debris was part of the failed floor slab, which consisted of limestone aggregate, and not from the failed prestressed precast single tee roof beams, which were constructed with 3/8 inch lightweight aggregate.

Exterior Walls

The east and west exterior walls of the GBT Room were in generally good condition. The cast-in-place reinforced concrete frame and the brick masonry and concrete masonry infill at both walls were found to be plumb. Also, there was no damage observed at the brick and concrete masonry walls. We were told that the glass block windows at the east wall were broken by the Chicago Fire Department during rescue operations. There was no damage observed at the glass block windows in the west wall. Damage was observed at the top of the cast-in-place reinforced concrete frame at both the east and west walls where the single tee roof beams were supported. Also, damage to the bottom of the concrete frame columns was observed at the east wall. This damage to the bottom of the columns appeared to be due to the movement of the floor slab against and around the columns (see Figure 15).

South Interior Partition Wall

The south interior partition wall between the GBT Room and Gravity Concentration Tank area consisted of a reinforced cast-in-place concrete frame with glazed concrete masonry unit (CMU) infill walls. The reinforced concrete frame was significantly damaged at several locations. Approximately three-quarters of the south unreinforced concrete masonry infill wall that separated the GBT Room from the Gravity Concentration Tanks had completely collapsed. The debris from this wall was blown into and around the Gravity Concentration Tanks, which were empty and out of service at the time of the explosion (see Figure 16). The remaining quarter of this wall was damaged and leaning south toward the Gravity Concentration Tanks.

Operating Gallery Walls and Roof

The unreinforced brick and concrete masonry walls on both the north and south sides of the Operating Gallery were severely damaged. These walls were both generally blown to the north with much of the debris landing within the Polymer Room and the Sludge Screen Room. With both of the Operating Gallery walls severely damaged, the precast prestressed hollow core roof planks had fallen onto the electrical and mechanical equipment in the Operating Gallery (see Figure 17).

Floor Slab on Top of Tanks

After the single tee roof beams and mechanical equipment were removed, the top surface of the collapsed GBT Room reinforced concrete floor slab was accessible for inspection. Also, some observations at the interior of the tanks were possible through openings in the floor slab. The following lists our pertinent observations. The following observations of the GBT Room floor slab are graphically shown on the annotated GBT Room floor plan in Figure 18.

1. At the east edge of the GBT Room floor slab structure, the slab pulled away from the east wall of the building. This slab was originally cast against the wall of the building and had pulled away from the east wall approximately 3 foot-6 inches at the north edge of the slab (at the interior stairs south of the northeast door) varying to only 2 1/4 inches at the southeast corner of the GBT Room. This portion of the slab that slid horizontally to the west was supported on an older slab that was cast at the time of the

original building construction over the fill material between the east building wall foundation and the east below-grade tank wall. This slab movement is shown in Figure 19.

2. At the east side of the GBT Room, the slab was severely damaged along the east wall of the below grade tanks. East of this location, the slab was in a horizontal position where it was supported on the original slab-on-grade between the east tank wall and the east building wall. At the edge of the east tank wall, the slab sloped downward steeply toward the west. Only the reinforcing bars remained at this damaged area of the slab. Generally the width of the area with exposed reinforcing bars ranged from 2 to 3 feet; however at one location between the north and south GBT equipment, the exposed portion of reinforcing bars extended 5 to 6 feet west of the east tank wall. An overall view of this damage is shown in Figure 20.

3. At the interior tank wall separating the east tank from the center tank, the slab was severely damaged with only the reinforcing bars remaining over the top of the wall, and on both sides of the wall (see Figure 21). At the east side of the wall, the width of this damaged area ranged from 2 1/2 feet at the south GBT equipment to 4 1/2 feet at the north end of the slab (see Figure 22). At the west side of the wall, the severely damaged portion of the slab with only the reinforcing bars remaining extended from 2 to 5 feet from the wall. Many of these reinforcing bars were damaged allowing the slab to drop on the west side of this interior wall. Portions of Beams B-12 and B-13, which are oriented parallel to the interior tank wall in this area were also severely damaged. An overall view of this damage is shown in Figure 23.

4. The floor slab area between the distress at the east tank wall (described in item 2 above) and the distress at the interior tank separation wall between the east and center tanks (described in item 3 above) was intact, sloping downward from the east toward the west with no significant damage to the top slab surface (see Figure 24).

5. The floor slab at the west side of the GBT Room was flat and generally appeared to be intact for approximately 20 feet east of the west exterior building wall. At 20 feet east of the west exterior wall, the slab was cracked along Beam B-1, which was oriented in the north-south direction. East of this crack along Beam B-1, the slab sloped downward toward the east at a moderate slope to Beam B-2 where the slab is severely damaged with only the reinforcing bars remaining at most locations (see Figure 25). Through the severely damaged areas of the slab along Beam B-2, we could observe that portions of Beam B-2 were damaged and the two southernmost square columns supporting this beam were pushed over toward the southwest. East of Beam B-2, the downward slope of the slab toward the east increases until it reaches a low point between the east and west GBT equipment. From this low point of the remaining slab, the exposed reinforcing bars steeply sloped upward toward the interior tank wall separating the east tank from the center tank. The slab was found to be intact between the severe damage over Beam B-2 and the damage (see item 3 above) on the west side of the wall separating the center tank from the east tank (see Figure 26).

6. From the north wall of the GBT Room and north walls of the below-grade tanks toward the northernmost depressed portions of the slab for the future GBT equipment, the eastern two-thirds of the floor slab sloped downward toward the south (see Figure 27).

7. At the south wall of the GBT Room, the center section of the slab (in the area of the GBT equipment) sloped downward toward the north (see Figure 28).

8. Beams B-3, B-4, B-5, and B-6 were all damaged on both sides of the interior wall separating the center tank from the east tank. The bottom reinforcing bars, which were not continuous through the interior tank wall, had dropped below their original elevation on the west side of the wall. The top reinforcing bars that were continuous over the tank wall had broken the concrete cover on both sides of the wall and were exposed for a majority of their length (see Figure 29).

Interior Tank Walls

After a majority of the floor slab over the tanks was removed, we were able to observe the condition of the two interior walls separating the three below-grade tanks and the south wall of the tanks separating the tanks from the overflow trough.

Interior Wall between East and Center Tanks **-** The interior wall between the east and center tanks was still in its original vertical orientation. Crushing was only observed at the top of the wall and at the beam pockets where the existing slab and integral beams failed over the top of this wall. Also, there were numerous scrapes on the wall surface from the reinforcing bars in the beams that collapsed (see Figure 30).

Interior Wall between Center and West Tanks **-** The interior wall that separates the center tank from the west tank had broken at approximately 3 feet above the bottom of the tank (at the center portions of the tank away from the north and south walls). The upper section of the wall was displaced westward and was lying flat on the tank slab west of the wall location between this center wall and the column row to the west (see Figure 31). At several locations, the top of the 3 foot 8 inch wide double corbel at the top of this wall could be observed. There were no indications that epoxy grouted dowels had been installed in the top of the wall to connect the wall to the floor slab (see Figure 32). It appeared that although the slab was cast on top of this wall it was not mechanically anchored to the wall.

South Wall between Main Storage Tanks and the Overflow Trough **-** The top of the wall separating the storage tanks from the overflow trough at the south end of the tanks was approximately 20 to 24 inches below the bottom of the floor slab (see Figure 33). This indicated that although the liquid product in the east and center tanks were separated, any gases in the east tank or center tank could easily travel to the adjacent tank. There is a separate overflow trough at the west tank.

Piping, Equipment, Tools and Miscellaneous

Initial observations of the working area in the GBT Room indicated that much of the piping and equipment were still in place, though much of it severely damaged in areas due to the tremendous impact of fallen roof sections and the movement of the GBT Room floor slabs. GBT canopy hoods were generally crushed. GBT units were partially crushed. Wash water piping was partially intact but damaged and cracked in many areas. Some tools were found in the area relating to the workers who were present. Some personal protection equipment including hard hats, face shield, gloves, etc. were found. Items of interest relating to the tasks being undertaken were preserved as evidence (see evidence list, Appendix A).

Manholes and Piping Seals through GBT Floor Slab

Various manholes over the underground tanks were affected by the explosion, as follows (see Figure 34 for orientation):

- Manhole A – found without bolts, the cover was upside down several feet to the south of its original location

- Manhole B – the cover and ring were found nearby to the east and upside down; two bolt heads were removed by flame cutting (see discussion in later report sections)
- Manhole C – found without bolts, the cover was broken in many pieces and moved to the southeast several feet, the ring was also broken with the ring pieces found in several nearby locations
- Manhole D – the cover and ring were found upside down, broken and located several feet to the southwest from its original location
- Manhole E – the cover and ring were found upside down and moved about 16 feet to the west
- Manhole F – was found undisturbed
- Manhole G – the cover and ring were found upside down, and located several feet to the west
- Manhole H – was found undisturbed

The manhole covers and rings that were ejected are consistent with blast pressure from the interior of the tanks.

The manhole hardware were all similar cast iron items, 34 inch diameter by approximately 1 inch thick, bolted down to cast iron rings cast into the floor slab. Most of the manholes that were reasonably preserved were found to be gasketed. Design information[3] indicates they were designed to be air tight.

Various piping seals in the basement gallery north of the GBT Room were partially extruded at pass-through pipe areas into the blending tanks. The extrusions were found to be in a direction that is consistent with blast pressure from inside the tanks.

Review of Witness Statements and Interviews

While numerous OSHA interviews have taken place, transcripts of these OSHA interviews were not available for our review. Several written statements have been provided for the following MWRD personnel.

Paul Sullivan	MWRD, Assistant Chief Operating Engineer (witness, injured)
Kevin O’Connor	MWRD, Operating Engineer (witness, injured)
Dean Corradino	MWRD, Assistant Master Mechanic, Trade Supervisor
John Dalton	MWRD Master Mechanic, Trade Supervisor
Stephen Brescia	MWRD, Assistant Master Mechanic
Thomas Durkin	MWRD, Assistant Master Mechanic
Reed Dring	MWRD, Operations Manager

WJE has conducted additional interviews and discussions for the purpose of obtaining more detailed eye-witness information and detailed plant process information.

Neil Dorigan	MWRD maintenance manager
Reed Dring	MWRD operations manager
Mark Austin	MWRD, process control engineer
Ed Karpinski	MWRD, safety manager
Kevin O’Connor	MWRD, operating engineer (witness, injured)
Laura Riley	MWRD, EITM foreman
Paul Sullivan	MWRD, assistant chief operating engineer (witness, injured)

[3] Contract Plans for Sludge Thickening Facilities, Calumet Water Reclamation Plant, Contract 96-251-2P, 2009, particularly drawing P-135

Patrick Coleman MWRD, iron worker, lead man

A few of the MWRD witness interviews provide firsthand description of the explosion event and are summarized below:

- Kevin O'Connor (MWRD Operating Engineer) - Kevin was in the GBT Room wearing a 4x gas meter. The immediate goal of his work was to isolate four 2 inch gate valves on the suction side of the wash water pumps, so that the locks, chains and tags could be applied for a proper lockout. Then the pipe fitters could replace four check valves on the discharge side of the pumps. Steve Stanek and Kevin O'Connor were waiting for Paul Sullivan to return with red locks. Paul Sullivan returned with the locks, and as Kevin walked a couple of steps to meet him, he heard a loud noise. He looked up to see a vertical column of white debris at the east side of the building and could not see the east wall of the building. Everything seemed to be moving up, even the roof and floor. He was then knocked to the ground in a westerly direction by a rush of air and curled up in a fetal position. Everything got darker. He heard loud banging and shaking started in quick succession. He called for Paul Sullivan who answered from under a tee roof section. Kevin helped Paul Sullivan and they exited the GBT Room through the northwest door.

- Paul Sullivan (MWRD Assistant Operating Engineer) - Paul went to retrieve locks to begin the process of isolating a set of booster pumps. The pipe fitters were to replace a number of broken check valves, gate valves, and sections of piping. At about 11:00 a.m., he was standing in the room and heard a loud explosion. Almost simultaneously, a rush of hot air blew him to the ground in a westerly direction. Before he could get up, large chunks of ceiling, overhead piping, etc., all fell on top of him. He was able to wiggle out of the area in which he was trapped. Kevin O'Connor helped him get to the digester office located across the street.

Operational Background Information Provided by MWRD Personnel

Figure 2 shows the location of the building and the subject room in the Concentration building complex. The building houses several unit processes that concentrate sludge for use in the digesters, where sludge gas is harvested and used as a fuel for process and HVAC heating. Twelve gravity concentration tanks are south of the GBT Room, eight of them operated at the time of the loss. The GBT Room is located near the north end of the building, with approximate dimensions of 110 feet long, 72 feet wide and 16 feet high inside. Two blending tanks (center and east tanks) and one centrifuge feed tank (west tank) were located under the floor slab. The blending tanks were originally used as collection and buffer tanks for fluid effluent resulting from the GBT unit process. MWRD reported that the GBT process equipment has not been utilized, and the centrifuge feed tank was empty and not used since 2009. Since 2014, the room's underground blending tanks have been used as buffer tanks fed from the upstream gravity tank thickening processes to supply the downstream digesters. Tank inlets for concentrated sludge (16-inch diameter) and outlets for GBT filtrate (24-inch diameter) and drain (12-inch diameter) to digesters, were at the north low end of each tank.

Process effluent flow through the GBT Room is reported as approximately 750,000 gallons/day[4]. Blending tank sludge solids content is reported as about 2 to 6 percent[5].

[4] Discussion with R. Dring , MWRD operations manager
[5] Discussion with Neil Dorigan, maintenance manager MWRD

In early August of this year, certain process deficiencies were recognized that brought about a need to reactivate the GBT unit process and increase the feed concentration to the digesters[6]. Work was started to repair and ready that equipment[7]. On the August 29, 2018, a day before the loss, GBT No. 3 (northwest unit), one of four units, was repaired and started up to help assess what other work would be necessary to ready all equipment for operation. GBT No. 3 was run for a few hours that day, with good results.

According to MWRD staff engineers, the above-grade GBT Room was ventilated continuously at about 5 air changes per hour, 24 hours a day[8]. Supply air is provided at the east, west and north periphery of the room[9]. The exhaust is through the GBT canopy hoods over process equipment. Heat was provided to the ventilation system by a steam heat exchanger within the rooftop HVAC equipment, though heat was not utilized on the day of the loss. The room was electrically unclassified[10]. The underfloor tanks were classified Class 1 Division 1 and were not ventilated. There was no fixed gas detection equipment present in the GBT Room.

At the time of the accident, a large overhead door at the west side of the room was open, providing additional natural ventilation.

Signage installed at GBT Room entrances warned of a flammable gas hazard. Personnel gas meters were required for those entering.

In the past, periodic checks were reportedly made of the atmosphere in the ullage space of the blending tanks by opening inspection ports (at north end) and checking with a CGI (combustible gas detector). MWRD reported that high methane readings were never observed during such checks. As the typical set alarm level is 10 percent of the LFL or less, a high methane reading would be anything greater.

It should be noted that post-accident, as the blending tanks in the GBT Room were damaged and unusable, the tank inlets and outlets were valved off. A bypass pipeline was temporarily installed to allow the process effluent to flow from the gravity tank thickening unit processes directly to the digesters.

Accident Background Information Provided by MWRD Personnel

On the date of the accident, ten workers were in the GBT area, reportedly for the purpose of readying equipment in the area for reactivation[11]. This included three electrical workers in the operating gallery for repairing VFD motor drive components and other electrical equipment. The GBT Room contained three pipe fitters for repairing wash water check valves and piping (i.e. due to prior damage in the building from a freeze-up); one iron worker for opening manholes; two operating engineers who were assisting; and one truck driver who was nearby but outside the area.

[6] Discussion with R. Dring , MWRD operations manager
[7] MWRD, Maintenance work orders related to the GBT room
[8] Discussion with Chris Nam, engineer with MWRD
[9] Contract Plans for Sludge Thickening Facilities, Calumet Water Reclamation Plant, Contract 96-251-2P, 2009, particularly drawings M-103 to M-109
[10] Per National Electrical Code, NFPA 70
[11] Discussion with Neil Dorigan, maintenance manager MWRD

The ten workers are as follows:

Paul Sullivan	MWRD, assistant chief operating engineer
Kevin O'Connor,	MWRD, operating engineer
Steve Stanek	MWRD, pipe fitter
Bill Kissane	contractor worker, pipe fitter
Bill Ruiz	contractor worker, pipe fitter
Carl Malinowski	MWRD, iron worker
Matt Dillon	MWRD, electrician
Tim Moore	MWRD, electrician
Nick Andronis	MWRD, electrician
Hollis Hall	truck driver

Nine workers were inside the GBT area at the time. They reportedly all had a gas meter or were sharing one with another close worker. Four gas meters were in use there at the time. None of the gas meters had reportedly alarmed before the event. MWRD records indicate the following workers had gas meters that day[12]: C. Malinowski, M. Dillon, S. Stanek, and K. O'Connor. Thus, workers without meters included N. Andronis, W. Ruiz, P. Sullivan, T. Moore and W. Kissane.

In regard to these meters, the following is concluded based on the documents provided and discussion with MWRD staff[13]:

- All four gas meters being used in the GBT area before the explosion had been bump tested[14] that morning, with the exception of M. Dillon's unit, which he had tested the prior day, then had some battery warnings near the time of the explosion (note that he was working in the gallery area with the electricians).

- All four gas meters had completed the monthly calibrations and were not overdue.

- No meter failures are indicated.

On the day of the explosion, none of the GBT equipment was operating. Process flow input/output was from the north end of each blending tank.

Workers started work that day at about 8:00 a.m. At about 8:30 a.m., a manhole was opened in the southeast portion of the room, Manhole C[15]. (refer to Figure 34 for manhole locations.) That manhole was opened using a battery-powered impact wrench, and reportedly closed after observations were taken; though bolts were left off. A coffee break was taken at 10:30 a.m. The next manhole that was planned to be opened was the manhole north of that (i.e. assumed to be Manhole B). At about 10:50 a.m., an explosion occurred. Given the flint striker, oxy-acetylene cutting torch, hammer, and chisel found in that immediate area, and flame cut bolts and flame cutting marks observed at the Manhole B cover, it is clear that such equipment was being used to open that manhole.

[12] Discussion with Laura Riley, MWRD safety worker
[13] Discussion with Laura Riley, EITM with MWRD
[14] Bump testing of gas meters is a method of exposing the meter to a known concentration of test gas to assure the meters are calibrated accurately
[15] Discussion with Paul Sullivan, MWRD operating engineer

After the explosion, various trade supervisors and other staff went to site to assist as needed and account for all employees. Two workers were trapped in the debris, Bill Kissane and Carl Malinowski, and were removed by Chicago Fire Department personnel. The extent of injuries involved is not known at this time.

Plant Safety Information Provided by MWRD Staff

Plant safety information was provided through several documents and discussion with plant maintenance, operations and safety staff. Some of this information is reflected in the report discussions. Safety-related documents provided include:

- MWRD – Hot Work Permit Standard Operating procedure
- MWRD – Standard Operating Procedure for MWRD Portable 4-Way Gas Meters
- MWRD, Four Gas Personnel Detector records and downloads
- MWRD, Gas Detector Bump Test and Sign-out Log

Removal and Retention of Evidence

In the various stages of the investigation, documentation and evidence removal was undertaken for items of interest by all parties present. An evidence list is attached as Appendix A. Figure 34 shows the locations from which those evidence items were taken on a plan view of the room. This evidence is currently being held in a locked room within an adjacent building at the complex. Sludge samples are currently being held with WJE.

On October 16, 2018, WJE and other parties jointly manipulated the valves of the torch in evidence to determine their positions. Findings were as follows: the main oxygen valve was open 2.1 revolutions; the main fuel gas valve was open 0.4 revolutions; the secondary oxygen valve was closed.

On October 30, 2018, the Manhole B in evidence was examined nondestructively, in the area of the two flame-cut bolts. It was shown that when those areas are illuminated by a flashlight in a darkened room, some light shines through. This is consistent with some amount of opening being present through the manhole.

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Sample Removal

Concrete Cores

On October 12, 2018, WJE personnel removed cores from three of the precast single tee roof beam stems and three cores from the reinforced cast-in-place floor slab. The cores were removed from Roof Beams 1, 4, and 8. Cores were removed from the accessible portions of the slab at the south side of the GBT Room, and at the west side of the GBT Room. We also attempted to remove cores at the east side of the GBT room however we were not able to remove a solid core that we could test due to apparent cracking within the slab. Therefore, two cores at the west wall and one core at the south were tested.

Before the cores were tested, each core was measured and weighed to determine the density of the concrete. These measurements indicated that lightweight concrete was used to cast the single tee roof beams and normal weight concrete was used to cast the reinforced concrete floor slab over the below-grade tanks.

The cores were prepared and tested following the requirements of ASTM C42. Results of the compression tests are listed in Tables 1 and 2. As can be seen in Tables 1 and 2, the average compressive stress for the roof beams was 5,977 psi and 8,097 psi for the floor slab.

Table 1: Precast Single-Tee Roof Beam Concrete Core Compression Test Results

Roof Beam Number	Concrete Compressive Strength (pounds per square inch)
1	5,660
4	5,740
8	6,530
Average	5,977

Table 2: Reinforced Concrete Flor Slab Concrete Core Compression Test Results

Core Location	Concrete Compressive Strength (pounds per square inch)
South edge of slab near mid-point between east and west walls	7,830
Next to west wall 26 feet south of north edge of slab	6,780
6 inches east of west wall and 26 feet south of north edge of slab	9,680
Average:	8,097

Tank Contents

A number of sludge samples were retrieved from the underground blending tanks during the early task work. Three samples were retrieved from the center tank (west blending tank) on September 14, 2018 from the area of Manhole E. Three samples were retrieved from the east blending tank on September 21, 2018 from the area of Manhole A. A long-handled dipper was used to obtain the samples and pour them into 1 liter jars. During that process, it was noted that there appeared to be layering of more dense material near the bottom of each tank. It was also noted that bubbling was occurring in the sludge.

CGI (combustible gas indicator) checks of sample head spaces at intervals indicated the presence of significant flammable gas concentrations. A transfer of two tank samples was made to 250 ml septa containers and sent to a laboratory for GC (Gas Chromatography) major component analysis. Laboratory GC analysis[16] (see Appendix B) of sample headspace gases showed significant amounts of methane, carbon dioxide, nitrogen and oxygen, consistent with anaerobic sludge gas formation.

[16] GTI Testing Laboratory report

Structural Analysis

WJE performed analyses of various structural components of the GBT Room in order to estimate blast pressures based on the observed condition of the structure. Our analysis was generally based on the response of the structural components under uniform static pressures. Structural response to blast pressures generally depends on the relationship between the duration of the imposed pressure and the natural period of the structure. In this case of a confined gas explosion acting on reinforced concrete members, it is expected that, effectively, the loading experienced by the structure will be similar to the peak pressure generated by the explosion; therefore, it is reasonable to use static pressure to estimate the ultimate capacities of concrete members, and then to estimate minimum peak blast pressures[17].

Additionally, the measured strengths of concrete and of steel generally increase as the rate of loading increases. To account for the effect of a fast loading rate under blast pressures in the tanks, we applied a factor of 1.2 to the calculated ultimate capacities of the tank wall and floor structure[18].

Tank Wall

During our site visits, we observed that the tank wall that was part of the original construction and located between the center and west tanks had generally collapsed toward the west, indicating that it was loaded on its east face. In reviewing the debris, we observed locations where the wall laid on the tank floor slab mostly intact, with a break occurring near the base of the wall. This would suggest that the wall acted as a cantilever structure at these locations. We also observed that the top of the wall was not doweled to the concrete floor slab that was supported on it. Therefore, for the first failure scenario, we considered the slab deflected upward from the blast pressure as the wall was laterally loaded from the blast pressure. With the slab deflected upward, the wall would not have had a lateral support at its top end, and would act as a cantilevered wall for the lateral loads.

At other locations, we observed distress that appeared to indicate that the wall failed due to bending both at its base and at a location nearer the top edge of the wall. If the wall were laterally supported at its top edge, the ultimate bending capacity of the wall would be determined based on its bending capacity at its base plus its bending capacity in the opposite direction in its upper section. Although the slab did not appear to be doweled into the top of the wall, some lateral restraint may be provided by friction and bond between the slab and wall. Also, the slab would have to deflect upward approximately 2 inches to allow the wall to rotate and clear the slab. Therefore, we also estimated a pressure to fail the wall per this second scenario.
Assuming cantilever action for the wall, we estimated that the static pressure needed to fail the wall in bending would be on the order of 4 psi. We found that the shear loading of the wall did not control its lateral capacity.

In a second scenario, with lateral restraint at the top of the wall, we estimate the pressure needed to fail the wall would be on the order of 12 psi. Again, we found bending to be the controlling failure mode for this scenario.

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[17] R.J. Harris, "The Investigation and Control of Gas Explosions in Buildings and Heating Plant" (E. & F.N. Spon in association with the British Gas Corp, 1983), p. 83

[18] Departments of the Army, Navy, and the Air Force, "Structures to Resist the Effects of Accidental Explosions" TM 5-1300/NAVFAC P-397/AFR 88-22 (1990), p. 4-25

Beam-Supported Floor Slabs on Top of Tanks

We analyzed the cast-in-place beam-supported floor slabs to estimate the pressures within the tank that would cause the slabs and GBT equipment to lift and then to cause extensive failure of the slab. In the flat slab areas, the reinforcement is shown to consist of No. 6 reinforcing bars at a 12 inch spacing in two orthogonal directions, near the top and bottom of the 12 inch thick slab. In the depressed slab areas, the reinforcement is shown to consist of No. 6 bars spaced at 6 inches on center in two orthogonal directions near the bottom of the slab and No. 6 bars at a 12 inch spacing in two orthogonal directions at the top of the slab. These depressed slabs have a sloped top surface and vary in thickness form 8 to 14 inches. We also considered the contribution of the cast-in-place concrete beams to the strength of the floor structure.

We analyzed the beam-supported slab as a continuous one-way structure spanning between supporting walls and columns. The top reinforcement in the east-west beams is continuous over the walls and columns; the bottom reinforcement is discontinuous at these supports. Therefore, the beams had no significant bending capacity at their supports. At mid-span, the top reinforcement in the beam contributes to resisting bending stresses generated by upward blast pressures. For the slabs, we considered the contributions of both the top and bottom reinforcement at the supports and at mid-span. We also assumed that the concrete structures had sufficient ductility to develop their full bending capacity at their supports and at mid-span, effectively creating hinges in the structure and achieving the ultimate bending capacity of the beam-slab structure throughout its full span.

We considered two cases: 1) the floor structure over the east tank, loaded along its full length between supporting walls; 2) the floor structure over the center and west tanks, loaded only in the area above the center tank. For this latter case, we assume that the slab lifts off of the older tank wall located between the center and west tanks. Therefore, the effective span of the slab in the second case is nearly twice that of the slab span in the first case. We estimated the ultimate bending capacity of the beam-supported slabs assuming full plastic moments developing at the supports and at mid-span. As noted, we also included a 20 percent increase in bending and shear capacity to account for rapid loading of the concrete and steel reinforcement.

For the first case, we found that the bending behavior of the floor structure over the east tank would control capacity, rather than shear. This analysis estimated that the pressure required to lift the slab and equipment weight and to fail the slab in bending at the supports and at mid-span is approximately 12 psi.

For the second case, we found that the pressure required to fail the beam-supported slab in bending over the center and west tanks would be on the order of 10 psi. Again, the shear capacity did not appear to control the slab failure initially. Although we did not find that shear would control the slab resistance to upward pressure, the shear capacity would have decreased with increasing cracking and curvature of the slab under both bending and shear stresses. The upward blast loading of the beam-supported slab would produce diagonally oriented (shear) cracks and vertically oriented bending cracks in the area of the supports.

In the field, we observed extensive destruction of the floor structure above both the center and east tanks, in the regions along the supports. However, we also observed that the destruction appeared to be more extensive over the center tank. This indicates that the pressures in the tank were greater than the 10 psi we have estimated it would take to initiate a bending failure in the floor structure. It is likely that the pressures within the east and center tanks were similar, based on the similar volumes in the ullage space and the connection between these spaces at their south ends. The level of destruction of the floor structures over both tanks indicates that the pressures would have exceeded 12 psi, so as to fail the floor structure over both the east and center tanks.

Roof Structure

An analysis of the precast prestressed lightweight concrete single tee roof beams was performed to determine how they would perform when subjected to a static upward pressure in two configurations in the area above where the reinforced concrete floor slab failed over the east and center tanks.

This analysis considered the existing single tee beam weight for a 120 psf lightweight concrete density (see concrete core tests) and estimated weights for the gravel ballast and roof membrane, sloped fill at the roof drains, and a uniform allowance for suspended mechanical equipment and piping. Two configurations of applied upward pressure were considered.

The first pressure configuration considered that the uniform upward static pressure oriented along the length of the interior tank separation wall between the east end center tanks measuring 10 feet wide (5 feet on each side of the wall) approximately in the area where the floor slab over the tanks had failed. This configuration considered that when the concrete floor slab failed, the pressure would be concentrated in the open areas of the floor slab and remain concentrated until the pressure contacted the bottom surface of the roof structure. For this pressure configuration, a pressure of approximately 9 psi would result in the roof beams lifting up from their support on the east wall.

The second pressure configuration considered that after the pressure escaped through the open (failed) areas of the slab the area of pressure continued to expand until it was equal to approximately the area over the east and center below-grade tanks when it reached the underside of the roof structure. For this configuration, the width of the assumed static upward pressure is approximately 45 feet. Our analysis indicated that a static upward uniform pressure of less than 1.5 psi would lift the roof beams up from their support on the east wall.

For both of the pressure configurations considered, the net bending moment from the upward pressure is in the same direction as the bending moment from the prestressing tendons and causes compression at the bottom of the section (negative moment). The tees are designed to resist gravity effects, which cause compression at the top of the section. The effects of upward pressure and prestressing overcome gravity effects such that the calculated net bending moment (prestressing moment and upward pressure moment) exceeds the calculated capacity for the prestressed single tee roof beams. Failure results from crushing of the concrete at the bottom of the T-section and is based on the average concrete compressive strength measured from the removed cores.

Unreinforced Masonry Walls

An analysis of the GBT Room south wall (12 inch CMU) and the north Operating Gallery wall (4 inch brick with 8 inch CMU), revealed that the maximum lateral pressure to induce failure was approximately 1 psi for both. Failure was assumed based on achieving mid-height stresses that exceeded the modulus of rupture values published in TMS 402/ACI 530/ASCE 5.

Blast Analysis

Blast analyses were carried out to provide some estimate of what conditions were necessary to result in the damage observed. Analyses included the utilization of results from structural analyses, coupled with an adiabatic mixing model, and stoichiometry to estimate the minimum amount of sludge gas involved to fuel the explosion and cause the observed structural damage.

A stoichiometry estimate of the sludge gas was necessary to determine optimum concentrations of a typical sludge gas fuel, simplified to be 60 percent methane, 40 percent carbon dioxide. An estimate of the amount of fuel/air mix in the blending tanks at the time of the explosion is possible if we assume that the fuel is methane. Using stoichiometry including the typical carbon dioxide content, the stoichiometric concentration of methane is estimated at 8.9 percent[19].

An adiabatic mixing model[20] was used to calculate the amount of flammable mixture in the blending tanks' ullage space that was necessary to cause the damage. This model uses two consecutive events: constant volume burning of the fuel-air mixture in the blending tanks' ullage spaces followed by the adiabatic mixing of burnt gas with the surrounding air in the GBT Room enclosure.

The previously described structural analysis estimated approximately 1.5 to 2 psi overpressure necessary to lift the roof in the building. Using 2 psi as the resultant equilibrium pressure in the room after blending tank rupture, it was calculated that a partial volume of at least 4213 cubic feet of stoichiometric sludge gas/air mixture is required to fuel that event. A larger amount is required at the low and high limits of flammability, filling the ullage space. It is also estimated that the pre-burst peak pressure of the blending tank is 22.4 psi. However, such a pressure may have never reached that point due to breaching of the floor slab at a pressure of about 12 psi (see Structural Analysis). It should be noted that the overhead door was open at the time of the explosion, but was not considered in the analysis for the sake of being conservative.

DISCUSSION

Floor Slab Structure

For our analyses of the floor structures, we estimated the upward pressures that would be needed to fail the structures in shear and in bending. Shear capacity was analyzed independently of bending behavior in order to determine which behavior likely initiated failure of the floor structure. In reality, the concrete distress resulting from large bending stresses would have severely reduced the slab shear capacity. Similarly, the floor structure over the center tank was considered separately from the floor structure over the east tank although some interaction between these structures would be expected due to transfer of bending stresses across the support and due to the excessive concrete distress in the slabs, beams, and wall in the region of the shared wall support.

During our inspection, we observed damage that is consistent with large displacement and severe upward bending of the beam-supported slabs. At the support wall that was constructed with the floor slab in 2009, we observed severe bending of the reinforcing bars and destruction of the slab and beam concrete. In a large area of the beam-supported slab structure, only the reinforcing bars remained in place after the explosion. Between supports, we observed slab cracking, but with the concrete still intact and covering the reinforcing bars. The slab area located directly over the original tank wall between the center and west tanks was generally intact, indicating that the slab lifted off of this wall without being restrained by it.

As noted, the slab and beam damage was severe where it was supported on and dowelled into the supporting walls and columns. Based on the extent of the slab damage, with little or no remaining concrete over a strip

[19] For the overall fuel-air mixture
[20] SFPE Handbook, and Ogle reference

several feet wide along the supporting walls, it appeared that the pressures significantly exceeded the values needed to fail the slabs in bending or shear. Therefore, we believe that the blast pressures not only caused the slab to fail in bending and shear but then it caused it to continue to displace upward and extend the damage zone at its supports, removing a majority of concrete in this area.

Roof Structure

Based on our observations of the collapsed roof and our analysis of the precast prestressed single tee roof beams, we believe that when the explosion failed the floor slab, the vented gas from the explosion filled the GBT Room. Additionally this pressure would have been at a rather high intensity coming out of the failed open areas of the floor slab. As this escaping pressure filled the GBT Room, its intensity would have been reduced from the initial intensity escaping through the failed areas of the slab. Mr. O'Connor's observation of a wall of white debris at the east side of the GBT Room and Mr. O'Connor's and Mr. Sullivan's accounts that a pressure wave pushed them down toward the west would be in agreement with a high intensity pressure escaping the failed portions of the slab over the east and center tanks, and reducing intensity as it filled the room with pressure. Based on NFPA 921[21], the overpressure that would have pushed Mr. O'Connor and Mr. Sullivan (who were at the west side of the room) to the ground in the west direction would likely be in the rage of 1 to 3 psi.

Also, based on our analysis, a static pressure less than 2 psi would be all that was necessary to lift the roof tee beams from their supports at the east wall where the tee beams were not mechanically attached the wall. Once the tee beams were lifted off their supports, the bending moment from the upward pressure on the single tee beam in combination with the prestressing moment from the 44 draped tendons would combine to fail the beam. The failure of the beam would have occurred at the center section where all of the draped tendons were at their lowest point and the prestressing moment combined with the moment from the upward pressure would have been highest. When the pressure lifted the single tee roof beams, the walls and roof of the Operating Gallery were also likely failing at the same time. The combination of the collapsing Operating Gallery and lifting of the single tee roof beams would have allowed the pressure and any airborne debris to escape from below the GBT Room roof and onto the roof of the Sludge Screen/Polymer Rooms. This would account for the small pieces of concrete from the floor slab found on top of the Sludge Screen/Polymer Room roof.

After the pressure in the GBT Room dissipated, the failed roof beams would begin to fall, causing additional distress to the failed center section of the tee beams when they impacted the floor and equipment below. The impact of the failed roof beams on the floor slab's column-supported Beam B-2 caused the observed failures of this beam and its supporting columns.

The Origin of the Explosion

It is believed that the initial sequence of events involved an ignition scenario (see detail in Ignition Source section) and explosion in the east blending tank, transitioning to a more energetic explosion in the center tank. The overflow area at Manhole C is one pathway between the tanks for such a transition.

The west wall of the center tank was blown westward during the event, allowing the west tank to pressurize, as evidenced by the manhole G popping open, although adjacent Manholes F and H remained closed. This is consistent with a low pressure event in that volume, as a result of the center tank wall breach.

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[21] NFPA 921, Guide for Fire and Explosion Investigation

All manholes were popped open over the two blending tanks, and many were found a short distance from their origin. Some manhole covers were cracked, probably due to impact with other items. These manhole ejections are consistent with the origin in the blending tanks.

The two blending tank ullage spaces were connected in terms of common overflow facilities, at a level of about 13 1/2 feet and above (see Figures 33 and 36) which allowed for explosion propagation between the blending tanks. The liquid spaces are not connected in any manner. However, process tank level data show the two tank levels were tracking each other quite closely, assumed to be due to similar process flow through each tank.

We believe that, while the floor slab was damaged on both sides of the wall between the east and center tanks, it did not lift up off of this common wall. The extensive damage in the slab created a major relief vent for the center and east tanks.

This set of events would produce two blasts in close succession. A few witnesses recall hearing two blasts in rapid succession. Others did not. Events that would be expected to produce loud reports include (in order of occurrence), the explosions in the two blending tanks in succession, the crushing failure of each roof beam (which would not have all occurred at the same time) and then impact of the roof beams on the remaining floor slab. The failure of the individual roof beams may have been the loud banging in quick succession heard by Mr. O'Connor after he was knocked to the ground.

One of the witnesses in the building, Kevin O'Connor, witnessed an upheaval described as a vertical column of white debris with everything moving up (roof, floor, and equipment). This is consistent with a blending tank as the origin of the explosion.

If the origin was hypothetically in the room itself (i.e. room filled with a flammable gas/air mixture), damage patterns would be expected to be quite different. If the resultant explosion occurred within the room space above the floor slab and below the roof structure, we would expect to see severe damage to the single tee roof beam's thin, lightly reinforced 10 feet wide flanges. For a given pressure in the room, these single tee beam flanges would fail well before any significant damage occurred to the floor slab. Also, we would expect to see a significant amount of debris from the tee beams and roofing surrounding the buildings. Pressures would be necessarily much higher to achieve floor slab breakage from the top side. Exterior walls would probably have been breached, injuries would be more severe and would include more burn injuries. The damage patterns as found are consistent with a blending tank explosion.

Four workers in the area, or close to the area, were wearing the 4X gas meters before the accident. Reportedly, none of these devices alarmed at any time (though this is not confirmed for C. Malinowski's monitor, which is lost). These results are consistent with origin in the blending tanks, isolated from the GBT Room.

HVAC ventilation was reportedly on at the time of the accident as it normally would have been. The ventilation rate and configuration of ductwork are consistent with a high air exchange of the room (5 air changes per hour), which minimizes any accumulation of flammable vapors from upward seepage through floor and equipment openings. Also, the overhead door at the west side of the room was open at the time of the event, providing additional ventilation. This is also consistent with the origin being in the blending tanks, isolated from the GBT Room.

The Fuel for the Explosion

The structural post-explosion damage effects are of a type consistent with a diffuse fuel explosion, resulting in a somewhat uniform blast pressure development in the containment. It is also consistent with a deflagration explosion, having a subsonic combustion wave. Other types of explosions, such as condensed or high explosives, will result in more localized shattering of materials near the epicenter of the blast, and are ruled out accordingly. Therefore, fuels for consideration in the underfloor blending tanks include vapor, gas or dust that can be dispersed throughout a space, such as sludge gas, other fuel gases and flammable liquids.

Other fuel gases, such as acetylene gas usage in the area, are ruled out due to the relatively small quantity available, which is not consistent with the damage incurred. Also, natural gas distribution piping in the building was nonexistent, as heating requirements are supplied by steam from a central boiler plant.

Flammable liquids would necessarily originate in the public system and would require a very large industrial liquid dump event to result in a significant accumulation in the GBT area, particularly without any notice of a discrepancy in any other unit processes. Flammable liquids, fats, greases and other light materials are usually skimmed off the top of liquid in the primary settling tanks at the front end unit process because their density is lighter than water. Operators in that area would have noticed and smelled such an event; flammable liquid smells were not reported on the date of the loss[22]. Because of these factors, flammable liquids are ruled out as a fuel hypothesis.

An initial CGI examination of the sludge samples taken has shown head space readings consistent with the production of significant concentrations of flammable gas. Laboratory GC analysis[23] (see Appendix B) of sample headspace gases has shown significant amounts of methane, carbon dioxide, nitrogen and oxygen, consistent with anaerobic sludge gas formation. The chemical species resulting can be assumed similar to that at the time of the accident, as the sludge present should be similar. However the species concentration results are not to be construed as identical to that present at the time of the loss, as the samples were taken a few weeks after the loss event (i.e., longer residence time), and with proportionately larger air head spaces than the tanks involved, different temperature histories, etc.

The sludge gas hypothesis cannot be ruled out, as all the ingredients were present for that type of accumulation: a somewhat sealed ullage space in the tanks, relatively poor circulation of liquid sludge through portions of the tanks (given the flow configuration with inlet/outlets at one end) providing high residence time, an appreciable quantity of sludge in the tanks (approximately 9 feet), and warm temperature conditions.

At some time on the morning before the explosion, the Manhole C cover had been removed and was open for some period of time. An operating engineer looked in and saw that the tanks were not overflowing. Then the cover was put back on. The blending tanks may have partially ventilated during that time. No estimate of the effect of this on the fuel concentration in those tanks has been made to date.

It should be noted that the day before the loss, the GBT No. 3 process equipment was repaired, started and ran for several hours. During that time, any semi-solid layers of sludge may have been stirred up in that area of the tank. It is not known if that contributed to additional sludge gas formation.

[22] Discussion with Laura Riley, MWRD safety worker
[23] GTI Testing Laboratory report

The Cause of the Explosion

As sampled sludge from the blending tanks was shown to be able to produce a significant methane concentration within sample ullage spaces within a week or so after sampling, it is logical to infer that the anaerobic yield rates in the blending tanks would be sufficient to have filled the ullage spaces similarly before the explosion event. However, gas from the blending tanks accumulated over a longer time period and in a proportionately smaller ullage volume.

Given that the source boundary for sludge gas generation is at the surface of the liquid, the ullage spaces in a blending tank are expected to accumulate a fairly uniform mixture of the sludge gas and air. The blending tanks were somewhat sealed at the floor slab. The manholes in the slab also were sealed with an elastomeric gasket. Over the years of operation under reasonable conditions for anaerobic methane production, it is likely that flammable or near-flammable conditions existed in the tank ullage spaces at times.

To result in an explosion, the concentration of the gas must be in the flammable range. For sludge gas, that range is approximately 5 to 15 percent in air[24]. Anaerobic digestion processes are complex, but generally result in the production of sludge gas with about 50-75 percent methane, 25-50 percent carbon dioxide, 0-10 percent nitrogen, and small amounts of hydrogen sulfide and other gases. To make matters more complex, the amount of carbon dioxide may slightly constrict the flammable limits more than stated above[25]. Nevertheless, it is certainly possible to result in a flammable mixture that can provide significant explosion pressure to lift the floor slabs. An ideal (stoichiometric) confined mixture of methane in air at a concentration of 9.5 percent can result in a maximum overpressure of 102 psi[26] or greater; though a less ideal confined mixture of sludge gas can certainly produce significant maximum overpressure estimated to be about 87 psi.

It is possible to estimate the amount of sludge gas in the blending tanks at the time of the explosion using structural static pressure failure levels. Using stoichiometry involving the typical carbon dioxide content of sludge gas as fuel, the stoichiometric concentration of methane is estimated at 8.9 percent. An adiabatic mixing model[27] has been used to calculate the amount of flammable mixture in blending tanks' ullage space. This model uses two consecutive events: constant volume burning of the fuel-air mixture followed by the adiabatic mixing of burnt gas with the surround air in the enclosure. As approximately 2 psi overpressure is estimated as necessary to lift the roof (see Structural Analysis Section), and damage the lateral walls, a partial volume of at least 4213 cubic feet of stoichiometric sludge gas fuel/air mix is estimated to do the damage. A potential pre-burst overpressure of about 22.4 psi in the blending tanks' ullage space is estimated. However, such a pressure was probably never reached in the blending tanks due to breaching of the floor slab at about 12 psi overpressure, calculated by structural methods (see Structural Analysis section). During venting, the overpressure was probably higher than 12 psi for some part of the positive phase of blast. Note that the open overhead door was not considered in the analysis, as a conservative measure.

These overpressures can be further refined by estimating the vent jet opening as the floor slab fails. However, this is a dynamic calculation because the effective vent opening changes through the event and there are many other unknowns. Such an analysis was not attempted. NFPA 68[28] explosion venting

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[24] NFPA 820

[25] Kuchta, J., "Investigation of Fire and Explosion Accidents in chemical, Mining and Fuel-Related Industries"

[26] NFPA 68, Standard for Explosion Protection by Deflagration Venting

[27] SFPE Handbook, and Ogle reference

[28] NFPA 68, Standard for Explosion Protection by Deflagration Venting

calculation methods do not seem to be of much use here, due to many unknowns involved as well as the dynamic venting area.

The blast positive phase period in each blending tank is estimated to be a maximum of 3 seconds, based on the laminar flame speed of methane of about 11.5 ft/sec[29] and dimensions of the blending tank. However, the actual positive phase period is probably more on the order of 1 second or less, due to turbulent enhancement of the flames caused by obstructions and geometry effects[30]. As the origin may be in the east tank, the blast positive phase in the center tank may be even quicker due to more turbulence involved and stronger ignition. The blast dynamics can be explored in more detail using an appropriate CFD (Computational Fluid Dynamics) model such as FLACS[31] or FLUENT[32], and are not necessary for this report.

The Probable Ignition Source

Ignition sources to consider for the subject explosion include those within the ullage spaces of the blending tanks, or close to any opening, such as the manhole. Thus, consideration was given to electrical sparking, electrostatic discharge, mechanical sparking, and open flames.

No electrical equipment was found in the tanks, with the exception of low voltage-type proximity sensors at several manhole covers. However, these are reportedly abandoned equipment, appear to be a Class 1 installation with wiring embedded in the floor slab, and have not yielded any causative evidence to date such as faulting or arcing.

No obvious faulting/arcing evidence was observed in any above-slab electrical equipment. Reportedly, all process equipment was off line at the time of the explosion.

The hammer and chisel might be used to complete the removal of the bolt head after flame cutting. Also, they could be used to loosen the manhole cover after all the bolts are out; however, only two bolts were cut out at Manhole B.

An electrostatic discharge was also considered involving the operations of the personal in the room. While it is not known exactly what each worker was doing at the time, it appears that the iron worker was performing operations directly with the below-ground tanks. It does not appear that he would be doing anything that would promote electrostatic buildup and discharge. Given the weather conditions[33] that day, warm with moderate humidity, the probability of accumulating high voltage on equipment or a person is remote.

Based the interviews taken, during the morning prior to the explosion, the Manhole C cover bolts were removed using a battery-powered impact wrench. Then the manhole was removed, the interior inspected, and then closed up without reinstalling the bolts. The cover at Manhole B was to be removed next. That power tool has not been found to date. During the time that Manhole C was open, it is possible that the blending tank was partially ventilated. At this time, the effects of this action on the fuel concentration in the tanks has not been assessed.

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[29] Bjerketvedt, D., et al, <u>Gas Explosion Handbook</u>
[30] NFPA 68, Standard for Explosion Protection by Deflagration Venting
[31] https://www.Gexcon.com
[32] https://www.ansys.com/products/fluids/ansys-fluent
[33] https://www.weatherunderground.com

The physical evidence examined near manhole B includes, an oxy-acetylene hose and torch were in close proximity. A flint striker commonly used to ignite a torch was found within 10 feet of Manhole B, between Manhole B and E. A hammer and chisel were found a few feet east of Manhole B. Also, the temporary wood block supports and other items, e.g. medical supplies, found in that vicinity are consistent with rescue operations of the iron worker who became trapped there. Figure 36 shows the torch in evidence.

Shortly before the explosion and after a coffee break at about 10:30 a.m., pipe fitters and operating engineers were located at the northwest corner area of the GBT Room attending to pump/piping repair tasks. The iron worker was at the southeast corner area attending to manhole cover removal tasks.

A preliminary check of the torch valves, witnessed by several parties, showed the primary torch valves were open, for oxygen and acetylene, consistent with an open flame present. However, as the additional oxygen control valve was found closed, the flame would be without supplemental oxygen, i.e., a dirty flame. An explanation for the valve positions may be that, after the coffee break, the worker was restarting his torch and had not yet adjust it for cutting operations.

It is not known exactly what operations were conducted with the torch immediately before the explosion, though cutting marks are observed on the Manhole B components. Two adjacent manhole bolts had been flame cut (see Figure 37). From that evidence it can be deduced that the remaining bolts were planned to be flame cut. Thus, torch-related ignition scenarios considered include the following:

1. Worker while cutting bolts with the torch ignites flammable gas directly within the tank. However, this is inconsistent with evidence of the torch valve positions.

2. Worker heating bolts with the torch to then mechanically remove, resulting in ignition temperature levels on the underside of the manhole cover. However, this is inconsistent with the evidence (i.e. as two other bolts were flame cut), and would require a very high heating level to result in ignition temperature on the underside.

3. Worker using torch inadvertently contacts a pocket of flammable gas seeping up through a floor slab penetration and accumulating near the area torch. However, with the high airflows in the area, a large pocket formation is unlikely as it should be rapidly diluted. Calculations show that typical mixes of sludge gas compositions may have a specific gravity close to that of ambient air, and therefore do not readily flow upward from an opening, as opposed to pure methane which is considerably lighter than air.

4. Worker using or igniting torch at manhole B directly and inadvertently contacts flammable gas seeping upwards through the gaps at the manhole seal resulting from the previously cut bolts. This may have been in anticipation of reactivating the oxygen cutting valve on the torch to adjust the flame for cutting.

Given the position of valves on the torch, scenario No. 4 is the most likely. Also, an examination of Manhole B at the flame cut bolt areas shows evidence of small openings through the Manhole B cover.

Given that flame cutting was part of the operation, observance of the MWRD hot work policy was in order. The hot work permit[34] was retrieved for the date of the loss in the sludge Concentration building. The permit

[34] MWRD hot work permit, Concentration Building, August 30, 2018

is partially filled out and not signed by the operator or a fire watch. An interview with the permit-authorizing-individual[35] (supervisor) involved has indicated that he initiated the permit but was called away to another task before finishing it. The permit indicates that the work to be done is cutting. Normally, for that type of work involving a confined space with a flammable gas hazard, sampling of that space would be required as part of the hot work procedure, using a gas meter with a pump and sampling tube. Sampling should have been conducted through one of the tank ports. That apparently was not done. The gas meter used by the iron worker that morning does not have a sampling tube/pump capability, necessary for that task[36]. A 4-gas personal meter was used by the worker involved, and was bump-tested that morning, and calibrated as well. The MWRD 5-gas meters have the tube/pump capability, and could have been used.

There is no question of the viability of the open flame or striker ignition of sludge gas. However, if the torch ignition scenario was that of heating bolts, the temperature of the bolt area heated should necessarily be at a level of about 1166°F[37] to result in ignition.

It should be noted that experts representing IMI (for pipe fitters) have stated that some pipe fitters witnessed saw the lighted torch flame shortly before the explosion, though this needs to be confirmed.

Given the data and evidence to date, we cannot rule out the torch as an ignition source for the explosion.

CONCLUSIONS

Our conclusions regarding the cause of the explosion are listed below to a reasonable degree of engineering certainty. We reserve the right to amend these conclusions as new information becomes available.

1. The Origin of the Explosion was in a Blending Tank, under the Floor Slab of the GBT Room.

2. The Fuel for the Explosion was Sludge Gas.

3. The Cause of the Explosion Was a Flammable Accumulation of Sludge Gas in the Tanks, which came in Contact with an Ignition Source.

4. The Probable Ignition Source for the Explosion was a Torch Flame or Striker.

The Root Causes include the following:

- A lack of hot work procedure enforcement, coupled with a possible lack of worker understanding of the blending tank atmosphere.

  The MWRD hot work policy[38] as reviewed appears to be in line with OSHA[39] and NFPA 51B, the national industry standard[40] that applies. The permit procedure was not applied properly in this case.

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[35] Discussion with Pat Coleman, MWRD, iron worker lead
[36] MWRD, Gas Detector bump test and sign-out log
[37] Kuchta, J., "Investigation of Fire and Explosion Accidents in chemical, Mining and Fuel-Related Industries", for methane
[38] MWRD Hot work Permit Standard Operating Procedure
[39] 29 CFR1910
[40] NFPA 51B, Standard for Fire Prevention during Welding, Cutting and Other Hot Work

- A lack of purge ventilation and continuous gas detection systems in the blending tank ullage spaces.

  It is not known as to what safety standards were applied to the underground tanks in the building during their original construction, as they were apparently built without plans for purge ventilation and gas detection systems. However one or both of these safety features are required in NFPA 820, the current industry standard[41] that applies.

RECOMMENDATIONS

1. MWRD hot work procedures[42] must be strictly enforced in hazardous areas where there is the possibility of flammable gas present. In order to be effective, adherence to the written procedures must be the mutual responsibility of management, the permit authorizing individual (supervisor), fire watch personnel, and hot work operators. All contractors must adhere to the same guidelines as MWRD employees. Training procedures should be reviewed.

2. If anyone involved in the hot work procedure is unsure of the hazard involved, he or she must contact someone who does understand, such as the MWRD safety department, before the permit is issued.

3. Consideration should be made for rebuilding the unit process with additional safety features. Underground tanks may be utilized, but with required ventilation if required and a continuous combustible gas detection system in the ullage space of the tanks in accordance with NFPA 820[43].

   NFPA 820 provides requirements for unit processes in wastewater treatment plants. The NFPA 820 Table 6.2.2a provides fire protection requirements for sludge blending tanks and GBT buildings.

   > Sludge blending tanks, depending on the ventilation provided, currently require a Class 1, division 1 or 2[44] electrical installation and continuous gas detection system.
   >
   > A GBT unit process, depending on the ventilation provided, can be electrically unclassified or division 2. A continuous gas detection system is not required.

   Additionally, considerations can be made for structural features to enhance safety in the event of an explosion. These may include explosion relief panels in walls and/or roof, and damage-limiting construction of walls and roof.

4. Personal Gas Meter operating procedures must be enforced. While it does not appear that a failure of a personal gas meter was a causative factor in this explosion event, the Personal Gas Meter procedures[45] must be strictly enforced. There is some confusion over exactly which meters were involved as well as inconsistencies involving record keeping, procedural infractions, and possible missing data. It should be assured that bump tests are conducted daily for each meter that is checked out; and monthly calibrations are conducted for all meters. Some consideration should be given to simplifying the record keeping. Training procedures should be reviewed.

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[41] NFPA 820, Standard on Fire Protection in Waste Water Treatment and Collection Facilities
[42] MWRD – Hot Work Permit Standard Operating Procedure
[43] NFPA 820, Standard on Fire Protection in Waste Water Treatment and Collection Facilities
[44] Per National Electrical Code, NFPA 70
[45] MWRD, Standard Operation Procedures for 4-Gas Portable Gas Meters

Also workers should be made aware of what gas detectors/meters can be used for sampling the interior of enclosed vessels as part of hot work procedures[46].

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2. 80 DT/D Digester Capacity Expansion, Calumet Water Reclamation Plant, Contract 90-214-SP, 1992, 1992
3. Contract Plans for Sludge Thickening Facilities, Calumet Water Reclamation Plant, Contract 96-251-2P, 2009
4. MWRD, Interviews of several employees
5. Metropolitan Water Reclamation District of Greater Chicago – Hot Work Permit Standard Operating procedure
6. MWRD hot work permit, Concentration Building, August 30, 2018
7. MWRD – Standard Operating Procedure for MWRD Portable 4-Way Gas Meters
8. MWRD, Four Gas Personnel Detector records and downloads
9. MWRD, Gas Detector Bump Test and Sign-out Log
10. MWRD, Maintenance Work Orders, (related to GBT room work)
11. WJE, Protocol for MWRD GBT Room Explosion Site Examination, date?
12. GTI Testing Laboratories, Sample COC # 182591, Analytical Report, October 12, 2018

OTHER TECHNICAL REFERENCES

1. NFPA 921, Guide for Fire and Explosion Investigations, National Fire Protection Association, 2017 edition
2. NFPA 68, Standard for Explosion Protection by Deflagration Venting, National Fire Protection
3. Association, 2017 edition
4. NFPA 820, Standard on Fire Protection in Waste Water Treatment and Collection Facilities, National Fire Protection Association, 2016 and earlier editions
5. NFPA 70, National Electrical Code, National Fire Protection Association
6. NFPA 51B, Standard for Fire Prevention during Welding, Cutting and Other Hot Work, National Fire Protection Association, 2014 edition
7. OSHA Regulations, 29 CFR1910
8. AICHE, Guidelines for Evaluating Process Plant Buildings for External Explosions and Fires, Center for Chemical Process Safety, American Institute of Chemical Engineers
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[46] MWRD – Hot Work Permit Standard Operating Procedure

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17. http://weatherunderground.com (source of weather data)
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19. American Concrete Institute, "Building Code Requirements for Structural Concrete (ACI 318-14)"
20. Masonry Standards Joint Committee, "Building Code Requirements and Specification for Masonry Structures (TMS 402/ACI 530/ASCE 5)", 2013

Figures

Figure 1. Overall view of collapsed structure at GBT Room looking east

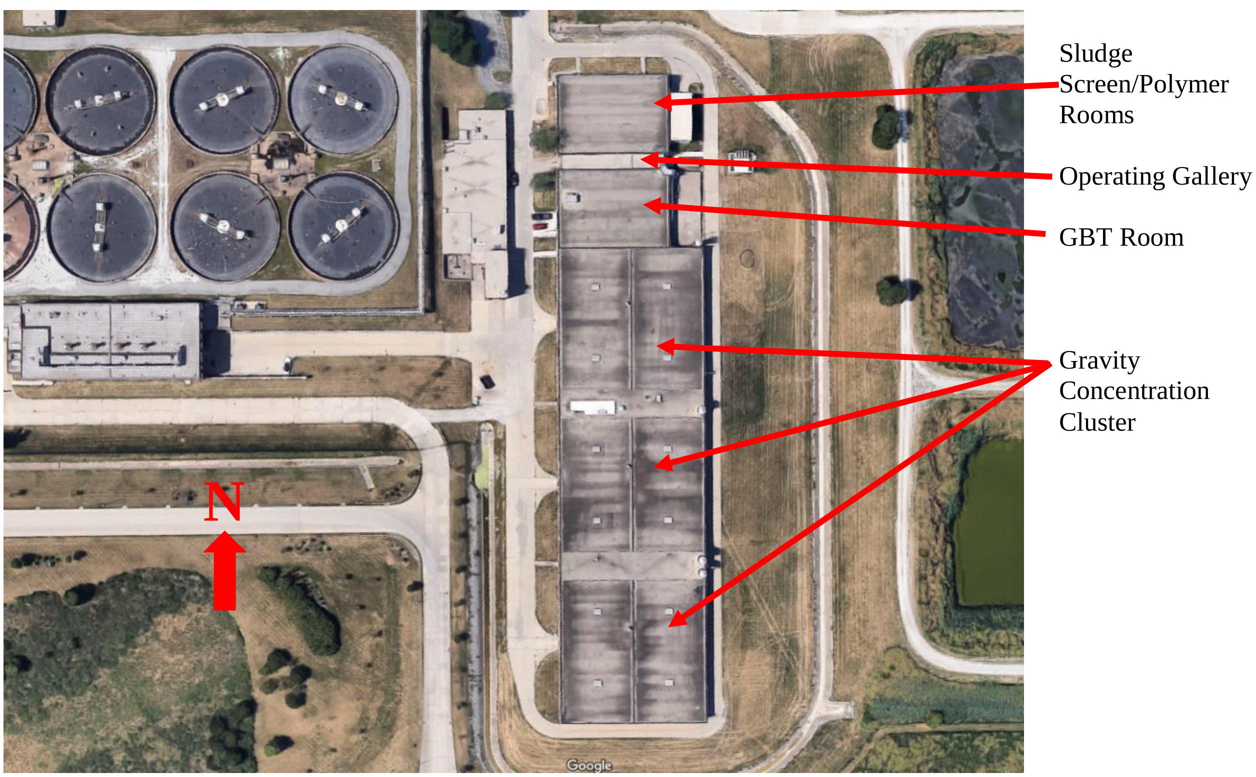


Figure 2. Aerial view of Sludge Concentration Building (aerial photograph from Google Maps)

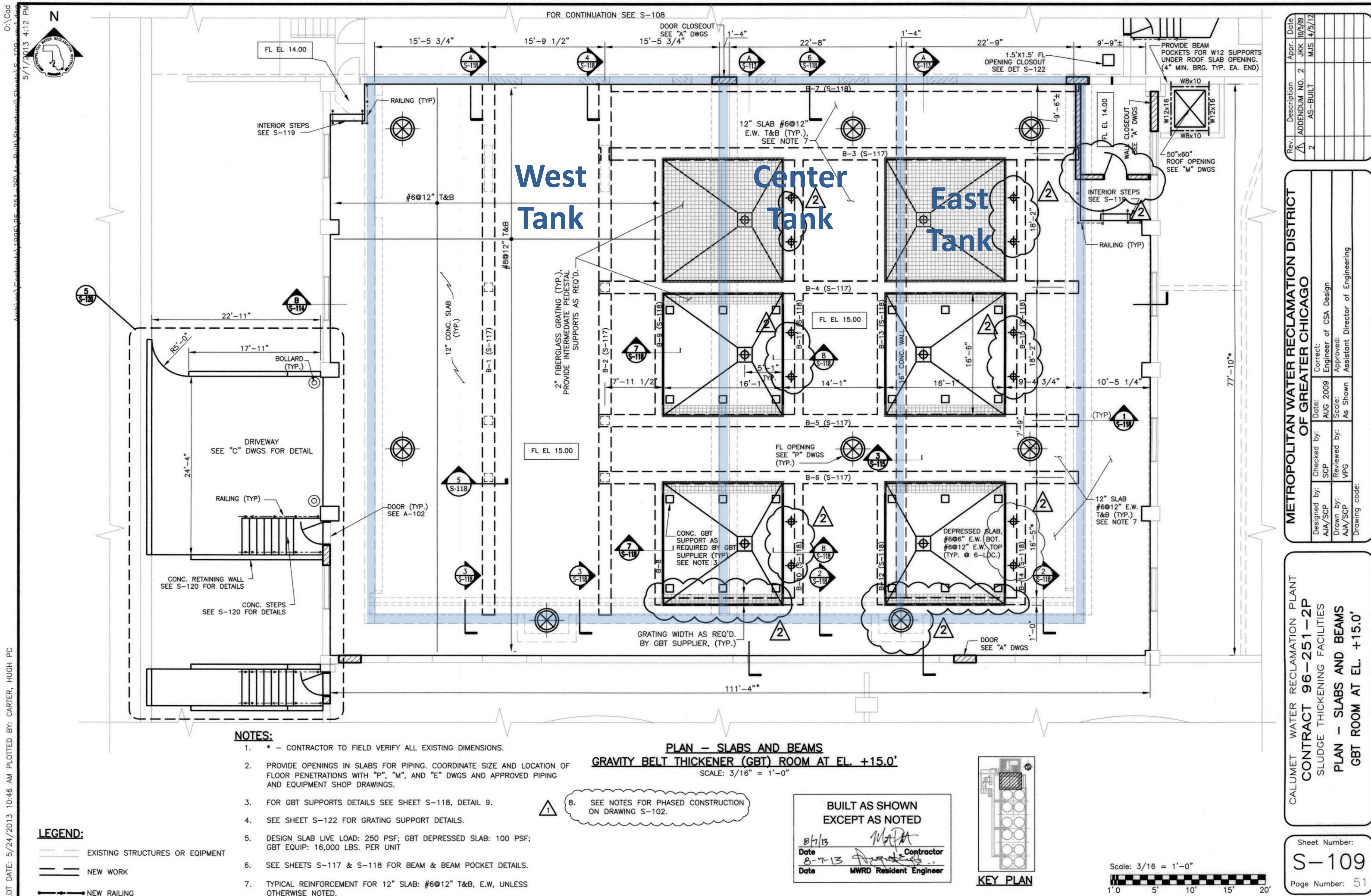


Figure 3. Drawing S-109 from Contract 96-251-2P showing the floor structure in the GBT Room

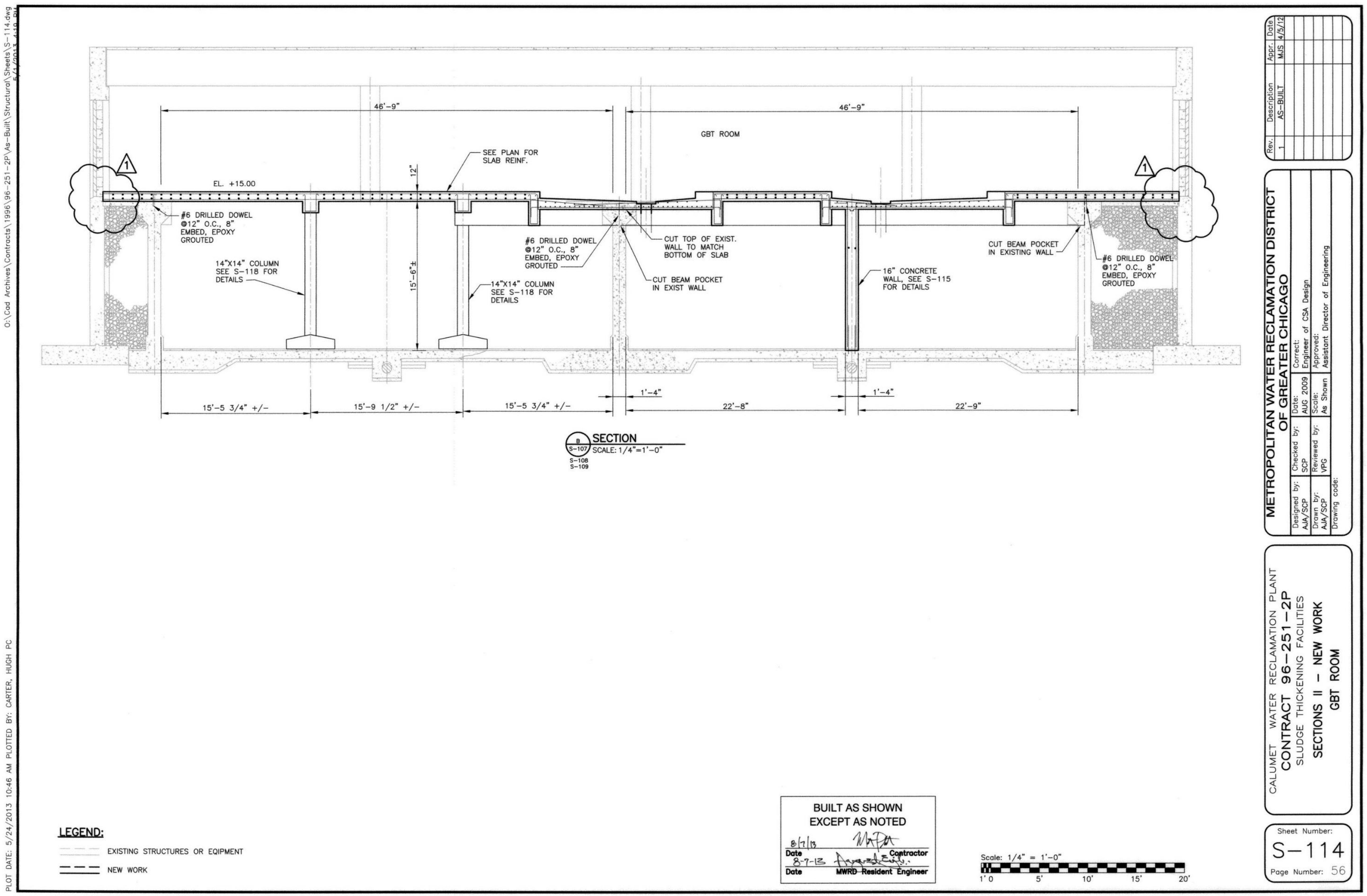


Figure 4. Section view through GBT Room looking north - Drawing S-114

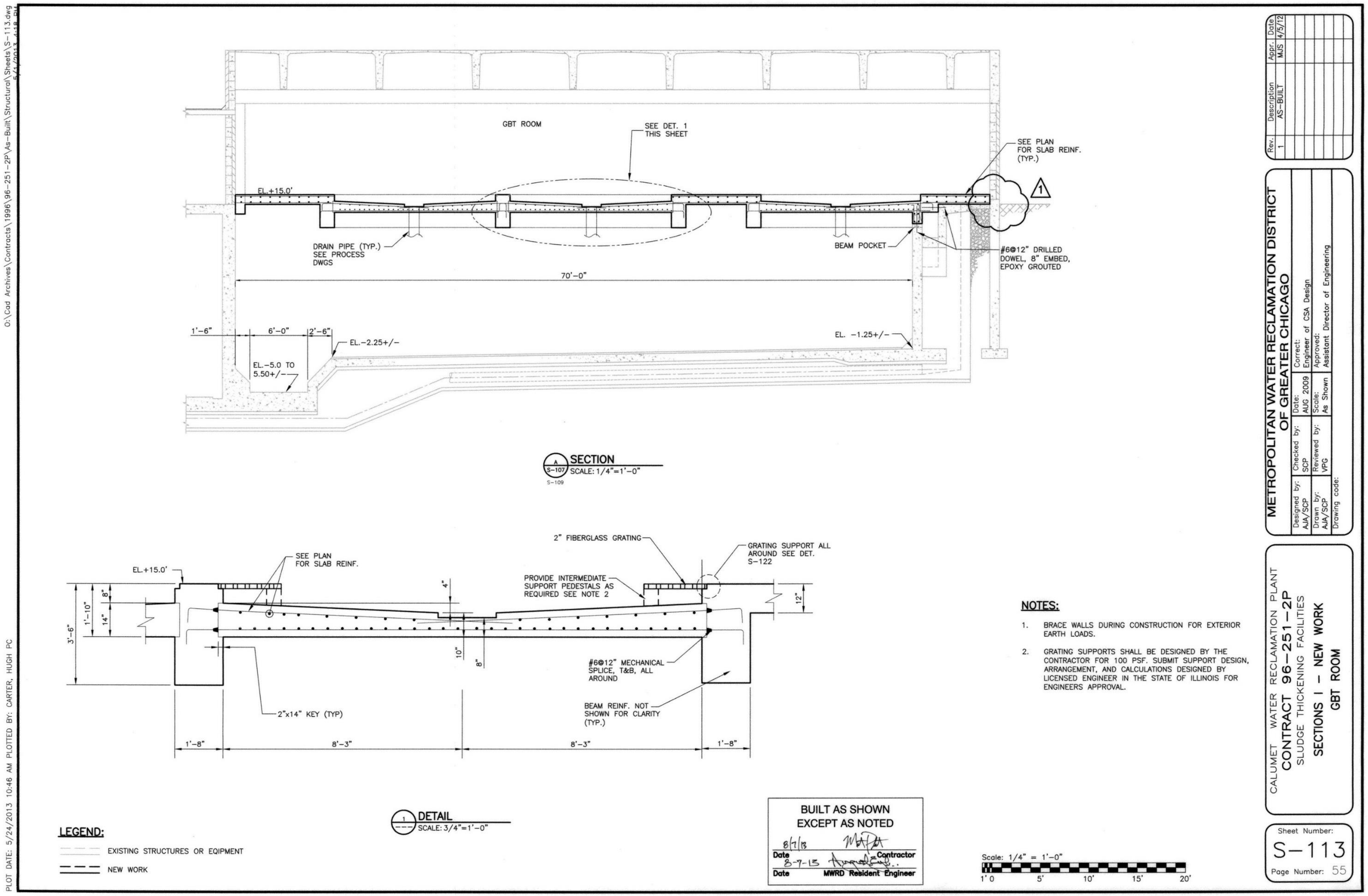


Figure 5. Section view through GBT Room looking east - Drawing S-113

Figure 6. End view of precast prestressed single tee roof beam

a) Undamaged connection for single tee roof beam over Sludge Screen/Polymer Rooms

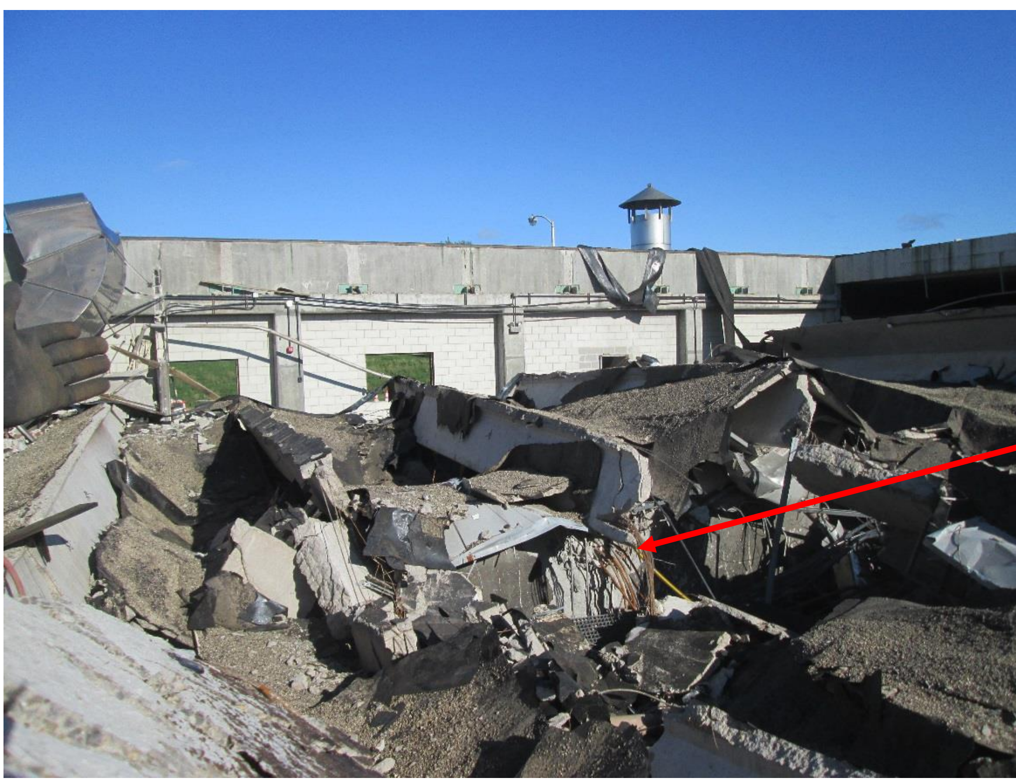
b) Damaged connection at failed single tee over GBT Room

Figure 7. Single tee roof beam bolted connection at west wall

Figure 8. Single tee roof beam bearing location at east wall of GBT Room

Interior wall between east tank and center tank

a) Looking southeast



Interior wall between east tank and center tank

b) Looking east

Figure 9. Continuous section of collapsed single tee roof beams at east end

a) Looking west

b) Looking southwest

Figure 10. Continuous section of collapsed single tee roof beams at west end

a) Looking southeast

b) Looking east

Figure 11. Center section of collapsed single tee roof beams broken in numerous small sections

Figure 12. East end of single tee roof beam fallen from bearing on east wall

Figure 13. West end of collapsed single tee Roof Beam 5 and 6 supported on rolling overhead door

a) Overall view

b) Close-up view

Figure 14. GBT Room floor slab debris observed on roof of Sludge Screen/Polymer Room

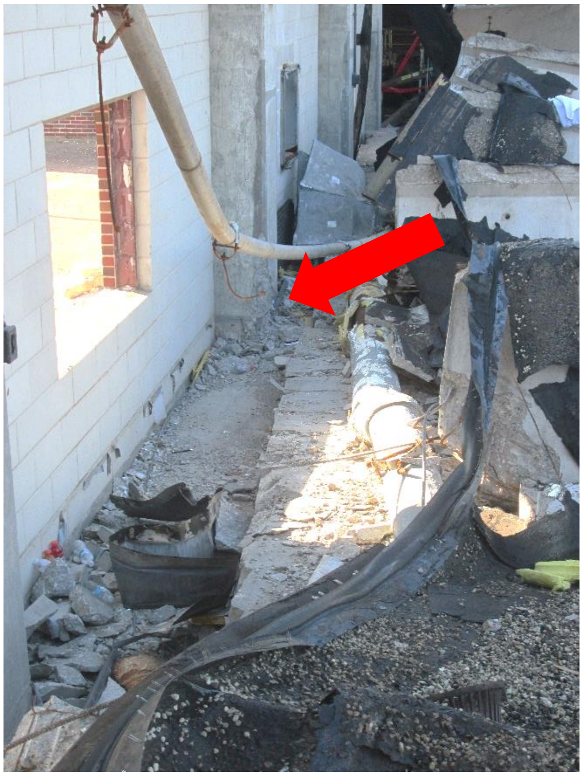


Figure 15. Damage at base of concrete column at east wall

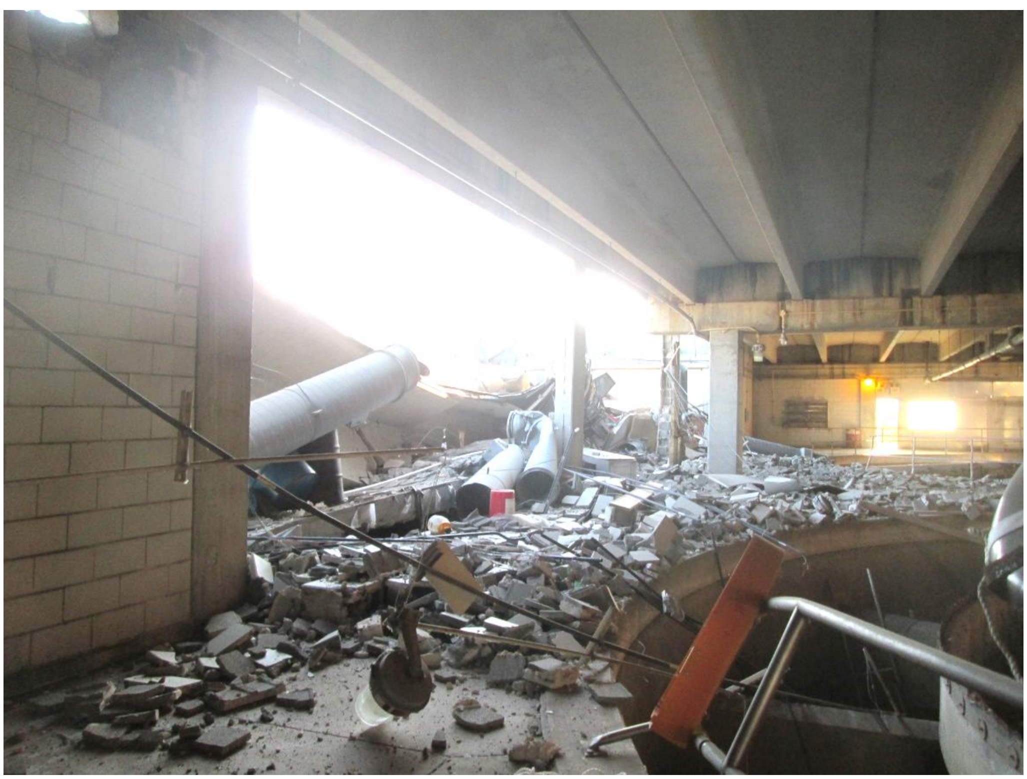


Figure 16. Collapsed concrete masonry wall separating GBT Room and gravity concentration tanks

a) Looking north

b) Looking southwest from above

Figure 17. Collapsed roof and masonry walls at Operations Gallery

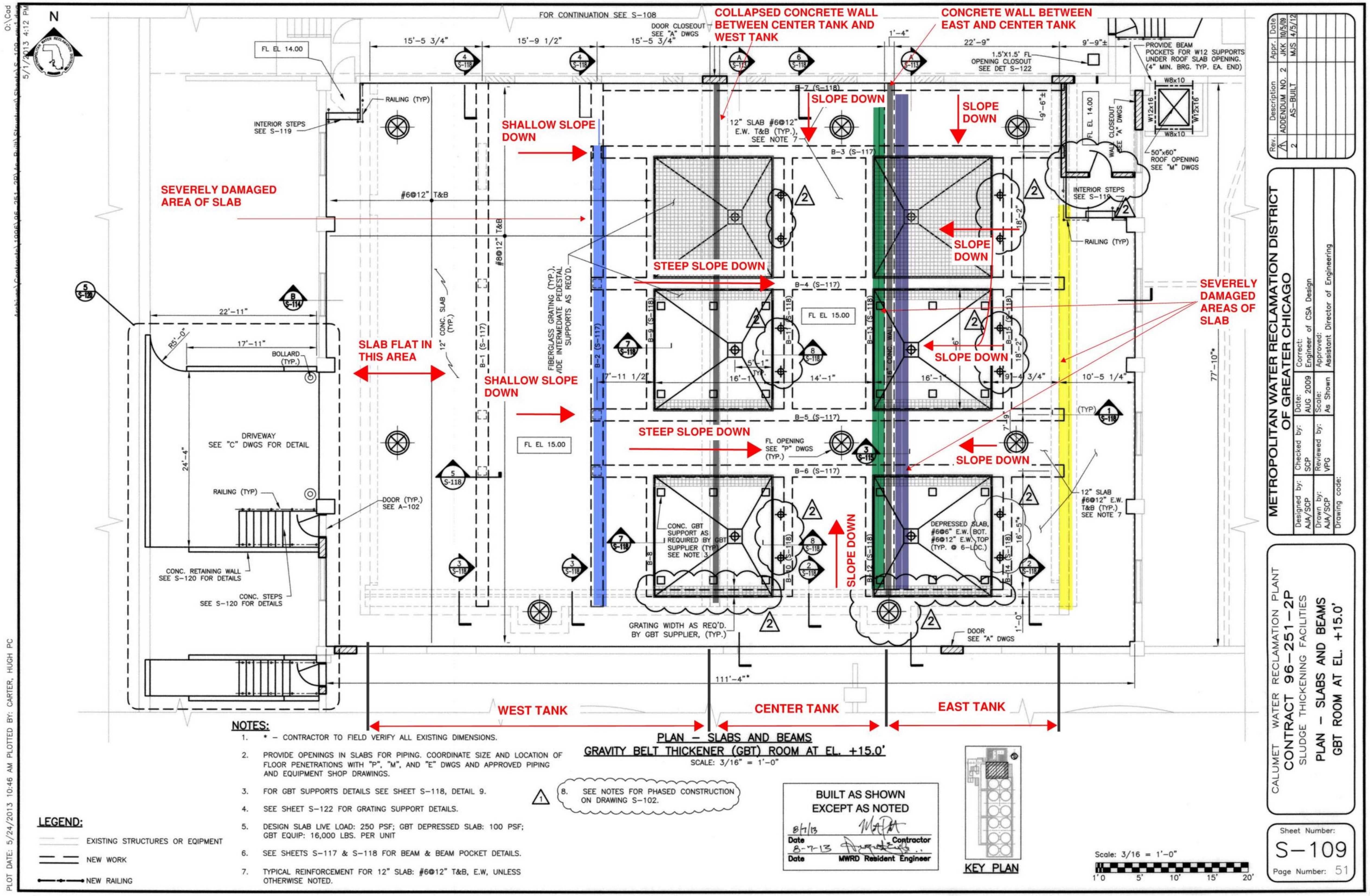


Figure 18. Annotated GBT Room floor plan showing location of observed distress at floor slab

Figure 19. Floor slab movement at east wall, looking south

a) Overall view

b) Close-up view looking east

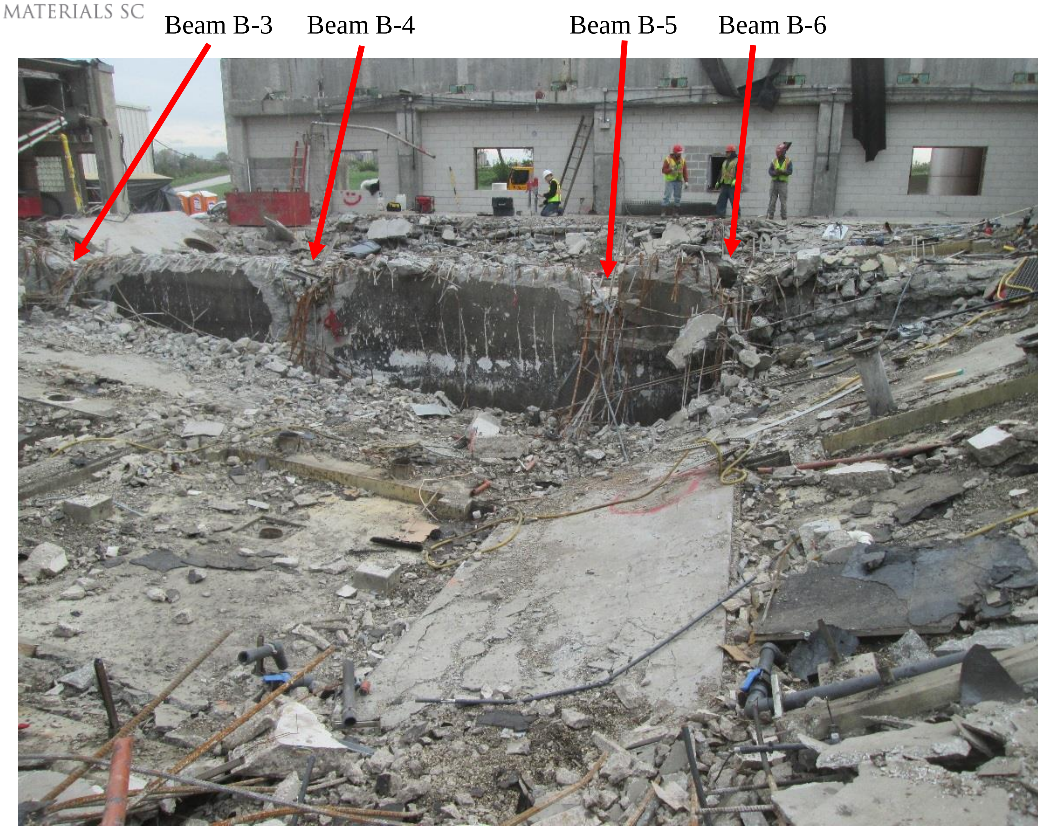
Figure 20. Damaged GBT Room floor slab along east wall of east tank

Figure 21. Damaged floor slab over interior wall between east and center tanks

a) Overall view

b) Close-up view looking west

Figure 22. Damaged GBT Room floor slab over east tank at east side of wall separating the east and center tanks



a) Overall view. Note location of floor slab beams

b) Close-up view

Figure 23. Damaged GBT Room floor slab and beams over the center tank on the west side of interior wall between the east and center tanks

Figure 24. Intact floor slab over center portion of east tank looking west

Figure 25. West side of GBT Room floor slab

Figure 26. GBT Room floor slab over center and west tanks

a) Looking east

b) Looking west

Figure 27. North GBT Room floor slab over east and center tanks

a) Looking west

b) Looking southeast

Figure 28. Center section of floor slab at south wall of GBT Room

a) Top continuous reinforcing bars

b) Bottom reinforcing bars

Figure 29. Beam B-4 at interior wall between east tank and center tank

a) Looking south

Interior wall between center and west tank

Interior wall between east tank and center tank

b) Looking northeast from above

Figure 30. Interior wall between east tank and center tank

a) Looking southeast

b) Looking south

Figure 31. Collapsed interior wall between center tank and west tank. The top of the wall is to the right (west).

Figure 32. Top of wall separating west tank from center tank with no epoxy grouted dowels present

a) From above looking west

b) Looking south

Figure 33. South wall of tank between tank and overflow trough

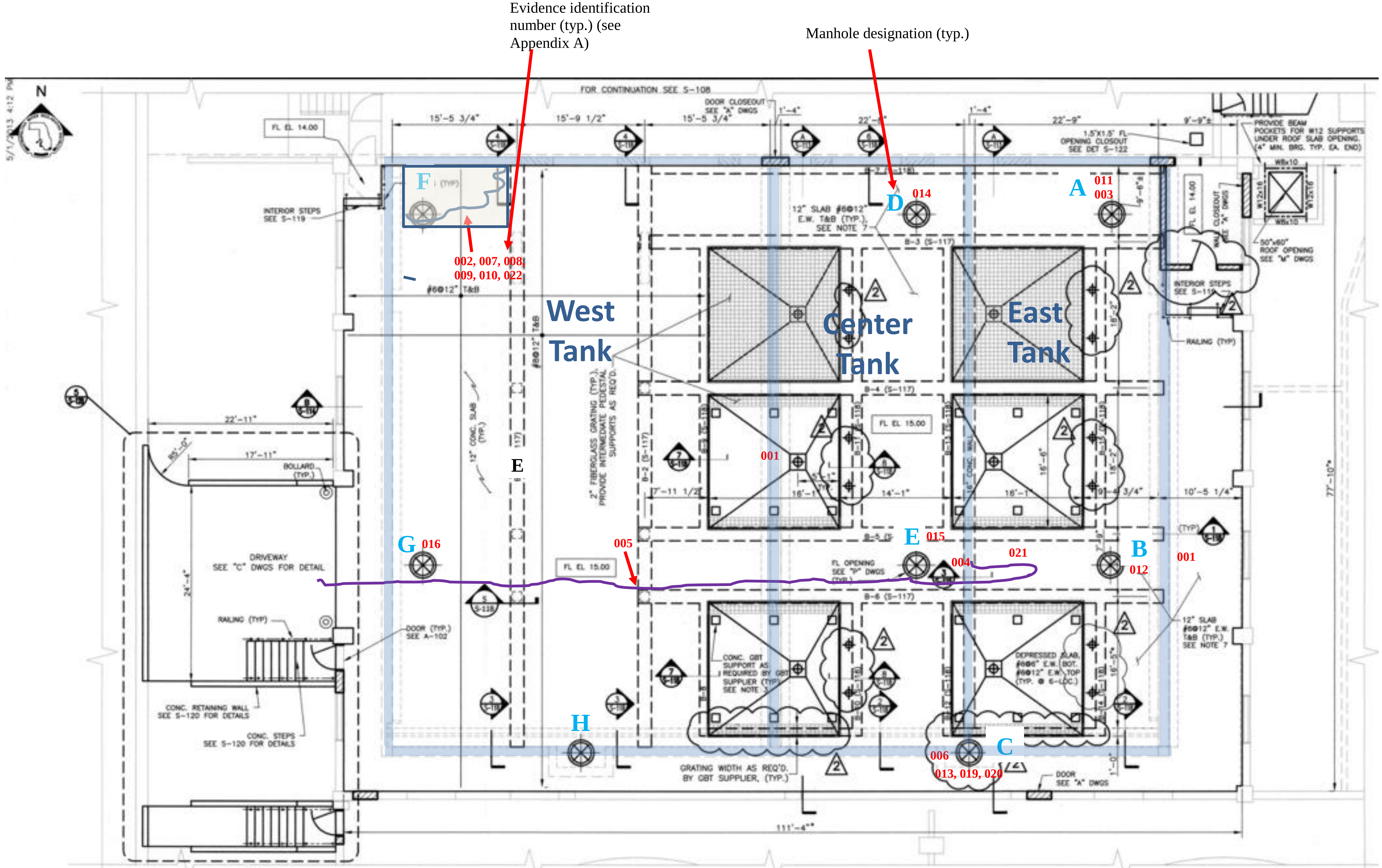


Figure 34. Evidence locations in GBT Room (See Appendix A for evidence list)

Figure 35. Blending tank common overflow facilities

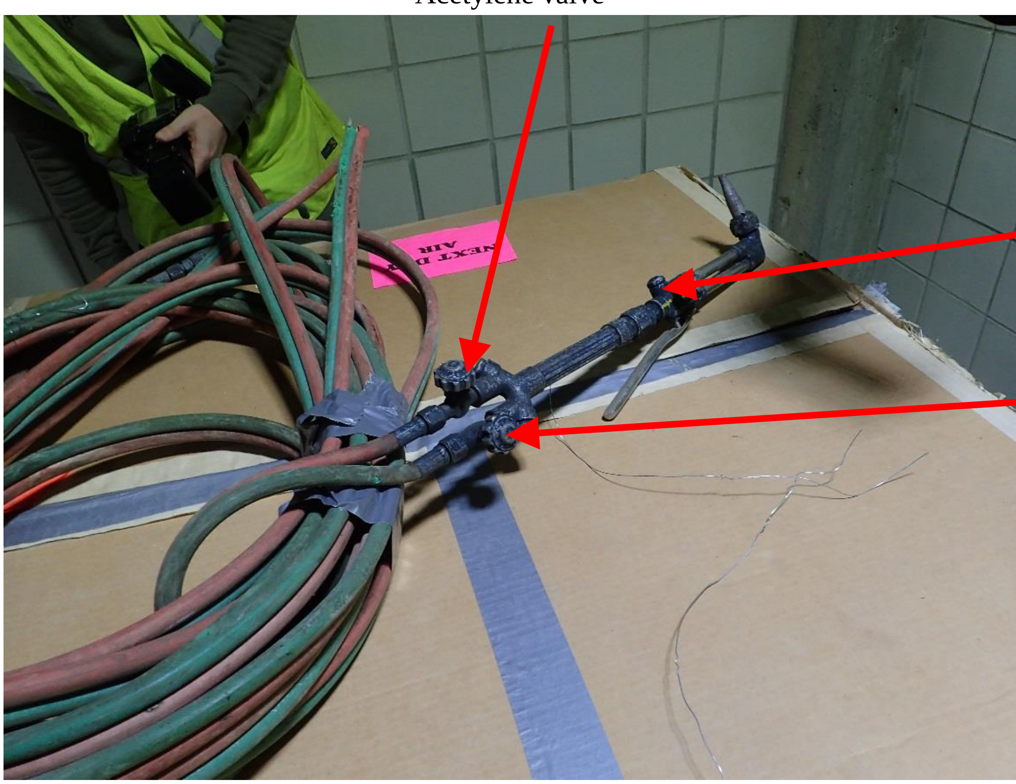


Figure 36. The subject oxy/acetylene torch

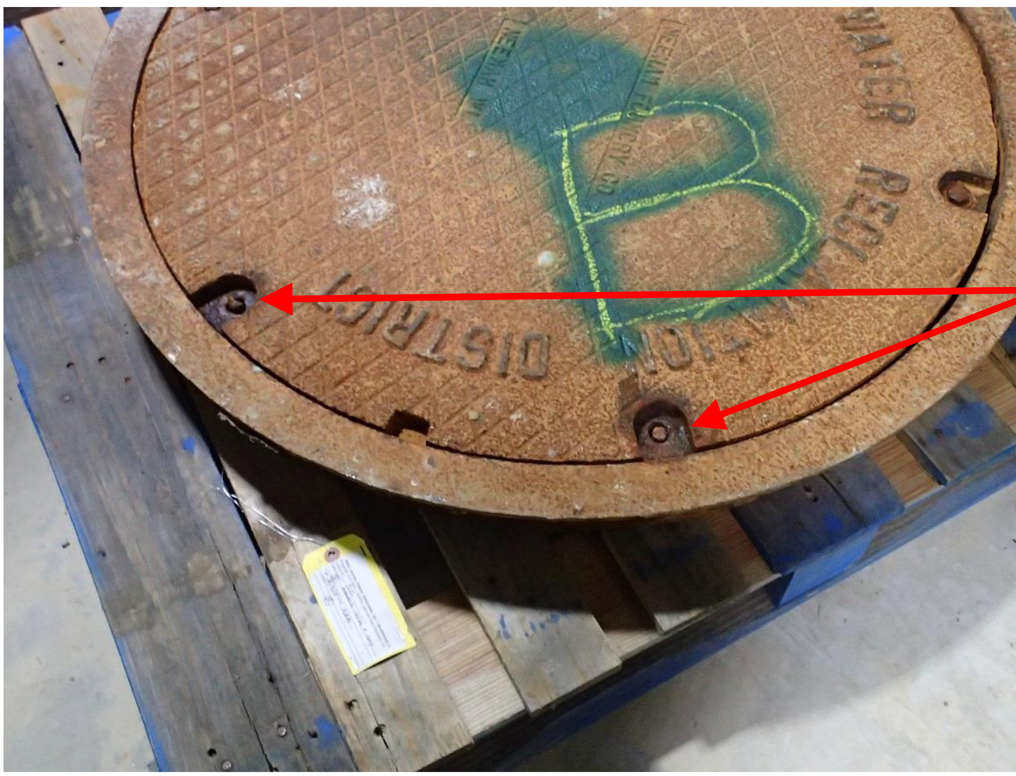


Figure 37. Manhole B with two flame cut bolts

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MATERIALS SCIENTISTS

Appendix A

Evidence List

Appendix A - Evidence List

ITEM #	DESCRIPTION	LOCATION
001	Hammer and chisel	GBT Room
002	Four new 2” valves	GBT Room
003	Proximity switch, manhole A	GBT Room
004	Torch and oxy/acetylene hoses	GBT Room
005	Additional oxy/acetylene hoses	GBT Room
006	Proximity switch, manhole C	GBT Room
007	Helmets, face protector	GBT Room
008	Lockout/tag-out items	GBT Room
009	Three new 2” check valves	GBT Room
010	Hammer	GBT Room
011	Manhole cover and ring – A	GBT Room
012	Manhole cover and ring –B	GBT Room
013	Manhole cover and ring – 10 pieces – C	GBT Room
014	Manhole cover and ring – 4 pieces – D	GBT Room
015	Manhole cover and ring – E	GBT Room
016	Manhole cover and ring – G	GBT Room
017	Helmet	GBT Room
018	Oxy/acetylene tank	Tool Crib Bldg. 29
019	Additional ring piece for manhole C	GBT Room
020	Additional ring piece for manhole C	GBT Room
021	Striker	GBT Room
022	Danger tag	GBT Room
023	Calibration gas for personal monitors, from Central Control	L. Riley Office
024	Calibration gas for personal monitors, from EITM shop	L. Riley Office
025	Calibration gas for personal monitors, from tool crib	L. Riley Office

ENGINEERS
ARCHITECTS
MATERIALS SCIENTISTS

Appendix B

GTI GC Analysis of Sample Head Spaces

Analytical Report

Sample COC #: 182591
October 11, 2018

Prepared for:

Kim Mniszewski
Phone: (630) 655-7180
Fax: (618) 655-7183
Email: kmniszewski@yahoo.com

FX Engineering, Inc.
240 East Ogden Avenue, Suite 10
Hinsdale, IL 60521

P.O. # Credit Card on file

Received Date: October 03, 2018

Disclaimer:

Neither GTI nor any person acting on behalf of GTI assumes any liability with respect to the use of, or for damages resulting from the use of, any information presented in this report.

The results within this report relate only to the items tested.

Submitted by: Karen.Crippen@gastechnology.org (847) 768-0604
Environmental and Chemical Research Services

Technical Contact:

Russell.Bora@gastechnology.org (847) 768-0693

gti. testing laboratories

ACCREDITED
Testing Laboratory
CERT # 2139.01 and 2139.04

Fixed Gas Analysis by Gas Chromatography

Client: FX Engineering
Batch Number: 182591
Date Analyzed: 10/10/2018
Analyst: KD

Sample #	182591-001	182591-002
Description	201827-7 Sludge from Tank	201827-8 Sludge from Tank
Hydrogen	< 0.1 mol %	< 0.1 mol %
Carbon Dioxide	17.8 mol %	21.2 mol %
Oxygen/Argon	2.71 mol %	1.38 mol %
Nitrogen	78.0 mol %	60.7 mol %
Methane	1.49 mol %	16.7 mol %
Carbon Monoxide	< 0.03 mol %	< 0.03 mol %
Hydrogen Sulfide	< 0.1 mol %	< 0.1 mol %

Samples were held at room temperature for 7 days before headspace analysis.

Gas Technology Institute | 1700 S. Mount Prospect Rd. | Des Plaines, IL 60018 | T: 847 768 0500 | F: 847 768 0970 | www.gastechnology.org/gtilabs

Sample COC Report

COC #:	182591	**Todays' Date:**	10/03/2018
Customer:	FX Engineering	**Date Received:**	10/03/2018
Contact:	Kim Mniszewski	**Date Due:**	10/10/2018

Notes: Fixed gas analysis of headspace. Hold for one week at room temperature prior to analysis.

Lab #	Received	Sample ID	Cyl #	Note
182591-001	10/03/18	201827-7 Sludge from Tank		
	Fixed gas			
	Disposal			
182591-002	10/03/18	201827-8 Sludge from Tank		
	Fixed gas			
	Disposal			

FX ENGINEERING, INC.

240 East Ogden Avenue, Suite 10, Hinsdale, Illinois 60521
Ph. 630-655-7180 Fax. 630-655-7183
Cell 630-240-2058 Email: kmniszewski@yahoo.com

EVIDENCE TRANSMITTAL/CHAIN OF CUSTODY FORM

Project No. 201827 Client/claim # MWRD - WJE
Date 10/3/18
Project Name MWRD - GBT Explosion
Location of Loss Chicago, Il

Date of Loss 8/13/18
Date Evidence Taken from Loss Site 9/14 & 20/18

The following artifacts are being transferred to the undersigned recipient.
Purpose of transfer Chemical Analysis
[to be disposed of after]

Evidence #	Qty.	Description
201827-7	1	Sludge sample from tank #2
201827-8	1	Sludge sample from tank #1

Kim R. Mniszewski
Released by (print name):

FX Engineering, Inc
Company

10/3/18
Date

Signature

Karen Crippen
Recipient (print name):

Gas Technology Institute
Company

10/3/2018
Date

Signature

Please email or fax a signed copy of this transmittal back to the sender.