Water Sealing With NOH2O on the Fukushima Site - 17477

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ABSTRACT

The Fukushima Daiichi nuclear site is still recovering from the natural disaster of March 11, 2011. Much of the recent recovery work has been focused on mitigating ground water intrusion into the radioactively contaminated basements of the reactor and turbine buildings of units 1 – 4. Other recovery efforts involve potentially sealing the vent lines in the primary containment vessels of units 1 - 3 to maintain a flooded vessel for core cooling and shielding. This paper details preliminary test results of a proprietary grout – NOH2O™ – in sealing/plugging those vent lines to allow flooding of the primary containment vessel. Several partial and full-scale tests were conducted on primary containment vessel vent line mock-ups between March and October 2015 to ascertain the effectiveness of NOH2O in sealing vent lines that have flowing water, which is problematic for conventional cement-based grouts that require relatively protracted set times. In contrast, NOH2O can be used with a proprietary accelerant to provide instant set. The other key advantage of NOH2O is its ability to penetrate even the smallest of cracks and porous soils, following and moving with the water flow and creating a continuous, impermeable barrier. It is also extremely flexible once set, conforming to its enclosure as upstream water head increases. Finally, the material's extremely high radiation resistance and longevity make it an ideal candidate for a permanent solution in high rad environments.

INTRODUCTION

On March 11, 2011 the Fukushima Daiichi site suffered catastrophic meltdowns on units 1 – 3 from a series of events precipitated by site impact from a tsunami (1). The 3 units utilize a General Electric (GE) Mark I primary containment vessel[1] which has 8 vent lines equally spaced around the PCV central axis. These vent lines connect to branch lines that provide a distribution header within the suppression chamber (SC). To control decay heat in the damaged units, water is pumped into

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[1] This paper assumes the reader is familiar with the Mark I containment system, so design specifics will be kept to a minimum.

the reactor pressure vessel (RPV) continuously. The water leaks from the RPV into the PCV, down thru the vent lines into the distribution header, and finally into the suppression chamber. Leaks in the SC have required cooling water to be supplied continuously to the RPV to maintain core cooling.

Future decommissioning of units 1 – 3 may require flooding of the PCV with water to maintain fuel decay heat removal and provide shielding for eventual remote removal of debris. With unknown leak points in the SC, the vent lines are being investigated for sealing to maintain a flooded PCV. A method has been proposed to seal each vent line at the vent/branch junction of all 8 lines, thus allowing the PCV to be flooded. The method involves remotely inserting an inflatable bag within each line at the junction, inflating and finally filling the bag with conventional (cement based) grout. The resultant "plug" will block off a majority of the vent cross section. However, tests of this method have shown that a complete seal is still not achieved, particularly in one of the vent lines that contains internal obstructions. Therefore, a supplemental seal is required for complete blockage of the vent lines.

Atkins has teamed with Sovereign-Thyssen J.V. (STJV) and IHI Corporation (IHI) to provide a water sealing solution for this application. NOH2O (pronounced "No H2O") is a proprietary grout formulation used extensively in the mining industry. It is a rubber-like material that has demonstrated industrial application for stopping water flow in mine shafts, underground construction tunnels, and agricultural and drinking water storage systems. Its effectiveness for quickly stopping water flow in difficult to access situations is unrivaled. The NOH2O grout material can be injected through engineered penetrations and will surround and fill the injection space, solidifying into a permanent rubber like mass to create a seal.

A comprehensive testing phase was conducted between March and October 2015 to ascertain the effectiveness of NOH2O to seal two representative types of gaps: a "V gap" and a "U gap"; the letters providing a simple visual representation of the gap cross section. These gaps are the result of incomplete sealing between the outer surface of the inflatable bag and inside surface of the vent line. The V-gap is attributable to obstructions in one vent line; the U-gap is the remaining opening in the other seven vent lines.

Background

The goal of establishing a flooded PCV starts with sealing the effluent from the vent lines using an inflatable bag to substantially plug the 2 meter diameter cross section - at the vent/branch junction - and injecting conventional grout inside and upstream of the bag[2]. Currently, water is flowing into the PCV at a rate of ~5 MT/hr, which equates to about 0.7 MT/hr (11 L/min) in each vent line. Once the

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[2] Details of the inflatable bag installation are proprietary to IHI Corporation and are outside the scope of this report. NOH2O installation is the last step in the sealing process.

sealing work is started (on one vent line at a time), the flow rate in unsealed vent lines will increase.

Mock-up tests performed by the International Research Institute for Nuclear Decommissioning (IRID) revealed the need for supplemental sealing to improve reliability of the inflatable bag seal. NOH2O was proposed as a supplemental material to conventional grout for sealing the gaps formed between the inside wall of the vent line and the inflatable bag.

Key advantages of NOH2O for the PCV vent line sealing application at Fukushima include the following:

- **ALARA** – installation of the material by injection is a relatively quick process that can be accomplished with a minimum time of human intervention. One NOH2O seal could be installed in under 2 hours via a remote manipulator.
- **Flexibility** – NOH2O is a rubber like material upon setting. Its flexibility in this regard will naturally resist subsequent tearing or breach by future seismic activity.
- **Adhesiveness** – NOH2O is a very adhesive material and will firmly stick to most material surfaces.
- **Permeability** – prior to setting, the NOH2O ingredients are fluid and permeable in a variety of media.
- **Durability** – Once set, the NOH2O will resist long term degradation by water (either seawater or groundwater).
- **Environmental Safety** – NOH2O is composed of non-toxic materials, and has successfully been tested using the U.S. TCLP protocol for environmental hazard analysis. NOH2O is commonly used for underground agricultural storage units (grain silos) and underground drinking water storage units.
- **Radiation Resistance** – NOH2O has demonstrated its ability to retain all necessary mechanical properties at radiation doses up to 100 MRad.
- **Temperature** – NOH2O in solid form is unaffected by freezing and is routinely used as a supplement to freeze walls for mine shafts.

NOH2O (a.k.a. SCEM66) is an aqueous based colloidal suspension. The material exhibits dilatant behavior and naturally thickens under shear (solidifies). Solid particles within the suspension average 0.6 microns in size, and the suspension has a typical viscosity of 1.5 cP during injection. The setting time for the material can be accelerated to as fast as 2 seconds using an accelerator, Actical 500 (also proprietary to Sovereign). For the PCV vent line application, the Actical 500 was injected simultaneously with the NOH2O grout to assure that unreacted suspension cannot travel very far prior to solidification.

Other typical properties of NOH2O:

- Tensile strength at 100% elongation: ~1.06 MPa
- Specific Gravity: ~0.94
- Elasticity: Up to 350%
- Successfully sealed at water pressure of 20 MPa (2900 psi)
- Demonstrated sealing ability for up to 40 years
- Reaction with activator is not exothermic and non-expanding
- Material is environmentally friendly

DISCUSSION

NOH2O grout is routinely used in the mining industry by injecting directly into the surrounding geology, usually under high pressures of around 14 MPa (2,000 psi). The grout follows the water flows thru cracks and fissures, thickening as it is sheared in these small spaces and creating a seal. In these applications, the shearing effect is usually enough to accelerate the grout set. Accelerants can be used to speed up the set for larger cracks. Conversely, inhibitors[3] may be employed to slow the set, allowing the grout to travel further into the geology. Both accelerants and inhibitors are typically injected before the grout, essentially “pre-conditioning” the entrained water to optimize grout penetration (or seal).

Compare this to the V and U-gaps in the PCV vent line application, which are large open voids orders of magnitude larger. Shear thickening alone is not enough to initiate set and hence, an accelerant is required. With flowing water, the goal is to have the grout set up almost instantly such that it is not simply washed out. Grout and accelerant would need to be injected simultaneously and mixed vigorously to initiate grout set. So the PCV application represents a new use for NOH2O and hence, a robust testing program was necessary.

Methods

The vent lines in the Fukushima Units 1 – 3 GE Mark I containment have an internal diameter of 2,057 mm (6’-9”) as shown in Figure 1. One of the eight vent lines has internal pipes that run along the length at the top. Upon bag inflation, the bag does not make a seal around the interfering pipes, resulting in a “V gap” of approximately 456 mm wide by 292 mm deep, along the bag length. In addition, numerous “wrinkles” in the bag surface around the remaining perimeter also allow water to bypass the bag.

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[3] Inhibitors and accelerants are specific formulations proprietary to Sovereign with chemistry tailored to the required NOH2O application.

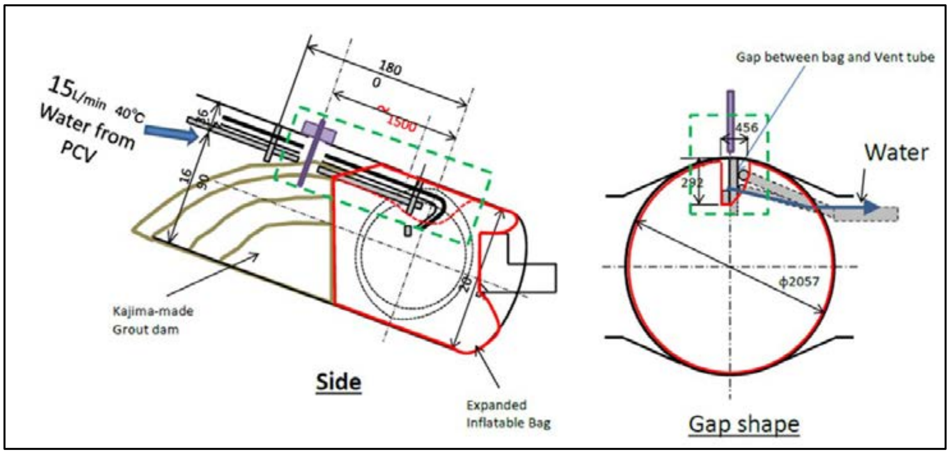

Figure 1 – Vent line at branch intersection; V-gap.

Similar to the V-gap phenomenon, the other seven vent lines (those without internal pipes) have bags installed the same way. In these cases however, settling of the grout inside the bag results in a "U-gap" as shown in Figure 2. The gap measures approximately 1050 mm wide by 50 mm deep, along the bag length. These bags also have wrinkles on the perimeter.

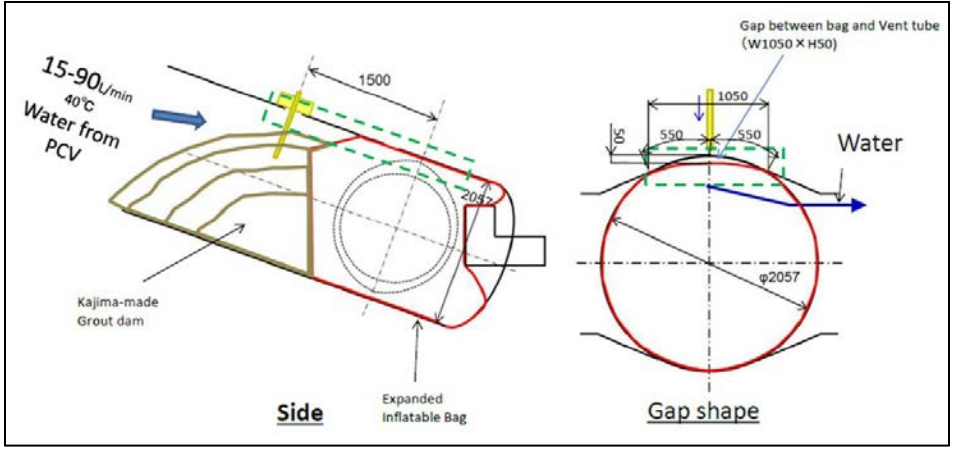

Figure 2 - Vent line at branch intersection; U-gap.

The dashed boxes in Figure 1 and Figure 2 highlight the gap void that remains following installation of the grout dam upstream of the expanded inflatable bag. Each unsealed vent line sees a cooling water flowrate of about 11 L/min. For testing purposes, this lower-end value was conservatively rounded up to 15 L/min. The upper-end value was conservatively rounded up 90 L/min (11 L/min x 8 vent lines = 88 L/min), which is what the last vent line sealed will see. The V-gap vent line will be sealed first - since it is the most challenging – and therefore will only see a flowrate of 15 L/min. Prior testing by Toshiba/Kajima demonstrated that cement based grout was not effective at sealing either the V or U gaps at water flows[4] much less than 11 L/min, hence an alternative material was necessary.

The first step in the NOH2O testing process was to idealize both gaps in mock-up units at partial scale. In actuality, the gaps were full scale and the remaining vent line cross section was reduced to minimize the water pool upstream of the bag. Figure 3 shows the V-gap partial scale mock-up fabricated from polycarbonate sheet. The gap is covered with the inflatable bag material and the small-bore pipes represent the obstructions. The two ports denote two different injection locations for the NOH2O and Actical 500 (both materials being injected simultaneously via the same port). The U-gap partial scale mock-up is shown in Figure 4 with similar construction attributes. Both units can be disassembled for cleaning and reuse.

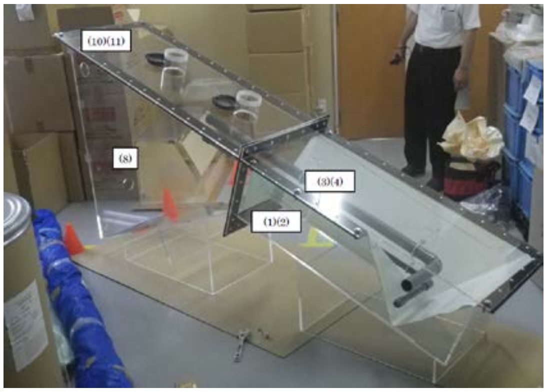

Figure 3 – V Gap partial scale mock-up.

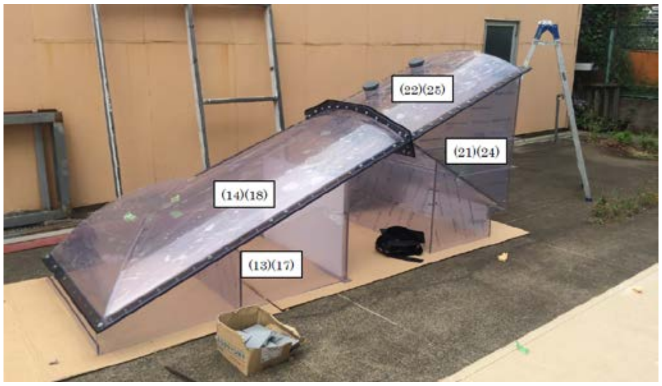

Figure 4 - U Gap partial scale mock-up.

The second step in the NOH2O testing process was to idealize both gaps in a mock-up unit at full scale. Due to the mock-up unit size, one vent line was constructed as

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[4] Cooling water flow must be maintained to the RPV at all times, hence there will always be water flow in the vent lines.

shown in Figure 5 and inserts made to represent the V-gap and U-gaps. In addition, the inflatable bag was idealized by a steel dam covered with the bag material on the upstream side (dam with reinforcement can be seen inside the vent line). The gap inserts were also covered with the bag material.

Figure 5 – Full scale mock-up with V-gap insert installed.

The final step in NOH2O testing is additional full scale tests with an actual bag and upstream grout dam installed. This testing is planned for the future and not included in this report.

Results

A total of 27 tests were conducted during 3 testing campaigns from March – October 2015. A proof-of-principal test campaign was first conducted at an IHI facility in Yokohama, Japan using the V-gap partial scale mock-up. A second campaign of partial scale tests followed on both V and U-gap partial scale mock-ups at the STJV facility in Queens, NY. Finally, a full scale testing campaign was conducted at another IHI facility in Hadano, Japan.

V-Gap Partial Scale Testing in Japan – Campaign 1 of 3

IHI constructed a clear polycarbonate test rig to represent the expected V-gap in a vent line that must be sealed with NOH2O. The test rig was designed such that visual observations of grout formation could be made in real time. In addition to the grout injection port[5], there were nozzles located upstream of the gap entrance for water inlet, drain and upstream overflow. A container was located at the gap exit to capture bypassing water and grout until the seal formed. The unit was inclined 20° to match the vent line. Figure 6 shows the complete V-gap partial scale mockup.

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[5] The first V-gap unit only had one injection port located 750mm upstream of the gap entrance. Subsequent partial scale mock-ups added a second port located 250mm upstream of the gap.

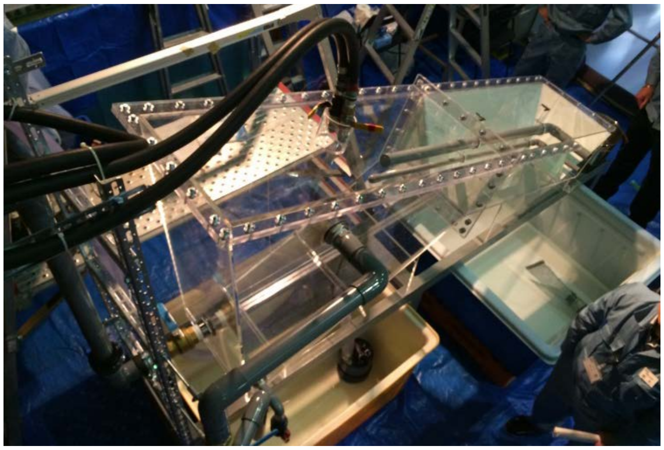

Figure 6 – Partial scale V-gap mock-up used in test campaign 1.

A series of 5 tests were performed in campaign 1. In general, large injection flow rates and alternating injections performed best and were successful at sealing the V-gap. The NOH2O grout and Actical 500 accelerant were injected via separate pipes co-located in the single injection port. Injection pressure was simply from induced head from the product containers positioned above the mock-up and amounted to about 1.2m (4 ft); pumps were not used in this campaign. The method of alternating injections produced a “layered” construction of solidified NOH2O that increased with each successive addition, until the entrance to the gap was sealed. Successful seals were produced in tests 4 & 5 at a water flow rate of 15L/min.

The first 3 tests did not result in successful gap sealing due to limited injection pressure and grout flowrate. Tests 1 & 2 were performed at 90 L/min, which was simply too fast compared to grout delivery and did not allow enough residence time and grout volume in the gap. Changes were made to the injection pipes after each test based on observed mixing patterns. The test 3 configuration resulted in a build-up of grout directly under the pipes that eventually blocked off grout delivery, so a seal was not achieved. Changes were also made to the water source to be more representative of actual flow conditions. The final seal for test 5 is shown in Figure 7. This view is at the vent/branch junction. The upper left of the picture is the gap entrance.

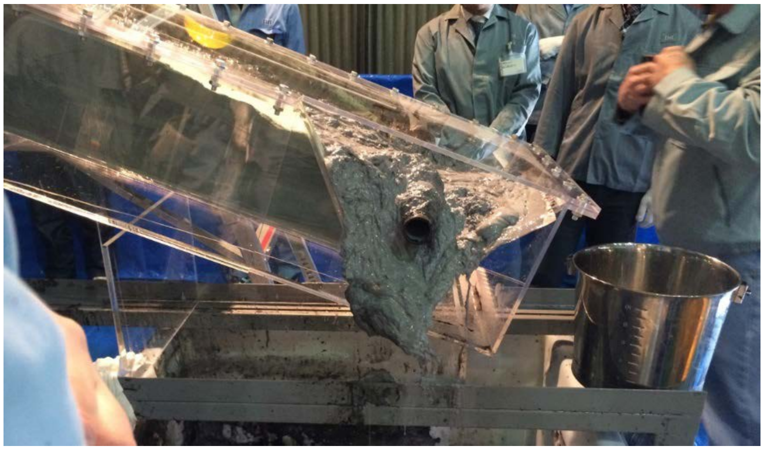

Figure 7 – Grout seal for test 5 of campaign 1.

V and U-Gap Partial Scale Testing in New York – Campaign 2 of 3

A series of 18 tests were performed in campaign 2. The V-gap mock-up was identical to the one used in campaign 1 with the changes made during that campaign (i.e. adding second injection port and modifying water inlet). In addition, a “flooded” V-gap test was added, which had the entire gap cross section full of water (and still flowing at 15 L/min) as opposed to the original “non-flooded” test. A reservoir was added to the mock-up outlet to allow the gap to remain flooded. The U-gap mock-up was introduced in this campaign as well.

During the course of testing, three key parameters were identified as having a significant influence on the ability of NOH2O to seal the gaps. They are as follows:

1. Injection port location – These are the 100mm ID ports located on top of the mock-ups. One is located at 250mm upstream of the gap entrance and a second at 750mm upstream of the gap entrance. During partial-scale testing it was noted that direct-injection into the gap may provide some benefit, so a third port was added 300mm downstream of the gap entrance (i.e. directly over the gap).

2. Pump pressure – Air-operated diaphragm pumps were used in this campaign to enhance grout/accelerant mixing. The discharge pressure range tested was 1.4 bar – 6.9 bar (20psig – 100psig).

3. Nozzle style – The nozzle styles were varied based on observations to produce the most effective spray pattern for grout/accelerant mixing.

Fifteen data obtaining tests were conducted first, which led to selection of each key parameter above as follows:

1. U-gap: 250mm injection port location, 4.1 bar (60 psig) pump discharge pressure and a “pipe in pipe” nozzle. The water flow decreased by about 50%, but a seal was not achieved as seen in Figure 8.

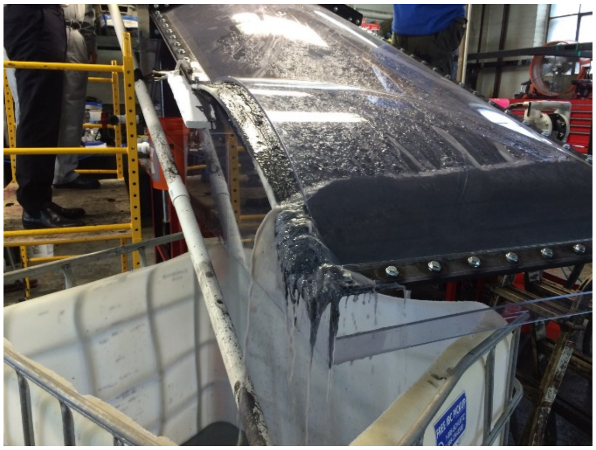

Figure 8 – U-gap results at 250 mm port.

2. V-gap, Non-flooded: -300mm injection port location, 4.1 bar (60 psig) pump discharge pressure and “remote placement” nozzle. The nozzle was actually installed in the 250mm injection port, but the nozzle design had the material being discharged directly under the theoretical location of the -300mm port[6]. The gap was sealed completely, with negligible leakage as shown in Figure 9.

Figure 9 – V-gap results at theoretical -300 mm port.

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[6] Nozzle measurement locations are relative to the gap entrance: positive signifies upstream and negative is downstream (i.e. within the gap area).

3. V-gap, Flooded: -300mm injection port location, 4.1 bar (60 psig) pump discharge pressure and same nozzle as non-flooded. The gap was sealed completely, with negligible leakage as seen in Figure 10.

Figure 10 – Flooded V-gap results at theoretical -300 mm port.

Offline development and water testing was performed to refine the nozzle design to ensure sufficient, aggressive mixing of the grout/accelerant. This design was used in all subsequent tests and is shown in Figure 11. Grout and accelerant enter in the two ports in the left of the picture and both materials exit via the slots shown on the right end. The spray pattern is 360°.

Figure 11 – “Mixer” nozzle design for aggressive mixing of grout/accelerant.

In addition, a third injection port was added to both mock-ups at the -300mm location. Three more tests were conducted with the following results:

1. U-gap: -300mm injection port location, 5.5 bar (80 psig) pump discharge pressure and mixer nozzle. This test used a different ratio Actical to slightly delay the grout solidification reaction, allowing the grout to reach further into

the extreme ends of the gap. The gap was sealed as shown in Figure 12. The new -300 mm port is seen in the upper left.

Figure 12 – U-gap results at -300mm port.

2. V-gap, Non-Flooded[7]: -300mm injection port location, 5.5 bar (80 psig) pump discharge pressure and mixer nozzle. The gap was sealed completely, with negligible leakage as seen in Figure 13.

Figure 13 – V-gap results at -300 mm port.

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[7] The V-gap flooded test was not performed again since the non-flooded application was deemed more critical.

Full Scale Testing in Japan – Campaign 3 of 3

The results of the partial-scale testing were used as the basis for full-scale testing in Japan. In particular, the following parameters were implemented:

1. Injection port location – A nozzle was added to the full-scale mockup unit at 300mm downstream of the gap entrance.

2. Pump pressure – 5.5 bar (80psig) was used for all tests.

3. Nozzle style – The same nozzle style used in partial-scale testing was used, with modifications to adjust the insertion depth to be at its lowest point within the gap (i.e. ~50 mm for U-gap and ~292 mm for V-gap).

Four tests were conducted on the full-scale mockup. The full-scale testing results were as follows:

1. V-gap - The discharge flowrate was stopped in about 1.5 minutes. There was good solids fill in the gap, extending into the branch and a minimal amount extruding into the upstream water pool. As the upstream water level rose, the increased hydrostatic pressure caused leaks. An additional injection of NOH2O and Actical 500 stopped the leakage as seen in Figure 14 and Figure 15.

Figure 14 – V-gap plug as seen from branch.

Figure 15 – V-gap plug as seen from gap entrance.

2. U-gap – The discharge flowrate was stopped in about 5.5 minutes. As the upstream water level rose, the increased hydrostatic pressure caused leaks. An additional injection of NOH2O and Actical 500 stopped the leaks, until the U-gap pan deformed from the pump pressure and grout formation, resulting in premature test stoppage. However, the entire gap was successfully filled with solidified NOH2O as shown in Figure 16 and Figure 17.

Figure 16 - U-gap plug as seen from branch.

Figure 17 - U-gap plug as seen from gap entrance.

CONCLUSIONS

NOH2O has demonstrated its potential for sealing large open voids, which is a new application for this material. With that said, more testing is required to ensure consistent and repeatable results. The injection port location of -300 mm was an important parameter that facilitated continued testing and concentration on other parameters such as pump discharge pressure. Prior to that modification, results varied greatly. Evolution of the nozzle design also had a profound effect on results. Yet more work is required to adapt that nozzle for remote application. Cleaning the mock-up after each test provided additional data on material penetration, homogeneity and validated adhesion to the bag material. The pressure retaining capacity (to withstand the head from a full PCV) still needs investigation.

The testing has also identified other possible water sealing applications on the Fukushima site and elsewhere. More traditional applications of direct injection of NOH2O into soil and other subterranean leak sources may prove beneficial compared to traditional cement-based grouts. The ability to control set time may also offer advantages for remote applications.

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