Degradation of Engineered Plastics in High Chlorine and Temperature Environments

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Abstract

Investigation into instances of blocked residential plumbing has revealed that degraded internal polymer water meter components, specifically Dual Check Valves (DCVs), backflow prevention devices installed at the outlet end of the meters, are the source of the blockage debris. Chemical attack on in-service polymer components results in a deterioration of their mechanical properties and is known to be initiated by chlorine free radicals in the potable water supply, with attack potentially being accelerated by relatively higher ambient temperatures in some regions. This project is looking to investigate the changes in chemical and mechanical properties of the polymer meter components due to in-service degradation, enabling the identification of primary ageing and failure mechanisms. This is being achieved through accelerated ageing of components and complementary laboratory testing to characterise key chemical and mechanical changes. Results from this project will inform Water Corporation's meter management strategy.

1. Introduction

1.1 Project Overview

For most residential properties, Water Corporation uses DN20 (Diameter Nominal 20mm) volumetric flow meters to measure and bill for water consumption. There are over 900,000 DN20 meters installed at properties around Western Australia. The wetted internal parts of any newly installed DN20 meters are manufactured from polymers. These include the DCVs (Dual Check Valves).

A DCV is an assembly consisting of two spring-loaded non-return valves, which are installed at the outlet side of the meter. During normal flow, the pressure differential acting on the check valve piston heads is large enough to compress the springs and keep the valves pushed open. If the pressure differential changes causing the flow to reverse direction, the pistons will be pushed in the opposite direction causing the valves to shut and seal (Standards Australia & Standards New Zealand, 2020a). Figure 1 shows a disassembled DCV from a DN20 meter and its location within the meter assembly.

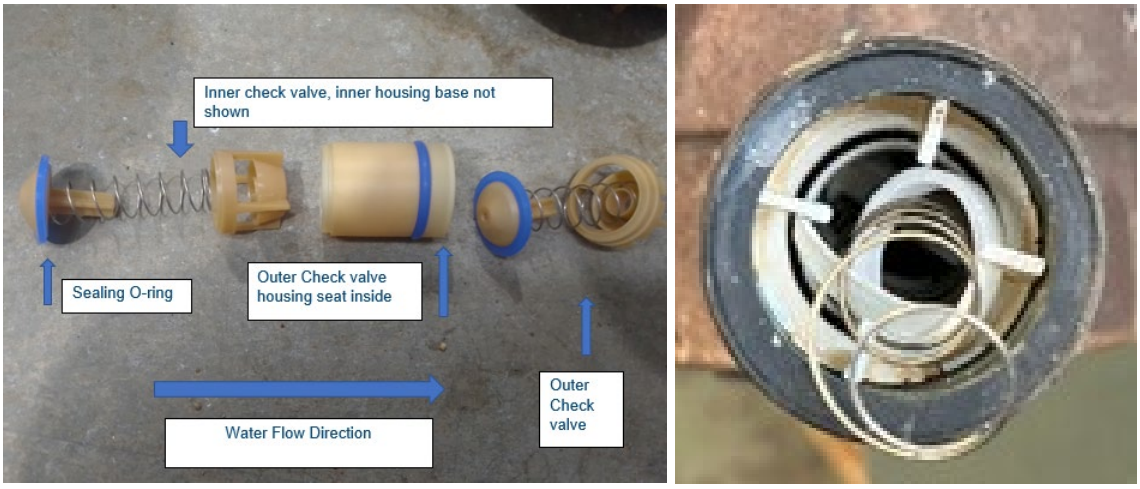

Figure 1 DCV Exploded View Showing both Valves and Housing (Left Image) and Exampled of Failed DCV (Right Image)

One region in WA has seen DCVs disintegrate, flow into, and block customer plumbing. As Water Corporation is responsible for the meters, any costs incurred to clear blockages are paid for by the Corporation. Elevated temperatures in the region in combination with chlorine dosing of potable water in the network are believed to accelerate the rate of chemical attack on polymer components, making them more susceptible to mechanical wear and shortening their service life.

DCVs in failed DN20 meters were previously constructed from Acetal (Polyoxymethylene) thermoplastic. In response to these reports of DCV disintegration and blocked plumbing, all subsequent DN20 meters purchased and installed by Water Corporation are fitted with DCVs made from Noryl (a mix of Polyphenylene Oxide/Ether and Polystyrene), touted by suppliers to be more chlorine-resistant. Although suppliers have suggested Noryl as a suitable, more chlorine-resistant alternative to Acetal, there has not been any investigation conducted by the Water Corporation to confirm the durability to Noryl and what its expected service life actually is. Similar issues with Acetal DCV failures were reported by Power & Water Corporation in the Northern Territory 6-7 years ago, along with a shift from Acetal to Noryl DCVs in their meters, which appear to have rectified the problem.

Understanding the material properties and degradation mechanisms of the DCVs is the key project objective. Accelerated life testing of DCV fitted meters in elevated chlorine and temperature conditions is being conducted, alongside field data analysis and laboratory testing of new and aged samples. The conclusions drawn from data analysis are helping to shape experimental procedure, with experimental results furthering understanding of the performance of meter polymer components and allow recommendations to be made on meter selection and maintenance.

2. Project Methodology

A key component of the literature review is understanding the mechanism of chlorine/free radical attack on polymers, which material properties are affected, and which properties affect the reliability of DCVs in functioning adequately in service. This provided a foundation to design or select appropriate experiments.

Polymers are susceptible to chemical attack via an autocatalytic process known as autooxidation. The most common path for this is a free radical chain reaction where several agents may function as the initiators for this reaction in the environment, including UV radiation, ozone, and other strong oxidising agents like chlorine (White & Turnbull, 1994). To counteract oxidative degradation, additive stabiliser antioxidants can be added to polymers during processing to reduce the degradation rate (Kutz, 2011). The depletion of any antioxidant in either the Acetal or Noryl polymer will be a major factor in the rate of chemical attack and subsequent mechanical weakening of the polymers.

2.1 Laboratory Testing

Laboratory testing to determine chemical and mechanical properties of polymer components will be conducted on new, artificially aged, and field component samples (field samples from the region have been retrieved with the assistance of the Meter Laboratory).

The molecular analysis will include Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectrometry (FTIR) on the samples. DSC determines the oxidation induction time of a sample, revealing its progression in antioxidant stabiliser consumption and hence resistance to oxidative degradation. FTIR will reveal the chemical composition of the samples. FTIR reveals a sample's infrared absorption spectra, identifying carbonyl and functional groups formed on the polymer chain following degradation by autooxidation.

With the DCVs being quite small and not regularly shaped, indentation hardness testing on the sample surfaces will be able to indicate the hardness and brittleness of the polymer material.

2.2 Experimental Setups

Accelerated life testing will be performed on meters with Acetal and Noryl DCVs which will generate aged polymer component samples for laboratory testing. To test for chemical degradation of the polymer components, modifications on an existing flow rig at Water Corporation's Subiaco Innovation Precinct are being finalised. These will enable the rig to connect DN20 meters, enable water temperature control (via an immersion heater in the water basin) and chlorine dosing (hand dosing and monitoring via a sensor in the basin). Flow through the rig and meters will simulate the intermittent flow from turning taps in the home on and off via a solenoid valve that will be programmed to periodically stop and allow flow through the system.

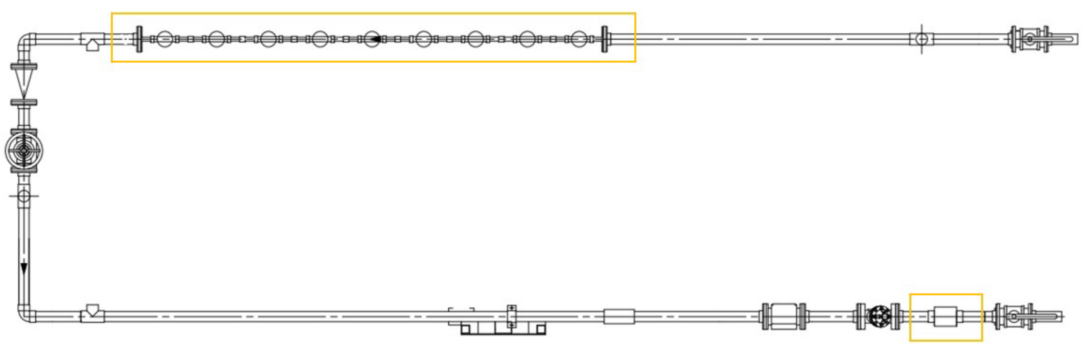

Figure 2 CAD Drawing of Accelerated Ageing Rig (Installed Meters and Solenoid Valve Highlighted)

Obtaining samples in different stages of degradation will be key in assessing progression of chemical and mechanical changes over time. Nine new meters will initially be installed in series on the rig with the experiment run for 9 weeks, one meter will be replaced weekly with a new meter for the first 8 weeks. Laboratory testing may be performed on the samples that are removed with the replacements remaining until the end of the final week. At the end of the ninth week, two sets of samples aged 1 to 8 weeks will have been obtained. Multiple trials will be run on meters fitted with Acetal and Noryl DCVs.

Results from experimental and laboratory tests will reveal the initial properties of the Acetal and Noryl DCVs, and will be able to show the onset and initial progression of any degradation in the samples. These results may then be extrapolated to predict the samples' conditions past the duration of the experimental runs. Laboratory test results of failed field DCV samples can be compared to results from the new and artificially aged samples to determine the threshold of degradation, and thus time in service, that will likely result in DCV failures.

In addition to laboratory testing and accelerated ageing, a standalone experiment will be conducted to observe flow through individual DCVs. This may provide additional insight into their mechanical operation and potential wear mechanisms. As the DCVs are enclosed within opaque brass meter bodies, fitting a single DCV fitted into a clear, flexible tube will allow flow behaviour to be easily observed (Figure 3). Once fitted into the pipe, this sample may be simply connected to a hose. A more formal setup, fitting the DCV into a clear acrylic tube, may be employed if further investigation is required. A partial depression of the DCV piston spring because of high spring stiffness or misalignment would partially obstruct flow and induce increased fluid velocities, further promoting mechanical wear and possibly inducing cavitation.

Figure 3 DCV in Clear Pipe with Tap to Control Flow

3. Preliminary Results

All DN20 meters are disposed of through the meter laboratory when they fail or reach end of life. As meters are replaced as they fail in the field, and often for reasons other than DCV failure, DCV failures are not easily tracked and may have worn out/broken and no longer provide backflow protection long before the meters they are installed in fail. Inspection of a sample of 186 meters from the region in scrap bins show a majority with missing/worn DCVs whose status have not been recorded in the work order system.

In order to analyse failures in the field, the state of the DCVs from a batch of failed meters from the region have been catalogued along with those from another region as a control. Besides temperature and chlorine levels that are known to affect the rate of chemical attack, network water pressure has been identified as a relevant parameter, potentially affecting the force on the DCVs as they shut and accelerating mechanical wear. Spatial mapping of the location of meter replacements and the visual state of each DCV in both datasets with regards to the three variables is being conducted to determine a relationship between these and DCV state.

The free chlorine concentration in potable water is kept within the 0.5-2ppm range as per Water Corporation standards to ensure sufficient disinfection without being unpleasant or harmful for human consumption. To determine the chlorine and temperature levels for accelerated ageing,water quality and metrological data starting from the 1st of January 2021 was collated. This revealed chlorine levels in the region were always within the acceptable range range, as show in Table 1 below. Increasing the free chlorine concentration for the accelerated ageing test would provide a quicker and more vigorous onset of chemical attack, allowing a better characterisation from the laboratory testing. Metrological data from the region showed maximum water temperatures in the mid thirties degrees celsius. These temperatures are however not measured at the meter locations on properties where they may be above ground and exposed to much higher temperatures during warmer months. A similar decision to increase the experimental temperature setpoint to at least 40 degrees will prove useful in providing further accelerated ageing during experimental runs.

Average Level (ppm)	**Max Level (ppm)**	**Min Level (ppm)**
1.11	1.32	0.76

Table 1 Free Chlorine Levels from 01/01/2021

The accelerated ageing experimental rig will be able to circulate temperature-controlled, chlorinated water through 9 meters connected in series as shown in Figure 2. Another component of this experimental setup is the simulation of intermittent flow as would be seen in the home with faucets being open and shut. Based on H_2ome study by Water Corporation which is looking into residential water consumption, average flowrates are just over 0.1L/s with maximum flowrates coming from irrigation systems at around 0.6L/s. After accounting for the additional pipe and fitting losses from the modifications, the current pumps available to attach to the rig will be able to provide close to the 0.6L/s max flowrate that will be made intermittent via the installed solenoid valve connected to a programmable logic controller. Flow may be varied if deemed necessary by throttling the globe valve that sits close to the outlet end of the rig.

4. Conclusions and Future Work

It was found that DCV failures are not well logged in the work orders, likely as they are part of the meter assembly and not always the primary reason for meter replacement. Laboratory testing is currently proceeding in parallel with the final assembly of the accelerated ageing rig. Through these steps, the project will be able to confirm if oxidative attack is indeed the primary mode of chemical attack, and also the rate and mechanism through which any antioxidants are being consumed.

Once the results of the experimental runs and laboratory testing from this project are completed, further work could include further fine-tuning of experimental test parameters and more detailed examination of the DCV components to determine exact mechanical and mechanochemical failure mechanisms. Finally, DCV construction varies subtly between meter brands. Once wear and failure mechanisms for the DCVs in DN20 meters currently employed by the Corporation are better understood, further work into the behaviour of other DCV designs from other suppliers to detrmine the more optimal design could make for an interesting study.

5. Acknowledgements

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