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Forensic Engineering Analysis of Toilet Connector Failures in a Class-Action Lawsuit

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Abstract

A major manufacturer of water supply lines that connect flushable toilets to house water piping was the object of a class-action lawsuit. The author examined a large number of failed and exemplar connectors, complete fill lines, and similar injection-molded products as well as visited failure sites with the goal of ascertaining the root cause of the failures. Forensic work included strength tests and finite element analyses to determine the expected life of the nuts, including single overload failure strength and creep analysis to predict life. Tightening tests using random subjects were conducted. A statistical analysis of the failures was also performed. The products of competing manufacturers were evaluated for comparison of similar designs. After much investigation and analysis, it was concluded that the design of the connector was not defective and met relevant industry standards.

Keywords

Forensic, plastic connector, finite element, creep, class action, water leak, water damage

Introduction

The author was retained to investigate the cause of failure in acetal ballcock coupling nuts used to attach the water supply line to the tank of a standard home toilet tank. Failure of the supply line connector can result in considerable water damage to homes and offices. Several incidents cited in the lawsuit involved failure of the connector while the owner/occupant was away for several days. Damage caused by water leakage can run into the hundreds of thousands of dollars in extreme cases.

The ballcock coupling nut, hereinafter referred to as the "nut" for brevity, is a component of a supply line manufactured and sold in the United States. Work performed to prepare an expert report for this case included many different tests and analyses to determine the cause of failure and expected life of the nuts (if used properly). A list of tasks undertaken to resolve this matter is provided below. The action taken for each task is discussed in this paper.

To qualify for a class-action lawsuit, the class must consist of a group of individuals or business entities that have suffered a common injury or injuries. Class-action matters typically result from an action on the part of a business or a particular product defect/policy that applied to all class members in a typical manner. The plaintiff must show that there is an underlying root cause common to all of the failures. Thus, to defend a class-action, one legal strategy is to show that there is no common root cause of such failures. For example, if failures in Texas are caused by chemicals in the water that are only found in a particular location, then they may be excluded from the class. Alternatively, if it can be shown that failures are caused by damage resulting from abuse, then there is no demonstrable product defect. By showing that failures have multiple causes and are not related, the evidence would suggest no common root cause. Of course, any necessary warnings and instructions regarding installation and proper use/care must be considered and may influence the outcome of the cases. Further, the product design can be defended by showing that all relevant codes and standards are met, that the materials used are suitable for the application and of sufficient quality, and that the manufacturer of the parts meets or exceeds industry standards. Finally, the design can be compared to similar products and other competitive products in the marketplace and shown to be of equal or superior design and quality.

Scope of Work

The following tasks were performed in this matter.

- Inspection of sites where failures occurred.
- Examination and characterization of nuts from failure claims.
- Examination and characterization of nuts from different production sources of the manufacturer.

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- Examination and characterization of similar products and competitors.
- Sectioning of nuts from various sources to determine the details of thread geometry.
- Creating RTV silicone rubber molds of the internal features of the nuts and characterization of thread details. (RTV is the abbreviation for room temperate vulcanization, i.e., the rubber “cures” at room temperature. The two-part silicone rubber material can be easily cast into a void. It hardens quickly, has little shrinkage, and does not adhere to most surfaces.)
- Statistical analysis of failure data.
- Material characterization to determine strength and creep rate.
- Human factors testing to determine “hand tight” torque.
- Torque-to-failure tests for several different nut geometries.
- Torque vs. rotation angle tests.
- Finite element analyses to determine one-time overload failure.
- Finite element analyses, including creep and time-dependent effects to determine the expected life of nuts in service.

Failures Observed

Figure 1 shows several typical “failed” nuts that were provided to the author for evaluation. Failure typically occurs in the first thread of the injection-molded plastic coupling (nut).

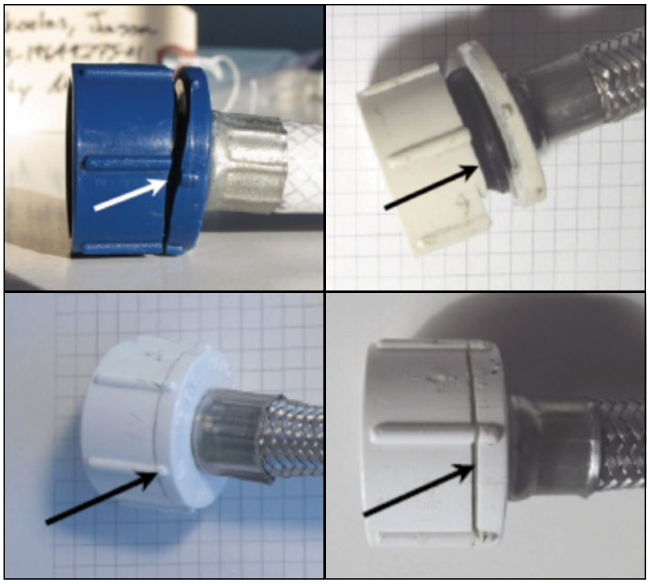


Figure 1
Failed coupling nuts.

Figure 2 is a photograph of a cross-sectioned nut showing the rubber cone washer and the end of the copper tube that form the water seal.

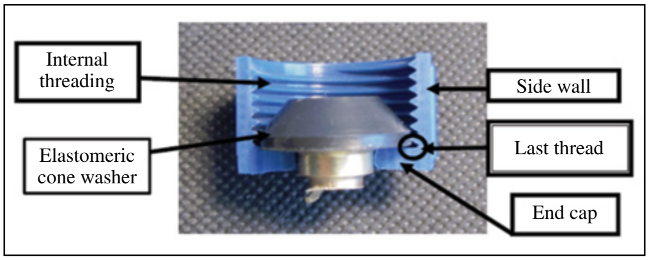


Figure 2
Cross-section of nut assembly.

Figure 3 is a photograph of a nut assembly that has been potted in a metallurgical laboratory, cut into halves, and polished. This nut fractured at the first thread.

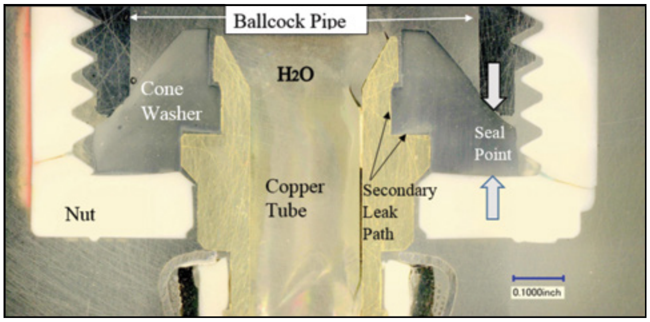


Figure 3
Cross-sectioned failed connector nut assembly.

How It Works

The connector nut is an injection-molded part that connects the supply line to the threaded ballcock pipe. The supply line terminates with a metal fitting that is swaged onto the supply line. The toilet nut has an internal thread to mate with the external ballcock pipe. A cone washer is stretched over the brass tube. This cone washer seals between the ballcock pipe and the nut by pinching the rubber cone washer.

If sufficient force is applied to this “seal point,” then water will not leak through the connector. This force can easily be generated by hand tightening the nut. However, there is another possible leak path, as shown in **Figure 3** (denoted as a secondary leak path). If the cone washer inner diameter is not pressed against the brass fitting at the inside radius of the cone washer with sufficient force, water will leak through along this path. If water begins to leak at the inner radius of the cone washer, water can drip out through the annular space between the hole in the nut and the outside of the brass fitting. Typical city water pressures range from a low of about 50 psi to over 100 psi. The cone washer is a rubber-like material (elastomer) with a Shore durometer hardness of approximately 70A. If water is leaking through the secondary leak path, then tightening the nut will not stop the leak.

Water-tight seals are typically provided in hydraulic equipment in two basic ways. The first is to apply sufficient force over a relatively small area such that the mating parts are tightly compressed together, removing all leakage paths. This is the mechanism employed at the ballcock. The second method is the "self-energizing" seal, such as an O-ring. This seal is affected by the pressure as it forces the sealing material against the sealing surface. The secondary leak path is sealed by the water pressure, forcing the rubber cone washer against the metal post. As previously mentioned, tightening the nut will not stop a leak along the secondary path.

What the Opposition Claimed

The counsel for the plaintiff claimed that the design of the nut was defective because the threads inside the nut formed a stress riser at the critical stress location, causing the nut to fracture when tightened. The sketch shown in **Figure 4** was produced by the plaintiff expert and was purported to accurately represent the nut design. Their expert cited plastic molding design guides that recommended against sharp corners and threads that end without tapering or rounding as design flaws.

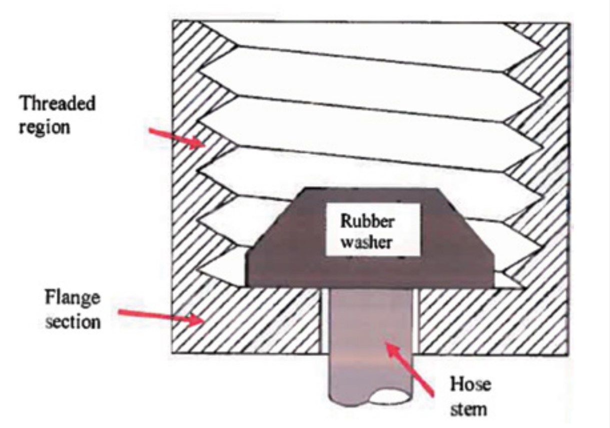


Figure 4
Schematic used by plaintiff to characterize nut.

The actual design, as shown in **Figure 5**, clearly incorporates local radii and a tapered or "feathered" thread termination. However, it is difficult to visualize internal threads even when a cross-section is used. A more visually effective technique was developed by using silicone RTV rubber to make a mold of the inside of the connector. As can be seen from **Figure 5**, the cast rubber replica provides a three-dimensional model of the thread profile. The RTV rubber castings provide a fast method of capturing and comparing thread profiles.

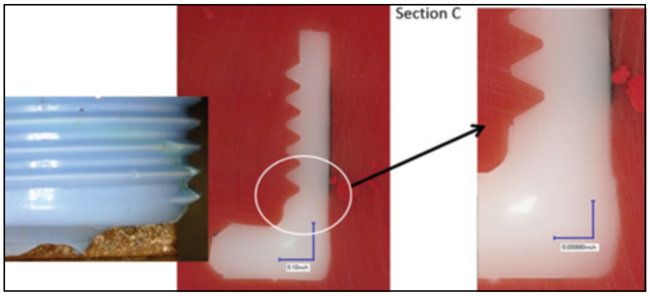


Figure 5
Cross-section of nut and RTV casting.

The plaintiff's accusation of "sharp corners" is clearly blunted by looking at the actual geometry. The next step in proving that there was not a design flaw is to show that the nut design (including the thread geometry) is capable of performing its intended service. The manufacturer testified that the design life of the connector is seven to 10 years (however, this information was not clearly conveyed to the customer). The nut is designed to seal with "hand tight only" torque. The "hand tight" instruction is imprinted on the nut during the injection molding process. The first question that comes to mind when attempting to analyze the loads on the nut is: "How tight is hand tight?"

Hand Tight Tests

A series of tests was conducted by an independent laboratory to attempt to ascertain the answer to this seemingly subjective question. The full extent and scope of the tests are too complex to describe in detail, and could probably serve as the basis of another paper. The tests used both registered plumbers and typical homeowners (picked at random) to tighten the nut. A complete bathroom environment was simulated, including toilet, lavatory, and walls that limited access similar to typical home bathroom installations. Thus, the test subjects functioned in approximately the same position as a typical toilet connector installer. Special torque measuring instrumentation was developed that was hidden in the toilet water reservoir. Tests were conducted using both the dominant and non-dominant hands. Subjects included both men and women. Test instructions were vetted such that the subjects were not aware of the purpose of the tests. Both "subject best estimate" of hand tight and "maximum possible" hand tight torques were measured. The data were evaluated statistically, and mean and standard deviations values were calculated. These values were then used to determine a representative range of loading values in the finite element analyses.

Material Properties

Before finite element analysis can be performed, the properties of the material must be determined to a high degree of engineering accuracy. Because the failure of toilet nuts appears to be time dependent, it is necessary to not only know the short-term yield and ultimate strength of the material, but also the time-dependent (creep) properties. A series of creep tests was conducted by yet another laboratory. Tensile "dog bone" specimens were molded and tested in specially designed equipment to determine the creep strain as a function of load (and thus stress). Both notched and un-notched specimens were tested. Because the times to failure for actual nuts (even with high loading) is typically years, the tests were conducted in an elevated temperature environment to accelerate the creep strain. The data were used to determine an analytical creep/relaxation curve for the nut material that could be used in the FEA analyses. Additional tests were conducted using exemplar nuts to obtain one-time overload fractures. The details of these proprietary tests are too voluminous to include in this paper, but suffice it to say that the tests produced creep curves for the material and one-time overload fracture values that were considered sufficiently rigorous in procedure and accurate for use in the finite element analyses.

Finite Element Analyses

Knowing both the material properties of the acetal plastic and a defensible range of loading torques that covered the expected loading conditions, a series of finite element analyses was conducted to estimate the time to failure. Several different FEA analyses were conducted to determine the life of connectors subjected to various loads. The torque tests described earlier were used to determine the most likely "hand tight" loads. The torques found from the tests were converted to equivalent force on the connector bottom. The effect of water pressure was added to the torque loads to account for the additional end load caused by the supply line water pressure.

The finite element models shown in **Figure 6** were developed to calculate stress and strain distributions in the nut for various loading conditions. There were four different geometries sold by the manufacturer, and FEA models of each were developed and analyzed. The applied loads (torque values due to tightening the nut) for each were different due to the external geometries. Some of the connectors had "wings," (i.e., protruding grips that facilitated the user hand-tightening the nuts) while others had only small "bars" that gave the user less leverage for applying torque when tightening the nut. The thread geometries for each type were also different.

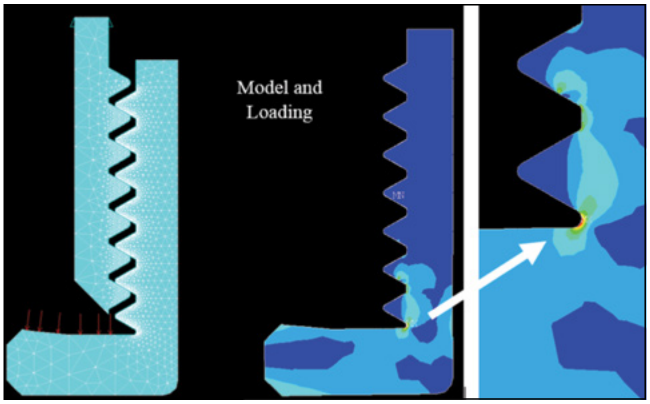


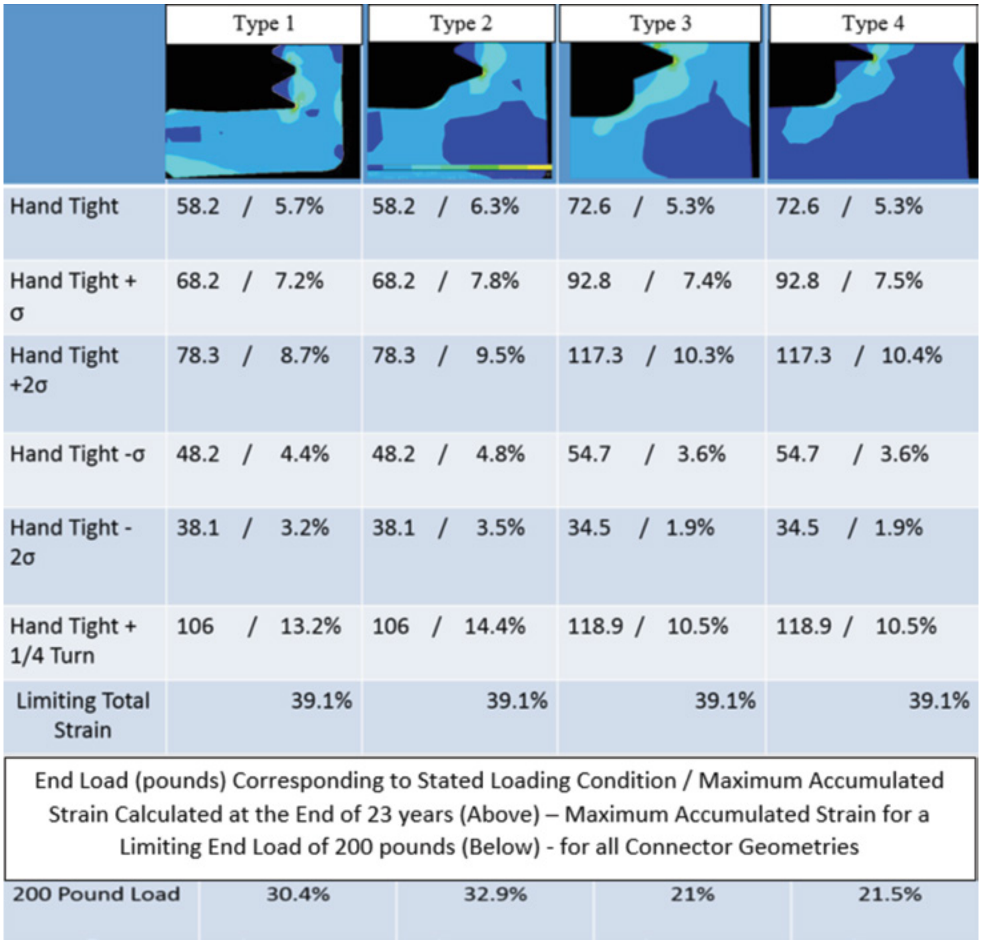
Figure 6
Finite element model of nut.

The first FEA analyses were conducted to determine if one-time overload failures, which were known from test results, could be calculated using the FEA analysis procedure. The one-time overload FEA models were run using an elastic-plastic material model (no creep because of the short time to failure). Test data from the tensile specimens indicated that the fracture strain for the tensile specimens was approximately 39%. The failure criteria for the FEA models were based on the assumption that fracture will begin when the peak strain (anywhere in the nut) reaches the fracture strain for the tensile specimen (i.e., 39%). The one-time overload analyses involved gradually increasing the applied load on the end cap until the nut failed. The analysis attempted to simulate the one-time overload tests.

The one-time overload FEA results correlated well with test data. The FEA-calculated peak strains occurred at the point of crack initiation. Because both the location of the failure as well as the load to cause failure were correctly predicted, this provided confidence that limiting total strain to 39% was a reasonable predictor of failure.

Having proven that the FEA was capable of predicting short-term failures of the nuts, the next step was to model the long-term behavior. Because most, if not all, of the reported failures occurred when the homes were unattended (when presumably there was no external loading), it was concluded that the mode of failure was due to time-dependent material effects. Creep is known to occur in plastic parts that are subjected to relatively high stress levels. The creep data obtained from the tests described earlier were converted to creep strain rate material properties. It was assumed that the nuts remained at room temperature for the entire life of the component. This simplified the creep analysis because most analyses involve both stress level and temperature variations over time.

The analysis procedure used to model creep was to apply an end load on the nut that was equivalent to the sum of the torque load and internal pressure loadings. The load was held constant for the duration of the analysis. The creep analyses were run to simulate a total of 200,000 hours (approximately 23 years). The maximum strain in the nut was monitored. When the strain reached 39%, it was assumed that the nut would fail. **Figure 7** provides the results for these analyses. The different nut geometries are shown as Type 1 through 4. The plots show the last thread before the end cap. The first column provides the load applied and the resulting strain after 23 years at that load. For example, column 1, row 1 represents a load of 58.2 pounds, which is the equivalent end load for a hand-tightened nut plus water pressure. The 5.7% is the total strain at the worst-case location at the end of 23 years. The failure strain is 39.1%, as shown in the seventh row down. The second row is the load for hand tight plus one sigma standard deviation. This load results in a maximum strain of 7.2% at the end of 23 years. As can be seen from **Figure 7**, none of the connectors failed under the applied loads in the 23-year time frame. Type 2 exhibited the greatest accumulated strain. The last row shows runs made to determine the expected life of a nut loaded well beyond the expected worst-case loading. For a 200-pound end load, the Type 2 nut shows an accumulated strain of 32.9% at the end of 23 years.



	Type 1	Type 2	Type 3	Type 4
Hand Tight	58.2 / 5.7%	58.2 / 6.3%	72.6 / 5.3%	72.6 / 5.3%
Hand Tight + σ	68.2 / 7.2%	68.2 / 7.8%	92.8 / 7.4%	92.8 / 7.5%
Hand Tight +2σ	78.3 / 8.7%	78.3 / 9.5%	117.3 / 10.3%	117.3 / 10.4%
Hand Tight -σ	48.2 / 4.4%	48.2 / 4.8%	54.7 / 3.6%	54.7 / 3.6%
Hand Tight - 2σ	38.1 / 3.2%	38.1 / 3.5%	34.5 / 1.9%	34.5 / 1.9%
Hand Tight + 1/4 Turn	106 / 13.2%	106 / 14.4%	118.9 / 10.5%	118.9 / 10.5%
Limiting Total Strain	39.1%	39.1%	39.1%	39.1%
End Load (pounds) Corresponding to Stated Loading Condition / Maximum Accumulated Strain Calculated at the End of 23 years (Above) – Maximum Accumulated Strain for a Limiting End Load of 200 pounds (Below) - for all Connector Geometries				
200 Pound Load	30.4%	32.9%	21%	21.5%

Figure 7
Maximum strains for various loading conditions.

Thus, the FEA analyses indicate that the nuts should not fail over the seven- to 10-year expected life of the nuts. This begs the question: "Why did the nuts fail?"

First, it is instructive to determine the frequency of failure. No matter how rigorous quality assurance requirements are, there will always be some components that are outliers on the normal distribution curve. A statistical analysis was performed by a consultant retained by the defense. Her analysis, based upon the total number of connectors sold by the manufacturer, indicated that the probability of a reported claim for a seven-year-old connector is three to four connectors for every 100,000 sold. Because the expected life of the connector is seven to 10 years (per the manufacturer), the statistics consultant opined that this failure rate was among the lowest of any consumer product. Clearly, there will be some failures when so-called consumer products are sold in the volume (more than 40,000,000 over a nine-year period) involved in this case. Based on the statistical analysis, the failure rate is exceedingly small. Therefore, it is highly unlikely that a single "root cause" can be identified. A root cause would imply that a defect was present, either in the design or manufacture of a product, which was responsible for a rash of failures. Further, in a class-action matter, the plaintiff typically must show that a large number of people have been injured by the same defendant in the same way. Certainly, it is difficult to imagine that such a low failure rate could rise to the level of a systemic failure of a consumer product — and that the failure mode was the same in all cases.

Having shown that the rate of failure was exceedingly small, what could cause these "random" failures? The most likely cause is overtightening the nut. Despite the fact that the plastic nut has "hand tight only" embossed on it via the molding process, it is clear that most of the nuts were tightened using a tool. **Figure 8** is a photograph of a failed nut that has tool marks on the outside surface. Most of the nuts examined by this author had indications that a tool was used to tighten the plastic nut onto the ballcock threads. It is also possible to use channel lock pliers or similar tools to grip the nut while using a rag to protect the nut from being scratched or gouged.

Figure 8
Failed nut showing distress marks from tool used to tighten the nut.

Why overtighten the nut? One reason they may be overtightened is when an old connector develops a leak, or when it is removed and reinstalled. When compressed for years under high stresses, the rubber washer takes a "set." Permanent deformation of the cone washer can be observed when the nut is removed. When this occurs, the cone washer should be replaced. The rubber has hardened. If the initial seal is disturbed, it will no longer conform exactly to the surfaces to be sealed (see **Figure 3** for the seal points). In addition, chemicals in the water can cause deterioration of the rubber, resulting in surface cracking. When the nut is removed and then reused, the sealing surfaces may no longer "match up," and leak paths are formed. When water pressure is applied to the line, these small leak paths allow water to drip out of the connector. Instead of replacing it, the homeowner (or plumber) may use a tool to tighten the nut until the leak stops. This "brute force" fix overstresses the nut and accelerates creep at the highly stressed areas of the nut, particularly at the threads. If the leak returns later, more tightening of the nut is done, and eventually the nut will fail.

It is also interesting to observe that some of the experts for the plaintiff apparently did not understand how the nut seals against leakage.

As shown in **Figure 3**, there are two distinctly different leak paths in the nut assembly. The first seal is affected at the end of the threaded ballcock pipe and the cone washer. This seal point is at the top of the rubber cone washer. The seal is caused by forcing the end of the ballcock thread against the washer by torquing the nut. This seal requires only a low torque that can be applied by hand. The second possible leak path is at the inside of the cone washer. This seal is affected by the force of the water pressure pushing the cone washer against the copper tube. Tightening the nut will not stop a leak through this path. **Figure 9** shows a cone washer taken from a failed nut. Note the calcium deposits on the inside and bottom surface of the cone washer. This indicates that leakage had occurred for quite some time through this secondary leak path. The user apparently continued to tighten the nut, hoping to stop the leak and finally caused the nut to fail.

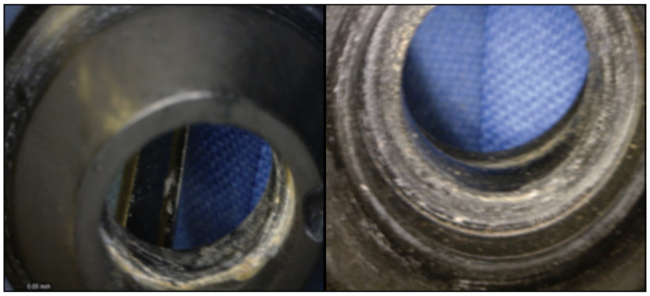


Figure 9
Inside and bottom of cone washer showing water deposits, indicating leakage.

Summary

This paper describes a number of tests and analyses that were performed in the course of defending against a plaintiff class-action suit. The injection-molded plastic connector nuts were failing in a time-dependent manner characterized by creep rupture of the plastic at or near the last thread. The plaintiff experts opined that the cause of the failures was a design defect resulting from a sharp thread configuration ending at or near the bottom of the connector. The potential liability to the manufacturer was in the hundreds of millions of dollars.

In order to investigate these claims, the experts retained by the defense attorneys performed a number of tests and analyses described herein. Material property testing was performed to determine the long-term creep properties of the plastic. Exemplar nuts were tested using an increased temperature environment to simulate longer term creep room temperature response. Test specimens were likewise tested to obtain the time-dependent creep properties of the material. The definition of “hand tight” was developed by another facility using more than 50 subjects selected at random. Some of the subjects were licensed plumbers; some were “typical” homeowners. These tests provided a range of torques and were sufficient in number to provide a statistically meaningful result, including mean, max, min, and standard deviation.

Having the material properties and a good approximation of the loading, detailed elastic-plastic-creep analyses were performed using two different commercially available finite element programs. The analyses confirmed the test data for short-term failure and provided an estimate of the expected life of the nuts. A statistical analysis of the failures was done that showed the failure rate is extremely low. It was shown that the nuts exceed the design life and that no defect in either the design or manufacturing was present. The matter was settled out of court.