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NON-DESTRUCTIVE TESTING METHODS FOR EXAMINATION OF FAILED PLASTIC PARTS

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Abstract

The purpose of this paper is to introduce unique non-destructive examination and testing techniques that can specifically identify failure modes in plastic parts while conforming to the current ASTM standard E860-07 titled "Standard Practice for Examining and Testing Items that are or may Become Involved in Litigation"

Examples of common failed plastic parts include reverse osmosis canisters, water supply line compression nuts and various components of toilet ball cock assemblies.

Non-destructive examination techniques incorporate the use of a variety of lighting methods, as well as X-ray and CAT scan imaging. This paper will illustrate how these techniques can be used to determine failure modes and validate forensic engineering conclusions.

Models, illustrations and Finite Element Analysis (FEA) results will be included in both the paper and presentation.

Introduction

As Forensic Engineers we are often requested by attorneys and insurance companies to conduct forensic analysis on failed parts. Due to the nature of our cases, and the scrutiny of litigation, our work is performed in strict compliance with a multitude of nationally recognized standards. The most pertinent standard to our testing and examination is ASTM E860-07, which addresses non-destructive and destructive testing as follows:

ASTM E860-07:

1.1 – This practice sets forth guidelines for examination and testing of actual items or systems (hereinafter termed evidence) that may have been involved in a specific incident that are or may be reasonably expected to be the subject of civil or criminal litigation. This practice is intended to be applicable when it is determined that examination or testing of evidence is required, and such examination is likely to change the nature, state or condition of the evidence.

5.2 – It is recognized that certain characteristics cannot be determined without destructive testing. Non-destructive tests and examinations should be carried out prior to any destructive testing, and destructive testing should be kept to a minimum, and thoroughly documented. If exemplars can be used instead of the subject items, then exemplars can be used to minimize consumption of the subject item. If proposed tests, examination, or other actions are likely to alter the nature, state, or condition of the evidence so as to preclude or limit additional examination or resting, the person, firm, or agency planning to perform the proposed action should take the following steps:

5.2.1 – Notify its client that the proposed action is likely to alter the nature, state, or condition of the evidence so as to preclude or limit additional examination or testing of the evidence

5.2.2 – Recommend that its client notify other interested parties of the proposed action described in 5.2.

5.2.3 – Recommend to its client that other interested parties should be given the opportunity to participate in the procedures described in 5.2 or to witness and record any such actions (1).

Non-destructive examination is defined as a quality control method that does not damage or destroy the material or product being examined. These techniques can be used to detect abnormalities in physical, chemical or electrical characteristics.

Typically, all parties involved are given the opportunity to conduct their own non-destructive examination of the part in question. If the case cannot be resolved based on these results, destructive examination and testing may be requested.

Non-destructive techniques. Visual examination (macro and microscopic techniques), lighting, X-ray/CAT Scan imaging, mechanical design evaluation (including finite element analysis, FEA), weight/mass evaluation, dimensional analysis, resistance characteristics testing, vibration analysis, ground penetrating radar, magnetic crack detection, ultrasonic imaging, and gamma radiography, are the most predominant non-destructive methods currently in use.

The general methodology followed in examining a failed part begins with an initial visual inspection. This is done to determine what types of further examination/testing might be required. Typical subsequent examination techniques include, but are not limited to, microscopic examination, usually in conjunction with a variety of lighting techniques, and/or X-ray/CAT Scan imaging.

In order to evaluate the failure of a plastic component, it is important to understand what types of forces and stresses may have been experienced throughout the life of the part. It is vital to determine both the magnitude and type of each force acting on the part, as well as the effect of various stress risers.

Due to the nature of plastics, and the applications in which they are used, there are three modes of failure that encompass the majority of cases; *yielding*, *fatigue*, and *creep* (rupture). For specific definitions, reference nomenclature section.

Nomenclature

Acetal – Acetal is a high strength, low friction engineering plastic that has excellent material properties in both wet and dry environments.

Exemplar – Component/system that is similar to the component/system being analyzed.

Failure – An undesirable event or condition

Subject – Refers to a component/system that is directly involved in the matter being investigated

Stress – The amount of an applied load experienced by a given area. Stresses typically have units of pounds per square inch (psi).

Stress Riser – Location in a part where stress is amplified. Stress risers usually occur in areas with rapid changes in geometry (i.e. corners, holes, etc.)

Yielding occurs when the stresses within a material/part become high enough to deform, or permanently alter the part (i.e. when the forces are removed the part will not return to its original shape). A yielding failure in a plastic part will typically be denoted by ductile stretching of the material in the region of high stress. In colored plastics the stretching will often create a white region or significantly lighten the color of the plastic. Yielding is the most commonly considered failure mode in mechanical design

Fatigue failures occur in materials/parts which experience cyclical loading. The amount of cycles that a part can endure is inversely related to the magnitude of the applied load(s). Typically the level of stress required to cause a fatigue failure is below the material's yield strength (a material will yield after one cycle, experiencing a stress equal to its yield stress). With each cycle of loading, a crack propagates through the material of the part. The greater the load applied to the part, the faster the crack grows. Characteristic "beach marks" on the fracture surface are often indicative of this mode of failure. It is very important to note that the crack must have an origin. Cracks typically originate as the result of a surface defect or a defect located within the material itself.

Creep rupture – Failures occur in materials/parts that are subjected to sustained stresses (mechanical and thermal) over an extended period of time. In most design applications Creep is not considered unless elevated temperatures are expected. However, in plastic materials creep can occur at nominal temperatures (i.e. room temperature). Creep failure occurs as micro-cracks within the material coalesce over time, merging and forming larger cracks, until the ultimate failure occurs. Creep failures typically occur as a result of stresses well below the yield stress of the material.

Non-Destructive Examination Techniques

Advances in technology have encouraged the development of more aggressive non-destructive examination tools that assist in specifically identifying failure modes in plastics.

The following will provide examples of non-destructive techniques that have been used in practice to determine the cause of various failures. Specifically discussed and illustrated will be the use of various lighting techniques as well as CAT scan and X-ray imaging, and mechanical design analysis.

Lighting Techniques. Lighting techniques are well known and play very crucial role in any visual examination. Two specific lighting techniques will be discussed herein; back lighting and side lighting.

Back Lighting. Back lighting is very powerful and highly utilized technique. Back lighting is commonly described as "a spotlight that illuminates from behind so that the subject is separated from the background; used in photography"(2). These techniques are useful when examining a translucent object, such as acetal plastic parts or clear plastic tubing. The observer peers through the thickness of the part, identifying specific features that are not seen under normal lighting conditions.

A visual examination of a failed polypropylene water line revealed multiple locations with adhesive residue, as well as a number of surface abrasions and cuts. However, a microscopic evaluation, utilizing backlighting techniques identified specific features that led to the determination of the cause of failure. Figure 1 provides a view of the compromised portion of tubing discovered during this examination.

In Figure 1, the solid arrow indicates the point of breach and the thin dashed arrow denotes the probable direction of the puncture that caused an uncontrolled release of water.

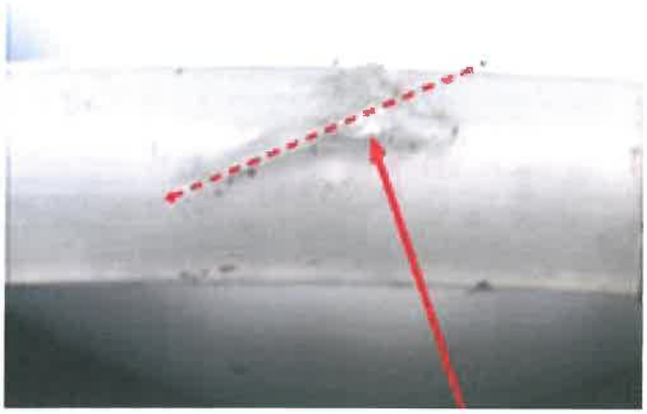


Figure 1: View of compromised section of tubing

Side Lighting. Side lighting is a technique the use various intensities and colors of light to the exterior of a component at various angles. The amount of penetration, and/or the diffusion of light will often indicate any defects or abnormalities within the part. Due to the translucent nature of most plastics, side lighting can be used to examine the homogeneity of the material. The result of this technique is similar to that of an X-ray image, which is brighter or darker depending on the density of the material.

Side lighting is also used in examination of fracture surfaces. Placing different intensity and color of lights at different angles bring out fracture surface features. These features are microscopically examined and aid in identifying the failure mode determination, which results in engineering analysis.

A situation where the side lighting technique proved valuable in the examination of a failed toilet water line is the following. The plastic nut responsible for attaching the waterline to the tank failed resulting in extensive water damage. The fracture occurred about the circumference of the nut and along the root of the last engaged thread. This thread carries the highest load and experiences magnified stresses due to stress risers in that region.

The visual examination of the fracture surface revealed it to be uniform in appearance with little to no signs of plastic deformation. Side lighting was used in a microscopic examination of the subject nut that identified the problem. This technique used a high intensity light, placed in close proximity to the exterior of the part. This technique visually identified a light transmission interruption within the material. This interruption was revealed as a "white band" or layer at the outer edge of the fracture surface. This white band was not observed anywhere else within the part.

The interruption of light transmission (denoted by a white band) is an indication of a discontinuity within material. Such a discontinuity would be consistent with the existence of a crack or knit line in the material matrix, created during manufacturing, causing an unforeseen weakness in the material.

X-Ray Imaging. X-ray imaging is defined as high-energy radiation with waves shorter than those of visible light. X-rays are capable of penetrating most substances (to varying extents), of acting on a photographic film or plate (permitting radiography), and of causing a fluorescent screen to give off light (permitting fluoroscopy). The x-rays penetrate a material and photographic film captures the various penetrations. Component of a parts are often easily identifiable in an x-ray image due to changes in materials, material densities and part geometries. Examining a part intended to be homogenous material, low density regions become apparent.

X-ray imaging has been used to identify internal components within a part and the engagement geometry, as seen in Figure 2.

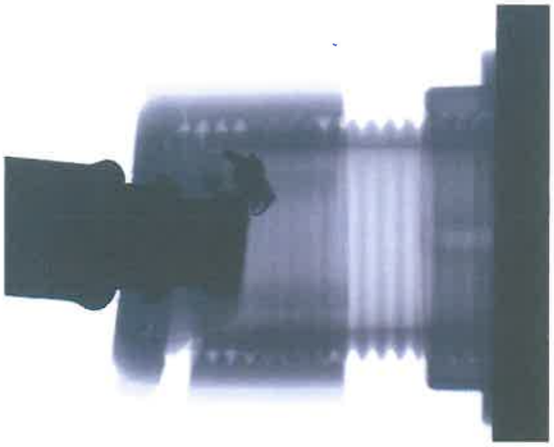


Figure 2: X-ray image of the subject nut

Figure 2, shows the internal threading of the nut and the corresponding external threads of the ball cock valve. Immediately apparent is the presence of some foreign material on the surface of the rubber grommet. Due to the similarity of light porosity shown on the X-ray, it is expected that the density of the foreign material is only slightly less than that of the neighboring metal insert, shown on the left hand side of Figure 2. Nevertheless, this foreign substance is not likely related to the crack failure, since it does not contribute to stresses on the subject nut.

The view of the crack from this image, Figure 2, shows that it lies in the valley of the last internal thread of the nut, located near the base of the grommet. This can be observed at the bottom portion of the image as well as at the top. In addition, the X-ray photos provide information about the depth of insertion of the male pipe into the fractured nut. Since this point of failure has not been moved, this view would indicate the depth achieved at the time of installation, which can be quantified.

CAT Scan Imaging. Computed axial tomography, commonly known as a CAT scan, uses a series of calibrated X-ray images to generate a three dimensional representation of an object. This imaging method produces visualization of both an objects exterior as well as its interior structure, and can be used to examine material density changes. CAT scan and X-Ray examinations are non-invasive and do not affect the material properties of plastics.

Reverse Osmosis systems (R.O.) contain plastic components often fail as the result of material defects. Therefore, CAT scans are used to identify their existence and location within the part.

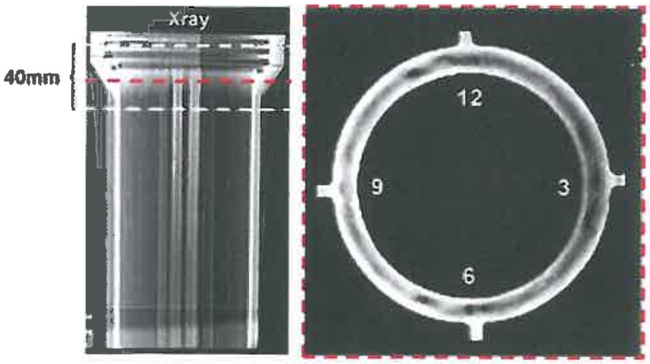
R.O. systems are commonly used to treat household drinking water. These systems usually have several plastic canisters in series, purifying the incoming water. R.O. system canisters have been known to fail in the region indicated by the red dashed line in Figure 5.

CAT scanning was used to capture images of the upper portion of three canisters taken from a R.O. system, one of which had failed. Data was captured at a resolution of 2mm per slice, and a cross section can be seen in Figure 5.

The image on the left side of Figure 5 is an X-ray profile view of the failed canister. The section above the white dashed lines indicates the scanned region of the part. Looking closely at this image, it can be seen that the fracture is located just above the red dashed line.

The image on the right side of Figure 5 provides an image from the CAT scan data. The image shown corresponds to the red dashed line visible on the X-ray profile image. The CAT scan data revealed the part to be solid through its cross-section. However, the image did show a number of variations within the material.

Some variations are partially due to geometry changes in the part. However, due to the symmetry of the part, the majority of these variations can be attributed to changes in material density. All three canisters were scanned and demonstrated similar variations in material density, although the magnitude of density change for each is not known.



Canister Side View

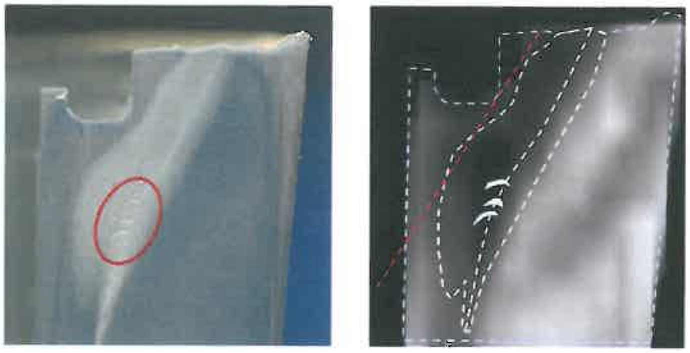
Image Slice

Figure 5: CAT scan images of failed filter.

In this instance, destructive testing was preformed to validate the results of the CAT scan images.

Using the CAT scan information as a guide, the upper portion of each of the canisters was sectioned into quarters. One of the exposed cross-sections can be seen in Figure 6.

As seen in Figure 6, destructive testing confirmed the location of low density regions within the material as well as the location of a number of voids that had formed. The formation of voids and low density regions are directly related to the manufacturing process.



Cut Surface

CAT Scan

Figure 6: CAT scan edge view comparison: subject pre-filter canister.

Mechanical Design Analysis – Mechanical design analysis is preformed to determine and confirm cause of premature failure. This can be achieved by using solid mechanics techniques in the evaluation of loading such as but not limited to the tightening torques induced onto a plastic part, creep analysis and fatigue analysis.

Tightening torques induced onto a plastic part can be evaluated by experimentation and the microscopic examination of the exterior surface of a part. Torque testing of a specific part with unique geometry was performed. Torque testing was done to understand the influence that two to three "grip" (i.e. as number of times the part was gripped by a tool) rotations may have on the plastic nut using a tool. The test was performed twice, each starting at a different level of hand tightening. The results of these two tests are presented in table 1.

	Tightening Torque				
Hand Tight	+0 turn	+1/4 turn	+1/2 turn	+3/4 turn	+1 turn
Nominal	15 in-lbs	25 in-lbs	35 in-lbs	42 in-lbs	52 in-lbs
Maximal	25 in-lbs	30 in-lbs	40 in-lbs	45 in-lbs	55 in-lbs

Table 1 - Torque testing results.

Creep - Once the induced forces are determined, then creep analysis can then be performed. Creep is a mode of failure that occurs over time under sustained loads, i.e. like constant water pressure. Creep deformation accumulates damage in the form of micro-cracks within the structure of a part. Over time these micro-cracks merge to form larger cracks, until ultimately failure in the form of creep rupture occurs.

Failure by creep rupture is dependant on several factors, such as applied stress, temperature and time. Figure 7 is graph showing the creep rupture threshold plotted in terms of applied stress and time, temperature was held constant. Using this figure, expected service life of the part can be estimated. This figure was adapted from data provide by Maier and Calafut (3).

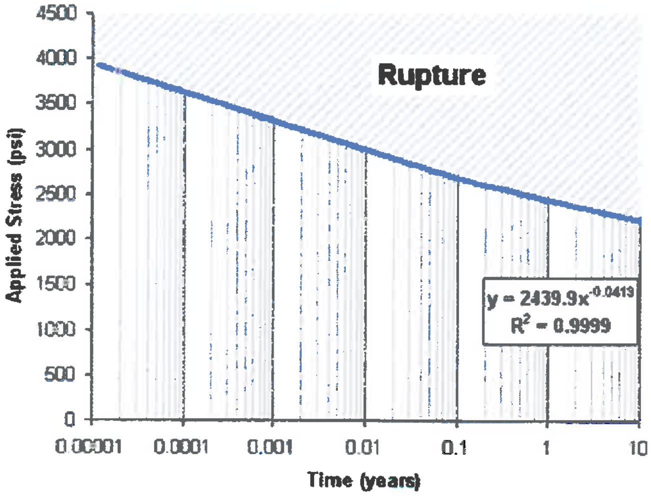


Figure 7: Tensile creep rupture for polypropylene, tested at 20°C (68°F)

In any part design that is composed of a single material, a designer's primary assumption is that the material properties are uniform. To protect against minor, unforeseen defects that may be manufactured into parts, a designer will apply appropriate factors of safety. As an example, a factor of 2 is typical in many designs. However, including a factor of safety can only protect against so much manufactured material variation. It is the responsibility of manufacturing production to produce as consistent and uniform strength parts as possible.

Fatigue analysis - Fatigue is a failure process which propagates crack growth due to a cyclic loading. A fatigue crack begins at a surface and extends its way through the thickness of the material. The fatigue surface can be from either internal or external features, like voids (internal) or scrapes (external). The fatigue process is highly sensitive to stress riser conditions.

We examined a clear plastic filter canister that was a component of a high pressure misting system. This canister was placed on a bracket and mounted to a misting system. The canister was mounted to a small flexible bracket that is oriented approximately 30 degrees out from a typical vertical orientation. Most filter canisters hang in a vertical orientation from their bonnet attachment. A view of an exemplar unit is shown in Figure 8.

It is known that both clear plastic and blue plastic filter canisters exist. The canister examined was a clear plastic canister.

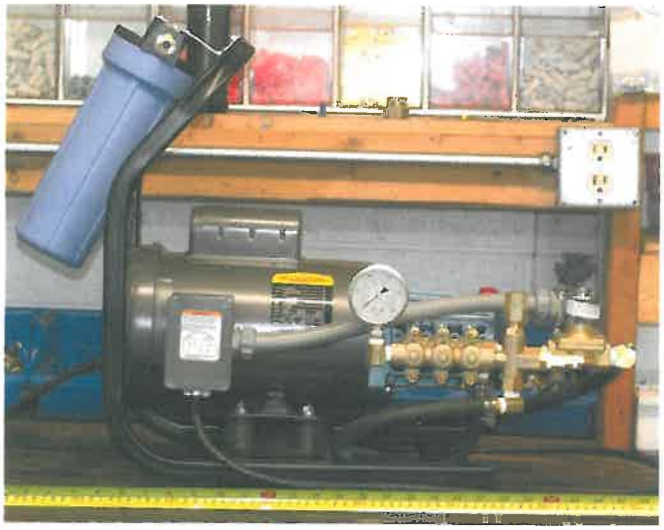
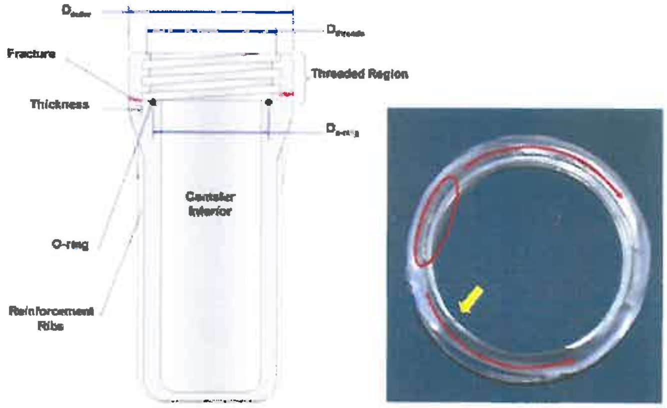


Figure 8 – Exemplar Misting System Pump Unit

A view of the clear plastic canister cross section schematic and view of the fracture surface is seen in Figure 9. The red line at the top of the cross section on the left, represents the fracture location. Features known as "beach marks" were observed on the fracture surface, which is indicative of a fatigue failure process. The red circle on the fracture surface on the right identified the failure origin – an unusual surface feature from which the beach marks seemed to emanate.



Canister Cross-Section **Subject Fracture Surface**

Figure 9: View of the clear plastic canister cross-section and subject fracture surface

The operation of the high-pressure pump exposes the overhanging canister to additional loading due to vibration, particularly during machine startup. The cyclic vibration loading is consistent with the periodic striations observed on the fracture surface of the canister.

The fracture surface gave the appearance of fatigue striations on the canister fracture surface. The vibration loading induced onto the canister was quantified.

An operational test of subject system was performed and vibration information was measured (using an accelerometer).

Testing consisted of four vibration sample measurements. Two of the four measurements included both start up and shut down cycles. A resultant acceleration plot of the measurements from one of these tests is seen in Figure 9.

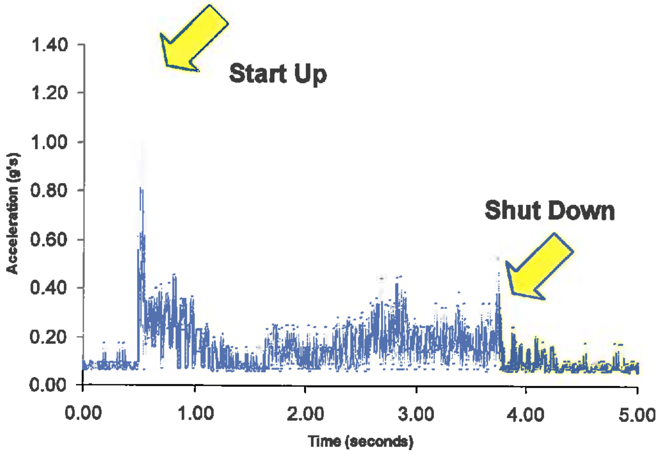


Figure 10: Acceleration data resultant (x, y, z axes combined) from Test04,

Figure 10 shows a resultant calculated data trace of the vibration information collected in test number 4. Test 4 had the highest measured vibration peak, at 1.3 g's. Whereas steady state vibration accelerations measured between 0.2 to 0.4 g's for each of the tests. As seen in the figure, the start up cycle produces the largest vibration peaks.

Vector resultant of the accelerometer traces provides the magnitude of g loading and its directionality. The predominant peak vibration orientation was along the Y-axis. This direction of vibration is parallel to the orientation of the pistons within the pump.

A material failure occurs when a part experiences stresses and loading that is greater than the material itself can withstand. For the subject canister, there were four primary modes of loading acting on the part; 1) Tension due to screw tightening, 2) Tension due to water pressure, 3) Bending due to slanted mounting and 4) Bending due to vibration. In addition, the geometry of the part can act to create areas of stress concentration, which raise the stresses locally in the region of that concentration. A summary of the calculated stresses can be seen in Table 2.

The stress loading on the subject canister is mixed; both tension and bending loads are present around the lowest thread root. Typically bending induces its highest stresses (tension and compression) at the outer surfaces of a part. However, in the case of our subject canister highest stress would be at the thread root due to its geometric stress concentration effect.

In addition, the stresses induced by *vibration* and *bracket mounting* orientation act in independent planes. Relative to the subject canister this means that these stresses do not interact. However, for the purposes of this analysis, we shall add each of these terms together as if they do, thus maximizing the loading effect.

Mode	Load	Induced Stress (psi)	3x Stress (psi)	Thread Root Stress type
Tightening Torque*	100 in-lbs	44	**132**	Pure Tension
Water Pressure	88 psi	155	**465**	Pure Tension
Mounting Induced Torque	8.4 in-lbs	1.6	**4.8**	Bending in Vertical Plane
Vibration	1.3 g	4.4	**13.2**	Cyclic Bending in Horizontal Plane

*Exemplar testing of bracket mounting limited the amount of tightening torque possible before the bracket collapsed

Table 2: Peak vibration accelerations summary

The total stress calculated at the thread root, cycles between 588 and 615 psi. This total includes the influence of both vibration and stress concentration.

In terms of the subject filter canister, the SAN material used in its construction offers good fatigue resistance. The fatigue life limit for SAN is reported to be approximately 3,500 psi at 10 million cycles. To operate below this level of stress implies that a part made from SAN would likely last more than 10 million cycles without fatigue failure (4).

A calculation of high cycle fatigue, including the effects of vibration and water pressure fluctuation show that our subject canister should not have failed in fatigue. We noted that the subject fracture occurred in a location common for failures of filter canisters of this style, regardless of the material. Finite element analysis conducted on essentially identical canisters confirms this as a region of high stresses due to the combination of applied loads and geometry.

However, these applied loads - water pressures and tightening torques combined - induce stresses normally well below the strength of the material. Further, the vibration measured did not contribute stresses sufficient to expect failure of the subject material. The combined loads should not have been sufficient to fail an otherwise nominal canister, other factors must have been present.

Products of this type are manufactured through injection molding, with an injection point at the base of the canister. Liquid or semi-liquid heated material is forced into a heated mold under pressure and fills the mold cavity from the bottom up. We note that the region of the failure has a high wall thickness relative to other areas of the canister. Because of this relative thickness, control of the manufacturing process is critical to allow for proper cooling, shrinkage and ultimate part strength. It is this region of the canister, which has a great potential for manufacturing problems.

The failure of the subject part was by fatigue – with stresses too low to induce fatigue failure – indicates that the subject part had a pre-existing manufacturing defect.

Destructive was done to confirm this prognosis. The areas of interest were sectioned from the minor upper portion (i.e. threaded region) of the failed subject canister. During the initial cut a significant amount of residual stress release was noted in the part. The residual stress acted as a compressive force attempting to reduce the overall diameter of the canister.

A diagram of Section #2 is shown in Figure 11. The diagram illustrates general part geometry examined and the relative locations of fracture surface features and SEM imaging.

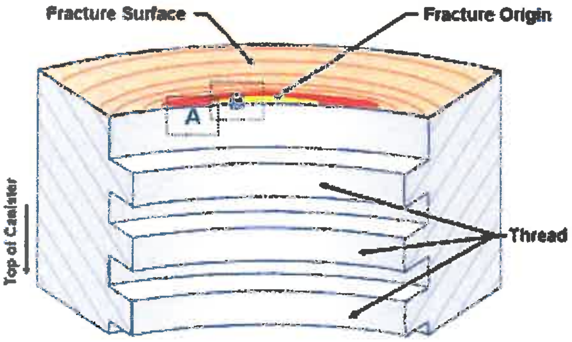


Figure 11: Diagram of SEM sample Section #2 and fracture surface features.

The diagram represents a view the interior/threaded portion of the canister section examined. The fracture surface of this section features a brittle failure area identified by the yellow and red filled ellipses and is the failure origin. Emanating from the origin are bands or striations indicative of fatigue crack propagation.

Figure 12 is inverted from a canister's typical installation position. The fracture origin is located in a typical failure region, at the lowest loaded thread root (stress riser). However as detailed in the previous report, the geometry and material selection were appropriate for this canister design. Also, the applied loading was well within the canister's strength capabilities and should not have resulted in fatigue failure.

Figure 12 shows two of the SEM images recorded during the examination. The relative locations where these two images were taken are illustrated by the boxed A and B in Figure 11.

Both Figure 12 images were taken at a similar viewing angle as Figure 11. The thick solid red line highlights the corner of the examined part. Above the thick red line is the horizontal fracture surface. Below the thick red line is the vertical face of the thread root.

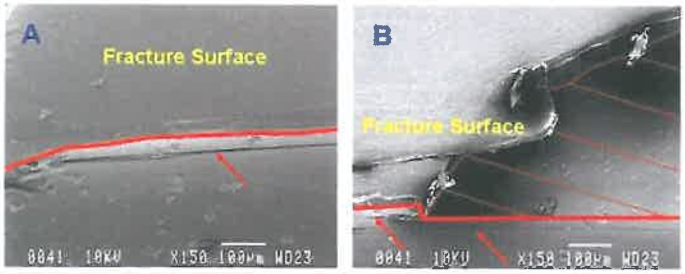


Figure 12: SEM images results.

Figure 12A is an image taken near the outer edge of the brittle fracture region. The red arrow in Figure 12A shows a crack formation that is parallel to and just below the fracture surface, indicating a secondary layer of separation.

Figure 12B is an image taken closer to the center of the fracture origin area. Again the thick red line indicates the transition between the horizontal surface of the fracture and the vertical face of the thread root. The red line hatched region in Figure 12B indicates a lower elevation from the primary fracture surface. The two surfaces are parallel to one another. In fact, a closer examination of the step up region between them appeared to show the lower surface continuing to extend beneath and parallel to upper fracture surface.

The red arrows in Figure 12B show very straight grooves on the vertical face of the thread root that are parallel to the flat fracture surfaces in this region. Following the bottommost groove to the left, it eventually becomes the crack observed in Figure 12A (red arrow).

The parallel layering of the canister material in the region of the failure origin implies a lack of bonding between these layers. Un-bonded layers of SAN or any material will significantly reduce a part's overall effective strength. A weakness in the threaded region of the subject part is consistent with the findings before destructive testing and the failure is congruent with a manufacturing defect.

Conclusion. Non-destructive testing and examination techniques are used to specifically identify and understand various failure modes seen in plastic parts, while conforming to the current ASTM standards for the examination of items that may be involved in litigation.

Lighting techniques are crucial in all visual examinations of failed plastic parts. Lighting techniques reveal identifying characteristics of a fracture surface, often identifying the mode of failure. Examining translucent materials, through lighting and shadowing can show indications of internal defects near the surface of a part, such as voids and cracks.

X-ray images are also very useful in the examination of failed parts. X-rays are particularly useful in the examination of plastic parts that house metal components. This technique can give verification of internal part geometries and features. In addition, X-ray images show internal fractures and regions of low densities.

CAT scan imaging is a through and through examination, because it takes several images at different sections/slices through a parts geometry. CAT scans are very useful in the examination of parts with complex geometries or inconsistent material properties, providing detailed views of the internal structure of the part at different depths.

Mechanical design analysis provides a detailed design analysis of a part, leading to a deeper understanding of the part and its role in a system. In combination with the aforementioned examination techniques, mechanical design analysis gives an indication of the life expectancy of the part.

As mechanical forensic engineers, strictly evaluating visual characteristics of a failed component does not always explain the exact cause of the failure but rather provides a failure mode. Therefore, a mechanical design analysis is often necessary to determine the cause of the failure. In the specific example given within the mechanical design analysis section, the exact failure cause would have been missed if a mechanical design analysis was not performed. The evaluation of the fracture surface showed an obvious fatigue failure. Given the R.O. canister mounting configuration, the first hypothesis was that the part was overloaded and failed due to the induced vibrations. The evaluation of the mechanical design revealed the part to be significantly under its fatigue life limit from the induced vibrations. Further non-destructive examinations provided conclusive evidence that the canister failed due to a manufacturing defect. Destructive testing was performed and verified these conclusions. Had a mechanical design analysis not been performed these results would have been missed.

Plastic parts are not anything a person would give a second thought to, but in the right situation and time a failure of these plastic parts could occur. In our experience, major water losses can occur if left unchecked, resulting in hundreds of thousands of dollars in damage.

The non-destructive techniques in examining failed plastic parts described and presented in this paper are very powerful and are invaluable in determining the cause of a failure.

Acknowledgments

Mark Roglin and everyone at Augspurger Komm Engineering, Inc.

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