

Materials Project Report

To:

[REDACTED]

Report No. 20230667

From:

[REDACTED]

Date: April 12, 2024

Reviewed
by:

[REDACTED]

Copies to:

[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]

Subject: CF6 Input Housing P/N 5006834M Failure Investigation

Introduction:

A CF6 Fuel Pump Assembly (S/N SUS5170A) was returned to Collins Aerospace after an in-flight failure event occurred during which the pump experienced thermal damage. At the request of the National Transportation Safety Board (NTSB), Collins Aerospace Materials and Process Engineering examined the input housing and associated components of the Fuel Pump Assembly for root cause investigation.

Summary:

No evidence of a mechanical failure mode was identified due to the localized melting of the input housing. Indications of melting and re-solidification were present on surfaces of the input housing exposed to elevated temperatures during the failure event. The input housing exhibited evidence of thermal exposure based upon the coloration on the exterior surfaces of the input housing and material condition. Secondary cracking near the damaged location of the input housing also exhibited evidence of melting and re-solidification extending from the primary failure location.

Evidence collected during metallographic examination at multiple locations indicates a temperature gradient was present that changed the material microstructure at the failure location. Additional evidence showed that material away from the failure event exhibited a microstructure consistent with the heat treatment defined by the engineering drawing.

Materials & Process Specifications:

P/N 5006834M – Fuel Pump Assembly

P/N 5006911-1 (Boost Pump Housing)

Material: MIL-A-21180, alloy C355, class II Inv. (T61 Condition)

Casting shall conform to MIL-C-6021, class 1, Grade C.

Radiographic inspection per PN16.01. Cored passages 100% inspection per MS20.01.

P/N 5006923 (Impeller Balance Assembly)

P/N 5006924 – Impeller Inducer

P/N 1728029 – Impeller Assembly

Material: MIL-A-21180, alloy C355, class II Inv. (T61 Condition)

Data & Discussion:

Fuel Pump Assembly P/N 5006834M S/N SUS5170A was returned to Collins Aerospace after experiencing a thermal runaway failure event in flight. The fuel pump was shut down during flight but after initiation of the failure event. The fuel pump assembly was removed from the aircraft and provided to Collins Aerospace for root cause investigation.

Visual Examination (As Received)

The exterior surfaces of the housing exhibited darkened surfaces covered in a soot like material in the as-received condition. The soot like material was easily transferred to other surfaces when handling unit during preliminary examination. **Figure 1** and **Figure 2** show the condition of the fuel pump assembly as provided to Collins Aerospace Materials and Process Engineering for analysis. The pressure transducer was present with the assembly which exhibited discoloration and evidence of exposure to elevated temperatures (**Figure 3**).

A small section of the exterior surface was swabbed and cleaned with isopropyl alcohol (IPA) as a cleaning solvent to reveal part marking identification on the input housing (**Figure 4**). No other surfaces were cleaned or swabbed prior to disassembly of the fuel pump assembly with all party members present.

The input housing inlet takeoff and the remnants of the mounting flange that was retained with the fuel inlet tube were arranged to show condition of the input housing after failure (**Figure 5**). The shape of the opposing failure surfaces exhibited general alignment with respect to the features present in the image. Examination of the pieces revealed there is a section that is no longer present from the inlet takeoff arm of the input housing (**Figure 6**). Secondary cracking and discoloration / contamination of the failure surfaces were also observed in the remnants from this location (**Figure 7 & Figure 8**).

Multiple linear indications, cracks, and secondary damage were observed in the mounting flange remnant. Of note, two cracks were observed on either side of one mounting bolt that formed in the flange (**Figure 9**). Impact damage was observed on one corner of the mounting flange for the input housing that was retained with the fuel inlet tube (**Figure 10**).

Linear indications were also observed immediately adjacent to the failure surface of input housing takeoff. A secondary crack was observed on the ID surface of the inlet tube propagating transverse to the primary failure surface. Multiple smaller secondary cracks were also observed in approximately the same location (**Figure 11 & Figure 12**). The inlet housing takeoff was marked for sectioning to remove the failure surface for further examination (**Figure 13**).

Observations (Fiberscope)

Prior to disassembly, examination utilizing a Keyence fiberscope was performed to document the condition of the accessible internal features of the fuel pump assembly. Not all internal features could be examined due to the limited flexibility and length of the Keyence fiberscope being utilized for examination as well as the non-linear features and complex passages within the assembly. Evidence of metallic debris was discovered in the gear discharge gear mesh (**Figure 14 & Figure 15**). Continued examination of the internal features revealed damage to the inducer blades and the opposing interior surface of the input housing (**Figure 16**). Minimal debris was observed within the boost discharge filter inlet (**Figure 17**).

Radiographic Inspection / Observations

Digital radiographic inspection was performed on the fuel pump assembly prior to disassembly to examine for indications of failure or debris trapped within unit. The original digital radiographic (DR) images were enhanced using the digital Wallis filter to better visualize features of similar density or image contrast.

Evidence of damage to the inducer section of the impeller assembly was observed adjacent to the damage inlet tube (**Figure 18**). DR imaging of the lower half of the fuel pump assembly revealed debris that had collected or accumulated at the bottom with the pump in the vertical orientation (**Figure 19**). The debris exhibited a higher density than the surrounding pump assembly features as it was darker within the radiographic image. Additional debris was observed at the bottom of the assembly as well as in a filter when the unit was re-oriented for additional imaging (**Figure 20**).

Observations (Teardown and Disassembly)

The fuel pump assembly went through a controlled tear down / disassembly process with all party members present. The assembly displayed general signs of overheating and exposure to elevated temperatures. Visual examination of the assembly revealed the PTFE seals and O-rings had extruded out from several mating interfaces from their respective grooves due to sustained exposure to elevated temperatures. O-rings that did not exhibit material extrusion were found to be damaged or cracked but still in

place. Representative images showing various O-ring and seals within the fuel pump assembly are shown in **Figure 21 – Figure 24**.

Metallic and non-metallic debris was observed in the fuel pump assembly and individual piece parts, revealed during disassembly at various locations. Particles or debris that was present and visible during the teardown and disassembly activity were collected along with the location from where it was collected. Additional debris collection was performed using carbon backed tape to perform a tape lift, where loose debris agglomerated for further analysis.

Evidence of lead extraction was observed around the leaded bronze bearings. The lead had accumulated within the orifice of the bearings (**Figure 25**). Additional metallic debris was observed on the bearing after removal from the pump assembly. A large metallic piece that exhibited evidence of mechanical deformation along with small spherical particles consistent with metallic spatter were observed (**Figure 26 & Figure 27**).

The mounting flange was separated from the fuel inlet tube for further analysis of the failure surfaces. An optical image in the isometric view is shown in **Figure 28** showing discoloration and contamination of the surfaces. The mating surface (non-failed side) exhibited material transfer from the sealing ring (**Figure 29**). Degradation of the seal from thermal exposure which was observed as lost material or gaps in the sealing material is shown in **Figure 30**.

An optical image showing the input shaft after disassembly and removal from the fuel pump is shown in **Figure 31**. Coloration of the shaft was observed when removed from the fuel pump assembly during disassembly.

Limited debris was observed within the filter after removal from the fuel pump assembly (**Figure 32**). This is the same observation made during examination of the fuel pump assembly when utilizing the fiberscope for initial evaluation. Evidence of discoloration was also observed on the exterior surface of the filter mesh (**Figure 33**).

Debris Analysis

Debris was collected throughout the fuel pump disassembly process for identification. The analysis and results can be found in Mpr20230667-3. Evidence of aluminum metallic material, lead, and non-metallic debris were confirmed as the predominate constituents for the debris through analysis.

3D Computed Tomography (3D CT)

The input housing was scanned using 3D Computed Tomography (CT) to create a volumetric data set to evaluate the condition after the failure event. The impeller assembly was retained within the input housing for the 3D CT scan. Attempts were made to remove the impeller assembly by hand using only minimal applied loading.

However, those attempts were unsuccessful, and no further attempt was made to separate the piece parts prior to 3D CT inspection of the input housing assembly.

A new input housing was provided for evaluation and comparison to the unit from the failure event. A comparison between the volumetric data set of the event unit and the volumetric data set of the stock unit (i.e. scan-to-scan comparison) was performed to show dimensional variation between the two units. Volume Graphics software was utilized to produce a best fit registration between the two volumetric data sets utilizing the stock unit as the baseline data set for analytical purposes.

Representative images showing the colorized comparison between the two units are shown in **Figure 34 – Figure 36**. Dimensional variation existed primarily around the inlet tube where material was missing from the event unit. The thermal event contributed to material deformation and distortion in the event unit that deviated from the nominal unit provided from inventory. Pink coloration represented deviation greater than the defined 0.030" tolerance limit from nominal (e.g. +0.030"). Purple coloration within the image represented deviation less than the defined 0.030" tolerance limit from nominal (e.g. -0.030"). The remainder of the event input housing was a green coloration and exhibited minimal deviation from the nominal unit provided from inventory.

Examination of the 3D CT volumetric data for the event unit revealed evidence of damage to the inducer blades (**Figure 37 & Figure 38**). Material was observed to be adhered to the discharge side of the input housing interior surface. Only limited adhered material was observed on the input side of the housing interior surface. Representative images showing the input housing inlet takeoff in multiple cross sections are shown in **Figure 39 & Figure 40**. A series of images showing evidence of deformation along the length of the inlet takeoff are shown in **Figure 41 through Figure 44** with the greatest deformation present at or near the failure surface.

Fractographic Analysis - Primary Failure Location

Fractographic Analysis was performed using the Scanning Electron Microscopy (SEM) on the two exposed surfaces of the inlet tube as a method to determine the failure mode of the inlet housing. Each sample was cleaned using a 1% Alconox solution, a light alkaline detergent, in an ultrasonic bath for up to 10 minutes to remove soot and loose debris from the exposed surfaces. The process was repeated until the surfaces were adequately cleaned and visually deemed acceptable by party members for further examination. The samples were then rinsed with deionized water to remove the Alconox solution followed immediately by rinsing with a solvent and drying.

The surface immediately adjacent to the mounting flange was sectioned transverse through the upper half of the exposed surface. The topographical features of this surface prevented a comprehensive analysis from being performed as the working distance within the SEM chamber between the surface and the electron source would have changed too much to evaluate the entirety of the surface.

A representative optical image the upper section of the surface is shown in **Figure 45** for reference purposes. Fractography of the surfaces associated with the mounting flange revealed evidence of melting and re-solidification. The surface was typically smooth in appearance where the aluminum base metal had melted from exposure to a heat source above the melting temperature of the base metal. No evidence of a mechanical failure mode was observed during the analysis. Representative SEM images from this segment of the exposed surface are shown in **Figure 46 – Figure 48**.

An optical image showing the lower section of the surface captured within the SEM chamber for positioning is shown in **Figure 49**. The remainder of the surface exhibited similar melting and re-solidification features observed in the upper part. Representative SEM images showing evidence of melting and re-solidification are shown in **Figure 50 and Figure 51**.

An optical image showing the fracture surface originally retained with the input housing and the relative orientation within the SEM chamber is shown in **Figure 52**. Fractography analysis of the surfaces associated with the housing (impeller side) exhibited evidence of melting and re-solidification similar to the opposing surfaces. The indications of material melting were present across the entirety of the surface examined. Representative SEM images of the surface at magnification are shown in **Figure 53 – Figure 55**. No evidence of a mechanical failure mode was observed during the analysis.

Fractographic Analysis - Secondary Cracking, Inlet Tube

Secondary cracks were observed located primarily on the interior surfaces of the inlet tube extending from the failure surface. The largest of these cracks was excised and a back cut made to enable a lab overload condition to expose the fracture surfaces. Optical images showing the exposed fracture surface of the secondary crack are shown in **Figure 56 - Figure 58**. Three locations (A, B, and C) were identified for analysis of the fracture surface and are labeled in the images.

Examination of location A revealed evidence of melting in the fracture surface immediately adjacent to the event location (**Figure 59**). Similar features were observed at location B of the excised secondary crack along the ID surface (**Figure 60**) and mid wall thickness locations (**Figure 61**).

Evidence of melting was observed near the ID surface at location C of the secondary crack (**Figure 62**). The morphology of the intermetallic particles at this location was unique in appearance and differed from the features present at locations A and B. The findings indicate the temperature at this location was high enough to cause melting and re-solidification of the aluminum matrix and only partial melting of the intermetallic particles. Fractographic features consistent with overstress rupture (microvoid coalescent fracture) were present at the “back end” of the secondary crack near the OD of the inlet tube where the back cut terminated (**Figure 63 & Figure 64**).

The findings indicate a thermal gradient was present from the end of the inlet tube to the bottom of the secondary crack. There was also a temperature gradient from the interior surface to the outer surface of the inlet tube. Evidence of an overstress rupture failure mode was observed near the outer surface of the housing that was formed during the lab overload process to expose the fracture surface.

Input Housing Sectioning, Observations and Analysis

Prior to disassembly, the impeller assembly was confirmed to be retained within the input housing. The cause for retention could not be identified using non-destructive inspection methods. An optical image showing the impeller retained within the input housing is shown in **Figure 65**. A sectioning plan was established to isolate the center shaft of the impeller assembly by selective machining and removal of the top of the input housing (**Figure 66**). Once the input housing was machined, the impeller assembly was pushed out with limited force required.

An optical image of the impeller assembly is shown in **Figure 67** that documents the condition of the inducer blades after removal from the input housing. As was observed during 2D radiographic imaging and 3D CT inspection, deformation of the inducer blade tips and adhered material to the inducer blade profile was prevalent. Gross deformation of one inducer blade was observed after removal indicating this area was the cause for retention within the input housing (**Figure 68**). The inducer blade at this location had become adhered to the interior surface of the housing. Additional images of the inducer section are shown in **Figure 69** and **Figure 70** where the impeller assembly had been rotated.

The wear surface from the top of the impeller assembly exhibited no indications of wear damage such as scoring from hard or abrasive particles. A representative image showing the wear surface is shown in **Figure 71**. This surface was determined to be in good condition and did not contribute to retention of the impeller assembly within the input housing. Similar observations were made of the journal bearing that was easily removed during extraction of the impeller assembly from the input housing. The journal bearing was free to move axially in the housing and was easily removed from the housing during disassembly. The journal bearing did not exhibit any indications of wear damage consistent with hard or abrasive particle contamination on the primary wear surface (**Figure 72 & Figure 73**).

Examination of the interior surfaces of the input housing revealed adhered metallic material with a circumferential pattern of material adhesion (**Figure 74**). The inlet housing was sectioned in half to expose the interior surfaces for further evaluation. The sectioning line approximately coincided with the center of the housing separating the inlet from the discharge. The discharge side of the housing exhibited non-uniform accumulation of metallic material on the interior surface (**Figure 75**). Additional images of the accumulated material at increased magnification are shown in **Figure 76****Error! Reference source not found..** Material was collected from the interior surface for identification of the material composition.

The inlet side of the input housing also exhibited evidence of metallic material adhesion on the interior surface. However, the adhesion indications were discrete with minimal accumulation of material away from the surface (**Figure 77** & **Figure 78**).

X-ray fluorescent spectroscopy (XRF) analysis was performed the representative sample of adhered metallic material collected from the discharge side of the input housing. The primary constituent of the adhered material was revealed to be aluminum with trace amounts of silicon, magnesium, and copper.

Metallographic Examination

Two metallographic cross sections were excised from the inlet tube that incorporated the failed end surface (**Figure 79** & **Figure 80**). Metallographic examination of the polished cross section from location 1 showed the failure surface primarily followed pre-existing grain boundaries within the material microstructure (**Figure 81**). The material microstructure at this location exhibited evidence of intermetallic growth as well as propagation along grain boundaries. The square / rectangular morphology with sharp features and a continuous layer along the grain boundary in discrete locations are evidence of sustained exposure to elevated temperatures (**Figure 82** – **Figure 84**).

Metallographic examination of the polished cross section from location 2 showed similar features that were observed at location 1. More porosity was observed near the failure surface with silicon rich intermetallics having propagated along grain boundaries between adjacent porosity indications (**Figure 85** & **Figure 86**). While porosity was observed, review of the radiographic film showed the cast material from this general location of the input housing had met the acceptance criteria established by the engineering drawing. Examination at increased magnification revealed that the intermetallics exhibited the same square / rectangular morphology with sharp features (**Figure 87**).

A metallographic section was taken from a location of the input housing representing the furthest distance away from the failure event location (**Figure 88**). The metallurgical microstructure was generally uniform in appearance but did exhibit discrete grain boundary features with a morphology that was not consistent with the surrounding material as well as the heat treatment defined by the engineering drawing. Formation of longer grain boundary intermetallic features were influenced by the elevated temperature inducing a limited overaging effect on the cast aluminum material at this location. (**Figure 89**). The silicon rich intermetallics generally exhibited an appearance consistent with the defined heat treatment. Limited effects from heat input were observed within the material microstructure. The long, thin feature shown in **Figure 90** is an example of localized propagation of the intermetallic phase propagated along the grain boundary because of the heat input from the failure event.

Additional examination from a representative section of the material at increased magnification revealed the silicon rich intermetallics exhibited an appearance consistent with the heat treatment defined by the engineering drawing. The intermetallic particles are rounded and well distributed with very few larger particles which is consistent with the prescribed heat treatment (**Figure 91**).

Material Composition Analysis

A section of the cast aluminum housing was excised to collect material for composition analysis. Material was milled to create small chips that could easily be dissolved in an acid solution. The dissolved metal and acid solution was then utilized for inductively coupled plasma (ICP) analysis.

A separate material sample was sectioned and polished to create a uniform surface for wavelength dispersive x-ray fluorescent (WD-XRF) spectroscopy for bulk material composition analysis. Both methods were utilized in determining the elemental material composition of the C355.0 aluminum alloy in accordance with MIL-A-21180. The analytical chemistry results for material composition are included in **Table 1**.

Table 1 – Aluminum housing material composition

Element	Test Result (wt %)	C355.0 Spec Requirement (wt %)
Copper	1.4	1.0 – 1.5
Silicon	4.9*	4.5 – 5.5
Iron	0.17	0.20 max
Manganese	0.01	0.10 max
Zinc	0.02	0.10 max
Magnesium	0.58	0.40 – 0.60
Titanium	0.13	0.20 max
Beryllium	--	--
Silver	--	--
Others, each	<0.05	0.05 max
Others, total	<0.15	0.15 max
Aluminum	Remainder	Remainder

*Silicon was determined through ICP, all other elements were determined using WD-XRF

Hardness Testing – Input Housing

Attempts to use a direct hardness measurement using the Rockwell Hardness B scale (HRB) were unsuccessful. The direct hardness load using 100 kgf with a 1/16" ball indenter caused a deep impression due to the low material hardness. An image of the indentation in the cross section is shown in **Figure 92**.

Knoop hardness testing using a 100-gram load (HK₁₀₀) was performed to evaluate material hardness. Material near the failure location in the input housing exhibited too much porosity to provide accurate or reliable hardness measurements. Only material away from the failure location could reliably be measured to ensure the indentation had adequate material to support the applied load. A set of five indentations were made in the cast aluminum material with an average hardness of 62 HK₁₀₀. This average value could not be converted to another hardness scale because it is too low.

Hardness Testing – Center Shaft

Direct hardness testing using the Rockwell C scale (HRC) was performed on the outer diameter surface of the center shaft. The shaft exhibited varying coloration along the length and multiple locations were selected to quantify impact on material performance. Hardness was measured at two locations, in the middle of the shaft which exhibited a dark brown coloration and near the splined end where the shaft was purple / light blue in coloration. The center of the shaft measured 48.1 – 48.3 HRC while the shaft near the splined end measured 48.4 – 48.6 HRC. Multiple indentations were taken and fell within the provided range at each location. A 0.5 HRC correction factor was applied to the hardness readings to account for the diameter of the shaft.

**Figure 1**

Optical image showing the fuel pump assembly in the as-received condition.

**Figure 2**

Optical image showing the fuel pump in the as-received condition.

**Figure 3**

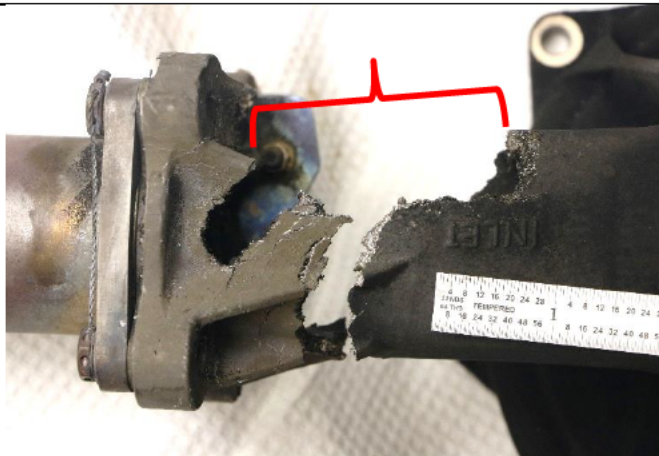
Optical image showing the pressure transducer exhibiting discoloration and visual indications of exposure to elevated temperatures. It was reported that this item was located directly in line with the heat source.

**Figure 4**

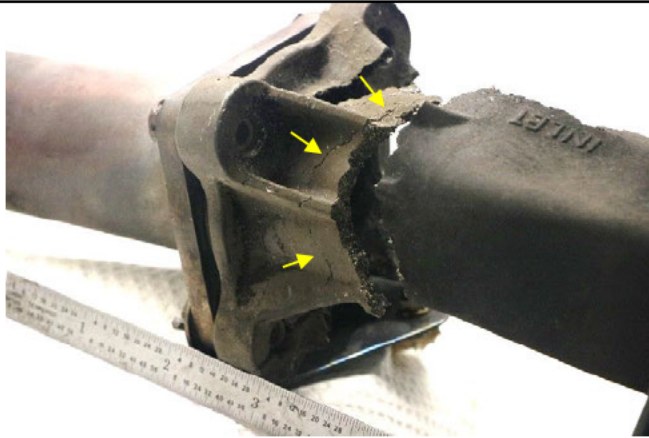
Optical image capturing the part marking identification for the inlet housing. The melt number, heat number, and serial number were cleaned with a solvent to remove the surface debris and contamination for better viewing of the text.

**Figure 5**

Optical image showing the fuel pump assembly arranged to show the relative position of the mating fuel inlet tube. The image was captured after disassembly and removal of the input housing from the fuel pump assembly which enabled this image to be captured.

**Figure 6**

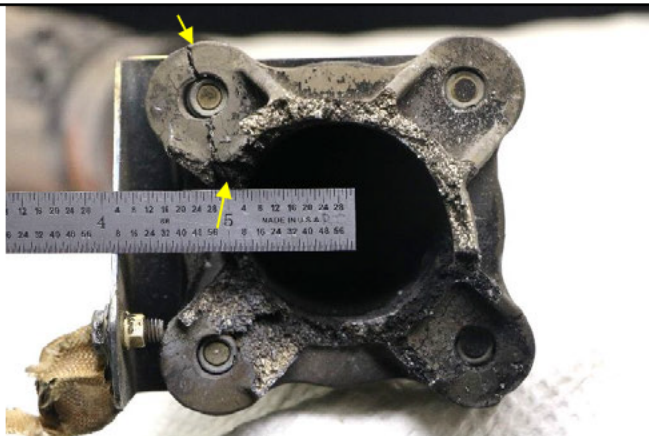
Optical image showing the remnants of the failure surfaces from the fuel pump assembly. The shape of the opposing failure surfaces exhibited general alignment with respect to the features present in the image. The bracketed annotation in the image is identifying material that is no longer present from the inlet takeoff arm of the input housing.

**Figure 7**

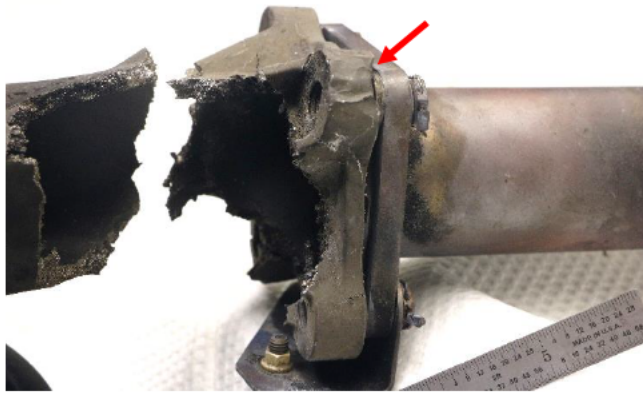
Optical image showing the failure location of the fuel pump assembly at a different orientation. There are several linear indications propagating through the mounting flange remnant material. The arrows in the image denote the largest of linear indications visible in this image.

**Figure 8**

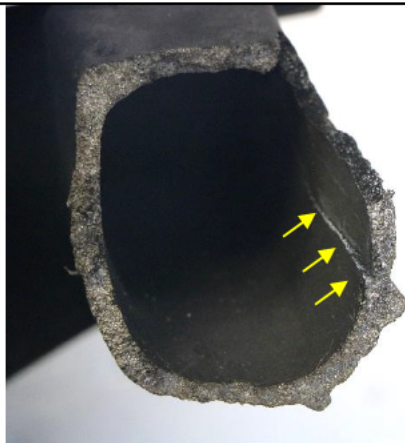
Optical image displaying the mating failure surfaces positioned next to each other. The mounting flange generally exhibits more discoloration and contamination on the failure surfaces than the opposing surface on the input housing takeoff arm.

**Figure 9**

Optical image showing the mounting flange section of the input housing that remained attached to the fuel inlet tube after failure. The upper left bolt location exhibits two cracks on either side of the bolt that formed in the flange.

**Figure 10**

Optical image showing the mounting flange still attached to the fuel inlet tube. The upper mounting point identified by the arrow in the image exhibited impact damage and secondary cracking present in the material.

**Figure 11**

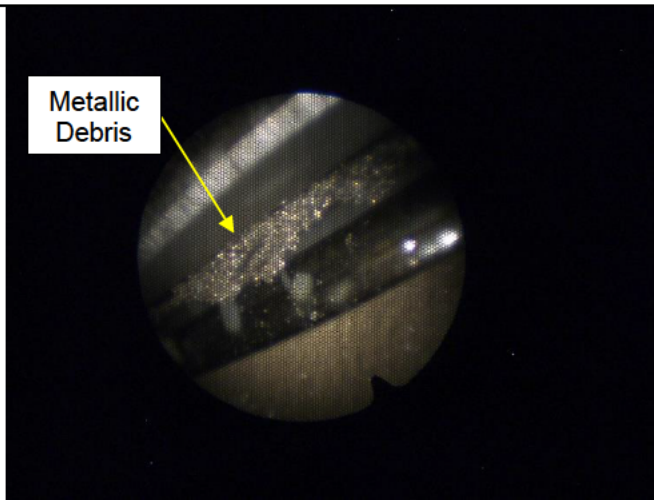
Optical image showing the surface of the input housing in the as-received condition. The inlet tube had separated from the housing flange during the failure event. A secondary crack was observed on the ID surface of the inlet tube propagating transverse to the primary failure surface. Multiple smaller secondary cracks were also observed in approximately the same location.

**Figure 12**

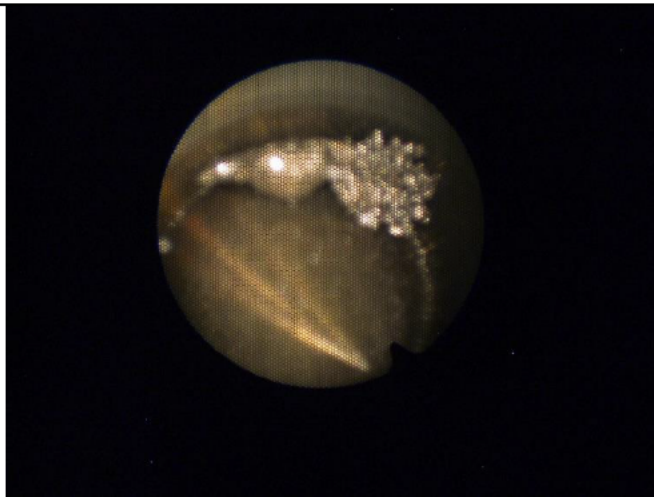
Optical image showing the fuel inlet takeoff in the as-received condition. Linear features were observed on the interior surface of the inlet takeoff.

**Figure 13**

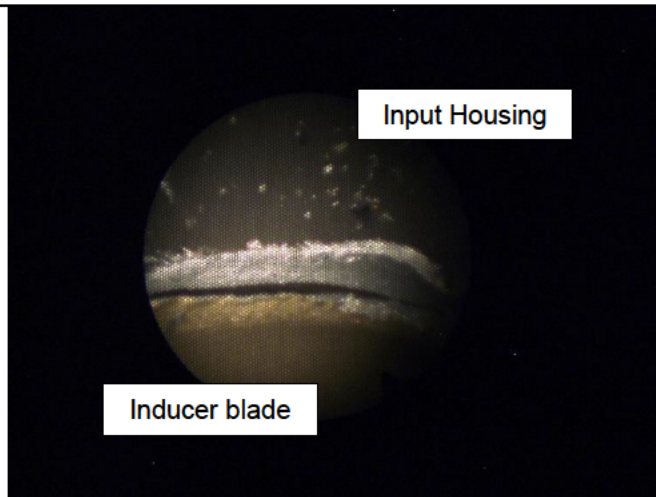
Optical image showing the top down view of the failure location in the input housing. The gray line across the input tube is the location at which sectioning were to take place for further analysis of the failure surface.

**Figure 14**

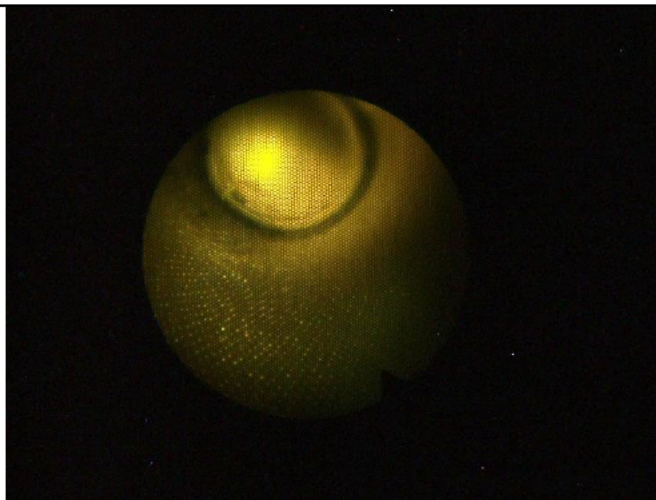
Fiberscope image showing accumulation of metallic debris within the gear discharge area. Metallic debris was observed on multiple gear teeth at this location.

**Figure 15**

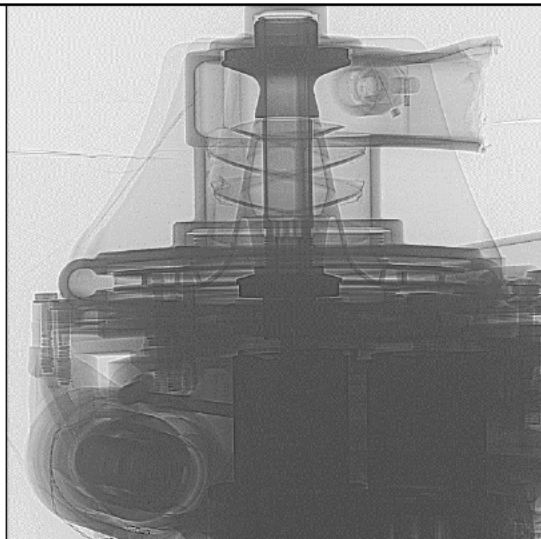
Fiberscope image showing accumulation of metallic debris within the gear discharge area.

**Figure 16**

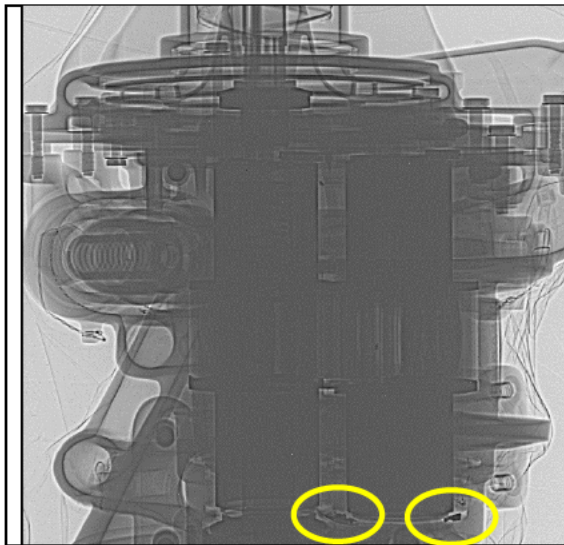
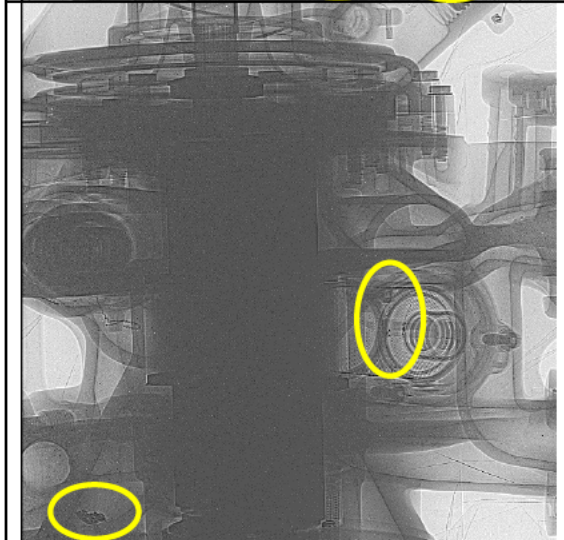
Fiberscope image showing evidence of damage to the inducer blade and interior surface of the input housing.

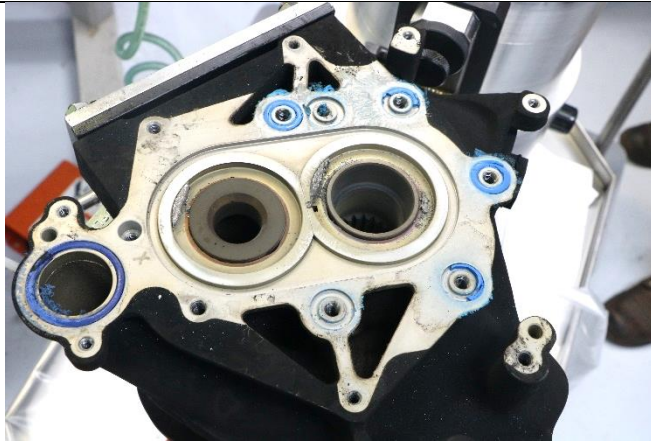
**Figure 17**

Fiberscope image showing the boost discharge filter inlet. A minimal amount of debris was observed within the filter.

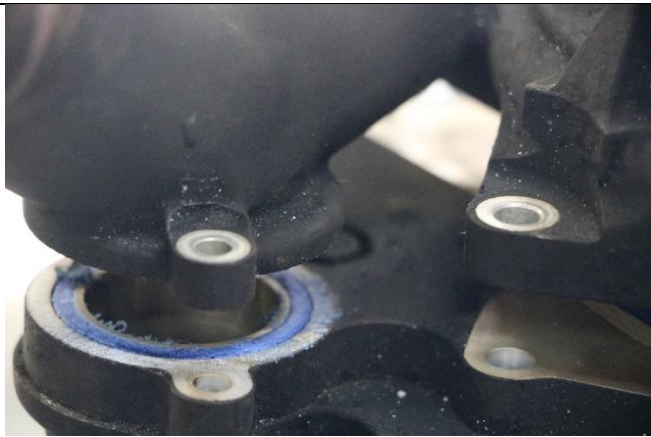
**Figure 18**

2D radiographic image using the digital Wallis filter to modify the image. Utilizing the Wallis filter helps to accentuate part features that would otherwise be too dense or obscured within the radiographic image. The damaged inlet tube is shown at the top of the image.

	Figure 19 2D radiographic image using the digital Wallis filter to modify the image. Evidence of debris was observed to have collected in a core near the bottom of the unit in this viewing orientation.
	Figure 20 2D radiographic image using the digital Wallis filter to modify the image. Evidence of debris was observed to have collected in a core near the bottom of the unit as well as in a filter.
	Figure 21 Optical image showing the seal around the larger diameter orifice. The seal exhibited cracking around the circumference of the part. Evidence of material extrusion was also observed as identified by the arrow in the image.

**Figure 22**

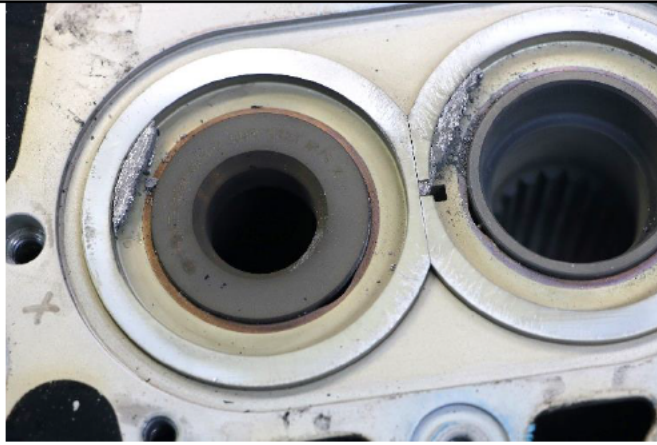
Optical image showing accumulation of metallic material. Thermally induced damage was observed for the seals in each bore interface at the split line. Evidence of material extrusion onto the mating surfaces and out of the assembly was present.

**Figure 23**

Optical image showing evidence of seal extrusion between the mating surfaces due to elevated temperature exposure.

**Figure 24**

Optical image showing evidence of seal material extrusion due to elevated temperature exposure. The seal material extruded in both directions from the defined groove.

**Figure 25**

Optical image at increased magnification showing accumulation of lead around the orifice of the leaded bronze bearings. The accumulated material is evidence of lead extraction of the leaded bearings during the failure event.

**Figure 26**

Optical image showing the journal bearings after removal from the fuel pump assembly. Impressions from the gear teeth were observed in the leaded bronze surface that were reported to have been generated during the disassembly process. Metallic material was also discovered on the surface of one journal bearing.

**Figure 27**

Optical image showing evidence of metallic material transfer on the journal bearing surface as evidenced by the metallic spherical particles present.

**Figure 28**

Optical image showing the mounting flange of the fuel pump assembly after removal from the fuel inlet tube.

**Figure 29**

Optical image showing the mating surface for the fuel pump assembly. The darkened circular feature on this surface was created by transfer of the non-metallic seal material that was assembled between this surface and the fuel inlet tube.

**Figure 30**

Optical image of the seal from the interface between the fuel pump assembly and fuel inlet tube. Discoloration of the part was observed as well as damage to the sealing material. The encircled shows where material was lost within the seal section.

**Figure 31**

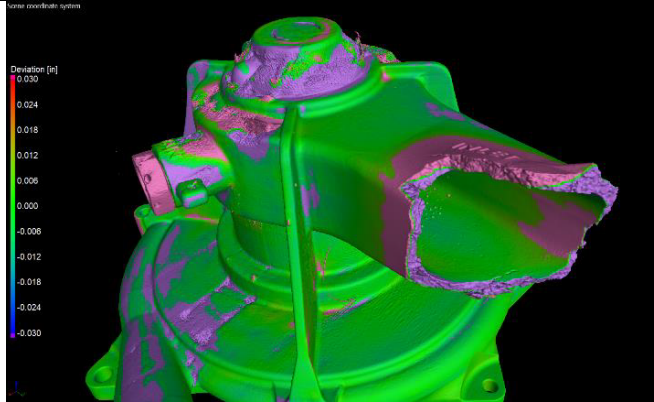
Optical image showing the input shaft after disassembly and removal from the fuel pump. Coloration of the shaft is from exposure to elevated temperatures.

**Figure 32**

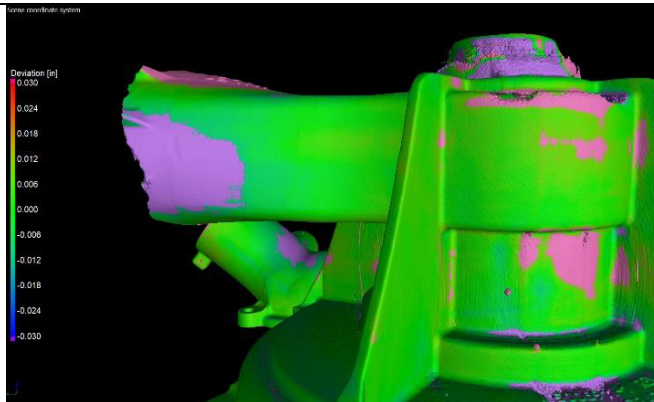
Optical image showing the filter after removal from the fuel pump. No cleaning or collection of debris occurred prior to visual examination and capture of this image. Evidence of discoloration was noted on the exterior surface of the filter.

**Figure 33**

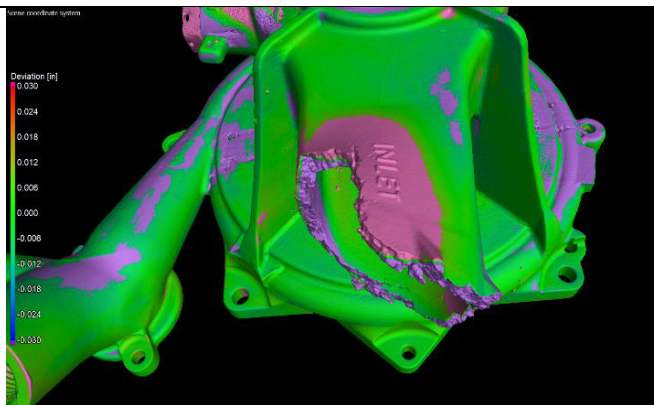
Optical image showing the inside of the filter. Limited contamination and debris / material was observed within the filter.

**Figure 34**

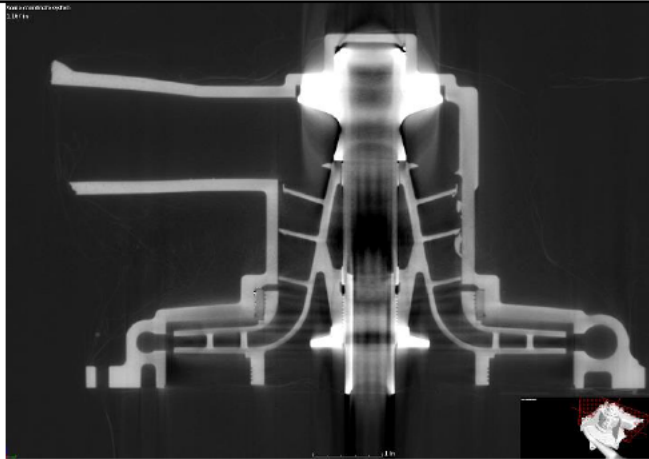
3D CT image showing the output of a comparison between the event housing and a nominal housing from inventory. The coloration represents distortion of the event housing from the nominal housing geometry. The inlet tube area and fracture surface exhibited the greatest deviation from the nominal geometry.

**Figure 35**

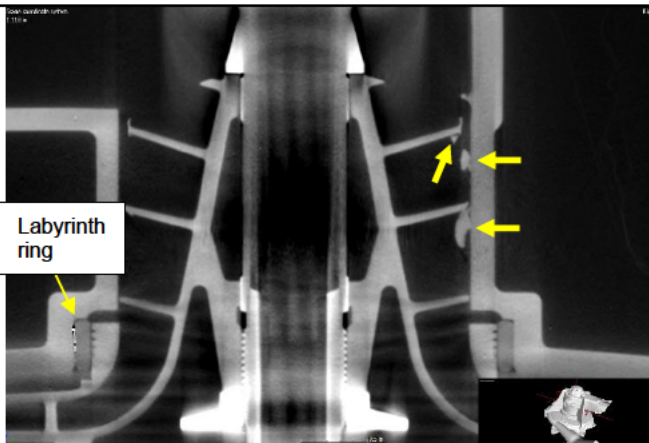
3D CT image showing the output of a comparison between the event housing and a nominal housing from inventory. The body of the event housing appeared well aligned with the geometry of the nominal housing. The inlet tube near the event location exhibited deviation as shown by the purple and pink coloration.

**Figure 36**

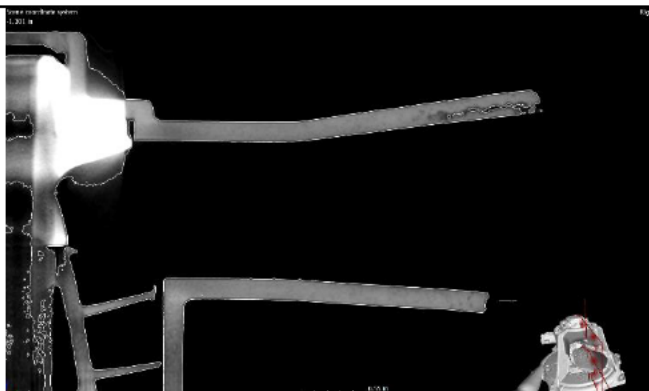
3D CT image showing the output of a comparison between the event housing and a nominal housing from inventory.

**Figure 37**

2D CT image showing a 2D cross section from the volumetric data set. The image shows a cross section of the inlet pump housing with the impeller assembly retained in the housing. The unit is in the as-received condition after disassembly of the fuel pump assembly.

**Figure 38**

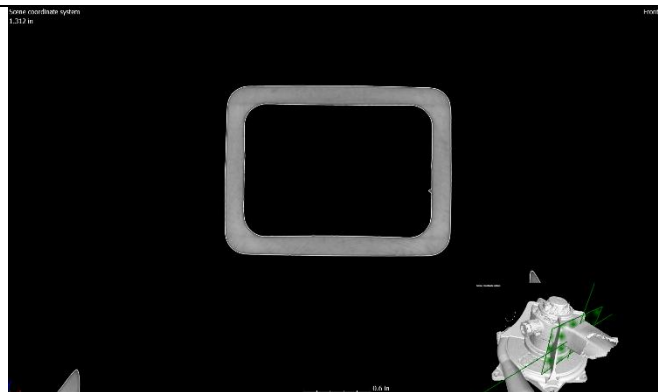
2D CT image showing evidence of material transfer to the interior surface of the inlet housing and inducer blade. The labyrinth ring between the impeller assembly and the input housing also appeared to be in good condition.

**Figure 39**

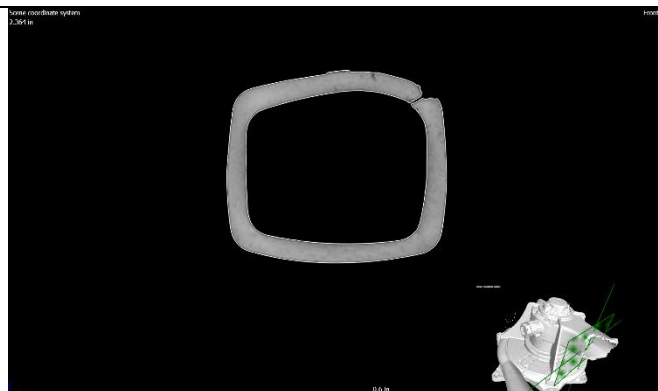
CT image showing a 2D cross section from the volumetric data set. Porosity and missing material were observed at the end of the inlet tube from the housing. The bright area of the image is the higher density leaded bronze bearing that absorbed some of the x-ray energy during the 3D CT scan.

**Figure 40**

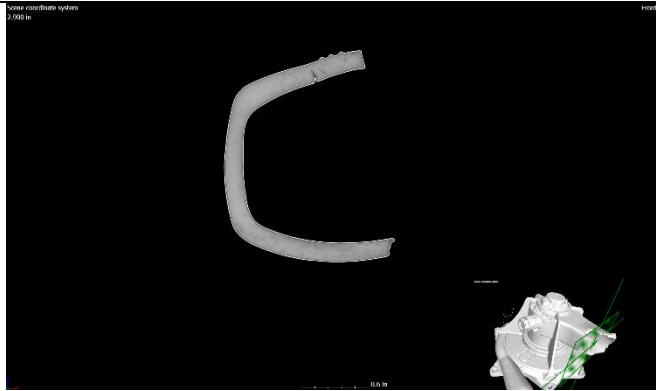
CT image showing a 2D cross section from the volumetric data set. The viewing plane was oriented 90 degrees to that shown in **Figure 39**. Porosity and missing material were observed at the end of the inlet tube from the housing.

**Figure 41**

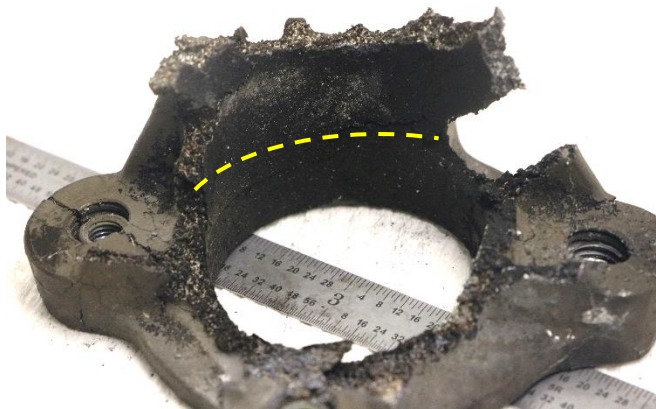
CT image showing a 2D cross section from the volumetric data set. The viewing plane was oriented transverse to the geometry of the inlet tube located near the body of the inlet housing.

**Figure 42**

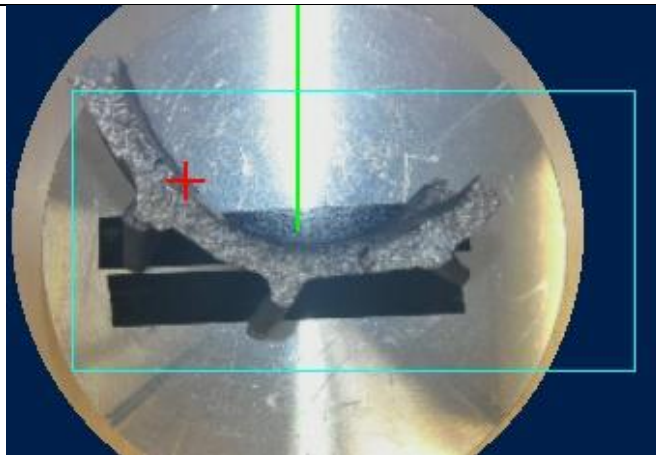
CT image showing a 2D cross section from the volumetric data set. The viewing plane was oriented transverse to the geometry of the inlet tube located near the body of the inlet housing. The image shows evidence of deformation of the tube at this location, with a linear indication and separation in the wall in the upper right of the tube.

**Figure 43**

CT image showing a 2D cross section from the volumetric data set. The viewing plane was oriented transverse to the geometry of the inlet tube located near the body of the inlet housing. The image shows continued deformation of the tube at this location.

**Figure 44**

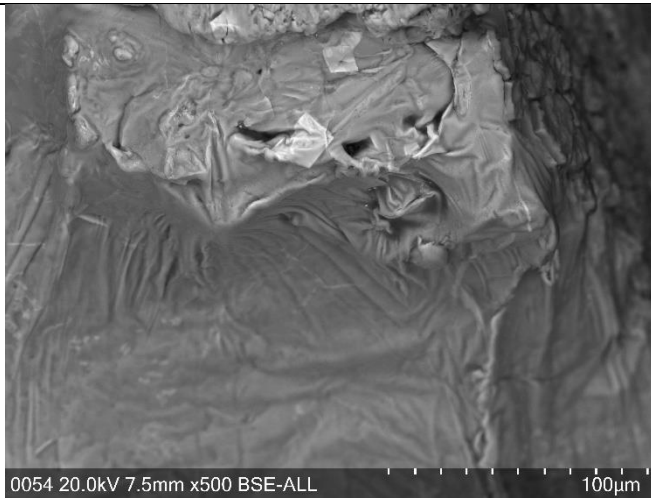
Optical image showing the housing flange after removal from the fuel inlet tube. The flange was sectioned transverse to separate the section of the failure surface standing proud of the mounting features to enable SEM analysis for more of the surface features (see dashed line for sectioning plane). The remnant pieces were then cleaned using a 1% Alconox solution to remove surface contaminants prior to analysis.

**Figure 45**

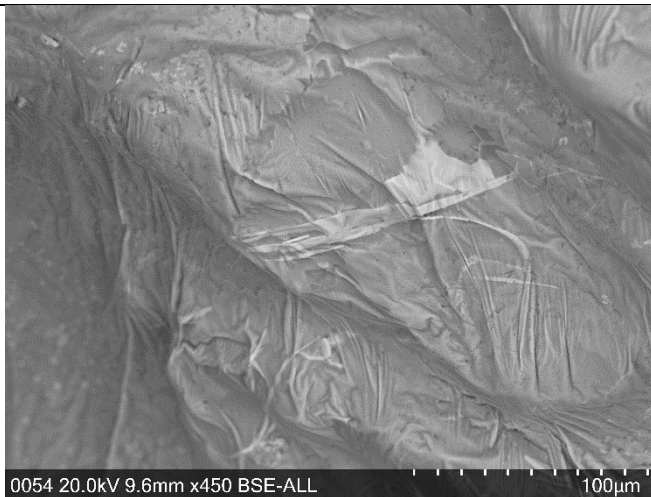
Optical image showing Section 1 of the housing flange remnant that was engine side. This piece was excised from the overall fracture to create a topographically uniform surface for SEM analysis.

**Figure 46**

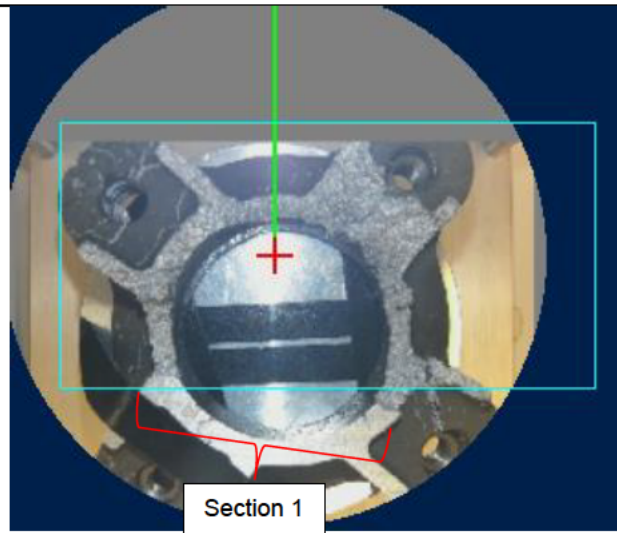
Representative SEM image showing the fracture surface from Section 1. The surface exhibited evidence of melting and re-solidification.

**Figure 47**

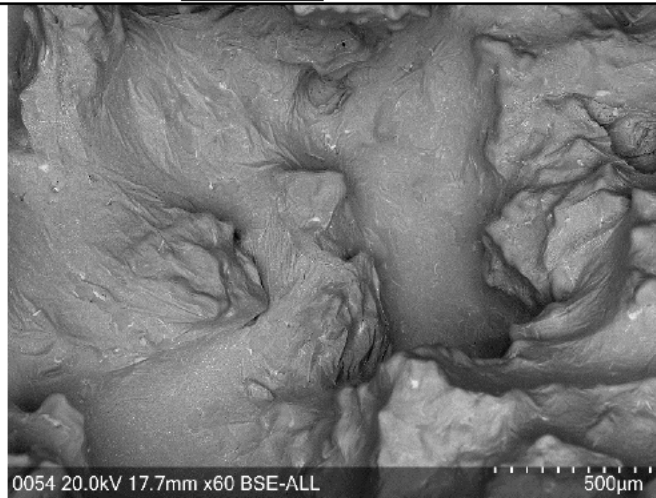
Representative SEM image at increased magnification showing the fracture surface from Section 1. The surface exhibited evidence of melting and re-solidification.

**Figure 48**

Representative SEM image showing the fracture surface from the middle of the wall thickness of Section 1. The surface exhibited evidence of melting and re-solidification as evidenced by the wrinkled appearance of the surface. No indications of a mechanical failure mode were observed at this location.

**Figure 49**

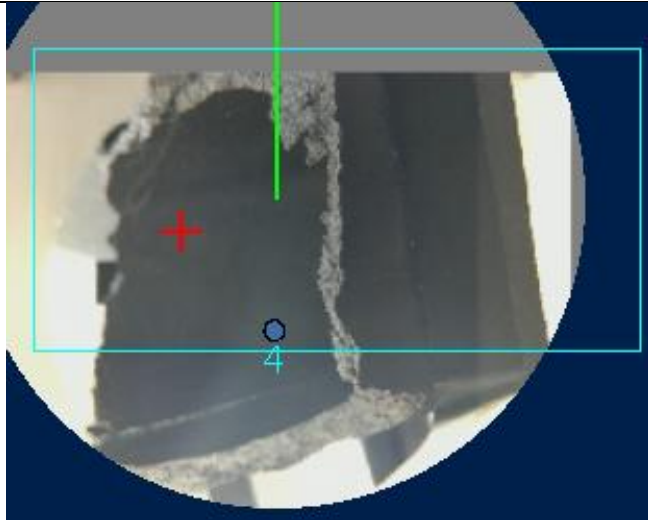
Optical image showing Section 2 of the housing flange remnant. The flat surface on the bottom is a cut surface and is the location from which Section 1 was excised. Removal of material from that location created a more uniform surface for SEM analysis of the remaining surfaces.

**Figure 50**

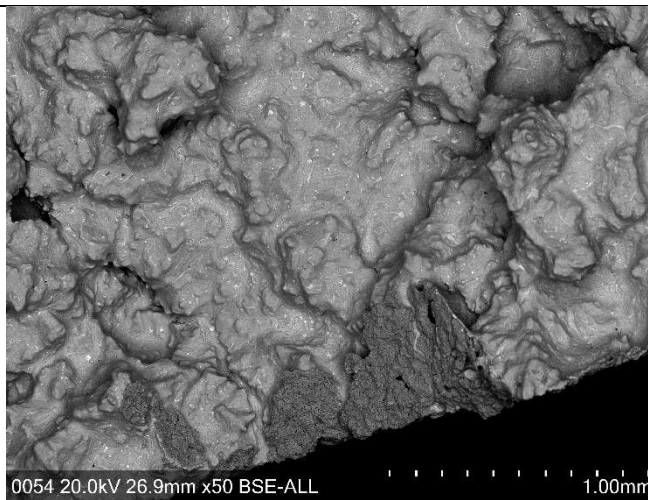
Representative SEM image from section 2 of the mounting interface showing evidence of a melted and re-solidified surface.

**Figure 51**

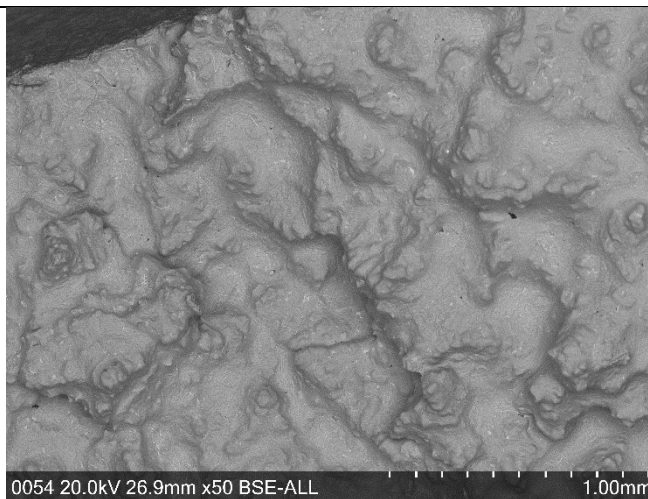
Representative SEM image from section 2 of the mounting interface showing evidence of a melted and re-solidified surface. The entirety of the fracture surface was examined at various magnification levels revealing similar features across this section.

**Figure 52**

Optical reference image showing the inlet housing fracture surface from the impeller side.

**Figure 53**

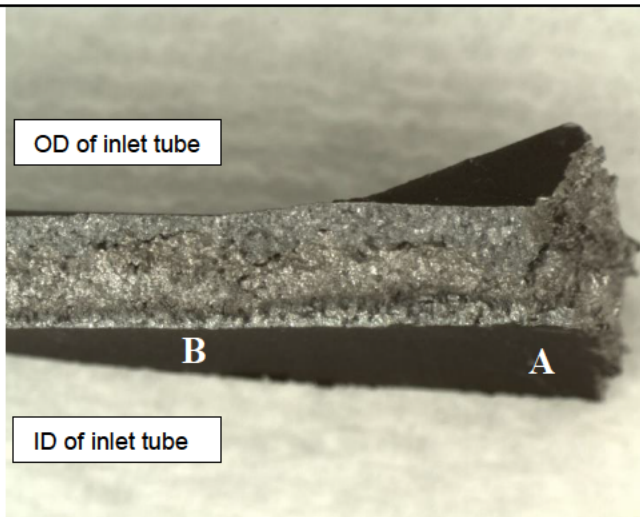
Representative SEM image showing the OD of the fracture surface from location 2. Evidence of melting and re-solidification was observed throughout the surface. The surface at location1 from this view / orientation exhibited similar features.

**Figure 54**

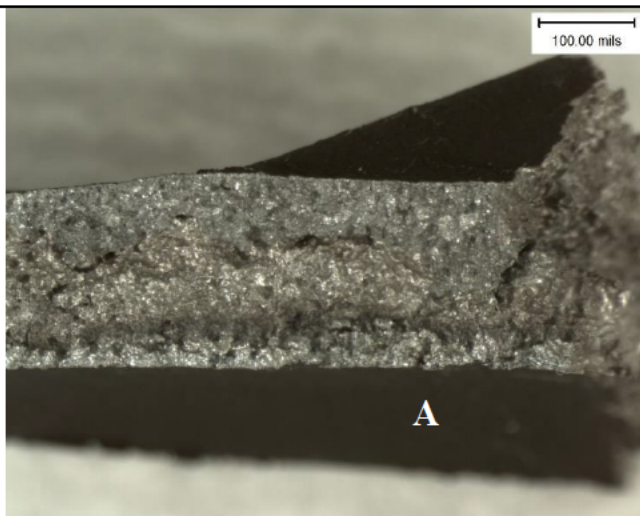
Representative SEM image showing the OD of the fracture surface from location 2. Evidence of melting and re-solidification was observed throughout the surface.

**Figure 55**

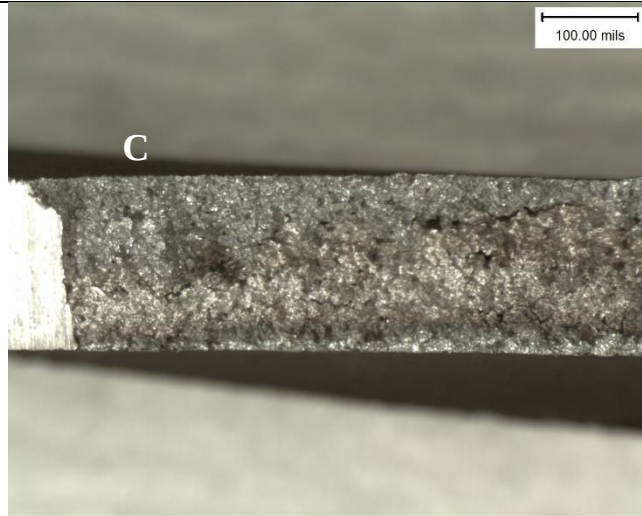
Representative SEM image showing the OD of the fracture surface from another viewing area of location 2. Evidence of melting and re-solidification were again prevalent throughout the surface.

**Figure 56**

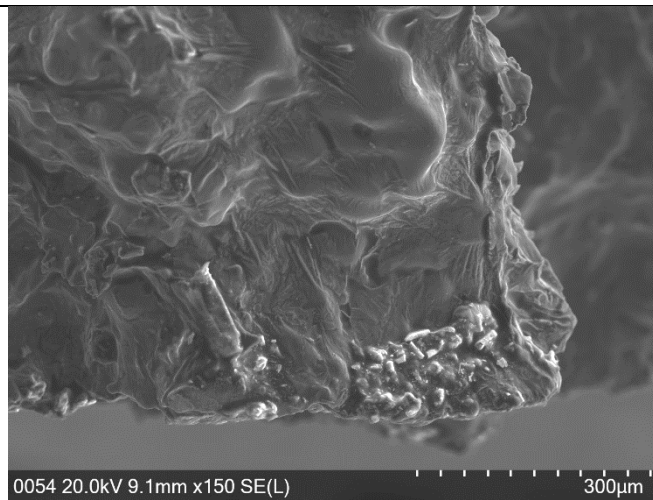
Optical image showing the exposed fracture surface after performing a lab overload failure. The ID and OD surfaces of the inlet tube are identified in the image. Locations A and B for SEM analysis are identified in this image.

**Figure 57**

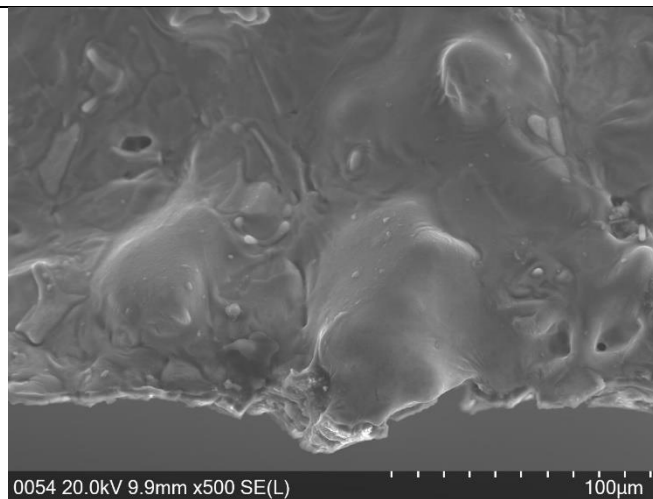
Optical image showing the end of the exposed secondary crack at increased magnification. Location A for SEM analysis is identified in this image.

**Figure 58**

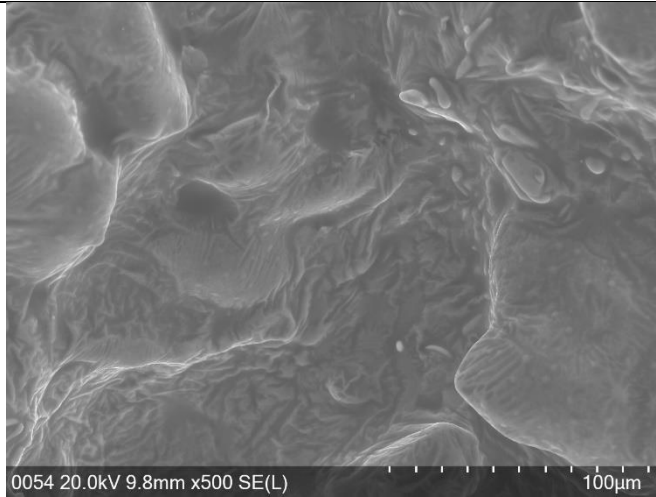
Optical image showing the back of the exposed secondary crack at increased magnification. The back cut surface where the end of the original crack was visually determined to be located is shown in the left side of this image. Location C for SEM analysis is identified in this image.

**Figure 59**

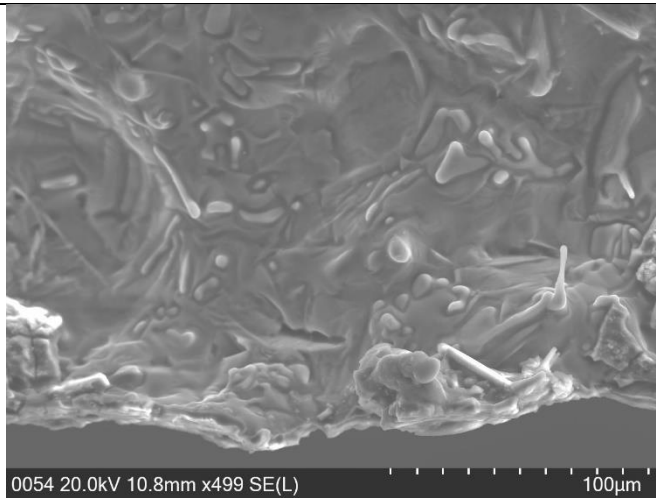
SEM image from location A along the ID of the tube showing a smooth surface and evidence of melting and re-solidification on the fracture surface.

**Figure 60**

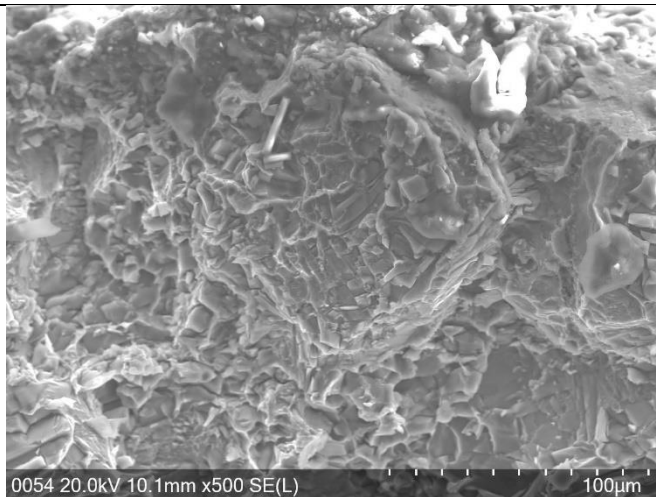
SEM image from location B along the ID of the inlet tube secondary crack showing a smooth surface consistent with melting and re-solidification.

**Figure 61**

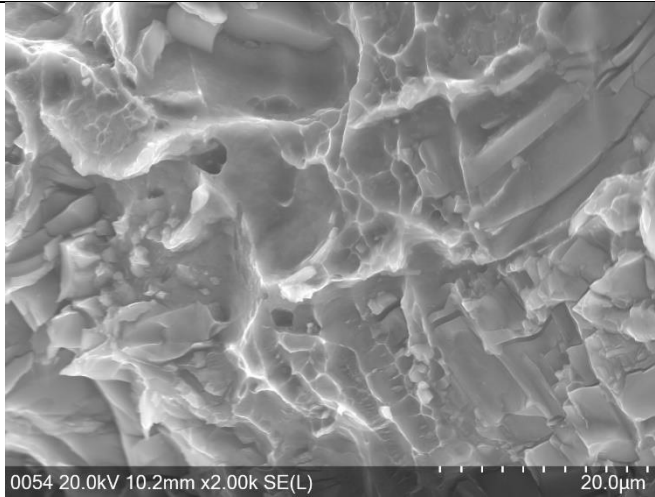
SEM image from location B in the middle of the wall thickness, showing a smooth surface consistent with melting and re-solidification.

**Figure 62**

SEM image from location C from the ID surface of the inlet tube showing evidence of exposure to elevated temperatures. The morphology of the silicon rich intermetallic particles within the aluminum matrix are globular in appearance. The surrounding aluminum matrix fracture surface was also smooth in appearance, consistent with a partially melted and re-solidified surface.

**Figure 63**

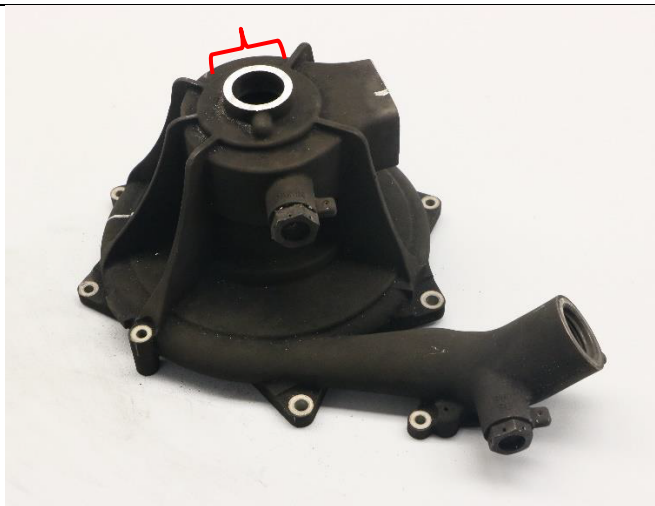
SEM image from location C from the OD surface of the inlet tube showing evidence of mechanical failure created during the lab overload testing to expose the secondary crack fracture surface.

**Figure 64**

SEM image at increased magnification from location C along the OD surface of the inlet tube and the same location that is shown in **Figure 63**. Evidence of ductile overstress rupture was observed at this location.

**Figure 65**

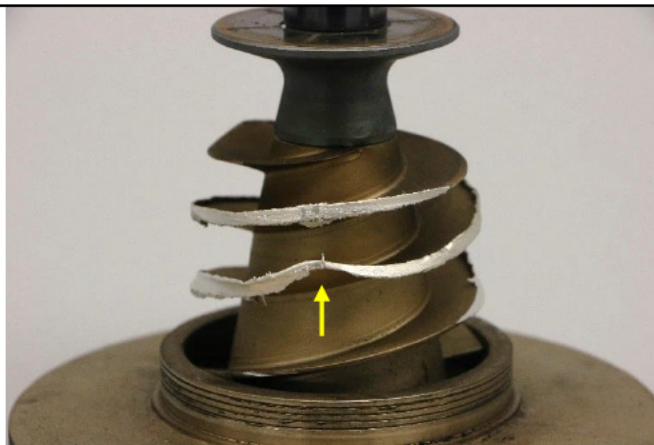
Optical image showing the impeller assembly that had been retained within the input housing after the failure event. It could not be removed without the aid of tools or other methods.

**Figure 66**

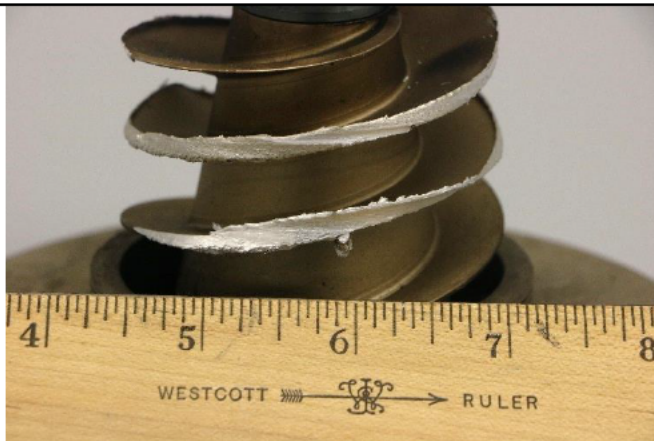
Optical image showing the input housing with the top end of the housing milled to expose the impeller assembly shaft for disassembly. The bearing, center shaft, and impeller assembly were accessible after material removal.

**Figure 67**

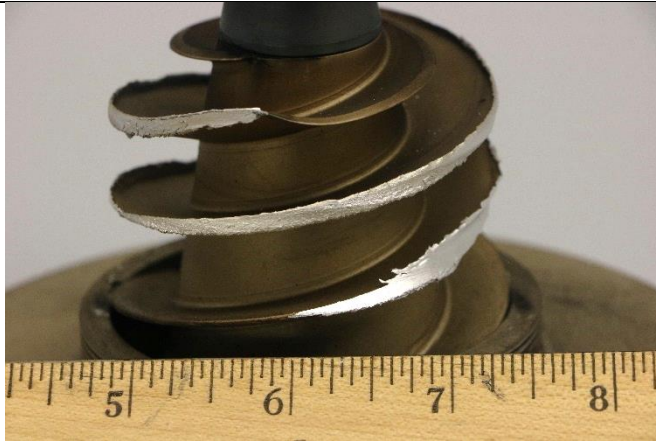
Optical image of the impeller assembly after removal from the fuel pump inlet housing. The edges of the inducer section were bright metallic in appearance after removal from the input housing.

**Figure 68**

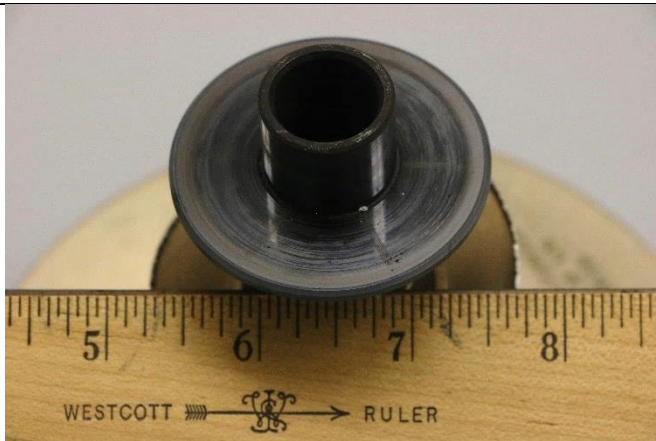
Optical image of the impeller assembly after removal from the fuel pump inlet housing. Deformation of the inducer blade was observed after removal. The deformation aligns with the location of adhered material on the interior surface of the housing observed during CT inspection of the assembly.

**Figure 69**

Optical image of the impeller assembly after removal from the fuel pump inlet housing.

**Figure 70**

Optical image of the impeller assembly after removal from the fuel pump inlet housing. The inducer blades were rotated to provide additional views of the component.

**Figure 71**

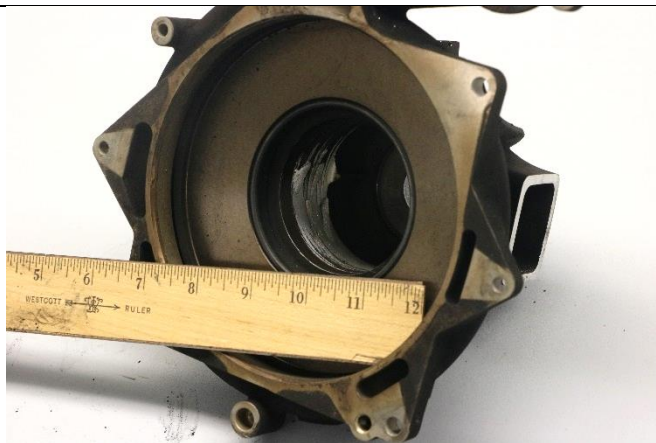
Representative optical image showing the wear surface from the top of the impeller assembly. This area exhibited no indications of wear marks or damage that would be consistent with entrapment of abrasive or foreign material.

**Figure 72**

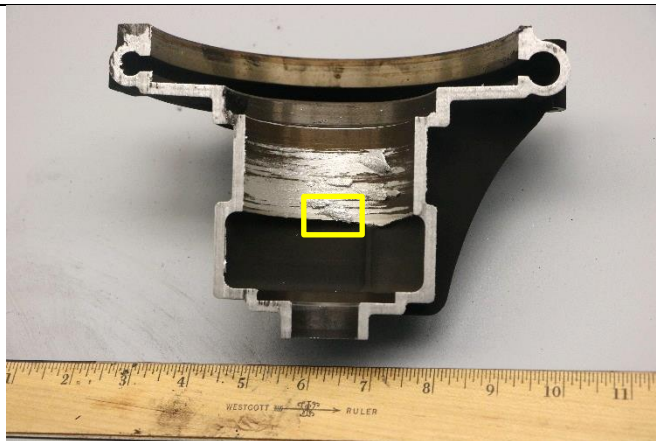
Optical image of the journal bearing showing the top or non-contact surfaces.

**Figure 73**

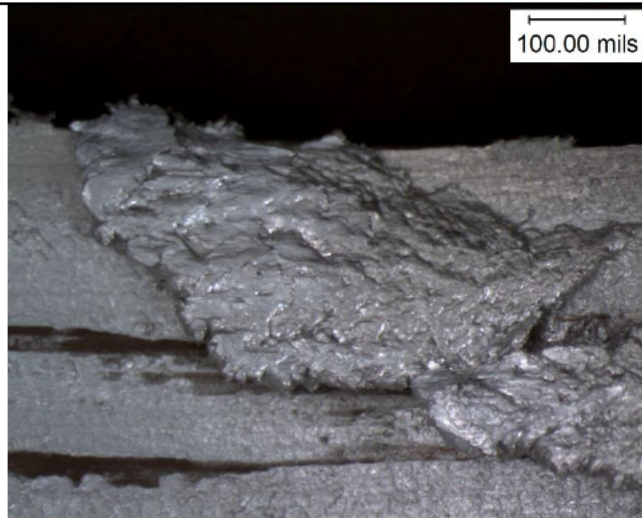
Optical image of the journal bearing. No evidence of material adhesion, adhesive failure, or material transfer was observed on the mating surface of the bearing.

**Figure 74**

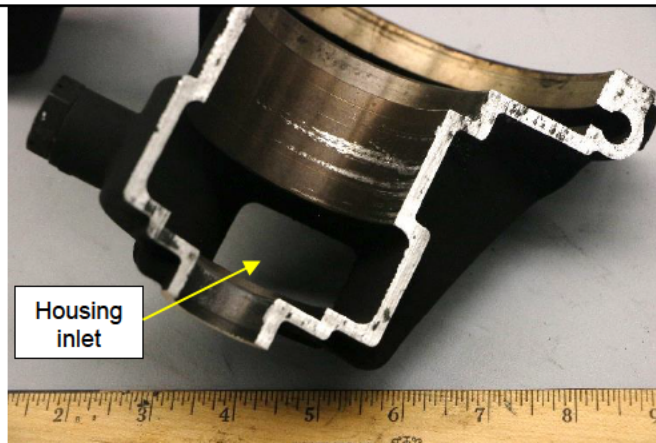
Optical image showing evidence of material transfer on the interior surface of the inlet housing.

**Figure 75**

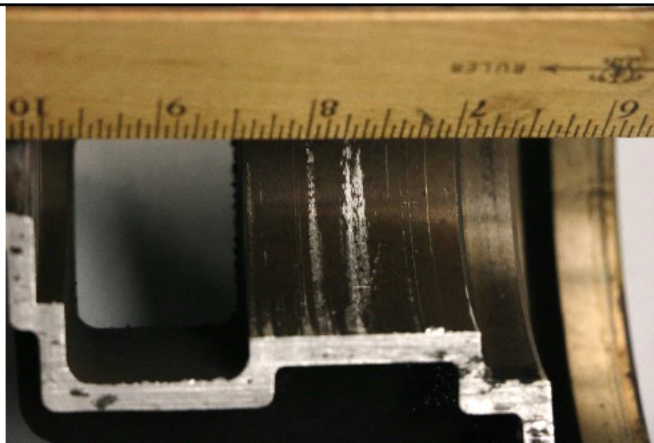
Optical image showing the interior surface of the input housing after removal of the impeller assembly. Material was found adhered to the surface that exhibited a lateral adhesion pattern consistent with the motion of the inducer during operation of the fuel pump. The side shown is from the discharge side of the housing.

**Figure 76**

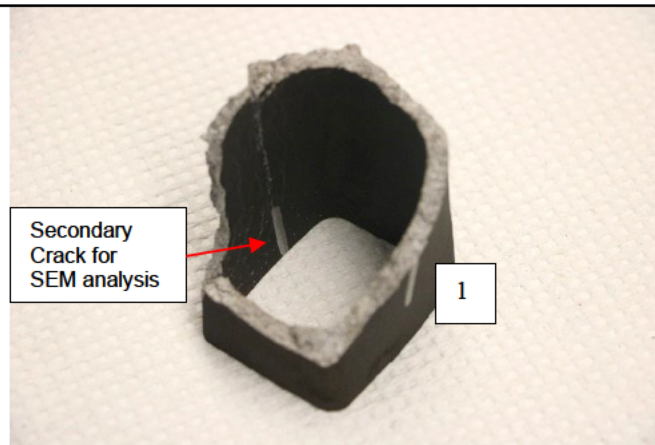
Optical image at increased magnification showing the adhered metallic material from **Figure 75**. A representative piece of adhered material was removed for X-ray fluorescent spectroscopy.

**Figure 77**

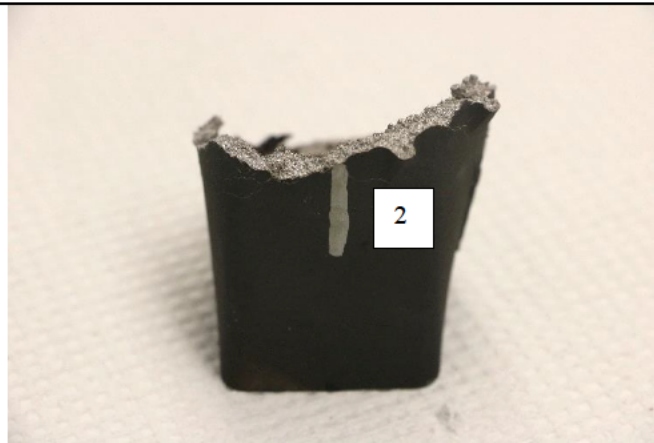
Optical image showing the interior surface of the input housing after removal of the impeller assembly. Evidence of adhered material was observed on the interior surface of the housing. The side shown is from the inlet side of the housing.

**Figure 78**

Optical image showing the interior surface of the input housing after removal of the impeller assembly. The pattern of adhered material is consistent with motion of the inducer during operation of the fuel pump.

**Figure 79**

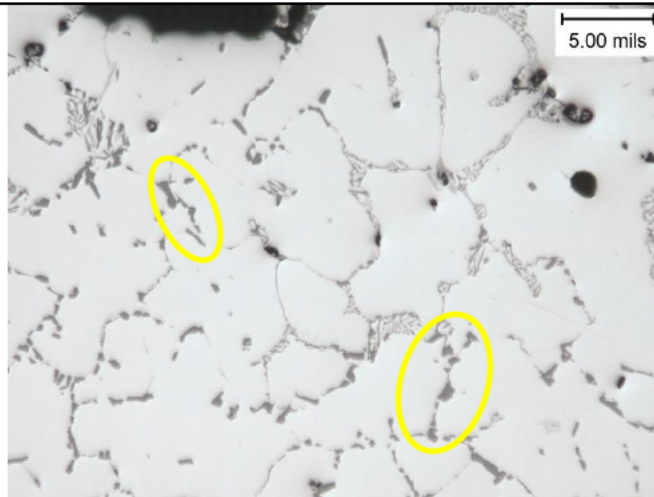
Optical image showing the location for sectioning of the inlet takeoff with the fracture surfaces. The interior mark denotes a secondary cut to open and expose a secondary crack in the longitudinal direction with respect to the direction of fluid flow. The fracture surface at this location was incorporated into the metallographic mount.

**Figure 80**

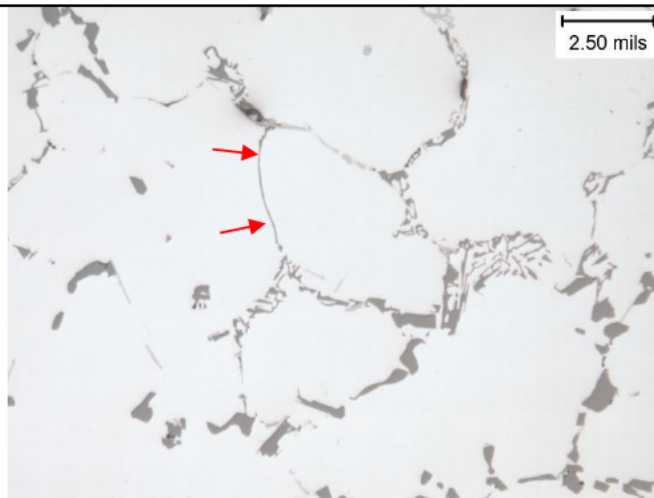
Optical image showing the location for sectioning of the inlet takeoff with the fracture surfaces. The fracture surface at this location was incorporated into the metallographic mount.

**Figure 81**

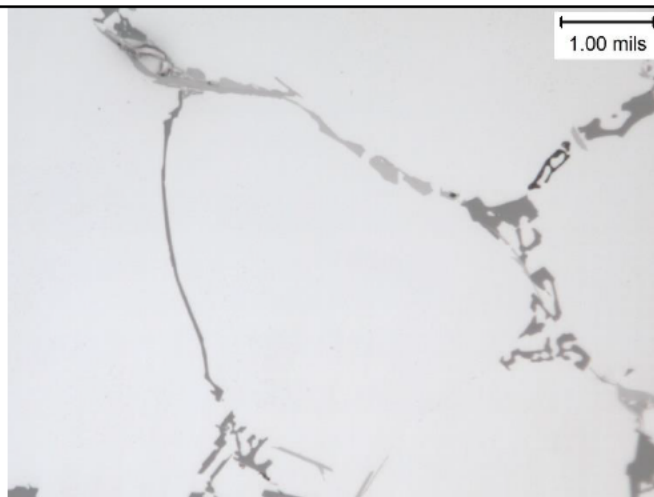
Metallographic image showing the cast aluminum base metal from Location 1 identified in **Figure 79**. Part of the fracture is captured within this image that primarily follows pre-existing grain boundaries within the material microstructure.

**Figure 82**

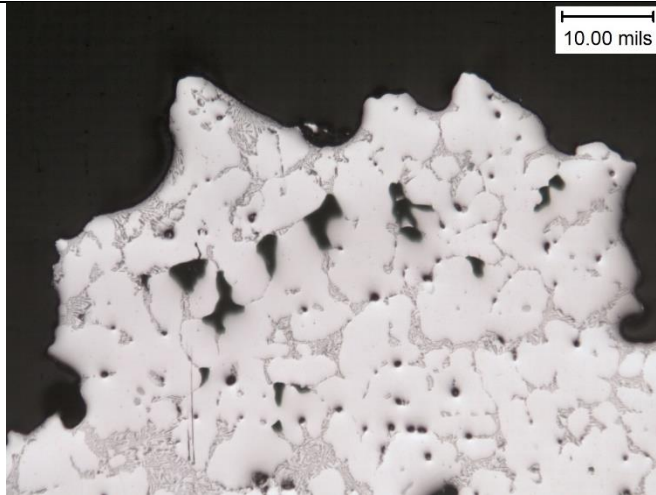
Metallographic image at increased magnification showing the cast aluminum base metal from Location 1 identified in **Figure 79**. Examination of the material microstructure revealed evidence of intermetallic growth in both overall size as well as along grain boundaries. The intermetallic features encircled in the image exhibit larger and more square / rectangular morphology.

**Figure 83**

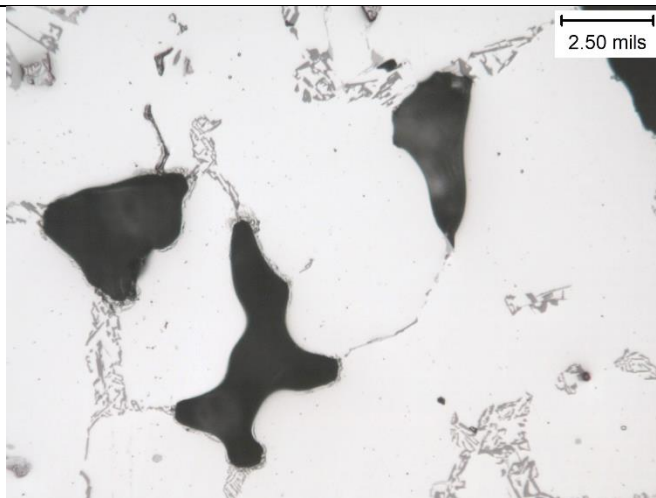
Metallographic image from location 1 showing the microstructure of the aluminum housing located immediately adjacent to the thermal event. The silicon rich intermetallics expanded in size, exhibiting a blocky appearance. The intermetallic constituent also forms a continuous layer along the grain boundary in discrete locations.

**Figure 84**

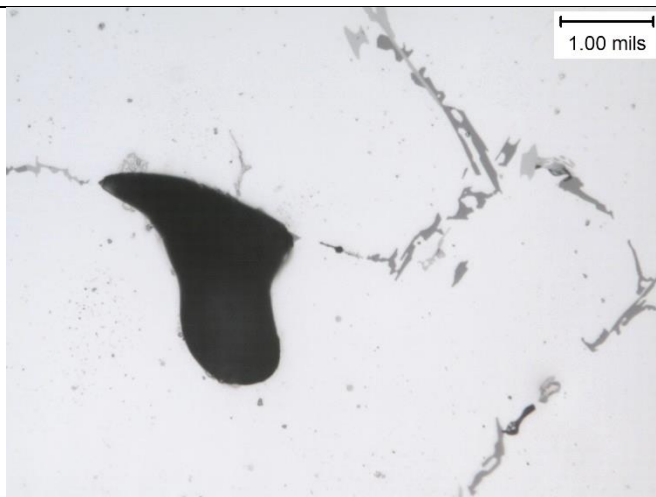
Metallographic image from location 1 at increased magnification showing a continuous intermetallic layer along a grain boundary as well as the block like / rectangular morphology observed throughout the microstructure at this location.

**Figure 85**

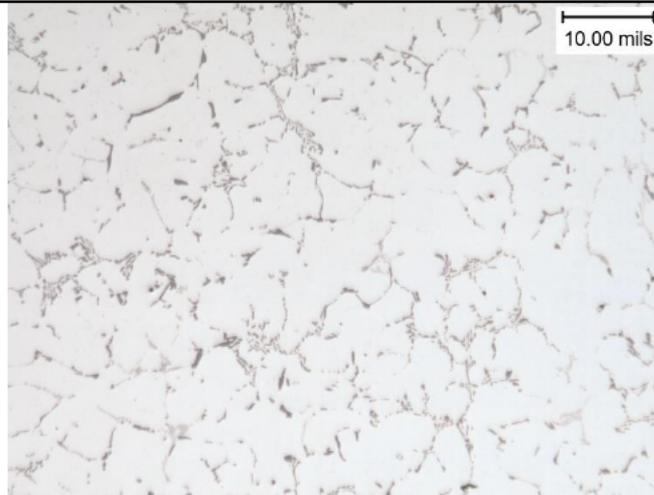
Representative metallographic image showing the microstructure from location 2 of the inlet tube shown in **Figure 80**. The top of the microstructure represents the edge of the failure location directly exposed to the thermal event. Porosity of varying size was observed throughout this location.

**Figure 86**

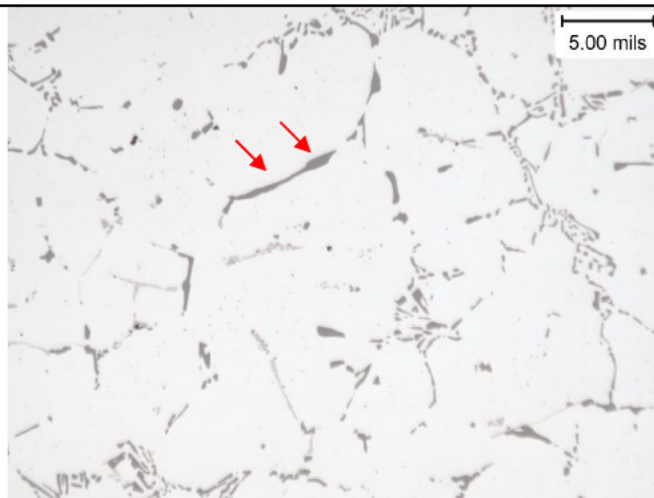
Representative metallographic image at increased magnification showing the microstructure from location 2. The silicon rich intermetallics propagated along grain boundaries, and in this image connected adjacent porosity indications.

**Figure 87**

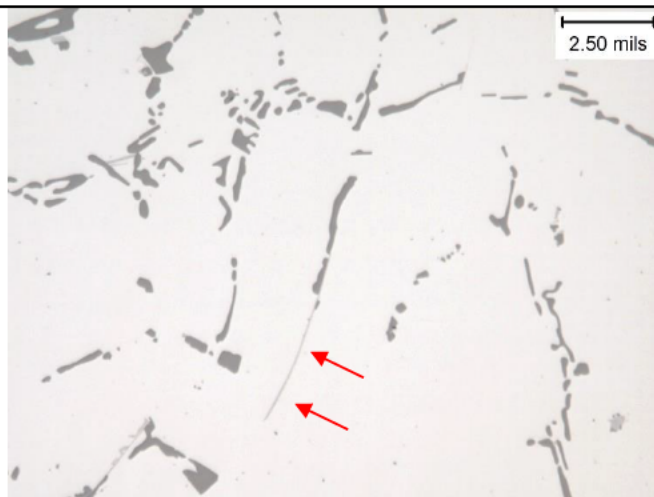
Representative metallographic image at increased magnification showing the microstructure from location 2. The silicon rich intermetallic morphology is angular and sharp in appearance, often connected through a grain boundary network.

**Figure 88**

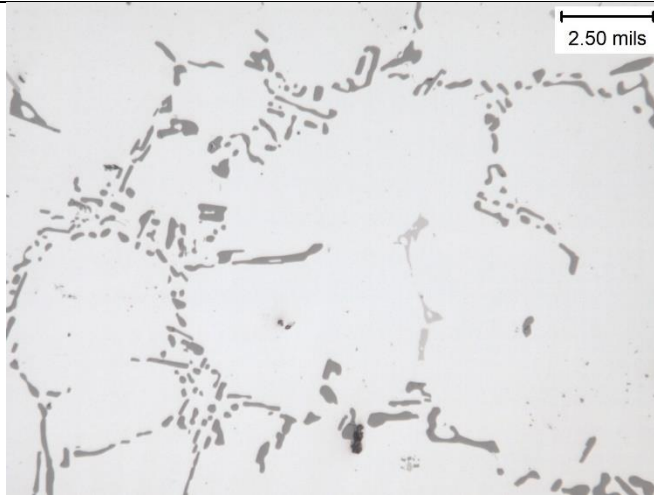
Metallographic image showing a cross section of the cast aluminum material from a location opposite thermal event location. The metallurgical microstructure was uniform in appearance but did exhibit grain boundary features not consistent with the defined heat treatment. Longer grain boundary features were observed scattered throughout the microstructure.

**Figure 89**

Metallographic image of the cast aluminum structure at increased magnification located opposite from the thermal event location. Limited effects from the failure event were observed in the microstructure at this location. Formation of the longer grain boundary intermetallic features were influenced by the elevated temperature inducing a localized overaging effect on the cast aluminum material at this location.

**Figure 90**

Metallographic image of the cast aluminum structure at increased magnification. The silicon rich intermetallics generally exhibited an appearance consistent with the heat treatment defined by the engineering drawing. The long, thin feature is an example of the intermetallic phase propagating along the grain boundary as a result of the heat input from the failure event.

**Figure 91**

Metallographic image of the cast aluminum structure at increased magnification showing a section of the cast material exhibiting evidence of a good response to heat treatment. The individual intermetallic particles are rounded and well distributed with very few larger particles along grain boundaries.

**Figure 92**

Representative image showing the direct hardness test indentation made using a 100kg load and 1/16" ball indenter for the Rockwell A scale. The material hardness was too low to obtain a measurement and created the indentation shown in the image during application of the test load.