NEW JERSEY DIVISION OF FIRE SAFETY

Firefighter Fatality and Serious Injury Report Series

Volunteer Firefighter Injured Upon Being Struck by Pieces of a Large Diameter Hose Appliance after it Failed Catastrophically

Hampton, New Jersey
July 27, 2009

Report Issued
January 25, 2012

STATE OF NEW JERSEY
Chris Christie, Governor

DEPARTMENT OF COMMUNITY AFFAIRS
Richard E. Constable III, Acting Commissioner

DIVISION OF FIRE SAFETY
William Kramer Jr., Acting Director

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Failure Analysis of Fire Hose Appliance Report

INTRODUCTION

The investigation of this incident was conducted by the New Jersey Division of Fire Safety / State Fire Marshal. This report was prepared in accordance with N.J.S.A. 52:27D – 25d, Duties of the Division.

The purpose of firefighter casualty investigations is to report the causes of serious firefighter injuries or deaths and identify those measures which may be required to prevent the future occurrence of deaths and serious injuries under similar circumstances. In some cases new information may be developed, or old lessons reinforced, in an effort to prevent similar events in the future.

Comments and/or inquiries concerning this report may be addressed to the address listed below:

New Jersey Department of
Community Affairs
Division of Fire Safety
101 South Broad Street
P.O. Box 809
Trenton, NJ 08625-0809

GLOSSARY OF TERMS

Fire Apparatus Designations:

E – Engine
SQ – Squad
L – Ladder
R – Rescue

Personnel Designations:

FF – Firefighter
DC – Deputy Chief
SO – Safety Officer
BC – Battalion Chief
IC – Incident Commander

CISD	Critical Incident Stress Debriefing
EMS	Emergency Medical Service
ICP	Incident Command Post
IDLH	Immediately Dangerous to Life & Health
IMS	Incident Management System
NFIRS	National Fire Incident Reporting System
LDH	Large Diameter Hoseline
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety & Health
NJDFS	New Jersey Division of Fire Safety
PAR	Personal Accountability Report
PASS	Personal Alert Safety System
PEOSH	Public Employees Occupational Safety & Health
PPE	Personal Protection Equipment
RIC	Rapid Intervention Company
SCBA	Self-Contained Breathing Apparatus
TIC	Thermal Imaging Camera
UASI	Urban Area Security Initiative

*NOTE: Some terms may not be used in this report.

EXECUTIVE SUMMARY

On Monday, July 27, 2009, at approximately 1920 hours, the Hampton Township, Sussex County Fire Rescue (HTFR) was conducting a training drill on the campus of the Sussex County Community College. The training drill involved shuttling water that was drafted from a pond on the campus, pumped into fire department water tenders and then transported to the other side of the pond. At the end point of the water shuttle, the contents of the tenders was dumped into above ground portable tanks where it would have been utilized to fight an actual fire had there been one at that location.

At the college campus the water was being drafted out of the pond by Engine 4862 (E-4862) and then pumped through a five inch diameter hose that terminated on the other end into a large diameter hose (LDH) appliance commonly referred to as a manifold. This manifold was used to convert the one five-inch hose that was feeding it into a maximum of four 2.5” hose discharges. Each discharge was equipped with a valve that could control the flow of water. On the night of the drill however, there were only two 2.5” hoses attached to the manifold. Each of these 2.5” hoses were then used to fill the water tenders. When a particular tender was full of water, the valves on the manifold would be closed, the hoses disconnected from the full water tender and then connected to the next tender to begin the process again. After two such fill cycles, Firefighter Rebecca Crawford was instructed to close the valves on the manifold as the third tender being filled was full. FF Crawford leaned over the manifold and began closing the valves simultaneously. With the valves approximately halfway closed, FF Crawford stated she heard a loud sound and just after that the manifold ruptured. The manifold roughly split in two with the top piece coming up and striking FF Crawford between the upper thighs and lower abdomen. The force of the object striking her lifted her off the ground and knocked off her fire boots and helmet. She was knocked unconscious for a short time and was treated by EMTs who were on location. She was ultimately transported by NJ State Police NorthStar helicopter to Morristown Memorial Hospital for treatment.

The NJ Division of Fire Safety / State Fire Marshal were promptly notified after the incident and within one hour had an investigator on location. The remains of the manifold were impounded by the investigator for future analysis.

ACCIDENT FACTORS / REMEDIES

In order to prevent a reoccurrence of this type of incident, NJDFS investigators identified key issues that must be addressed and remedies that should be implemented within all departments.

1. **FACTOR:** After exhaustive testing by a competent metallurgical testing laboratory it was determined that the failure of the LDH manifold was due to several factors including: the material had little to no fracture toughness, the casting quality was poor, the casting contained numerous voids, large casting defects (voids) were present in the housing wall at the threaded inlet, slag or dross (containing sodium, silicon, oxygen, iron, sulfur, and other elements) was present within some of the voids.

   REMEDY: *Better manufacturing practices would improve the fracture toughness of the casting by reducing the size and number of voids, removing slag or dross from the casting, assuring there is no trapped hydrogen to cause voids, improving the microstructure to minimize the deleterious effects of sharp, brittle second phases through various measures such as better control over solidification times, alloy modification, etc. Use of an alloy such as A356 with lower iron content would reduce the number of brittle second phase particles. Post-manufacturing inspection using x-rays could help to identify castings with large voids.*

2. **FACTOR:** The fire department did not conduct adequate testing of the manifold device; especially with regard to the pressure relief valve.

   REMEDY: *Manifolds such as the one that ruptured resulting in the serious injuries to FF Crawford should be tested and maintained in accordance with manufacturer's recommendations and applicable standards of the National Fire Protection Association (NFPA).*

3. **FACTOR:** FF Crawford was leaning over the manifold at the time of its failure which exposed her to a direct impact of large pieces of the device.

   REMEDY: *Firefighters should be instructed regarding the potential dangers involved with any pressurized equipment utilized by fire departments. Firefighters should always exercise appropriate care and utilize proper personal protective equipment (PPE) while handling and operating items such as this and positioning themselves in such a way as to minimize the potential harm they might suffer should a failure occur. In this particular instance FF Crawford was wearing appropriate PPE including helmet, turnout coat and pants, gloves and boots.*

INVESTIGATION

The Incident

On Monday, July 27, 2009, at approximately 1920 hours, the Hampton Township, Sussex County Fire and Rescue (HTFR) were conducting a training drill on the campus of the Sussex County Community College. The training drill involved shuttling water that was drafted from a pond on the campus, pumped into fire department water tenders and then transported to the other side of the pond. At the end point of the water shuttle, the contents of the tenders were dumped into above ground portable tanks where it would have been utilized to fight an actual fire had there been one at that location.

At the college campus the water was being drafted out of the pond by Hampton Engine 4862 (E-4862) and then pumped through a five inch diameter hose that terminated on the other end into a large diameter hose appliance commonly referred to as a manifold. The manifold that was being used was manufactured by Snap-tite Hose Company of Erie Pennsylvania. This manifold was used to reduce and divide the one five-inch hose that was feeding it into smaller 2.5 inch hose discharges. Each of these discharges was equipped a one-quarter turn ball type valve that could control the flow of water. The body of the appliance was constructed from cast aluminum and manufactured by means of a method known as “sand casting.” This process involves the casting of a material; in this case aluminum, in a mold made of sand. The device was equipped with a five inch intake fitted with a Storz coupling. On the discharge side of the appliance were four 2.5 inch discharges fitted with threaded couplings. There was also a five inch discharge fitted with a Storz coupling that would allow water to flow straight through the device if desired. All discharges were equipped with quarter-turn ball valves and metal handles to allow for the channeling of the water in any configuration desired. Additionally, the appliance was equipped with an automatic spring loaded adjustable pressure relief valve as well as a pressure gauge. The relief valve was designed to be set at a maximum allowable pressure as determined by fire department operations and when that pressure was reached, the valve would open and discharge excess water pressure. According to documentation supplied by the manufacturer, the valve was adjustable between 100 and 200 psi. The default factory setting for the valve is 150 psi. It was not able to be determined at what pressure the valve on the HTFR appliance was set at the time of the incident.

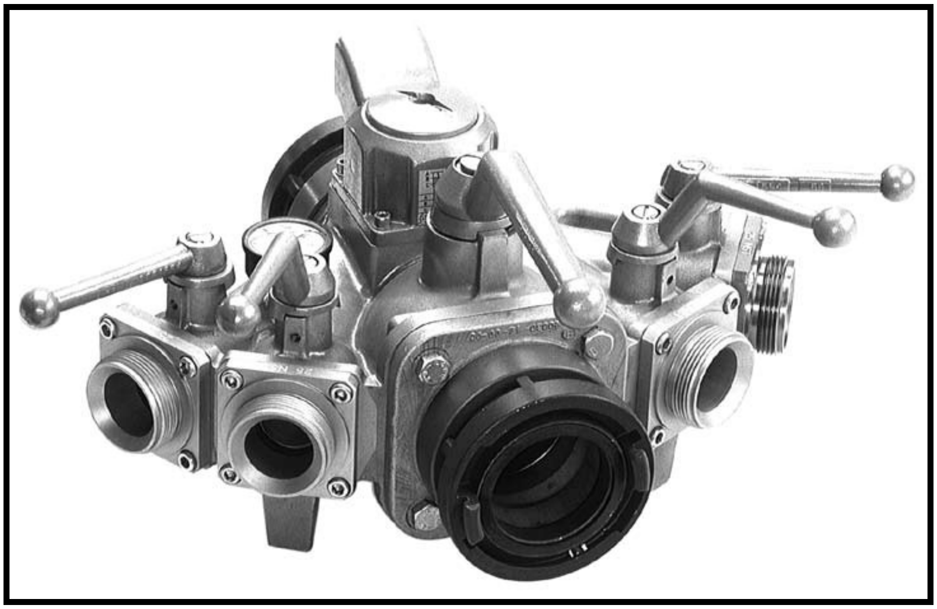

Figure 1 - Typical example of a Snap-tite Manifold & Relief Valve.
The HTFR manifold was identical to this depiction.

On the night of the drill only two 2.5 inch discharges were being utilized. Each discharge had a 2.5 inch hose attached. These 2.5 inch hoses were then used to fill the water tenders. The five inch discharge was not utilized and remained closed for the entire evolution. When a particular tender was full of water, the valves on the manifold would be closed. The hoses would then be disconnected from the full water tender and connected to the next tender to begin the process again.

After two such fill cycles Firefighter Rebecca Crawford, an 18 year old recruit with less than one year of service with the HTFR was instructed to close the valves on the manifold as the third tender being filled was full. Crawford was working with FF Brian Farence who had previously operated the appliance and was instructing her on how the manifold worked. Crawford asked Farence if she should close each valve separately to avoid a “water hammer” effect. Water hammer is defined as:

> *“a pressure surge or wave resulting when a fluid (usually a liquid but sometimes also a gas) in motion is forced to stop or change direction suddenly (momentum change). Water hammer commonly occurs when a valve is closed suddenly at an end of a pipeline system, and a pressure wave propagates in the pipe. It may also be known as hydraulic shock.”*

FF Farence told her it was all right to shut the valves at the same time but instructed her to ensure that the valves were closed slowly. FF Crawford leaned over the manifold and began closing the valves simultaneously. With the valves approximately halfway closed, FF Crawford stated she heard a loud sound and just after that the manifold ruptured. The manifold roughly split in two with the top piece coming up and striking FF Crawford between the upper thighs and lower abdomen. The force of the object striking her lifted her off the ground and knocked off her fire boots and helmet. She was knocked unconscious for a short time and immediately treated by EMTs who were on location. She was ultimately transported by NJ State Police NorthStar helicopter to Morristown Memorial Hospital for treatment.

Figure 2 - Main portion of manifold after the failure.

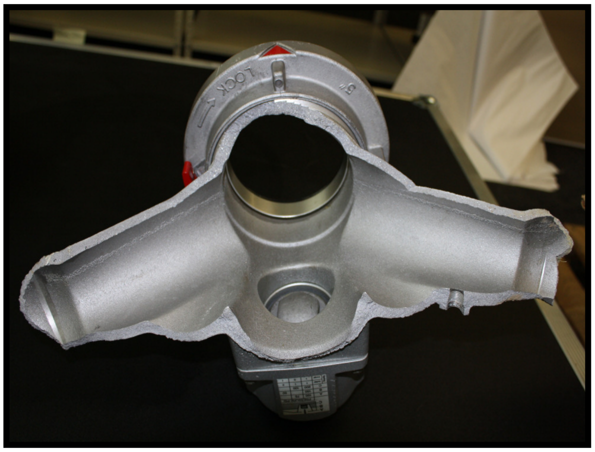

Figure 3 - Upper portion of the manifold after the failure. This is the section that struck FF Crawford (piece is lying upside down).

The NJ Division of Fire Safety / State Fire Marshal were promptly notified after the incident and within one hour had an investigator on location. The remains of the manifold were impounded by the investigator for future analysis.

The Casualty Scenario

FF Rebecca Crawford was an 18 year old member of the Hampton Fire Department with less than one year of firefighting experience as a senior member. She also had approximately three years of service with the Branchville, Sussex County Fire Department as a Junior Firefighter. As a result of this incident she suffered severe bruising in the area of her body that was impacted by the manifold part and required extensive physical therapy for her legs. She also suffered lacerations to her head. Fortunately she suffered no internal injuries. She remains an active member of the department.

Fire Department Profile

The HTFR is a volunteer fire department with 70 firefighters, one Lieutenant, one Captain, and one Deputy Chief operating under the direction of a Fire Chief. The EMS command staff consists of one Captain and two Lieutenants. The HTFR serves a population of approximately 5,000 over an area of 25.3 square miles. The department operates a fleet of fire and rescue apparatus consisting of two engines, one water tender, one light duty rescue, two BLS ambulances and an incident command vehicle. The department is dispatched by the Newton Police Department. The most current National Fire Incident Reporting System (NFIRS) records indicate that EFD responded to 340 calls for service at fire incidents and over 600 EMS responses in 2010.

ANALYSIS

**Note: Due to the highly technical nature of this investigation, the painstaking process of gathering data was prolonged and resulted in a delay in the issuance of the report.*

The following items are areas identified by NJDFS investigators as impacting directly upon the outcome of this incident:

Firefighter Crawford's Actions and Observations

Following the incident, members of the HTFR including FF Crawford were interviewed by DFS investigators regarding the actions that were undertaken at the drill. FF Crawford's statements were especially important as she was ultimately at the center of the event.

Since this event was a singular occurrence that happened very rapidly, information relating to the time just prior to the failure was of prime importance; particularly Crawford's knowledge of the operation of the device, how she operated it and what she observed when the device was operated previously by other firefighters.

FF Crawford stated that during the drill she did not observe the manifold's pressure relief valve operate. Other firefighters that were interviewed also did not observe the pressure relief valve operating. It was reported that the pump operating pressure on E-4862 was approximately 120-125 psi when the manifold was under pressure and flowing water through it. However, it was reported by one firefighter that when water was not flowing, the pressure at the pump was as high as 200 psi. This assertion could not be conclusively confirmed as there were discrepancies between the recollections of those interviewed.

When it was time for FF Crawford to close the valves on the manifold, it was reported that the operator of E-4862 was notified that the manifold valves were being closed and in response to this notification, the pump pressure would be reduced accordingly. It was not possible during the investigation after the fact to conclusively determine if the pump pressure had been reduced prior to; simultaneously; or after the valves on the manifold had been closed. FF Crawford stated during her interview that she was aware of the concept of "water hammer" and demonstrated a thorough understanding of it to investigators. Further, as stated previously in this report, she asked FF Farence how she should close the valves to prevent this phenomenon from occurring. Crawford stated that in response to Farence telling her to close the valves slowly, she did just that. As part of the investigation and inspection of the failed manifold, the valves were operated by a DFS investigator and found to be reasonably tight and slightly difficult to operate while not under water pressure. Thus it is unlikely that the valves would have been closed rapidly while under pressure. The inspection also showed that the valves that had been used the night of the incident had not exhibited any damage as a result of the event.

Metallurgical Testing of the Manifold

As stated previously in this report, an Investigator from the Division of Fire Safety / State Fire Marshal's Office responded to the scene of the accident and impounded the manifold to preserve it for metallurgical testing that was anticipated to be conducted in the future.

Division Investigators conducted interviews with those involved with the incident to determine the specific actions and events leading up to the manifold's rupture and obtain any other pertinent information regarding the manifold itself and its history. It was learned that the manifold was purchased by the department in April of 2003 and had been in regular service since that time. There were no reports of any previous issues or problems with the device. Fire Department personnel reported that the device's pressure relief valve had not been tested in the recent past in accordance with manufacturer's recommendations but they stated that the relief device had operated during use of the manifold at previous drills and fire incidents.

After interviews were completed, Division Investigators began the process of seeking out governmental agencies that might have the necessary equipment and expertise to perform metallurgical analysis of the manifold. The purpose of this type of testing would be the identification of defects in the metal of the device that could have contributed or directly caused its failure. In all, 13 state and federal governmental agencies were contacted; most notably among them the National Institutes for Safety and Health (NIOSH), the Consumer Product Safety Commission (CPSC), the National Institutes of Standards and Technology (NIST), and the National Aeronautics and Space Administration (NASA). None would agree to provide the requested testing of the device.

Investigators then contacted the Metallurgy Department of Rutgers University. The department chair agreed to examine the device but cautioned the university had limited ability to perform the full scope of testing that would be required to conclusively determine the cause of the failure. He stated that his examination would only point to possible failure causes but that further testing by a metallurgical laboratory would still be required.

The remains of the device were brought to the Rutgers University in New Brunswick, New Jersey. Upon examination the following conclusion was offered:

> *The failure origin was traced on the two pieces using chevron marks on the fracture surface to an area flush with the last thread on the coupling flange.*

> *This was approximately ¼" anticlockwise from the arrow mark on the flange next to the word "LOCK."*
>
> *An examination of the interior casting surface shows a crack running normal to the threads and opening slightly as it proceeds inwards on the casting. About equidistant from the end of the casting and the exposed fracture cross section is a dark, protruding inclusion with the crack located between the inclusion and the metal. The crack emanates from the inclusion in both directions. There is offset in the direction normal to the crack on the inner surface of the casting.*
>
> *It appears that the inclusion was the start of/origin of the failure. For further study, destructive methods would need to be employed. The flange would require removal and the fracture associated with the inclusion carefully spread and examined to develop a more complete understanding of the probable time history of initiation of the failure. It is quite likely that such examination will show formation of an initial crack at the inclusion/metal interface which propagated until a critical catastrophic failure dimension was reached.*

Following this initial evaluation of the manifold, a search for private testing laboratories was initiated.

After identifying several laboratories capable of performing the required testing and receiving price quotations, Corrosion Testing Laboratories (CTL) of Newark, Delaware was selected. The manifold was transported to the laboratory by a Division Investigator to maintain the chain of evidence custody. After extensive testing and analysis performed by CTL over the course of three months including optical stereomicroscopy, energy dispersive x-ray spectroscopy, Charpy V-notch impact testing and atomic emission spectroscopy, the following is the summary of conclusions and recommendations reached:

- *The manifold ruptured when brittle fracture propagated through the material.*
  - *Charpy V-notch tests confirmed the material had little to no fracture toughness.*
  - *The microstructure contained long, needle-like brittle second phase particles.*
- *The casting quality was poor:*
  - *The casting contained numerous voids.*
  - *Large casting defects (voids) were present in the housing wall at the threaded inlet. These voids took up a significant percentage of the wall thickness.*
  - *Slag or dross (containing sodium, silicon, oxygen, iron, sulfur, and other elements) was present within some of the voids.*
  - *Fracture likely initiated at these casting defects.*

- *The alloy conformed to UNS A03560, i.e., aluminum-silicon casting alloy.*
- *The tensile properties appear to be consistent with Alloy 356 in a T6 temper.*
- *Better manufacturing practices would improve the fracture toughness of the casting:*
    - *Reduce the size and number of voids,*
    - *Remove slag or dross from the casting,*
    - *Assure there is no trapped hydrogen to cause voids,*
    - *Improve the microstructure to minimize the deleterious effects of sharp, brittle second phases through various measures such as better control over solidification times, alloy modification, etc. These measures are routinely done in aluminumsilicon casting alloys.*
    - *Use of an alloy such as A356 with lower iron content would reduce the number of brittle second phase particles.*
- *Post-manufacturing inspection using x-rays could help to identify castings with large voids.*
- *It is possible or even likely that there are other manifolds in existence at risk for rupture due to similar causes. It may be prudent to undertake an inspection program to try to identify those parts and remove them from service.*
- *The relief valve should be tested to determine whether it was working correctly. However, the valve may not be designed to relieve transient stresses, which may have occurred in the manifold.*

Figure 4 - Note the large voids in the cut surface of the casting wall.

LESSONS LEARNED

The following items are areas identified as ways to correct issues regarding this incident and other general items designed to make incident scenes safer and more efficient:

Manifold Inspection

Manifolds such as the one that ruptured resulting in the serious injuries to FF Crawford, and for that matter any piece of equipment utilized by fire departments should be tested and maintained in accordance with manufacturer's recommendations and applicable standards of the National Fire Protection Association (NFPA). Of particular importance with regard to devices such as these is the testing and adjustment for the proper operation of pressure relief valves.

The results of the metallurgical testing of the Hampton FD manifold revealed flaws that were directly responsible for its failure. Further, it must be understood that the defects discovered in this device could not have been identified by fire department personnel during normal inspection and operation of the device. Fire Departments should contact their equipment dealer to attempt to locate a company that is willing to guide them in determining the reliability of their devices. This may also include any device that is manufactured utilizing the same sand cast method such as piston intake relief valves, Hydrasist^{TM} valves, etc. Alternately, consideration of replacing these devices with other technology may be an option.

Additionally, firefighters should be instructed regarding the potential dangers involved with any pressurized equipment utilized by fire departments. These can include hose and appliances, self-contained breathing apparatus (SCBA) cylinders and hydraulic and/or air operated rescue tools. Firefighters should always exercise appropriate care and utilize proper personal protective equipment (PPE) while handling and operating items such as this and positioning themselves in such a way as to minimize the potential harm they might suffer should a failure occur. In this particular instance FF Crawford was wearing appropriate PPE including helmet, turnout coat and pants, gloves and boots.

Critical Incident Stress Debriefing (CISD)

The purpose of a CISD Team is to provide individual counseling, group sessions and, if necessary, referrals to members of an emergency response organization involved in traumatic events. The teams are made up of specially trained fire, police and EMS personnel, along with mental health professionals who provide training and guidance to the team members and assist at the debriefing sessions.

The assistance provided by the CISD Team helps to sensitize the FFs to the possibility of stress reactions, hopefully avoiding future stress related problems. It allows the members to understand the range of normal reactions and provides a method to deal with the incident and its after-effects. The use of a CISD Team in situations such as this is not a sign of weakness on the part of emergency personnel. Failure to deal completely with the emotional stress of such a traumatic occurrence can negatively affect both the professional and personal lives of those involved.

The Division of Fire Safety recommends the notification and use of CISD teams when the CISD trigger events are found to be present. Such significant events may include:

- *line of duty death of a co-worker*
- *mass casualty incidents*
- *death of a child*
- *death occurring after prolonged rescue efforts*
- *when a victim reminds an emergency worker of a loved one*
- *during highly dangerous or highly visible events*
- *when the emergency worker influences death or injury*
- *co-worker suicides*
- *any other unspecified highly traumatic event*

Currently, CISD Teams are regionalized in New Jersey and are part of a statewide network. These teams will respond on a 24-hour basis whenever requested. Emergency contact numbers for activation of a CISD team are as follows:

The Statewide CISD Network – (609) 394-3600
The NJ Fire & EMS Lifeline – (866) 653-3367

CONCLUSION

It is the NJ Division of Fire Safety's sincere hope that the lessons learned from this and other similar incidents will serve to educate the fire service and inspire them to take all necessary measures to reduce firefighter injuries and deaths to the greatest extent possible.

After exhaustive testing by a competent metallurgical testing laboratory it was determined that the failure of the LDH manifold was due to several factors including: the material had little to no fracture toughness, the casting quality was poor, the casting contained numerous voids, large casting defects (voids) were present in the housing wall at the threaded inlet, slag or dross (containing sodium, silicon, oxygen, iron, sulfur, and other elements) was present within some of the voids.

It was noted in the report issued by Corrosion Testing Laboratories, the contracted vendor to perform testing on the manifold, that better manufacturing practices would improve the fracture toughness of the casting by reducing the size and number of voids, removing slag or dross from the casting, assuring there is no trapped hydrogen to cause voids, improving the microstructure to minimize the deleterious effects of sharp, brittle second phases through various measures such as better control over solidification times, alloy modification, etc. Use of an alloy such as A356 with lower iron content would reduce the number of brittle second phase particles. Post-manufacturing inspection using x-rays could help to identify castings with large voids.

As stated in this report, pressurized devices such as this and other equipment utilized by fire departments on a routine basis have the potential; although slight, to fail violently causing injuries and even fatalities. Firefighters must always be cognizant of these potential dangers and operate in such a way as to minimize risks as much as possible through the appropriate use of PPE and safe operational practices.

Due to the fact that no federal agency has been identified that is willing to address this issue, we will be asking national and international fire service organizations to assist in getting this information out to the fire service beyond New Jersey. We also ask that any readers of this report notify the NJ Division of Fire Safety if they have experienced a similar failure of a device.

As has been stated in previous investigative reports issued by the NJ Division of Fire Safety, firefighting is an inherently dangerous occupation. Keeping this in mind, firefighters should rededicate themselves to remove or reduce those hazards that can be eliminated or reduced.

REFERENCES

Practical Hydraulics (2nd ed.). Kay, Melvyn (2008). Taylor & Francis.

Interviews of members of the Hampton Township Fire and Rescue

Snap-tite Periodic Field Maintenance Program Manual - Manifold & Relief Valve Assembly - Snap-tite Hose Union City, PA 16438

Fire In New Jersey 2010 New Jersey Division of Fire Safety; Fire Incident Reporting Section

Failure Analysis of Fire Hose Appliance Report Corrosion Testing Laboratories; 60 Blue Hen Drive, Newark, DE 19713

APPENDIX A

Failure Analysis of Fire Hose Appliance Report

Corrosion Testing Laboratories, Inc.

CTL REF #27532

October 11, 2011

Christopher Eckert
Office of the State Fire Marshal
NJ Division of Fire Safety
P.O. Box 809
Trenton, NJ 08625

Re: Failure analysis of Fire Hose Appliance

Dear Mr. Eckert:

Presented herein are the results of the above referenced analysis. This work was authorized per the State of New Jersey PO#7382597.

Summary of Conclusions and Recommendations:

- The manifold ruptured when brittle fracture propagated through the material.
    - Charpy V-notch tests confirmed the material had little to no fracture toughness.
    - The microstructure contained long, needle-like brittle second phases, which contributed to the material's brittleness.
- The casting quality was poor:
    - The casting contained numerous voids.
    - Large casting defects (voids) were present in the housing wall at the threaded inlet. These voids took up a significant percentage of the wall thickness.
    - Slag or dross (containing sodium, silicon, oxygen, iron, sulfur, and other elements) was present within some of the voids.
    - Fracture likely initiated at these casting defects.
- The alloy conformed to UNS A03560, i.e., aluminum-silicon casting alloy.
- The tensile properties appear to be consistent with Alloy 356 in a T6 temper.
- Better manufacturing practices would improve the fracture toughness of the casting:
    - Reduce the size and number of voids,
    - Remove slag or dross from the casting,
    - Assure there is no trapped hydrogen to cause voids,
    - Improve the microstructure to minimize the deleterious effects of sharp, brittle second phases through various measures such as better control over solidification

  - times, alloy modification, etc. These measures are routinely done in aluminum-silicon casting alloys.
  - Use of an alloy such as A356 with lower iron content would reduce the number of brittle second phase particles.
- Post-manufacturing inspection using x-rays could help to identify castings with large voids.
- It is possible or even likely that there are other manifolds in existence at risk for rupture due to similar causes. It may be prudent to undertake an inspection program to try to identify those parts and remove them from service.
- The relief valve should be tested to determine whether it was working correctly. However, the valve may not be designed to relieve transient stresses, which may have occurred in the manifold.

Background

A cast aluminum large diameter hose appliance with adjustable pressure relief valve suddenly ruptured during a training drill on July 22, 2009 at the Sussex County Community College. The hose manifold was manufactured by Snap-Tite Hose, Inc. and was reportedly manufactured sometime in 2000. Water pressures are typically 120-150 psi at the 5-inch inlet. At the time of the incident, the pressure was not known, however it was believed to be about 120 psi. Firefighter Rebecca Crawford was reportedly slowly shutting two of the 2 ½-inch ball valves when the rupture occurred, **Figure 1**. According to literature published on-line by Snap-Tite, the valve body "is made from a high strength aluminum alloy and is hard coat anodized for long life."[1] Drawings of the manifold indicate that the manifold housing is made of cast aluminum, alloy 355-T6/356-T6. However, they appear to specify a pewter-colored powder paint finish and not an anodized finish.

NJ Division of Fire Safety provided CTL with the broken pieces of the ruptured manifold and requested that CTL perform a destructive evaluation in order to determine the cause of failure.

Laboratory Analysis

Two pieces of the ruptured manifold were received by CTL for evaluation, **Figures 1 through 6.** These pieces appear to represent the entire manifold, with the exception of the carrying handle, which had broken off. The larger piece was cracked all the way around at approximately the center-line of the manifold. Although the cracks appear to be through-wall, the piece was held together by the bolted-on connections at the five outlets. In addition, a large crack across the top portion of the manifold, which traveled around the housing on the bottom closer to the inlet, allowed a smaller piece to separate from the manifold. At the threaded inlet connection (on the smaller piece), the crack path was flush with the threads. The valves are shown in the figures in the positions they were in when CTL received the pieces. During the course of our investigation, we opened and closed the valves several times. We did not make any changes to the position of the relief valve.

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[1] Snap-Tite Hose Manifold, http://www.laemez.com/snaptitemanifold.htm, viewed on 6/3/2011.

The fracture surface was examined using optical stereomicroscopy. Near the inlet threads there were large voids in the casting, **Figures 7 and 8.** The voids were seen as either smooth craters at the fracture surface or holes on the fracture surface that led to subsurface craters. In some places, there was a clear or white substance or second phase in the voids. The fracture surface at this location on the larger piece of the manifold was removed for further examination (see Figure 2 for location). The cut surface showed numerous large voids, **Figures 9 and 10.** There was a white or clear substance within some of the voids. A piece was removed and prepared as a metallurgical cross-sectional mount, **Figures 11 and 12**. Additional voids were present within the manifold casting wall – both large voids near the center of the cross-section and smaller voids near the ID and OD surfaces. The voids in the cross-section spanned a significant percentage of the entire wall thickness. The white substance was present within the voids in the polished cross-section, **Figure 13**.

Prior to polishing, the white substance within the voids on the cross-section was analyzed for elemental composition using energy dispersive x-ray spectroscopy (EDS) in the scanning electron microscope (SEM). The white substance contained significant amounts of silicon, sodium, and oxygen (in addition to aluminum), plus lesser amounts of sulfur and iron and trace amounts of magnesium, manganese and, possibly, copper, **Figure 14**. For comparison, the freshly cut surface (without voids or any white substance) was analyzed and was aluminum and silicon, as would be expected for this alloy, **Figure 15.** The presence of the impurities (e.g. slag or dross) within the large voids in the cast manifold is a sign of poor manufacturing control.

Additional voids were present in the cross-section near the fracture surface, **Figures 16 and 17.** The microstructure consisted of aluminum dendrites with angular second phases of silicon and intermetallic phases of iron and magnesium. These phases are brittle and the cross-section contains cracking through then, especially at the long needle-like particles. At the location of this cross-section, the fracture face itself occurs at the breakage of some of these needle-like particles. The microstructure appears to be consistent with an aluminum-silicon alloy casting that has not been modified. Modification is done in order to refine the microstructure to improve mechanical properties such as ductility.

Samples of the manifold housing were removed and tested for strength and ductility (see Figures 2 and 5 for locations). Tensile test results showed that the tensile strength and yield strength were typical of Alloy 356 T6 castings, **Table 1**. Ultimate tensile strength was only slightly higher than the yield strength, indicating the material did not have much (if any) ductility. Charpy V-notch impact testing at room temperature was performed to measure the toughness of the material, **Table 2.** The results show that the material had almost no toughness (ductility), with extremely low energy needed to break the specimens and almost or completely brittle fractures (5% to 0% shear). What this means is that the material had very little resistance or ability to resist a sudden impact or load.

Table 1
Results of Tensile Testing

	Typical Mechanical Properties of Alloy 356.0 T6*		Snap-tite Manifold
	Sand Cast	Permanent Mold Cast	
Tensile Strength (ksi)	33	38	39.8
Yield Strength (0.2%) (ksi)	24	27	37.0
Elongation (In 4D) (%)	N/A	N/A	6.5
Reduction of Area (%)	N/A	N/A	3.3

*Source: A Guide to Aluminum Casting Alloys, Mid-Atlantic Casting Services, http://www.mid-atlanticcasting.com/alum-casting-alloys_FEB05.pdf, as viewed on 10/10/2011

Table 2
Charpy V-notch Testing Results*

Sample	**Test #**	**Temperature (°F)**	**Energy (ft-lbs.)**	**Lateral Expansion (inches)**	**% Shear**
Snap-tite Manifold	A	+70°F	0.41	0.002	5
	B		0.30	0.001	5
	C		0.36	0.000	0

A sample of material was analyzed by atomic emission spectroscopy (AES) for chemical conformance to specification. The material conformed to UNS A03560 (Alloy 356), **Table 3.**

Table 3
Chemical Composition by AES (wt%)

Element	UNS A03560		Snap-tite Manifold
	Min	Max	
Al	Remainder		Remainder
Cu	-	0.25	0.05
Fe	-	0.6	0.3
Mg	0.20	0.45	0.31
Mn	-	0.35	0.19
Others, each	-	0.05	<0.05
Others, total	-	0.15	<0.15
Si	6.5	7.5	6.7
Ti	-	0.25	0.14
Zn	-	0.35	0.01

Several additional analyses on the manifold were performed. Another metallurgical cross-sectional mount was prepared, **Figure 18.** This sample was taken from the smaller manifold piece, away from the location of the large voids (see Figure 5). This sample was prepared to document a typical cross-section of the casting that was not associated with known voids. Numerous small voids were present throughout the section. The needle-like brittle phase associated with the fracture surface was not as pronounced at this location. The fracture surface near this location was imaged in the SEM, **Figure 19.** The fracture was typical of brittle cleavage fracture. The fracture surface was examined at various magnifications and no evidence of fatigue was present.

Discussion, Conclusions, Recommendations

The hose manifold ruptured when a brittle fracture propagated through the material. Mechanical tests performed on the material confirmed that, although the tensile properties of the material were typical of type 356 aluminum castings, the impact properties (i.e., toughness) of this particular piece were very poor. Toughness or ductility is related to the microstructure. In the ruptured manifold, the microstructure was typical of an unmodified aluminum-silicon casting alloy and contained long needle-like intermetallic phases that were brittle. This microstructure does not impart good fracture toughness properties to the material. In addition, numerous casting voids were found within the part. In particular, large casting defects were present near the threaded inlet to the manifold at and near the fracture surface. These casting defects (voids) contained a second phase (dross or slag) rich in impurities such as sodium, silicon and oxygen, sulfur, iron and trace amounts of magnesium, manganese and, possibly, copper. [Although silicon occurs as part of this alloy, its concentration within the impurities was out of proportion (higher) to its concentration within the alloy itself.] The presence of impurities, dross or slag within the casting voids points to poor manufacturing control during casting. All of these factors – the voids, dross or slag within the voids, and the brittle needle-like second intermetallic phases within the microstructure – created initiation points and stress concentrators, which allowed fracture to occur at lower stresses than would normally be anticipated for the casting. Once initiated, the crack propagated rapidly through the brittle material. It is likely that the fracture initiated at the large voids near the threaded inlet.

There are several approaches to avoiding this problem in the future. An alloy with lower iron content may help to reduce the presence of brittle second phases. Aluminum casting alloy A356 is a modified version of 356 and contains less iron. This alloy reportedly has better fracture toughness than the higher iron 356 alloy. Microstructural modification through the use of other alloying elements or control over solidification rates can also help to improve toughness. These measures are routinely done in aluminum casting alloys in order to produce alloys with desirable mechanical properties. Voids in aluminum castings may be caused by shrinkage or by entrapped hydrogen. Better manufacturing control should be employed to reduce the voids to an acceptable level. In addition, better manufacturing practices should be implemented in order to avoid slag or other impurities within the cast parts. Once manufactured, parts could be inspected nondestructively (e.g. by x-rays) for the presence of unacceptable voids.

According to NJ Division of Fire Safety, a worker was slowly closing two of the valves on the manifold when the rupture occurred. There was no report of water hammer, however we were asked to consider whether water hammer could cause this type of rupture to occur. Water hammer can cause high pressure transient shock waves within a pipeline when a valve is closed. Based upon our examination of the manifold, it is clear that the cast manifold body contained numerous casting defects (voids and slag inclusions). In addition, the material itself was brittle (i.e., had little to no fracture toughness). Because of its poor quality, the manifold ruptured at stresses that were likely well below those that would be easily borne by a better quality casting.

According to a Safety Alert (Safety Alert 09-1) issued by the New Jersey Department of Community Affairs, Division of Fire Safety, a similar rupture occurred in a Snap-tite hose manifold around March 2009 in Hunterdon County, NJ. The photographs in that publication show a ruptured manifold broken into pieces in a similar fashion to the manifold we evaluated, including fracture through the threads at the inlet. The manifold from that event was evaluated by Snap-tite Hose, Inc. who concluded that the failure was due to severe overpressure such as caused by water hammer. It was recommended that all components that may have been subjected to pressure spikes be thoroughly inspected. This recommendation assumes that components subjected to a high, transient overpressure would have become damaged in some way that could be detected during inspection and yet not have already caused failure of the part. According to our results, this is an unlikely condition as the root cause of the failure was not a pressure spike (such as water hammer) but was the inherently poor quality casting, which allowed rapid brittle fracture to occur at stresses below those that would have ruptured a good quality casting. Visual inspection of other cast manifolds would not be sufficient to identify internal voids or casting defects that may exist and that would serve as initiation points for rupture.

It is possible or even likely that there are other cast manifolds in service that contain the same or similar casting defects. It would be wise to determine whether the manifold that we investigated was from the same manufacturing lot as the manifold that ruptured in March 2009, as the problem may be lot related. It would be prudent to undertake an inspection program using x-rays or possibly other non-destructive techniques capable of detecting internal flaws, voids and/or cracks to try to determine the extent of the problem and to make sure that defective units are taken out of service. In addition to non-destructive evaluation, selected manifolds could be evaluated destructively to determine the casting porosity, microstructure, mechanical properties, etc.

CTL did not evaluate the relief valve. It is not clear why the relief valve did not activate, however it is likely that the forces that caused the rupture to occur were transient and immediately relieved by the rupture. We would recommend further testing of the relief valve to determine whether it was functional. CTL does not provide this type of testing.

If you have any questions or comments, please do not hesitate to contact us.

Very truly yours,
Corrosion Testing Laboratories, Inc.

Reviewed and approved by:

David Crowe

Shari Nathanson Rosenbloom, Ph.D.
Director of Failure Analysis
and Biomedical Devices

David Crowe, Ph.D.
Senior Consultant

Policy Statement

This study has been performed and this report was prepared based upon information provided to Corrosion Testing Laboratories, Inc. (CTL) by New Jersey Division of Fire Safety. The information contained in this report represents only the materials evaluated, and such work performed in accordance with CTL's Quality Assurance Manual, Revision 13, issued June 2009.

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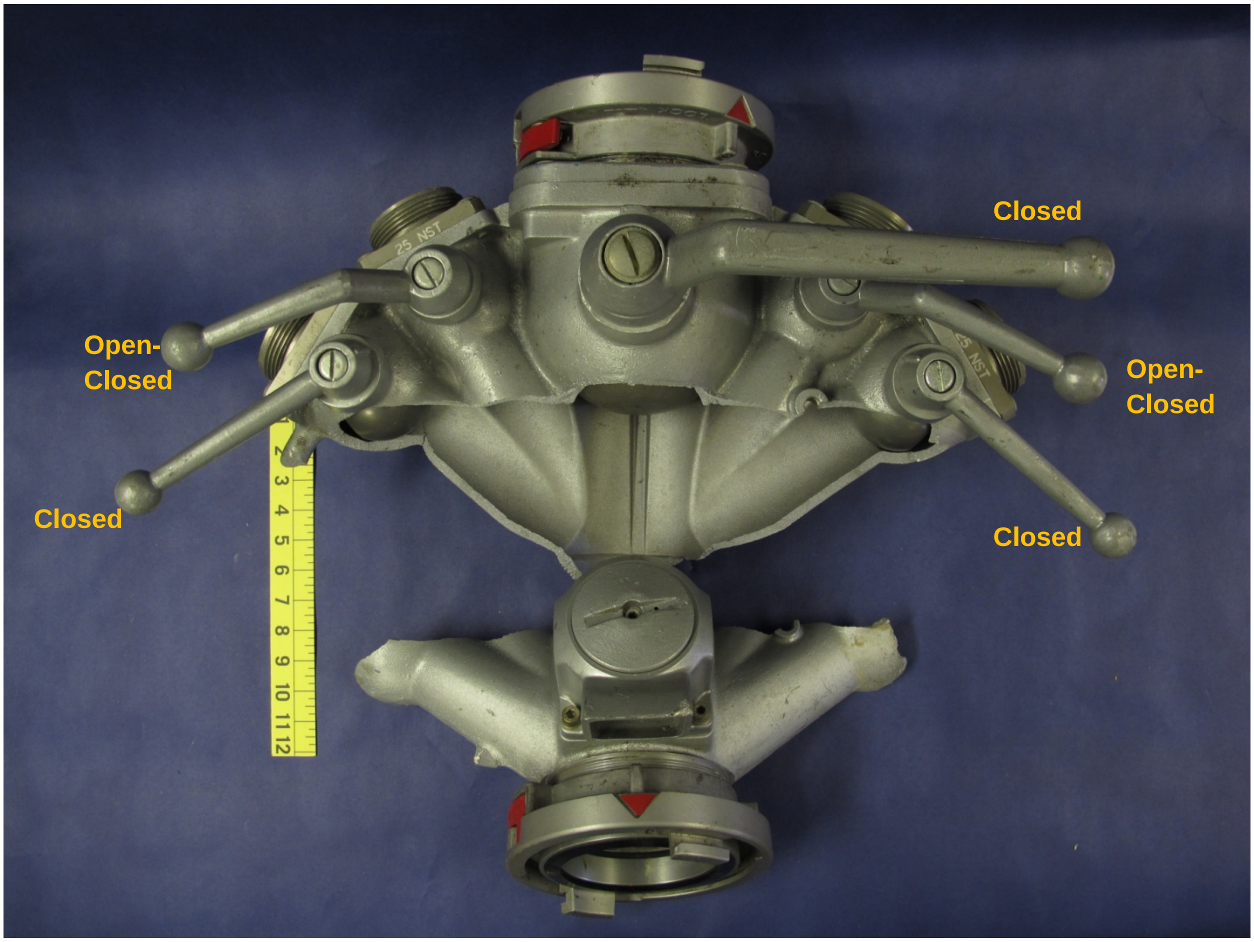

Figure 1. **Ruptured manifold, as received. The two pieces that CTL received appear to represent the entire manifold, with the exception of the carrying handle, which was broken off and missing. All valves are shown in the closed position. According to NJ Division of Fire Safety, two of the valves were in the process of being closed when the rupture occurred. Position of valves at time of incident is indicated on the photograph above.**

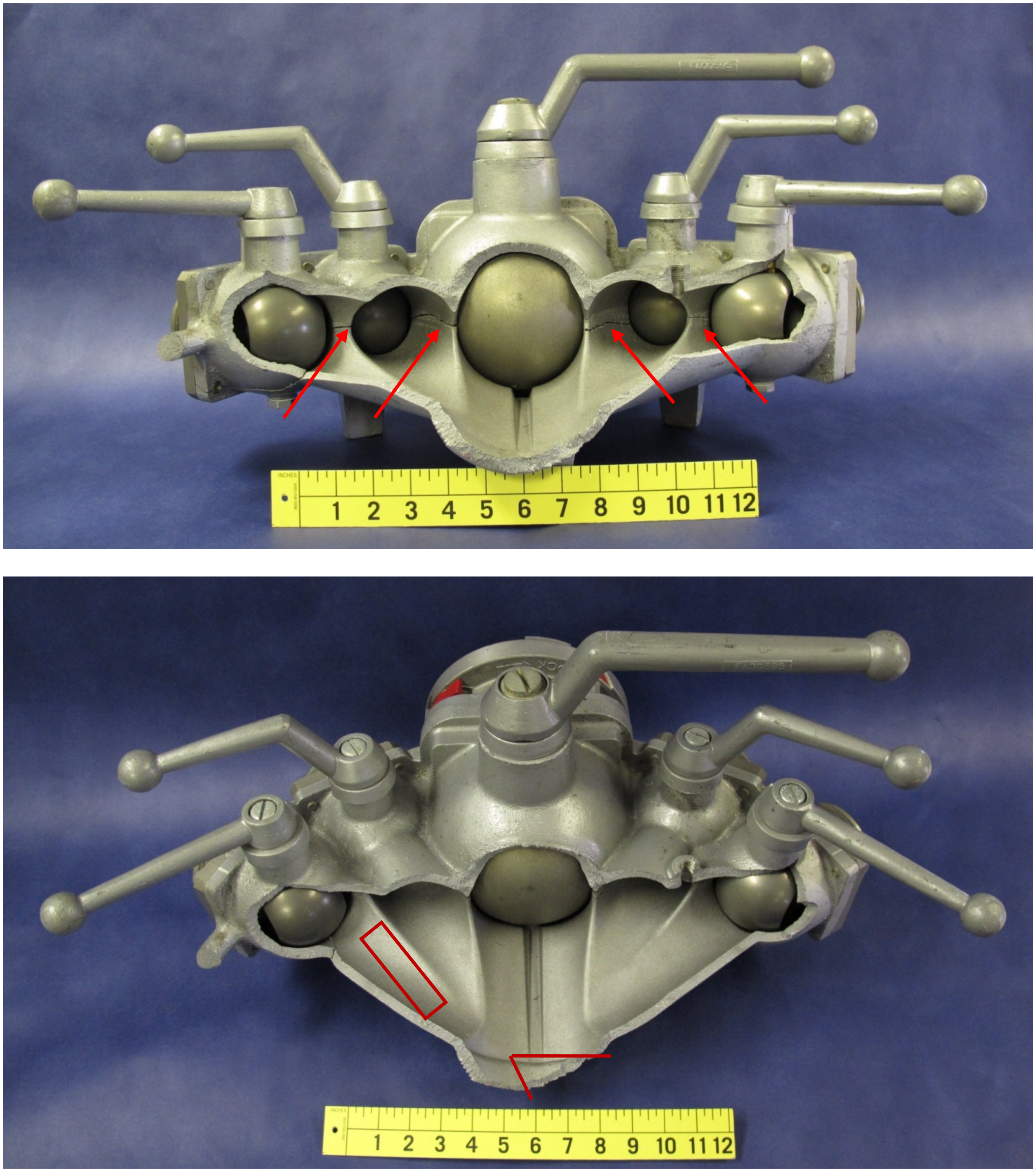

Figure 2. **Two views of the larger piece. In addition to cracking that caused one piece to break away, cracking occurred all around the piece, especially through the approximate center-line of the cast manifold. The red lines on the bottom photograph show the approximate locations of cuts to remove the fracture surface for further examination, including a cross-sectional metallurgical mount. The red box shows the approximate location of samples removed for Charpy V-notch testing and AES.**

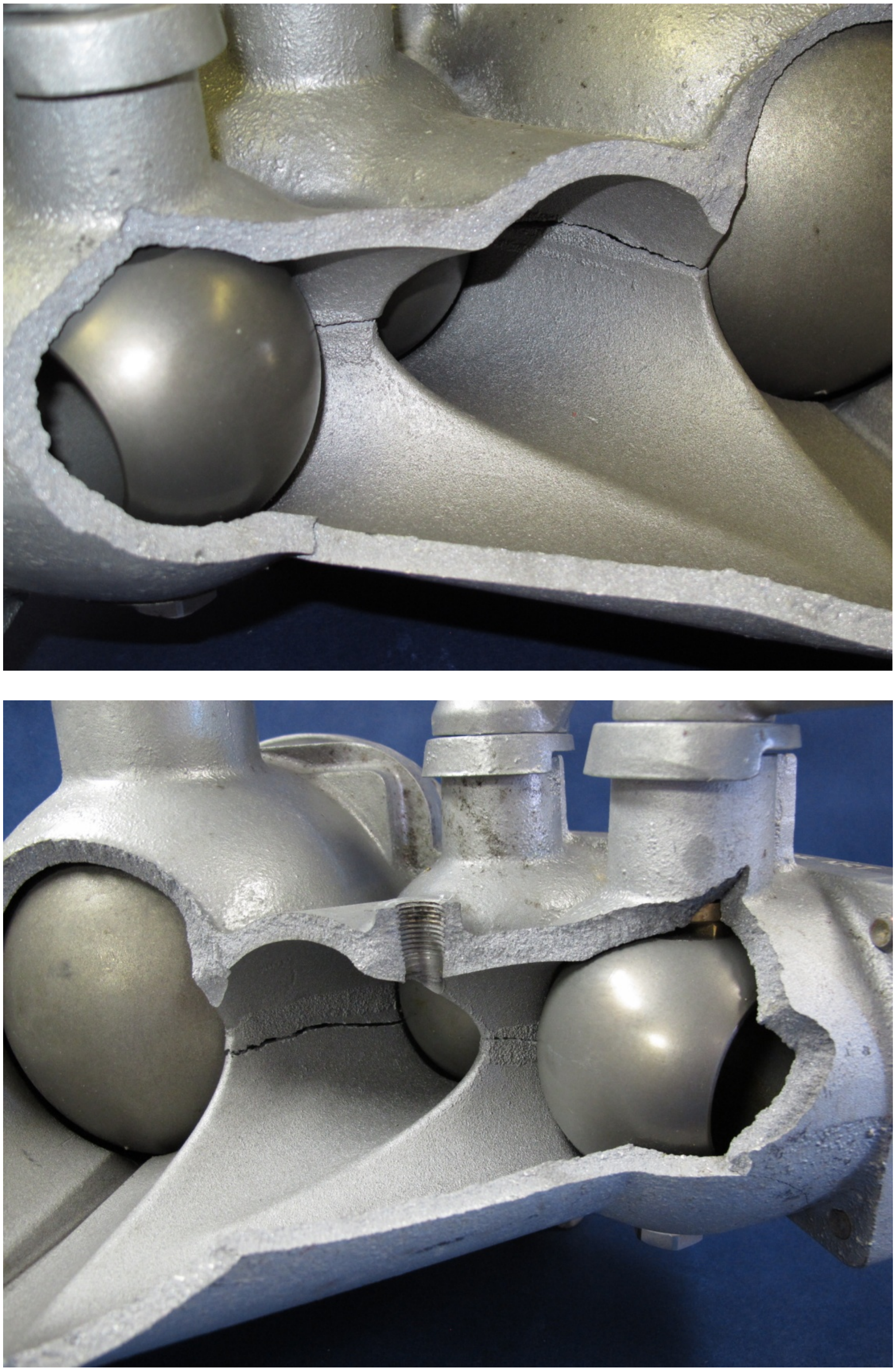

Figure 3. Closer views of the larger piece showing cracking.

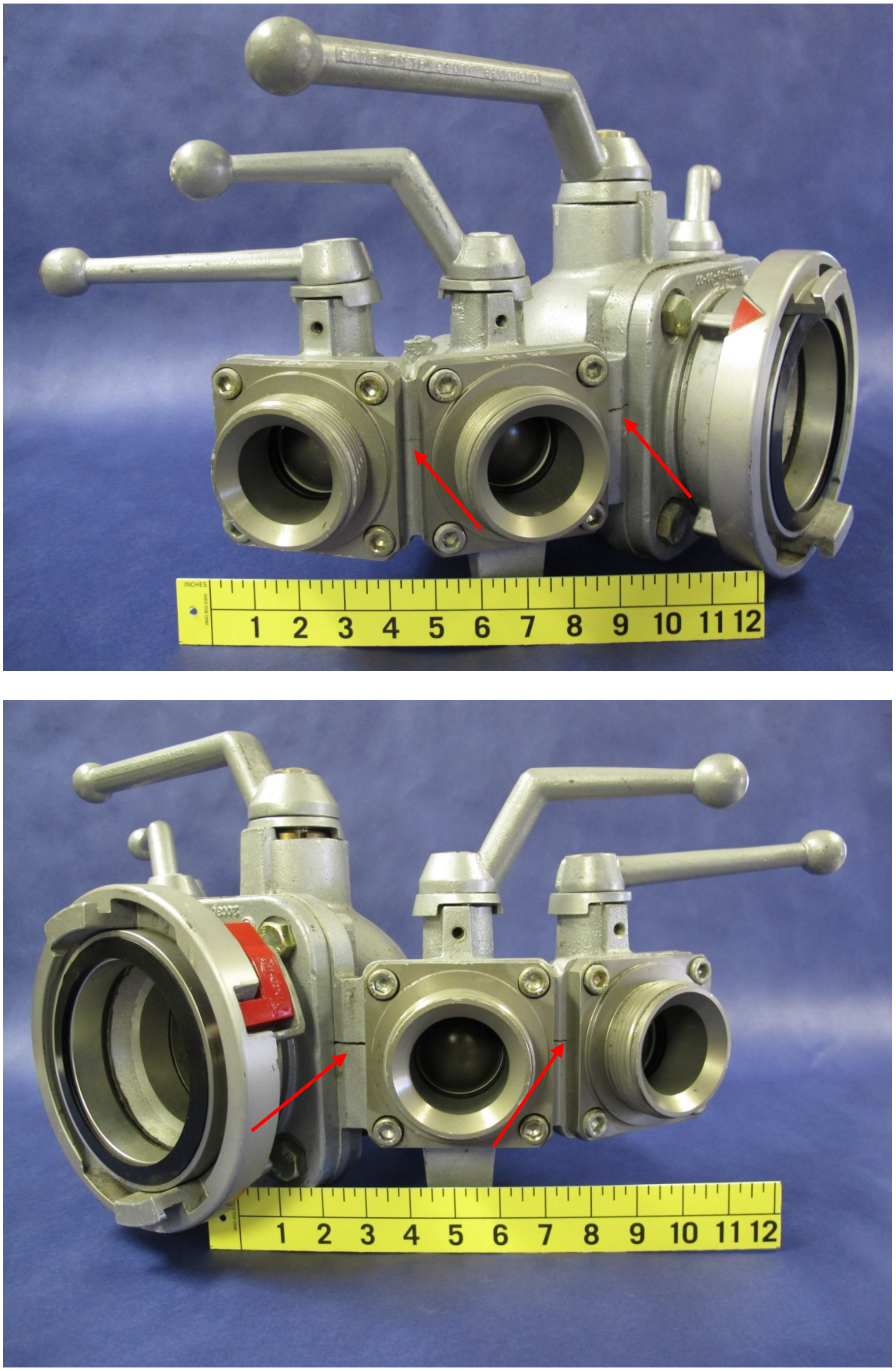

Figure 4. **Additional views of the large manifold piece, showing cracking through the approximate center line (arrows).**

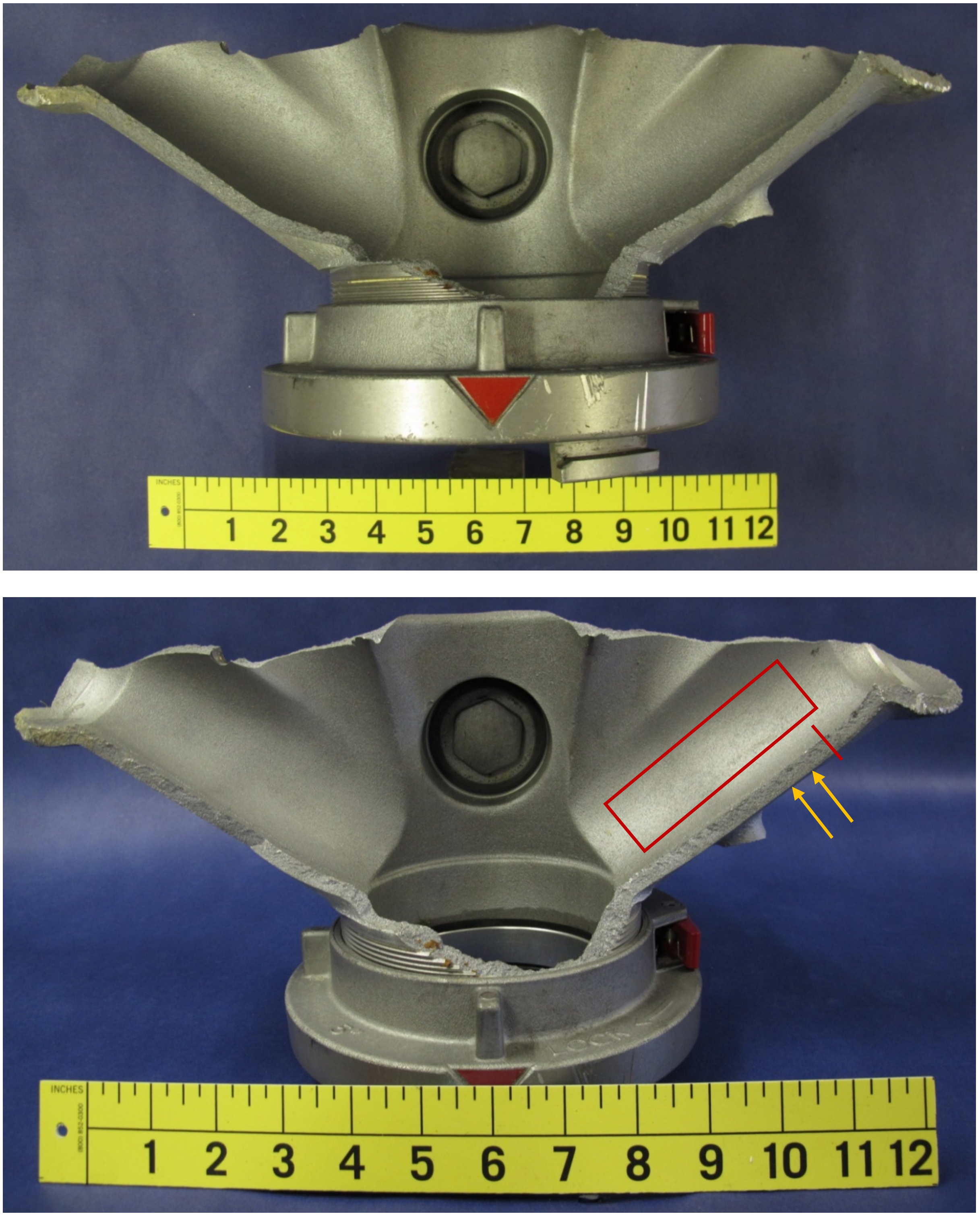

Figure 5. **Several views of the smaller piece. The fracture surface is flush with the threads where the manifold is threaded into the inlet connection. Red box shows approximate location of samples removed for tensile testing. Red line shows approximate location of cross-sectional metallurgical mount. Yellow arrows show approximate location of SEM imaging of fracture surface.**

Figure 6. **Closer view of fracture surface at inlet connection threads. Arrow shows location of Figures 7 and 8.**

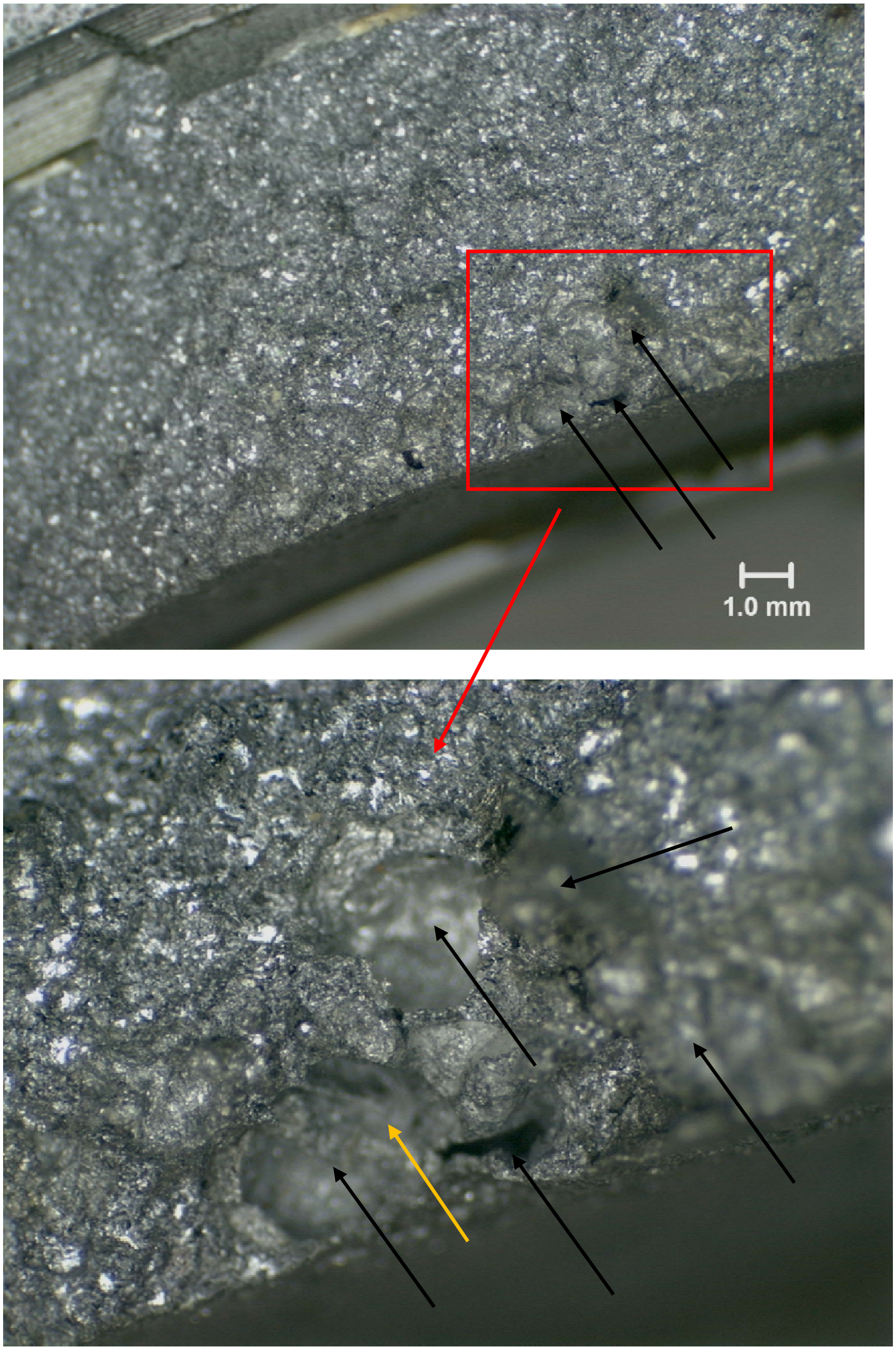

Figure 7. **Large voids in the casting near the threads at the manifold inlet. Some of the voids are seen as dark holes in the photograph. Others are seen as smooth craters. There appears to be a clear or white substance or second phase within some of the voids, yellow arrow. 7X and 20X original magnifications.**

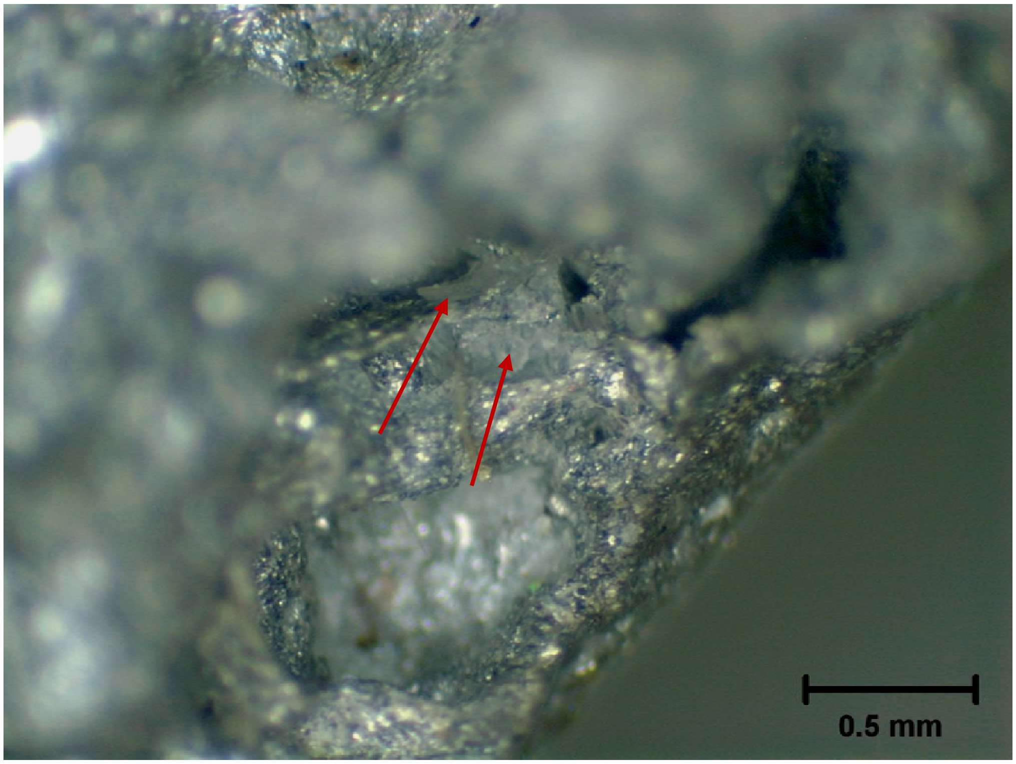

Figure 8. **Clear or white substance or phase within some of the voids at 40X original magnification.**

Figure 9. **Cut piece from larger manifold piece showing large voids on the cut surface. Inset shows location of piece. Yellow lines show location of additional cut for cross-sectional metallurgical mount.**

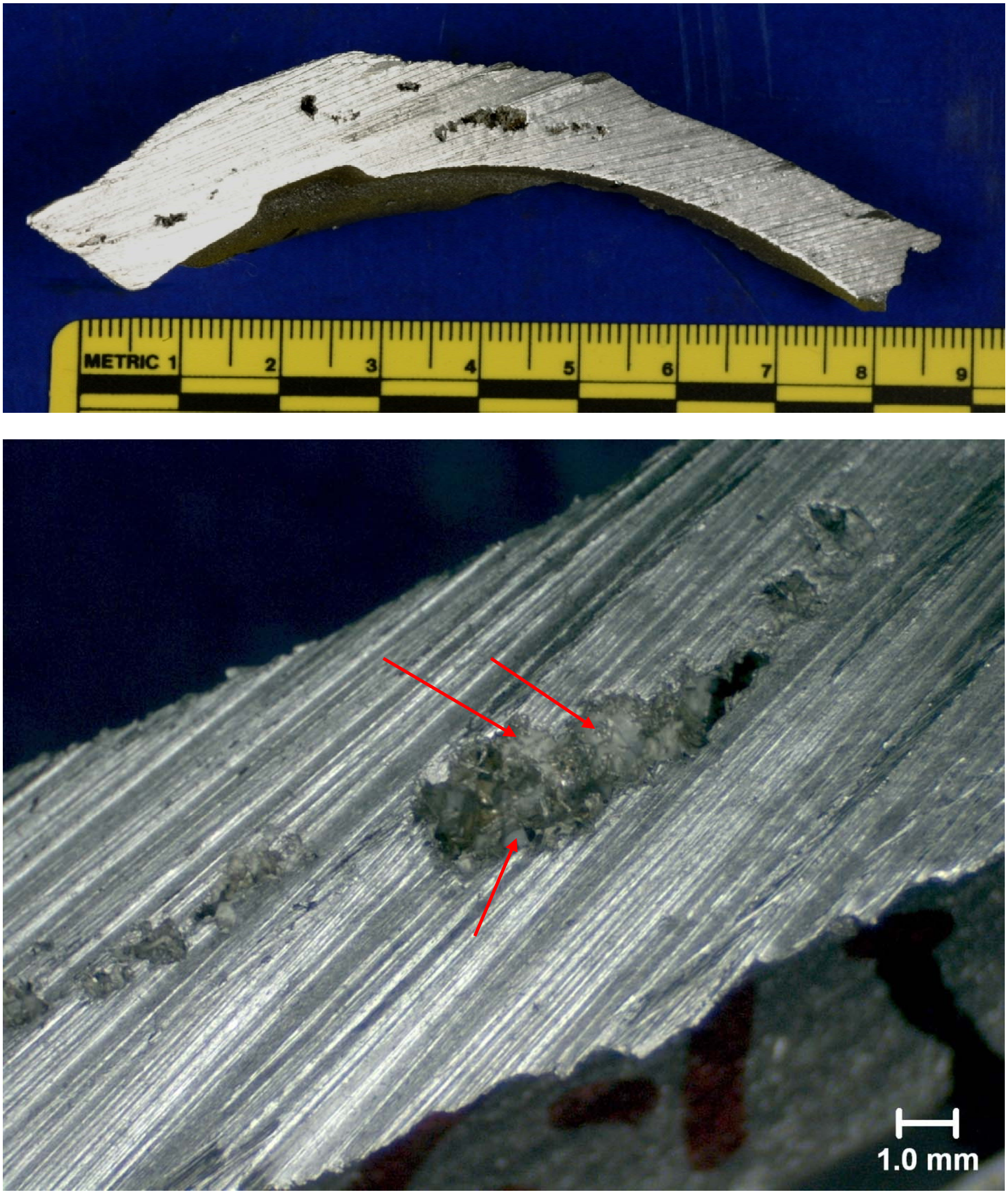

Figure 10. Cut surface showing large voids with white or clear substance within the voids (arrows).

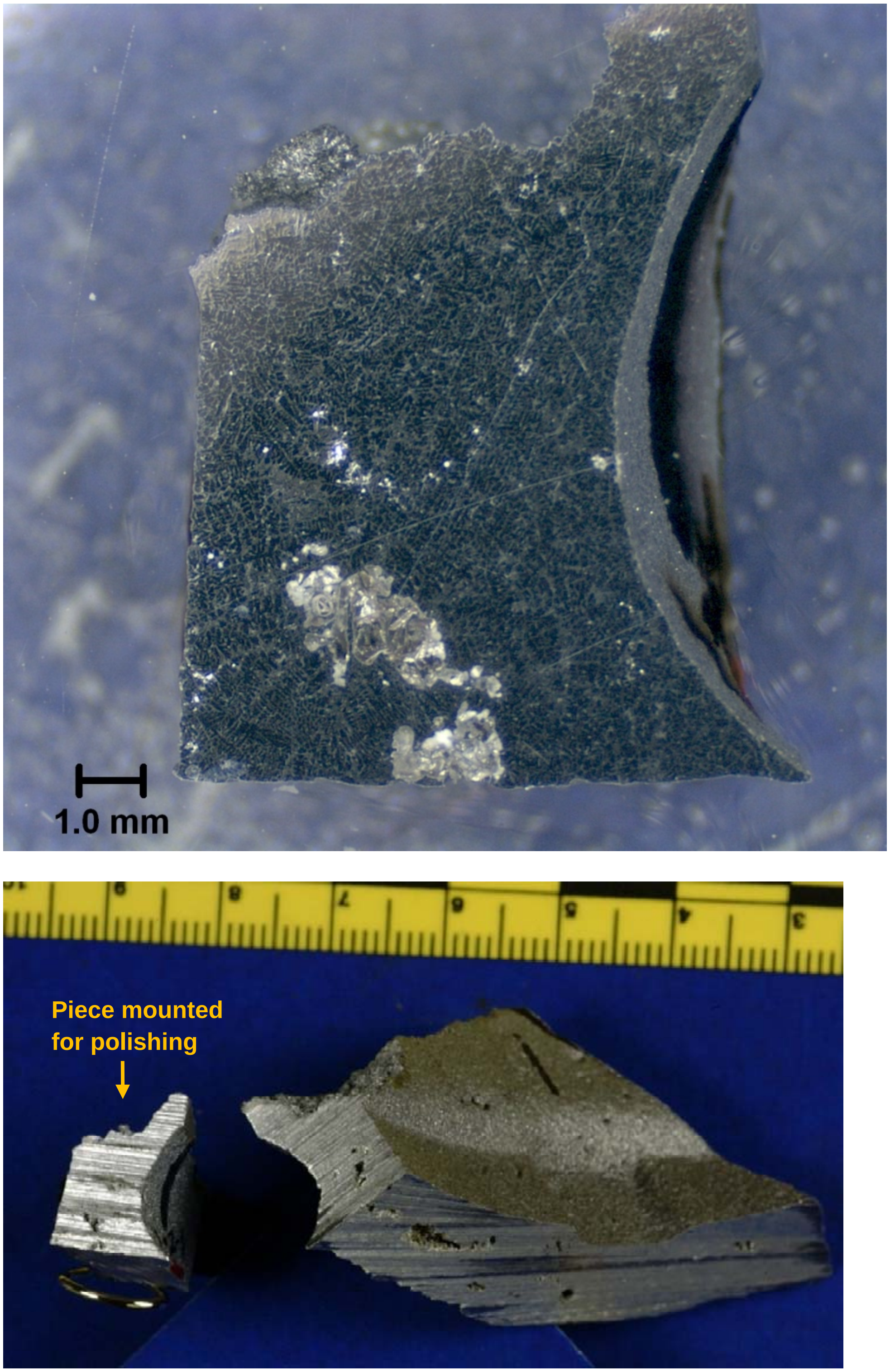

Figure 11. Cross-sectional metallurgical mount (polished, top; as cut, bottom) showing voids within the casting wall.

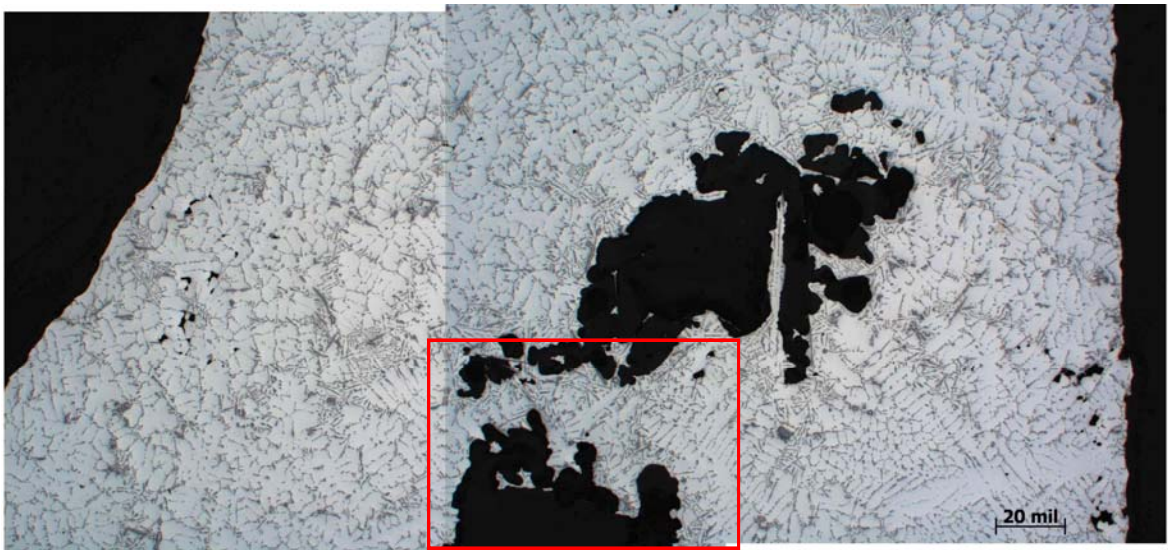

Figure 12. Extensive voids, large and small, were present within the casting wall, as seen in this polished cross-section. Red box shows approximate location of Figure 13. As polished. 25X original magnification photo montage.

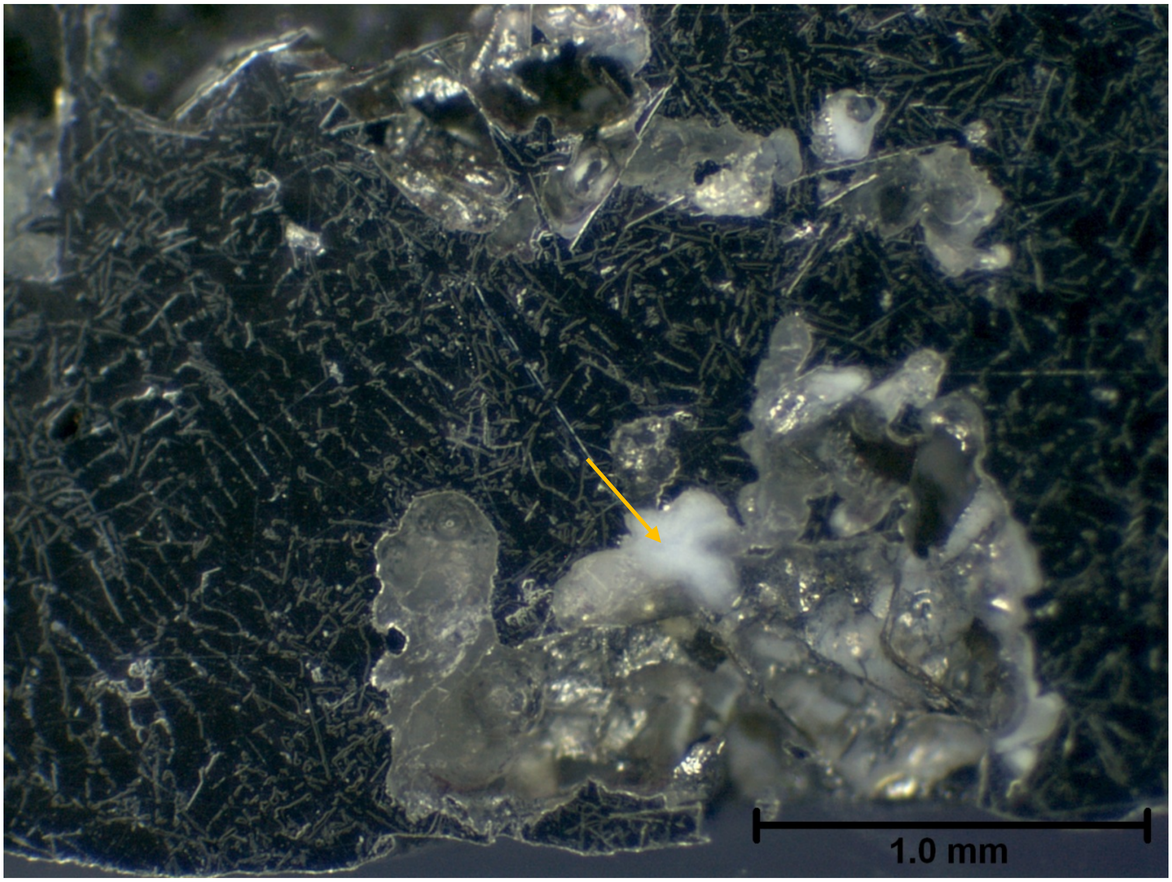

Figure 13. White substance within voids on polished cross-section. Note: due to the differences in optics in microscopes, this photograph is a mirror image of Figure 12. 40X original magnification.

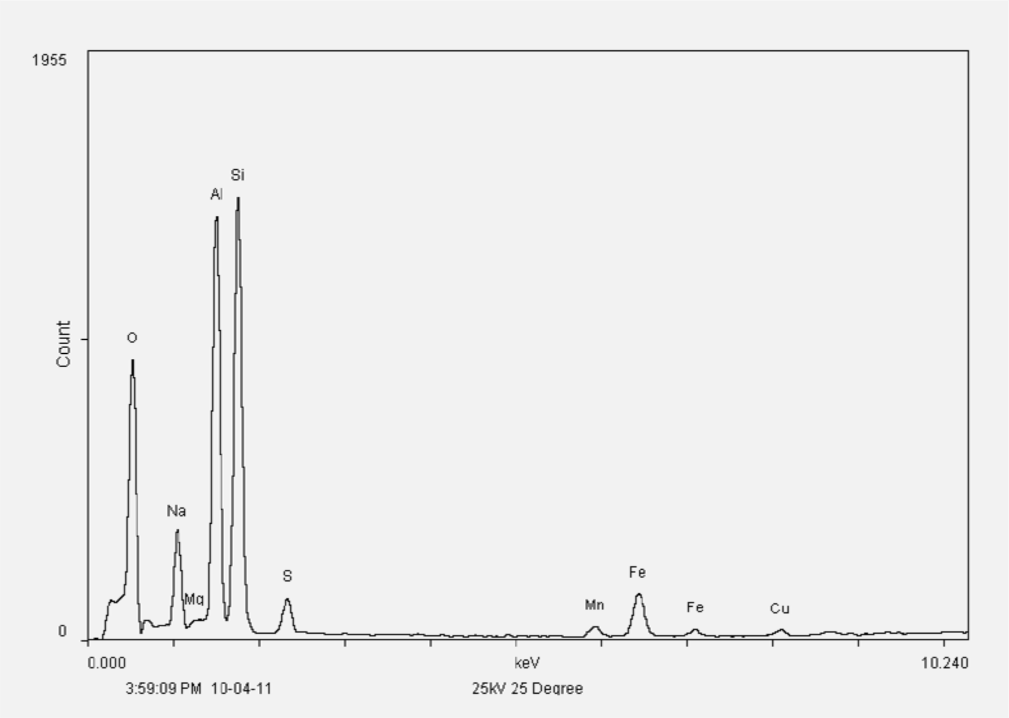

Figure 14. **White substance on as-cut surface of cross-section contained high levels of silicon, sodium, and oxygen, plus lesser amounts of sulfur and iron and trace amounts of manganese, magnesium and, possibly, copper.**

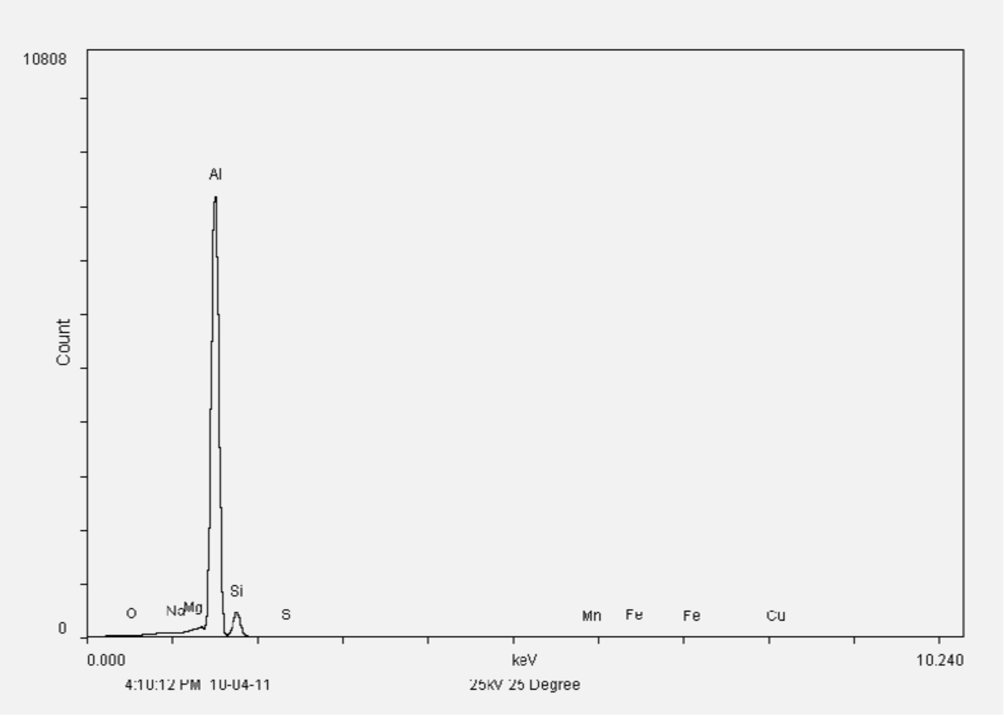

Figure 15. **Freshly cut surface of cross-section, without voids or white substance, is aluminum and silicon.**

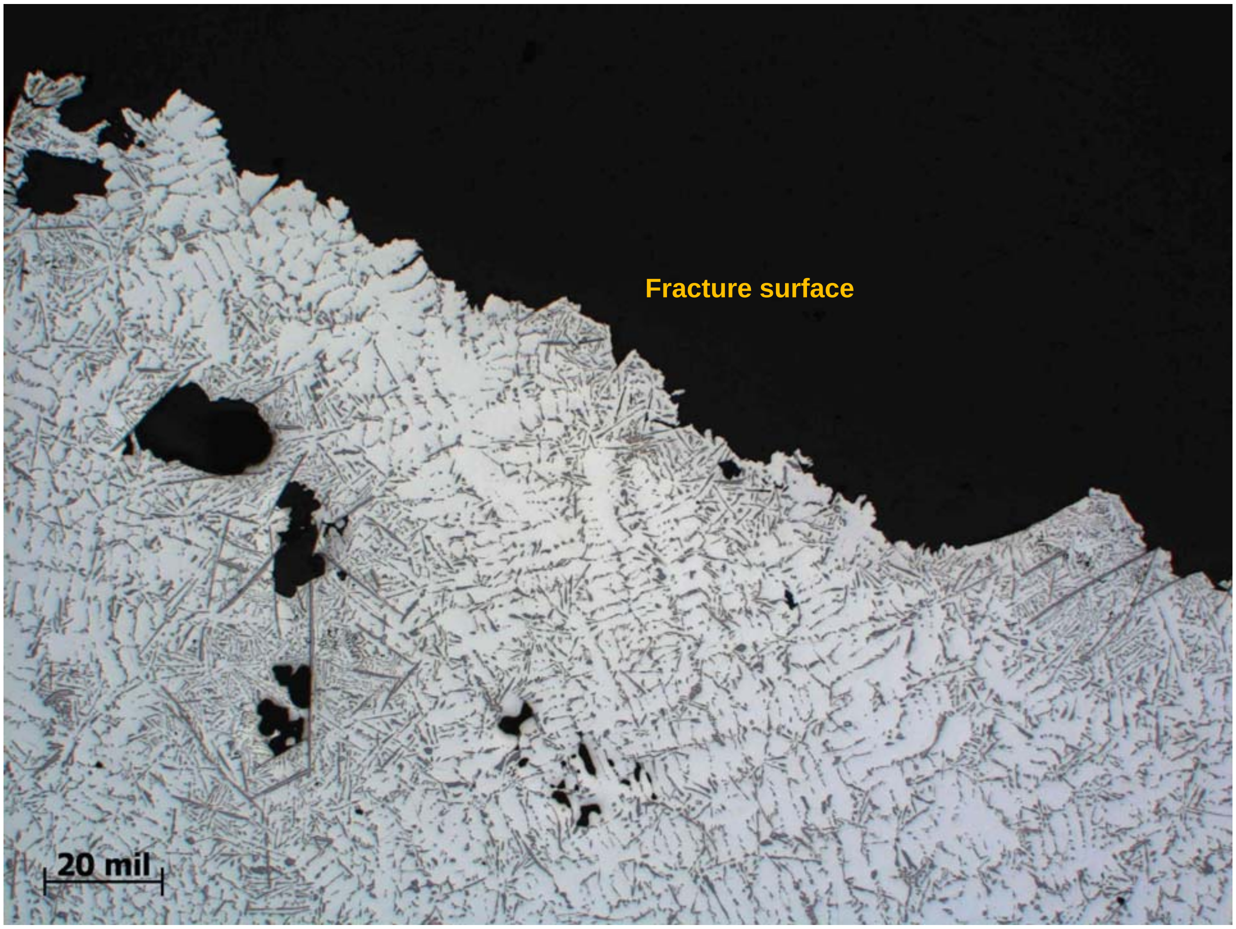

Figure 16. Cross-section near fracture surface contains multiple large and small voids. As polished. 25X original magnification.

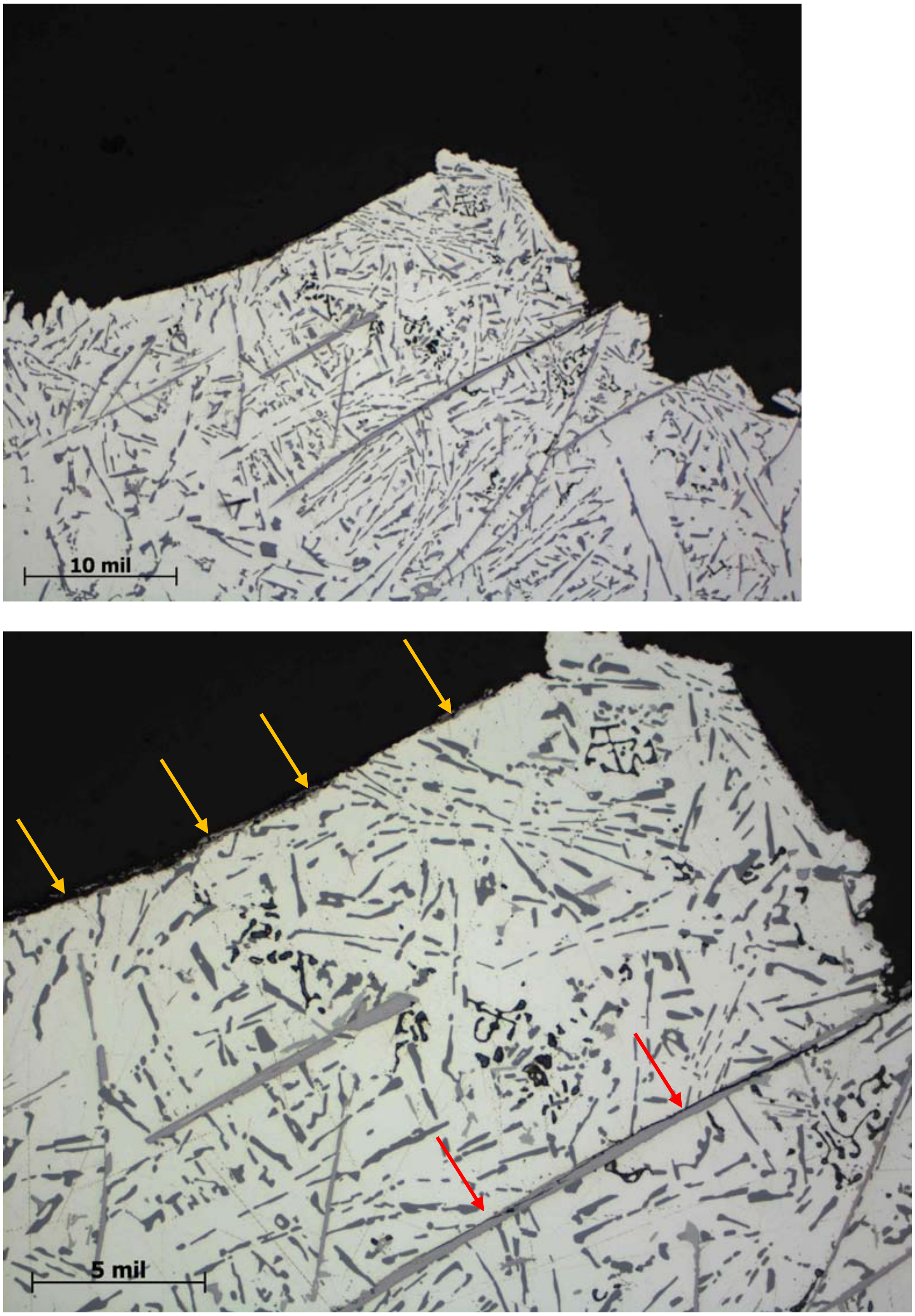

Figure 17. Higher magnification photomicrographs near the fracture surface (100X and 200X original magnifications, top and bottom, respectively). The microstructure consists of aluminum dendrites (white) with angular, brittle intermetallic phases containing silicon and, likely, iron and magnesium. Cracking has occurred through these brittle intermetallic phases (red arrows), especially the long needle-like phase. At this location, the fracture surface itself is due to the cleavage of one of these particles (yellow arrows).

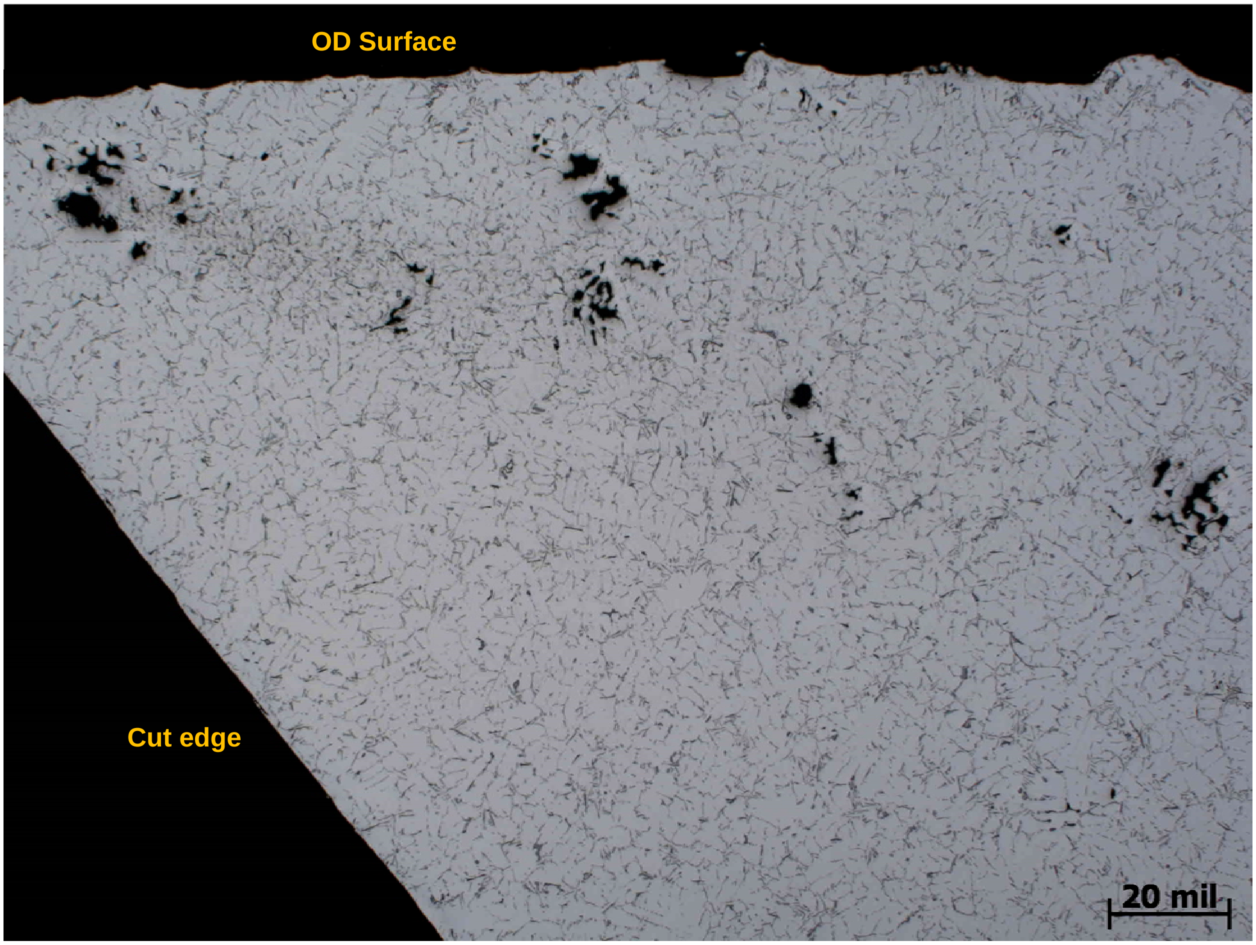

Figure 18. **Cross-section taken from smaller manifold piece. There were no obvious voids or other defects associated with this location. Numerous voids are present throughout the cross-section. This photograph shows voids near the outside (OD) surface. The long needle-like phase that was abundant near the fracture surface is much less pronounced here. See Figure 5 for location of this mount. 25X original magnification. Unetched.**

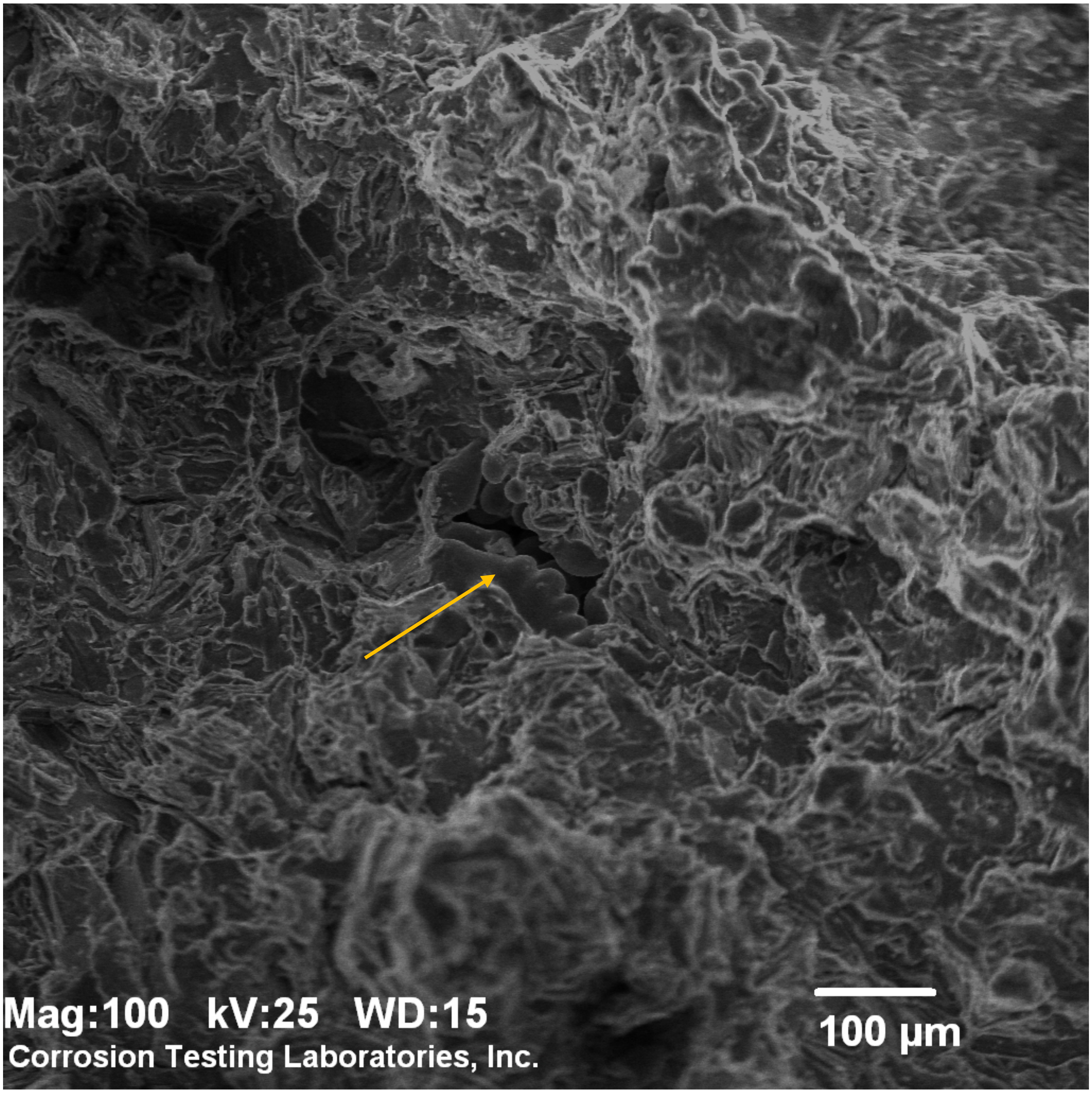

Figure 19. Fracture surface near the location of the mount shown in Figure 18 (also see Figure 5 for location). Fracture is typical of brittle cleavage. A casting void (arrow) is present in the center of the photograph. No evidence of ductility or fatigue fracture is present. 100X original magnification.