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# Aluminum: A Useful, Enigmatic Metal

Burl Donaldson, Fire Sciences Department, Sandia National Laboratories-Albuquerque

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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# Organization

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- Background
- Aluminum as a structural material
  - Aluminum behavior at near melt and melt
  - Molten aluminum experiments
  - Corrosion and oxidation at elevated temperature
- Aluminum as a component of solid rocket propellants
  - Justification for interest
  - Burning solid propellant and aluminum particle ejecta
  - Temperature measurements using AlO spectra
  - Individual particle ignition studies
  - Ignition criteria

# Some Aluminum Facts

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- In the Earth's crust, aluminum is the most abundant (8.3% by mass) metallic element and the third most abundant of all elements (after oxygen and silicon).
- The conversion of alumina to aluminium metal is achieved by the Hall–Héroult process. In this energy-intensive process, a solution of alumina in a molten (950-980 C) mixture of cryolite ($Na_3AlF_6$) with calcium fluoride is electrolyzed to produce metallic aluminum: $Al^{3+} + 3\ e^- \rightarrow Al$.
- Making aluminum cans from recycled aluminum takes 95% less energy than making cans from virgin ore.
- About 65 % of America's aluminum is currently recycled.
- The average aluminum can contains more than 50% post-consumer recycled aluminum.
- Because of its strong affinity for oxygen, aluminum is almost never found in the elemental state; instead it is found in oxides or silicates.
- Corrosion resistance can be excellent because a thin surface layer of aluminum oxide forms when the bare metal is exposed to air, effectively preventing further oxidation, in a process termed passivation.
- Aluminum melting point: 660 C.
- Aluminum boiling point: 2473 K.
- Melting temperature of aluminum oxide, alumina, is 2345 K
- Common alloys: 6061 · 7075 · 7068 · 5052; typical *alloying elements* are copper, *magnesium*, *manganese*, *silicon*, tin and zinc.

# An Organization 1532 Mission

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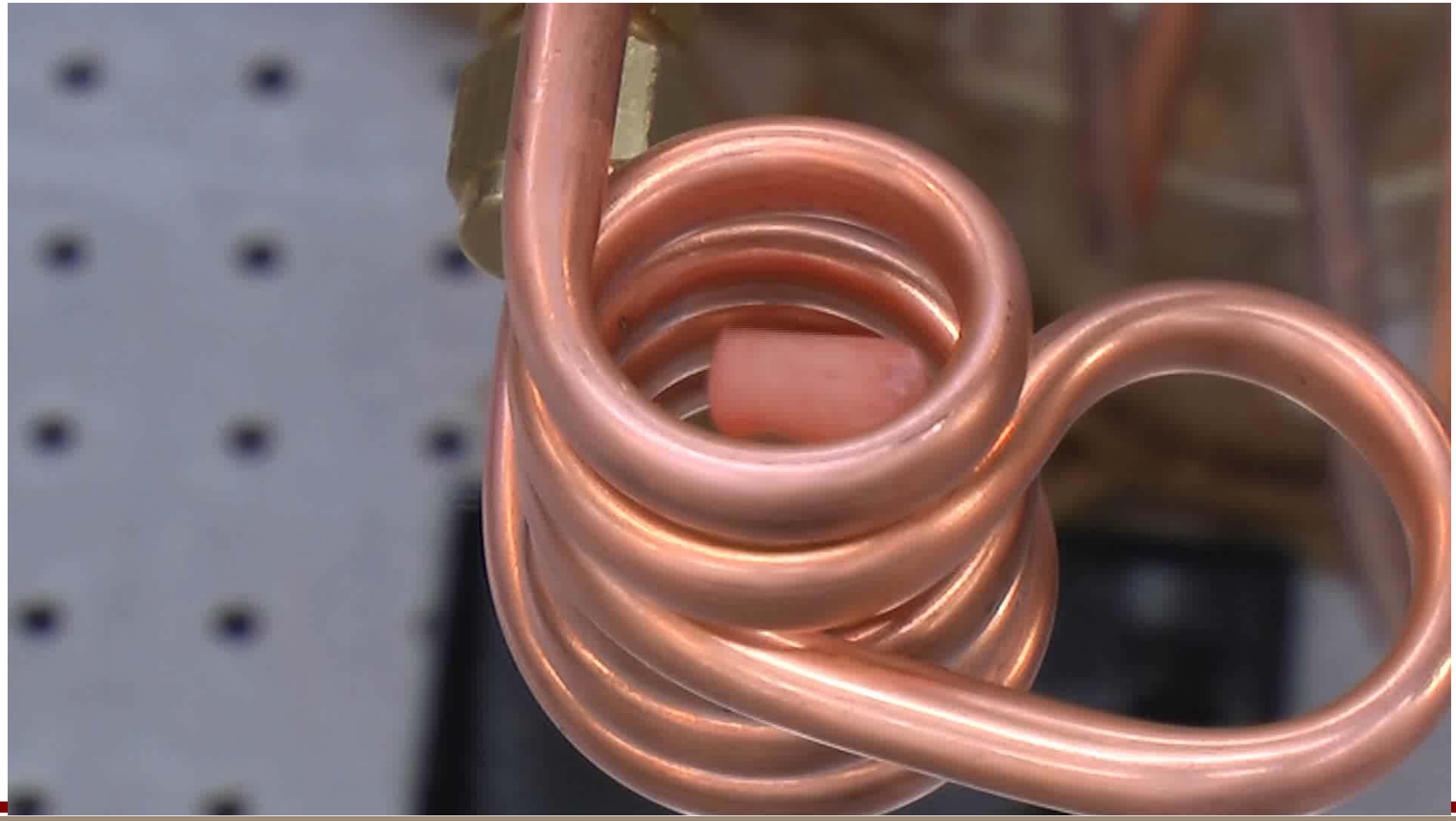
- Sandia Fire Sciences group is tasked with performing hazard assessment for accident or abort scenarios involving transport/delivery systems for DOD, DOE and NASA hardware.
- Aluminum, because of its high strength/weight, is used extensively in airframes. Crashes frequently involve fuel fires which can bring aluminum to melt. If molten aluminum relocates, it can contribute to heat load, and/or potentially lead to dissolution of other components.
- To improve solid propellant rocket motor stability and higher specific thrust, aluminum powder is frequently added to propellant formulations. Rocket launch pad aborts can expose hazardous or high value payloads to burning propellant and hence, heat flux is of critical interest. Contribution of aluminum to heat flux, or added heat load from combustion, can be significant.

# Deformation of aluminum block with transverse load

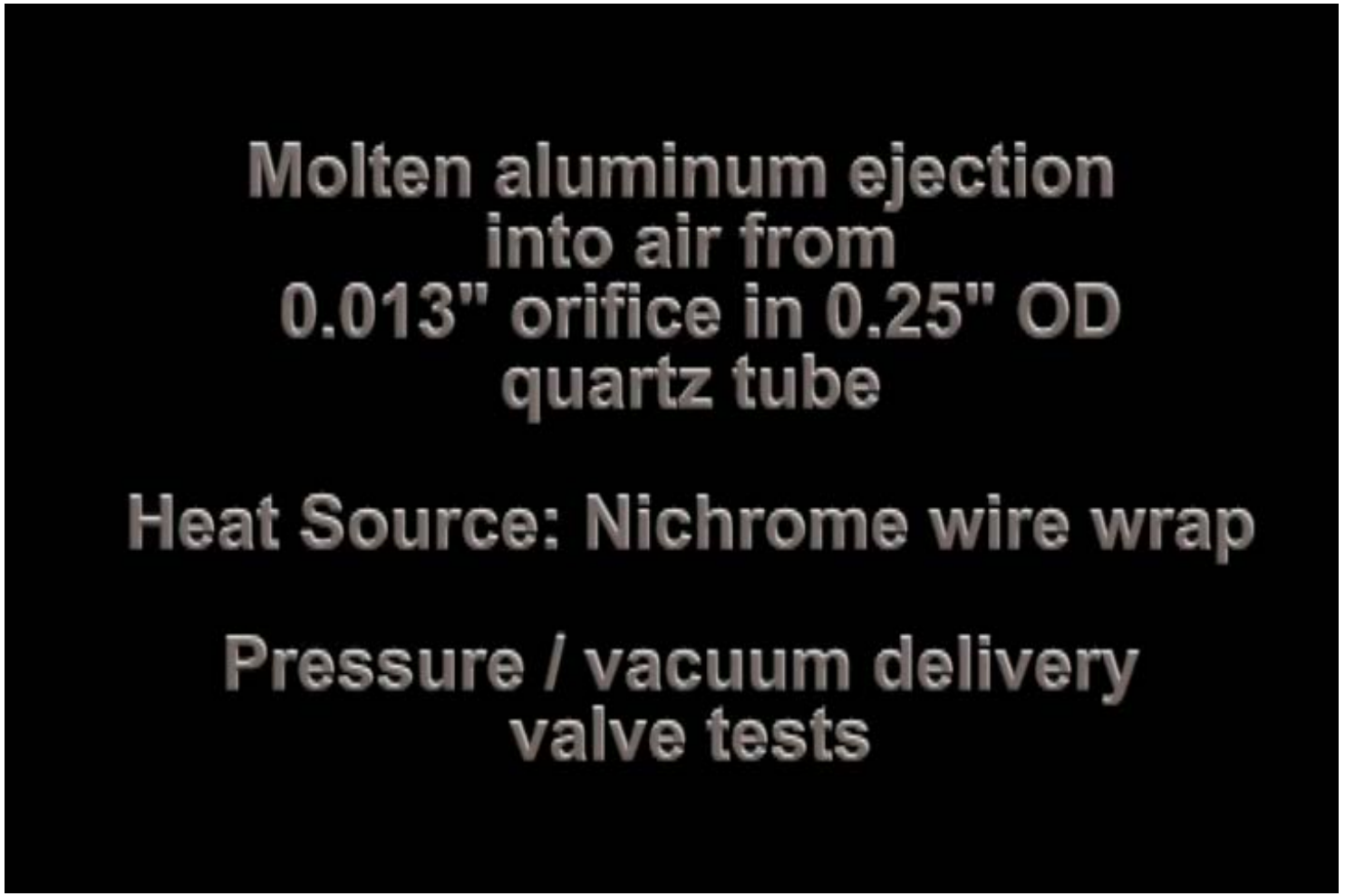
# Deformation of aluminum block with axial load

# Aluminum rod heated in air in furnace at 886 C

# Liquid aluminum exhibits high film strength

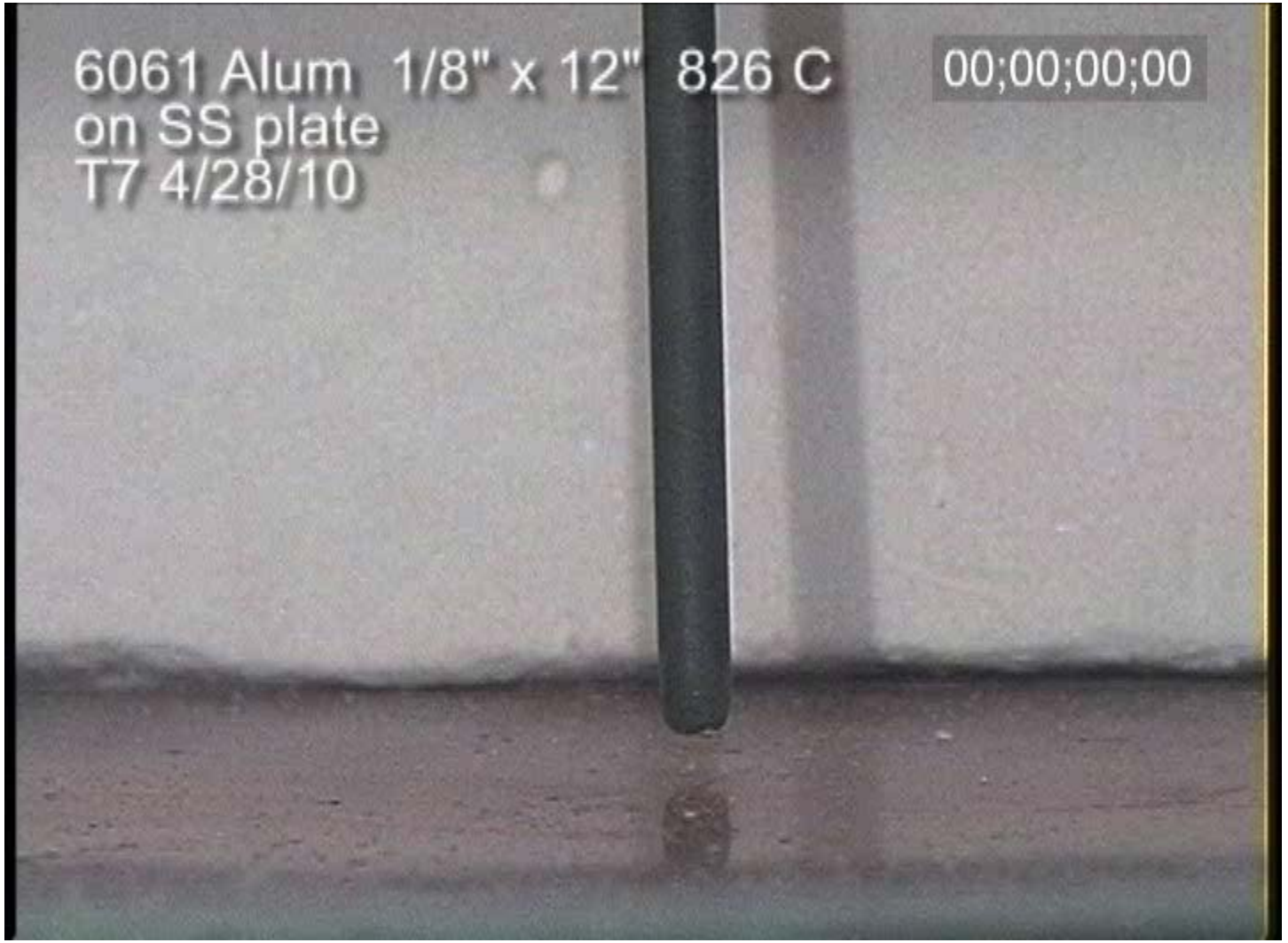


# Molten aluminum droplet formation

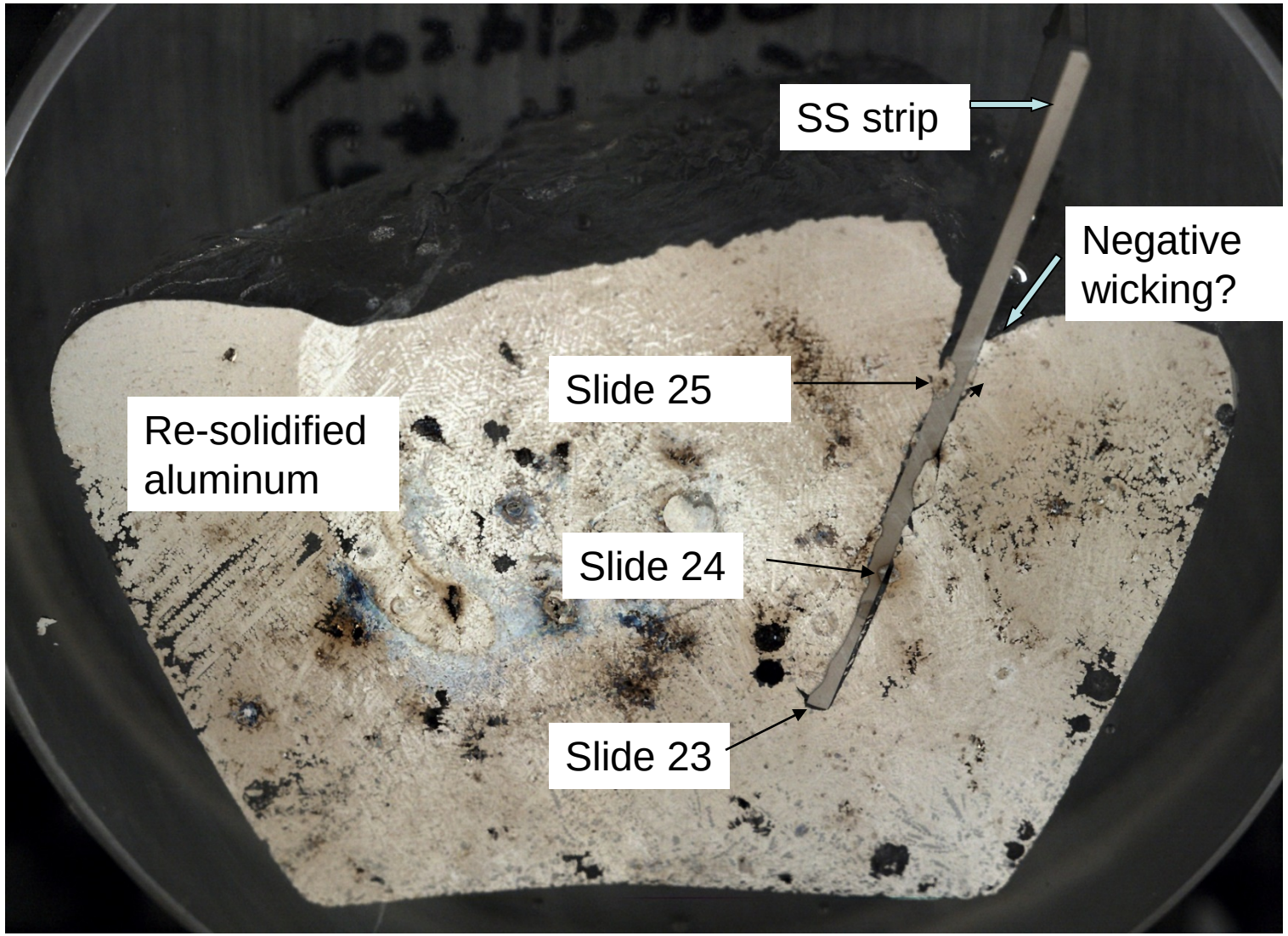



1087
DORIC
Trendicator 400A °C

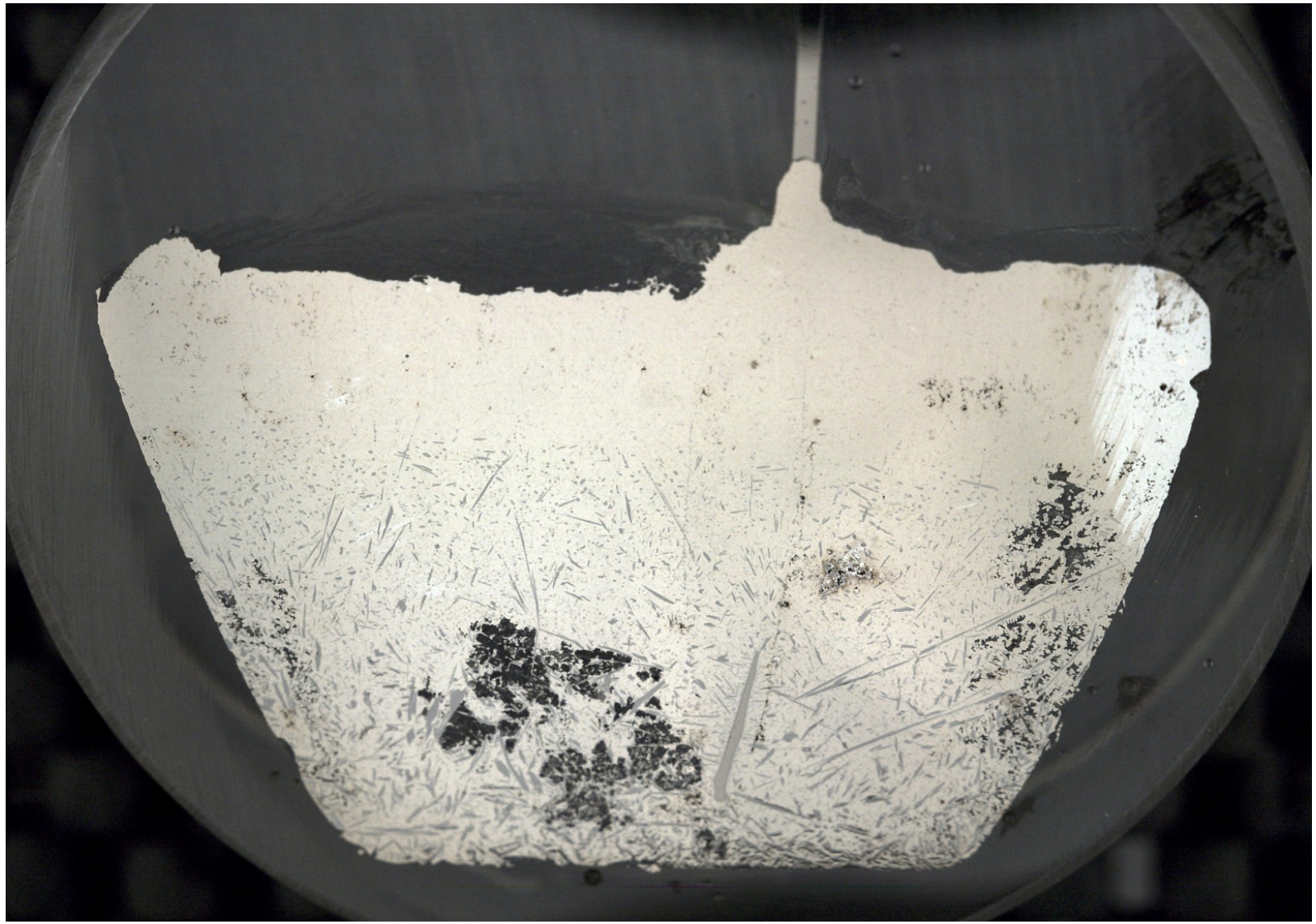
# Aluminum rod inserted onto a hot surface



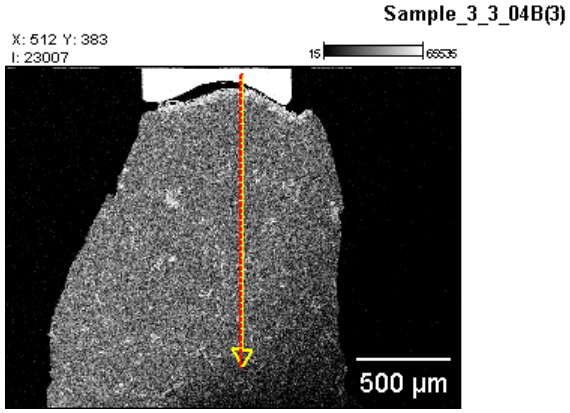
# Dissolution of 304 SS in 1000 C Al melt in 15 minutes in air



# Dissolution of 304 SS in 1000 C Al melt in 15 minutes with N2 purge

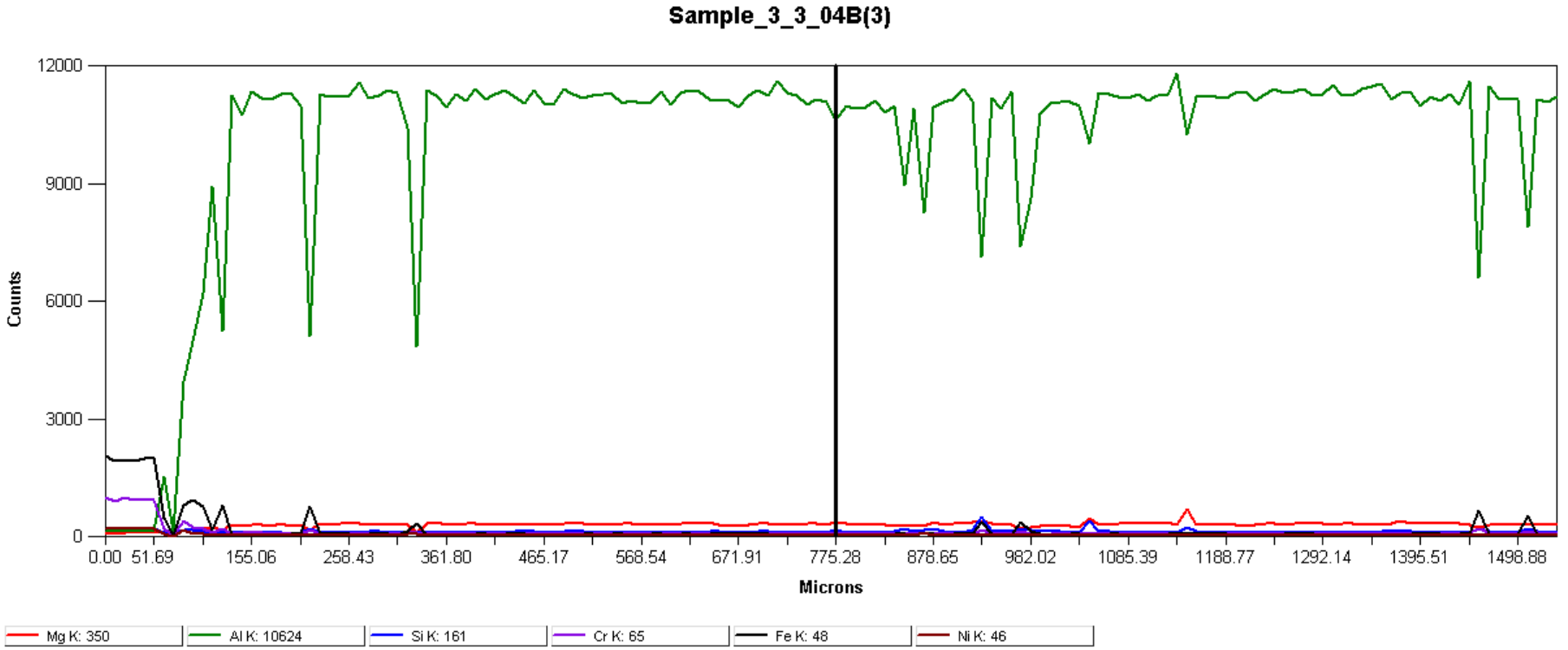


# Composition across tip of stainless steel strip

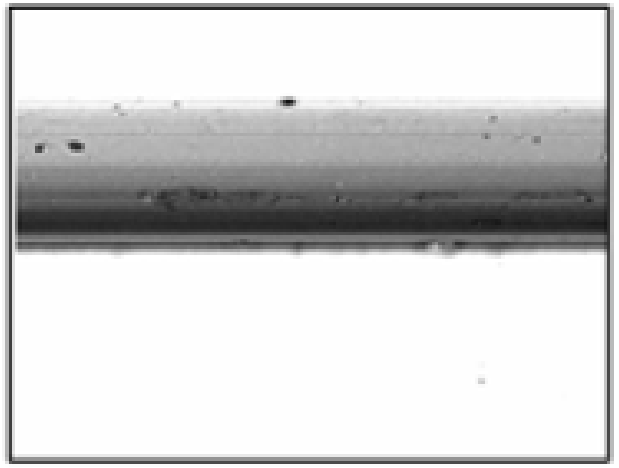



Accelerating Voltage: 15.0 kV

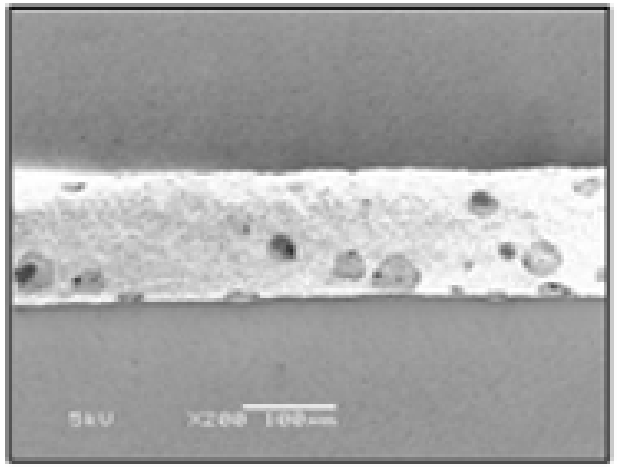
Magnification: 55



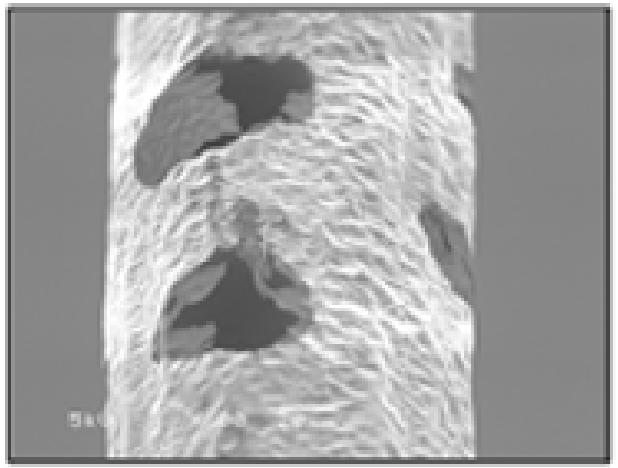
# Oxidized aluminum wire by passage of electric current



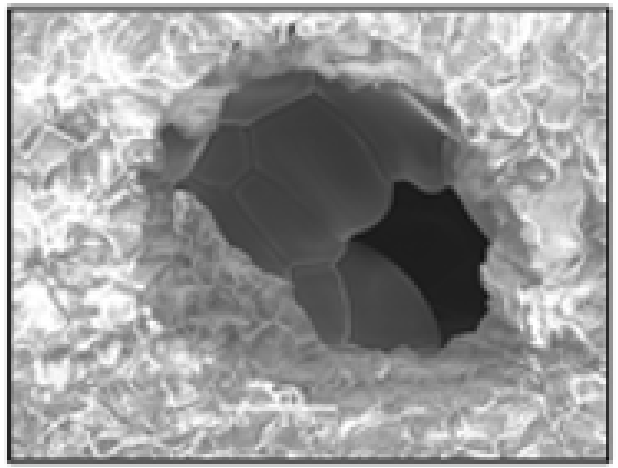
Al Wire (200x), As Received



Oxidized Aluminum Wire (200x)

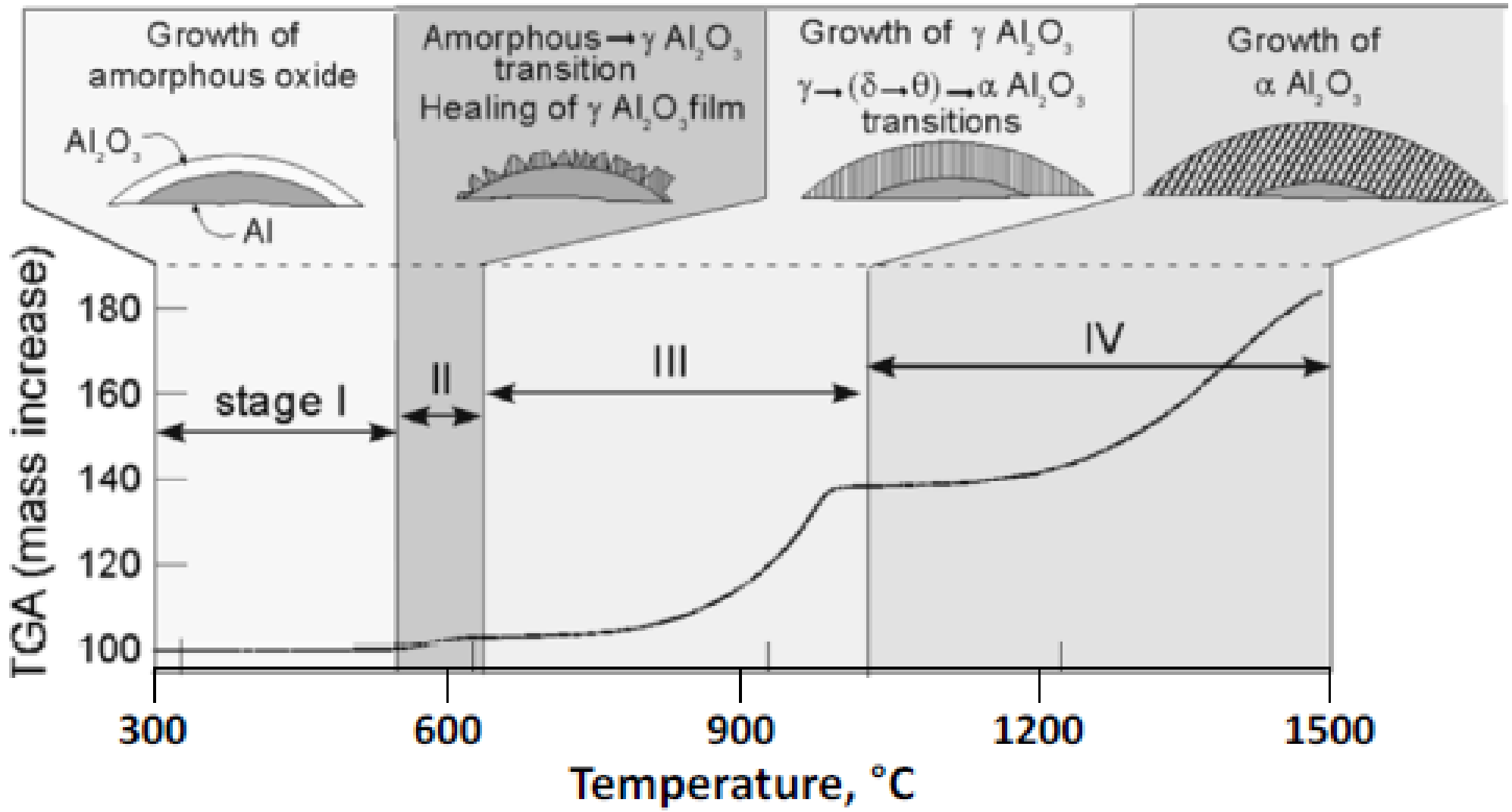


Oxidized Aluminum Wire (600x)

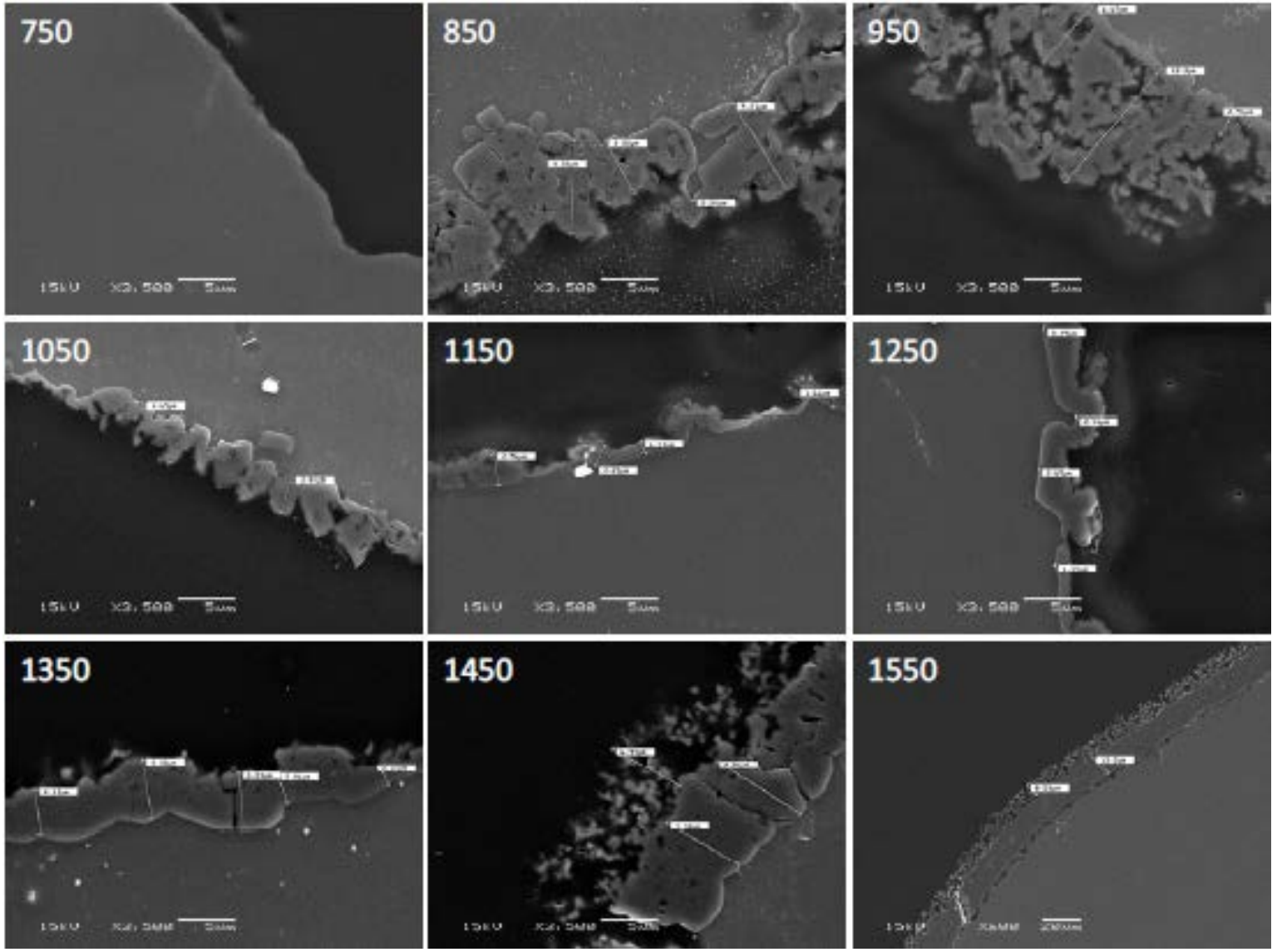


Oxidized Aluminum Wire (2500x)

# Alumina growth on aluminum vs temperature

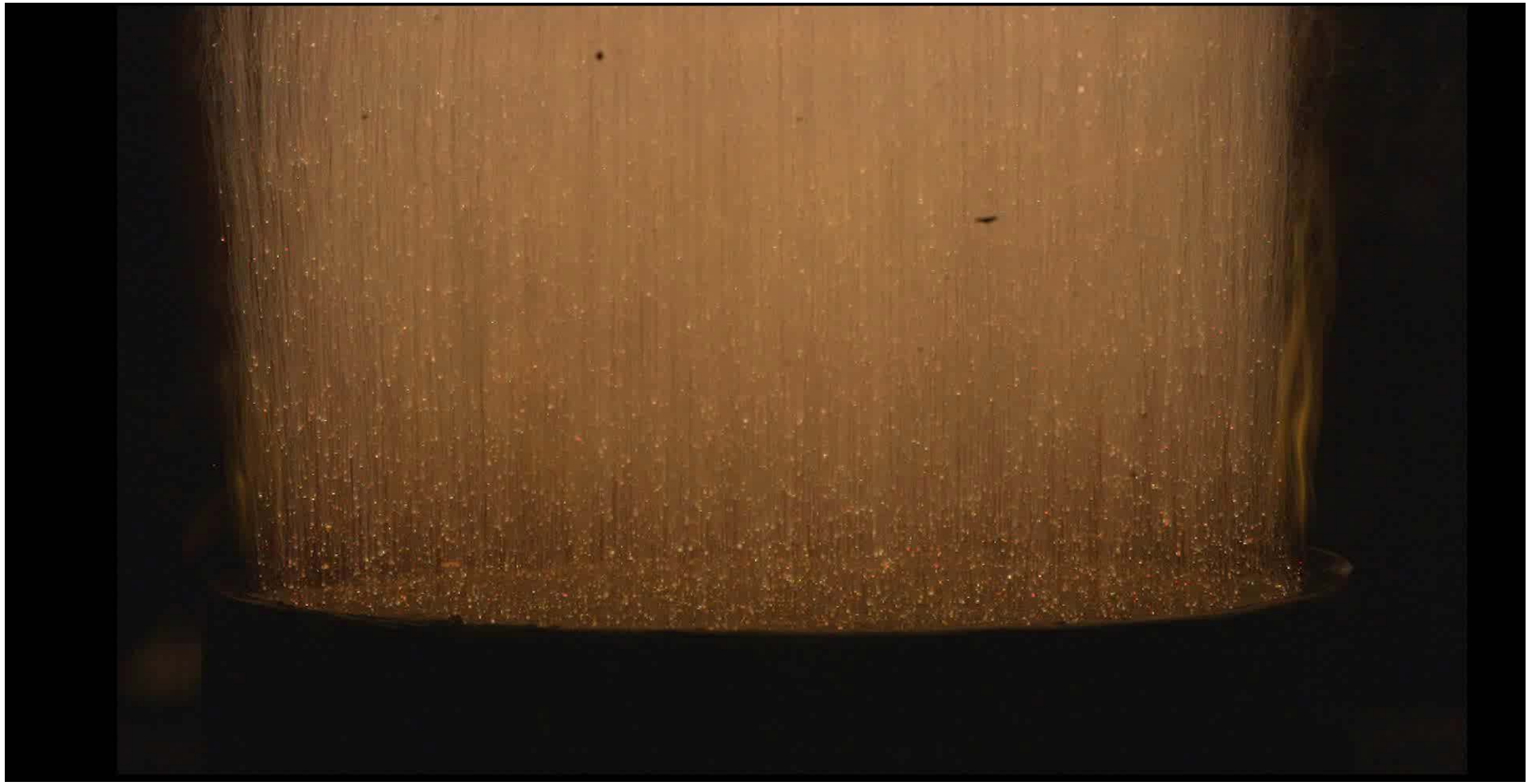


# SEM images of alumina layer on aluminum substrate



# Motivation for studying solid propellant combustion

# High speed, generic solid propellant burn showing Al particles



# Downward burning solid propellant onto concrete substrate

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# Magnified propellant burning surface

# Aluminum core surrounded by thick oxide shell

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**NASA-Propellant-Fire-Test-Burn2-6-22-10-Particles-001(1)**

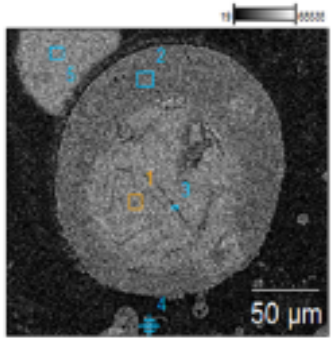
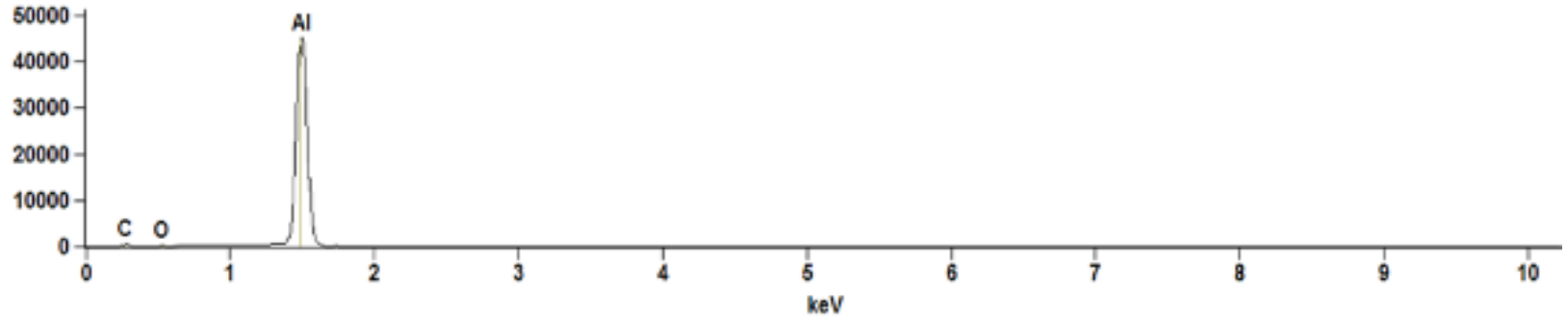



Image Name: NASA-Propellant-Fire-Test-Burn2-6-22-10-Particles-001(1)

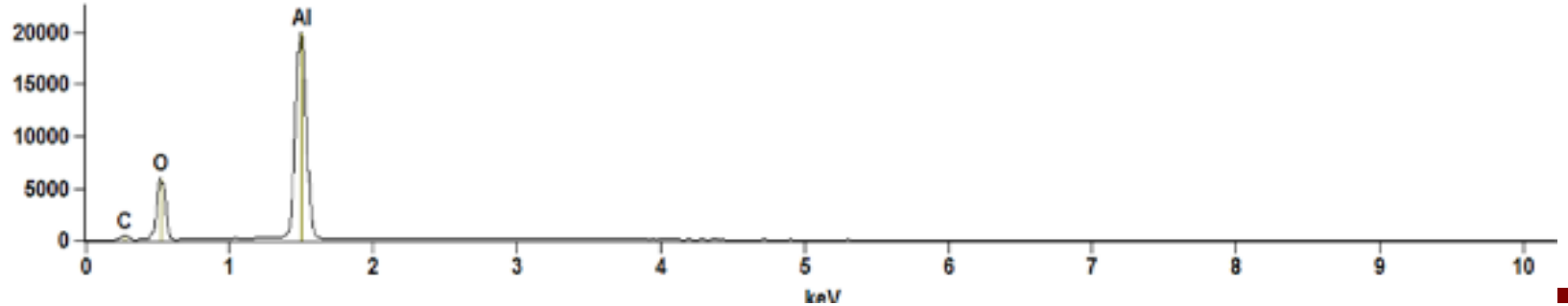
Accelerating Voltage: 15.0 kV

Magnification: 650

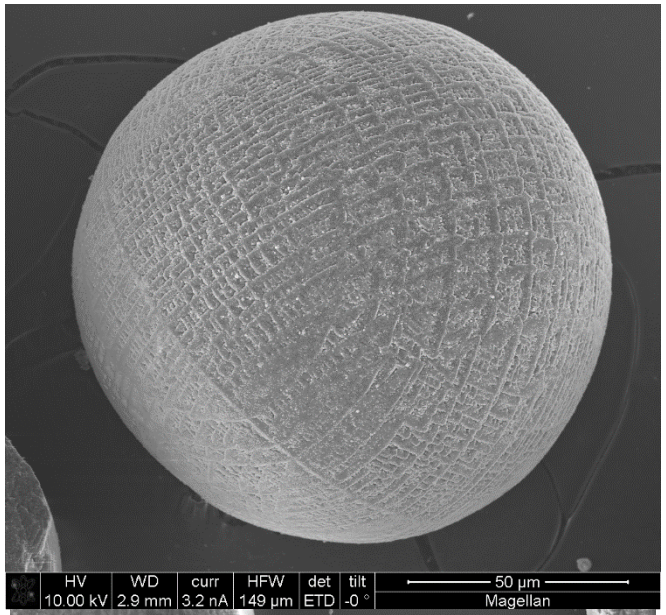
**Full scale counts: 44979** — **NASA-Propellant-Fire-Test-Burn2-6-22-10-Particles-001(1)_pt1**

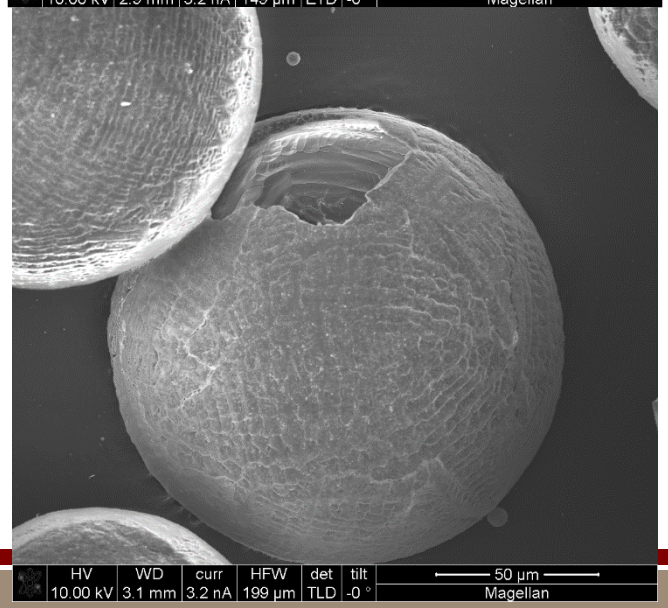


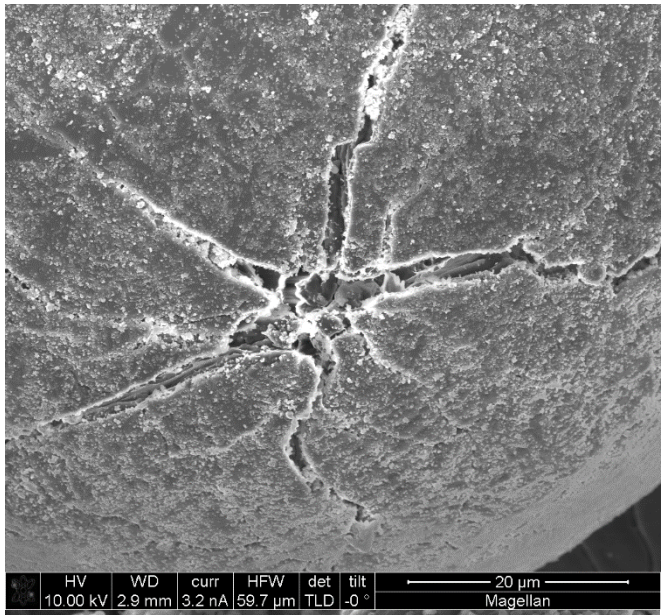

**Full scale counts: 19902** — **NASA-Propellant-Fire-Test-Burn2-6-22-10-Particles-001(1)_pt2**



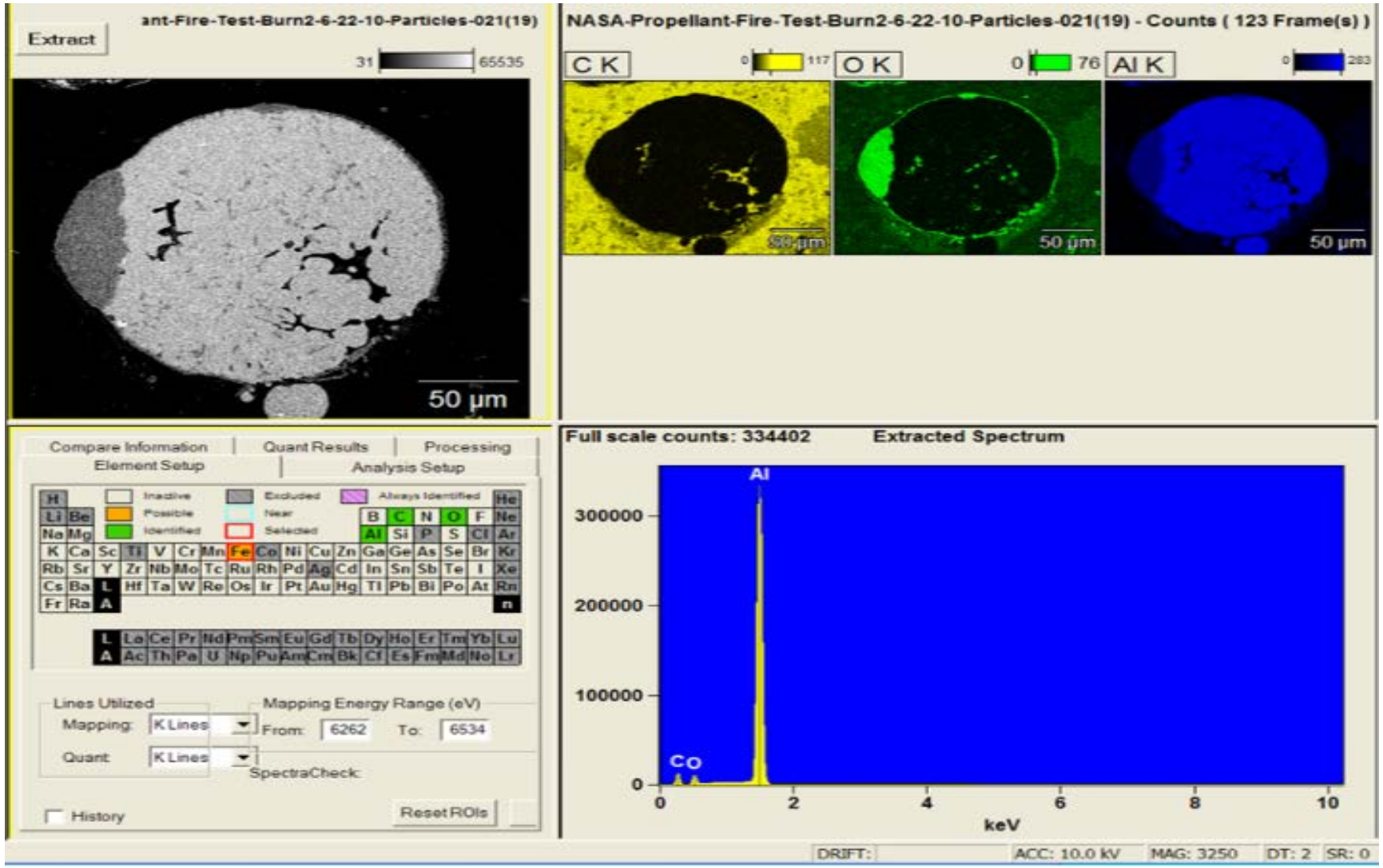
# SEM of Residue Collected from Propellant A Test



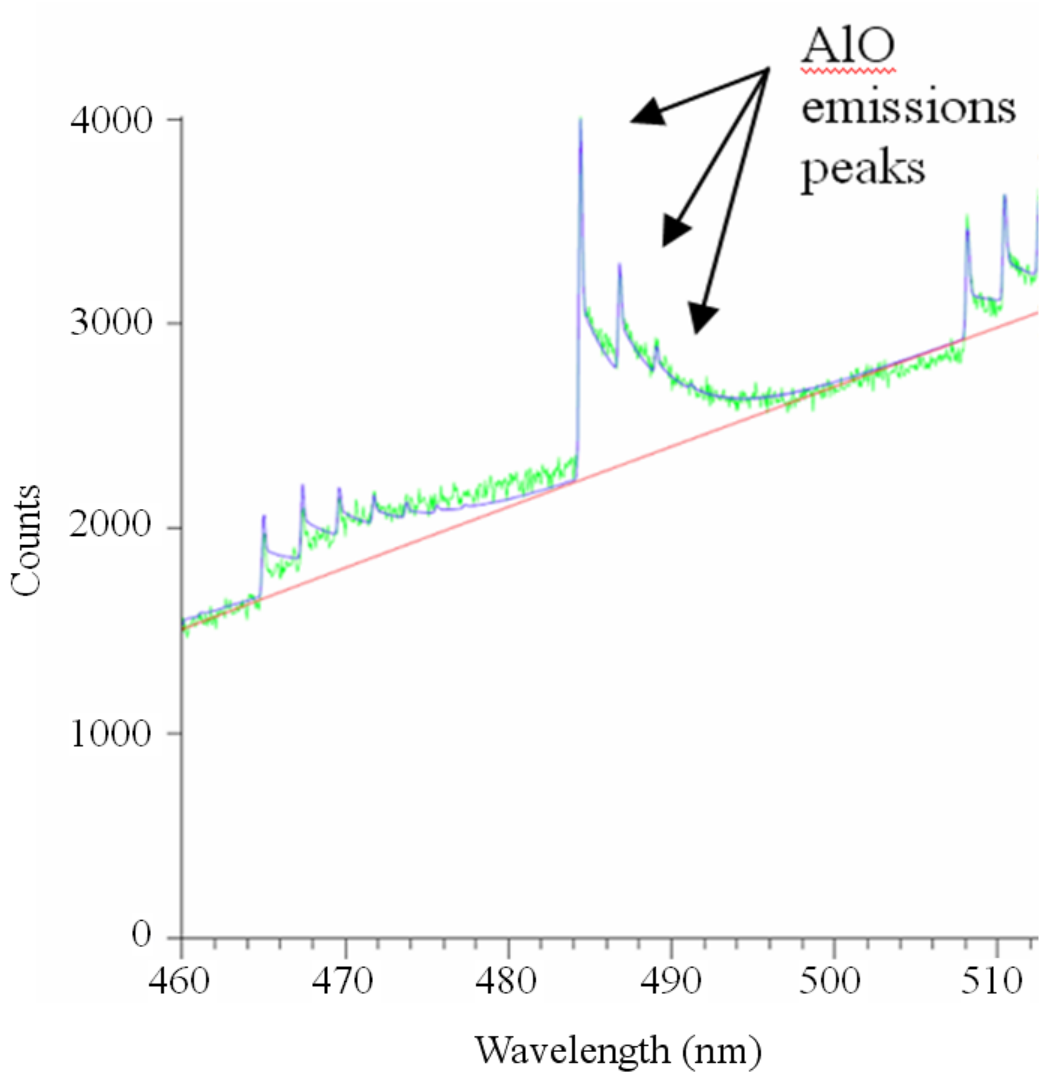




# Characteristic oxide cap which forms on many burning aluminum particles

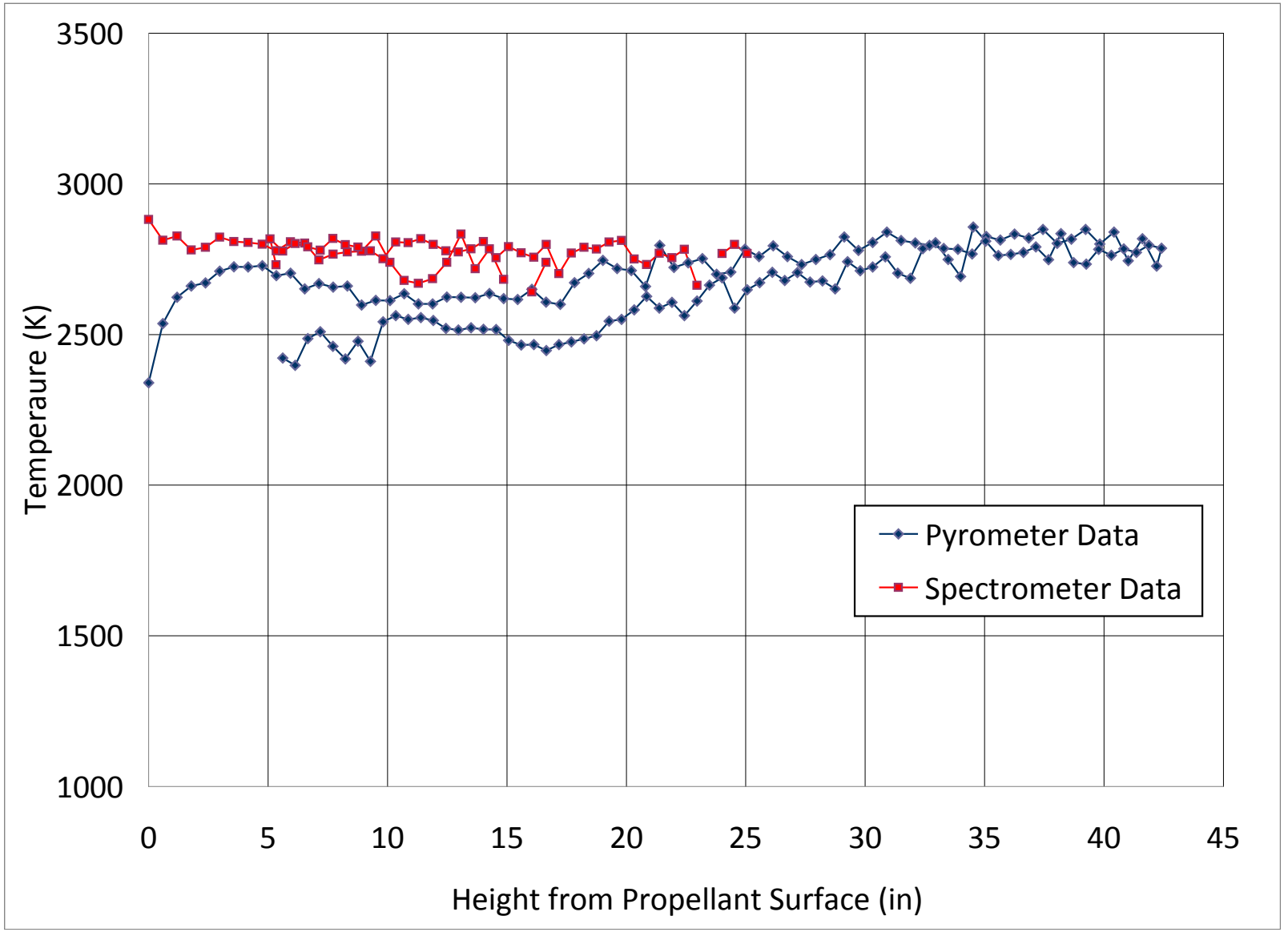


# Sampling propellant plume

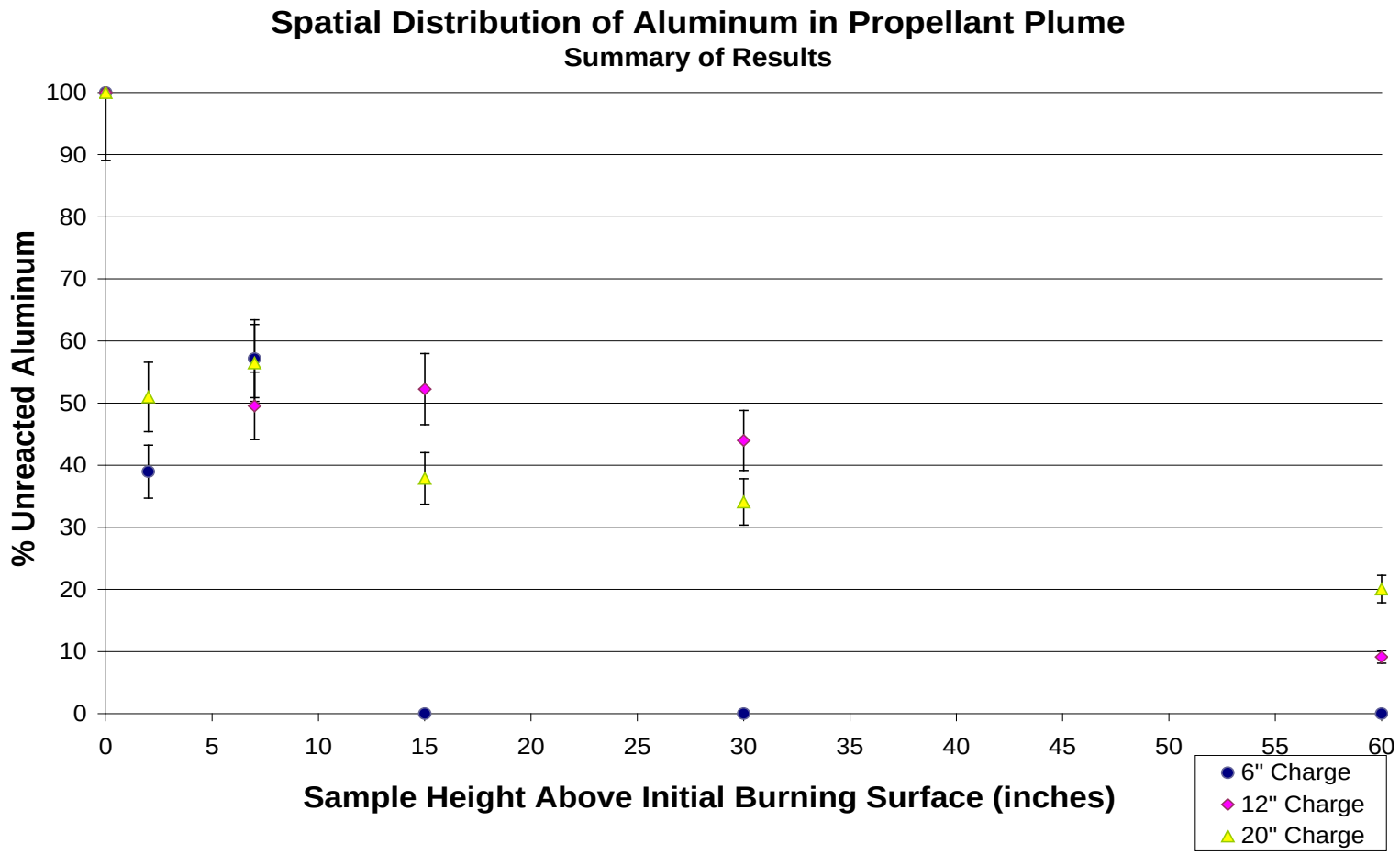
# Temperature of reaction can be inferred by matching AlO spectra to quantum state model



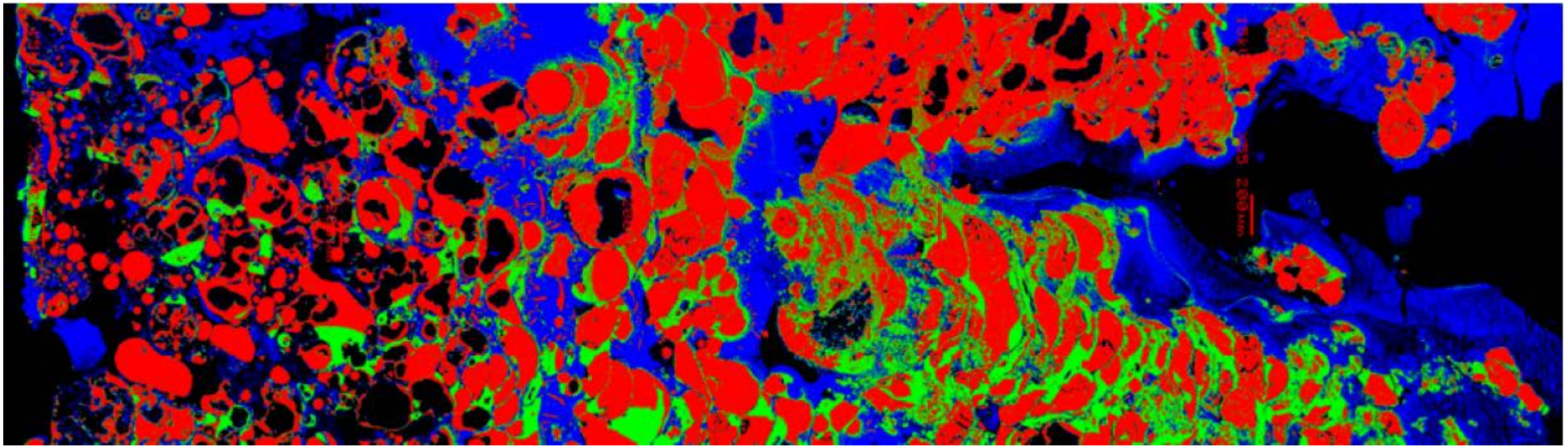
# AlO temperature in propellant plume vs height



# Extent of aluminum oxidation vs height, from coupon capture

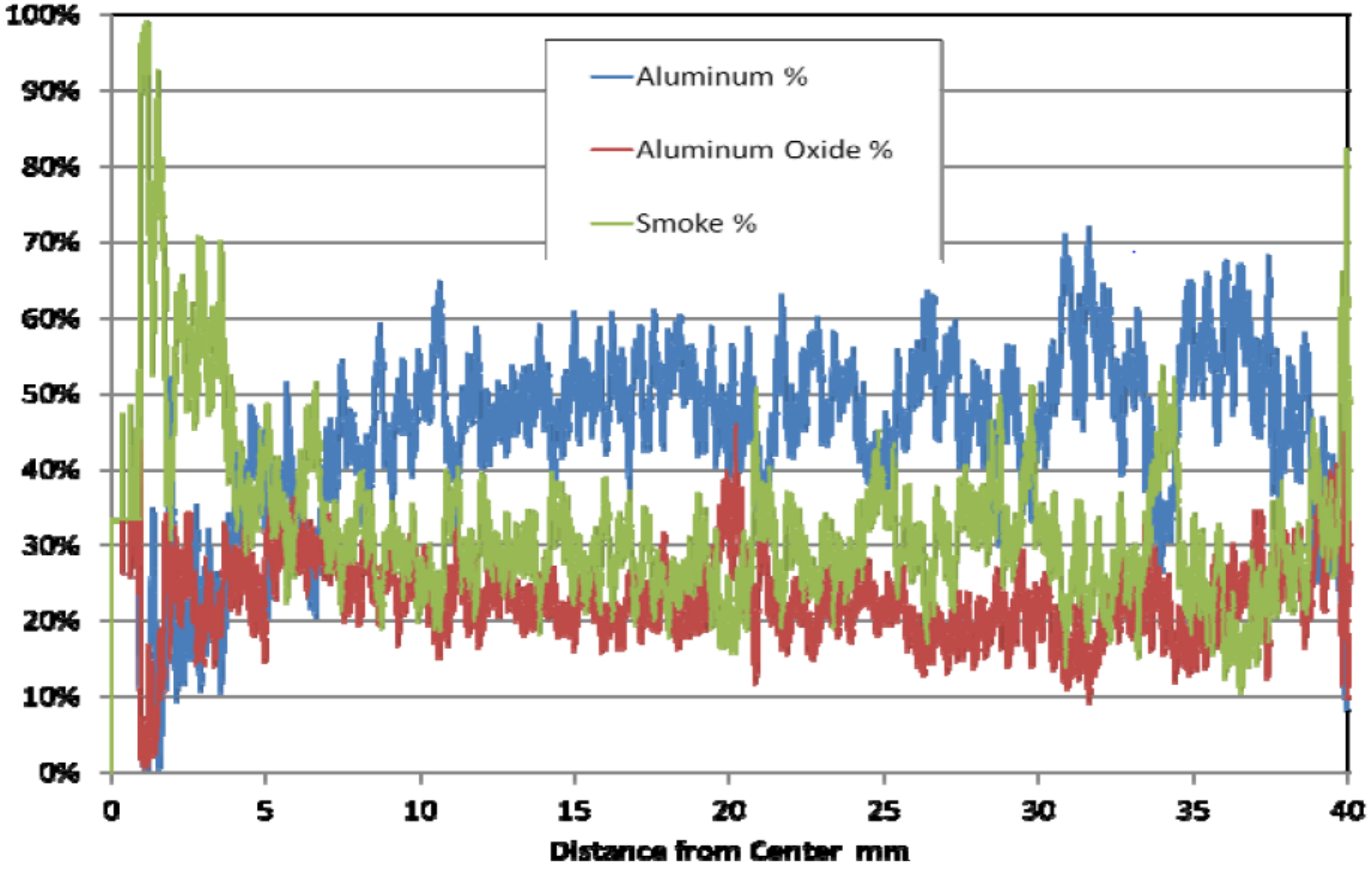


# Residue from propellant burn, free surface right, substrate surface left



Red is unoxidized aluminum, Green is AlO and blue is carbonaceous  matter, including chlorine

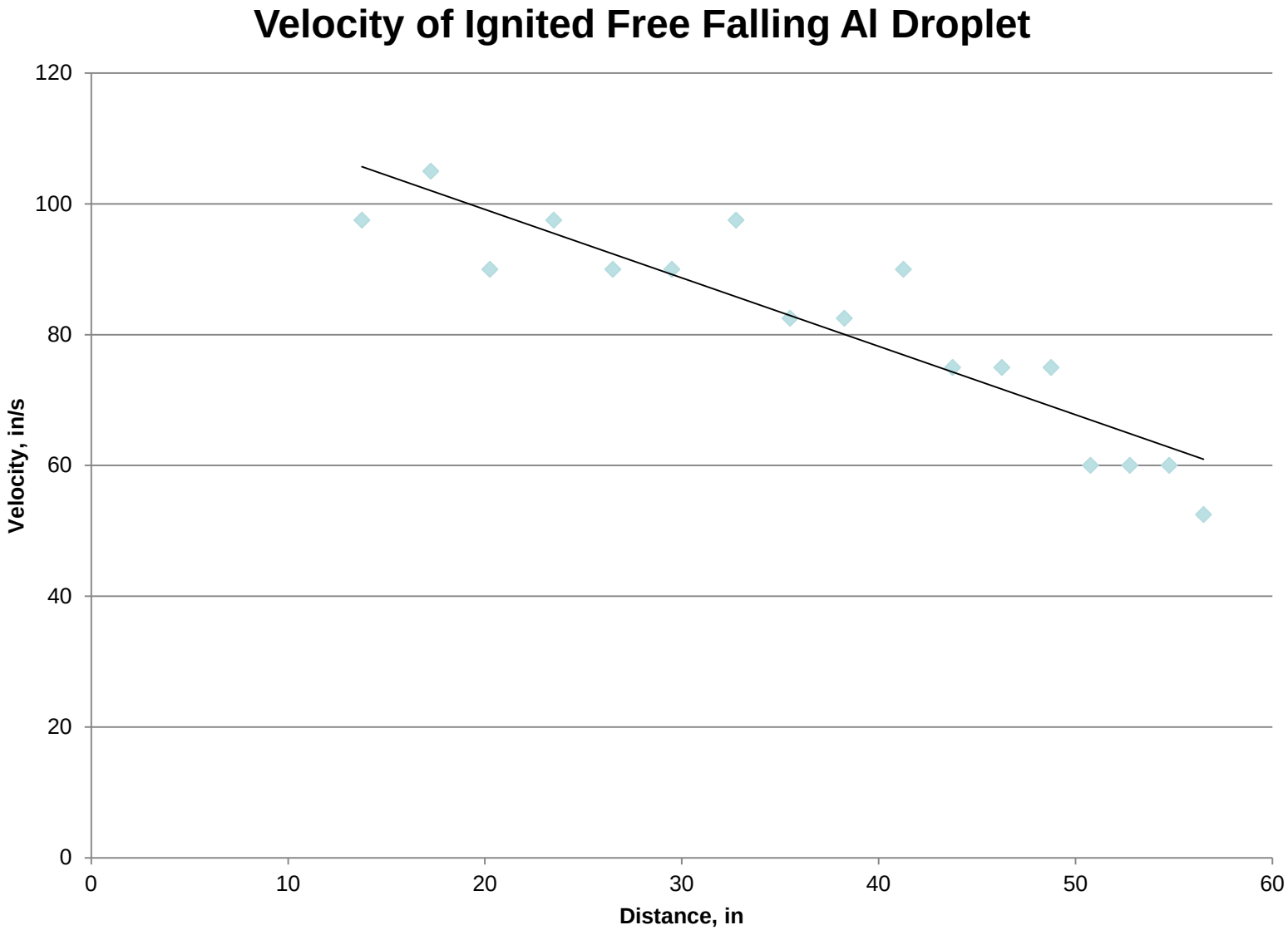
# Analysis of propellant burn residue on substrate



# Aluminum particle from MIG welder

# Single ignited aluminum particle freefall in air

# Burning aluminum droplet looses mass with increase in drag



# Ignited aluminum particles w/wo notch filter

# Al Particles from Electric Arc

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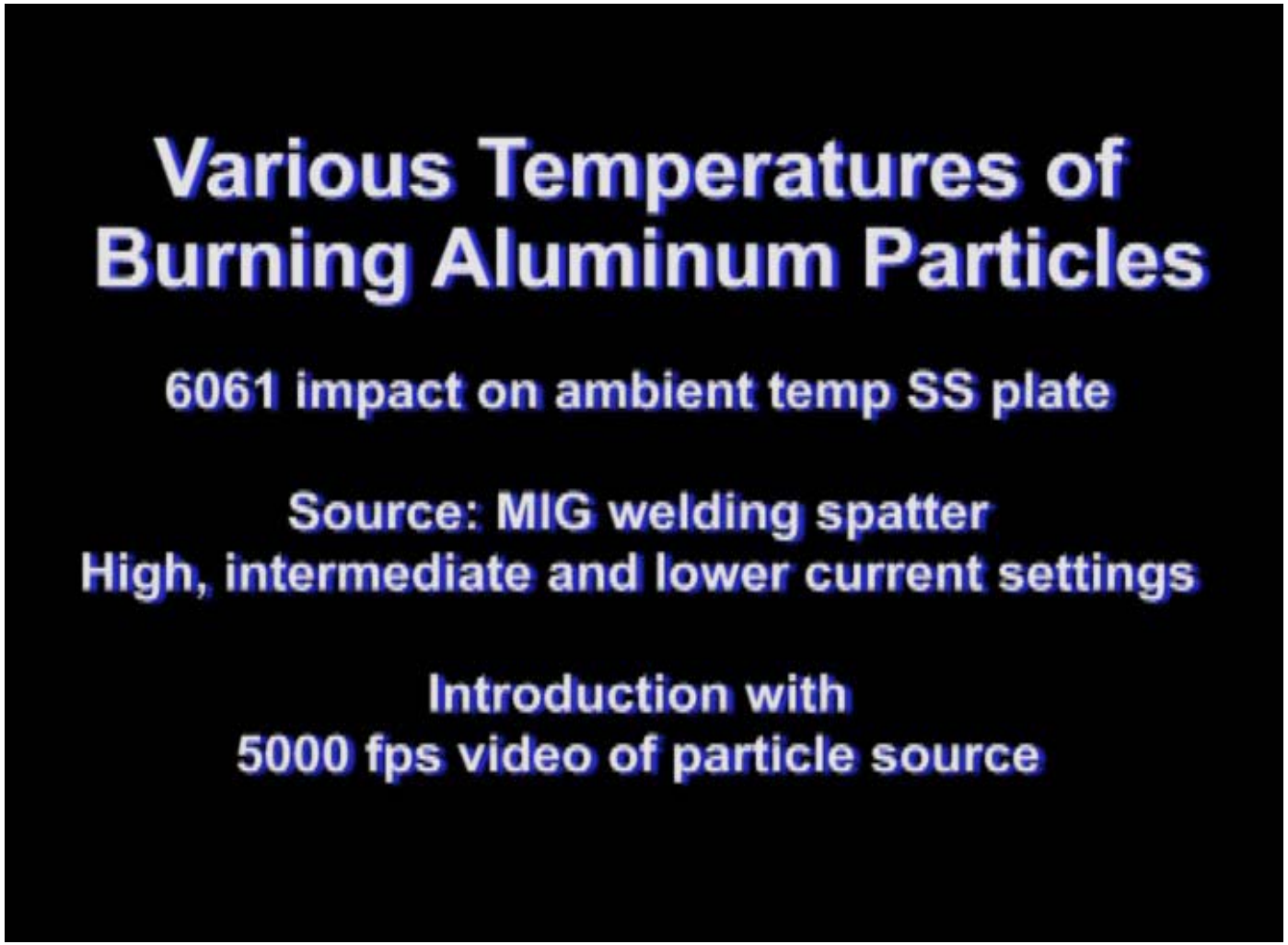
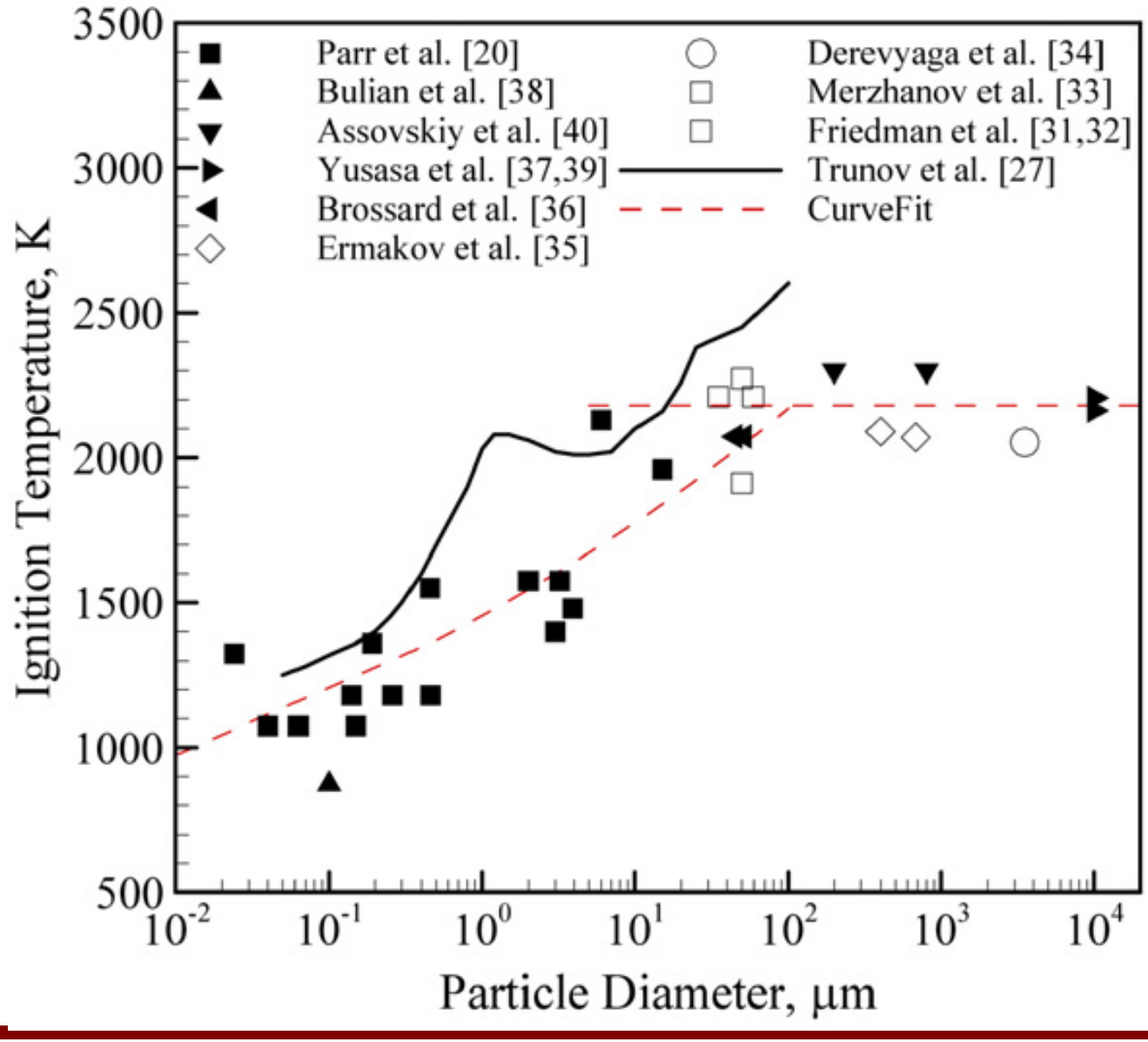
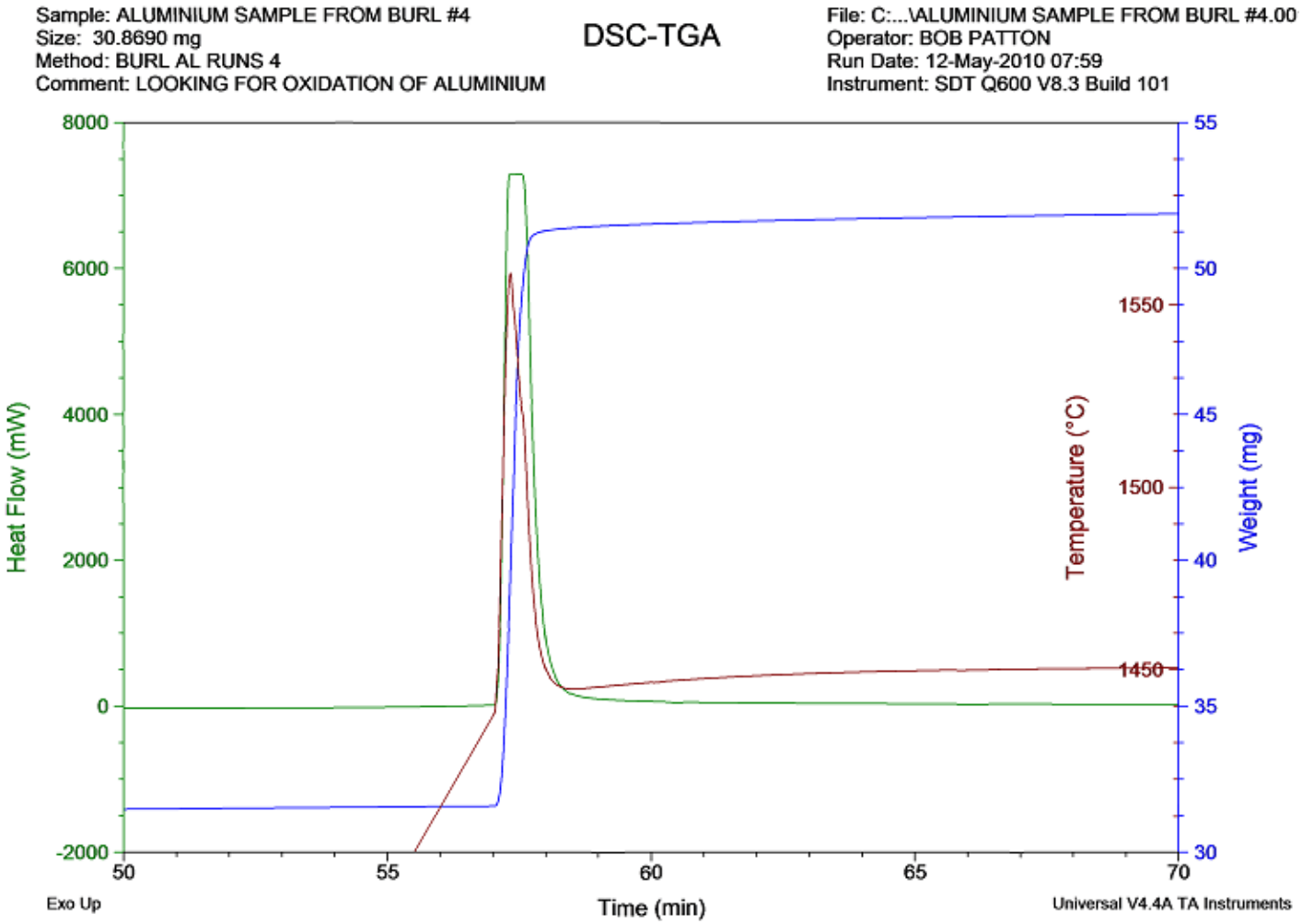


# Prior results on aluminum particle ignition temperature



# Aluminum powder ignition in air, after heating to 1450 C in argon



# Summary

- Molten aluminum exhibits high film strength
- Molten aluminum can be highly corrosive
- Oxide shell at near melt affects movement and strength increases with temperature
- Oxide shell inhibits ignition
- Melting of oxide shell may be a requirement for ignition, if the shell is allowed to grow thick under oxidizing conditions
- Aluminum ignition can be much lower for fast heating, or heating in absence of oxidizing atmosphere
- Much about aluminum ignition is not fully understood