Active Spectrum Inc.

Enabling Clean Combustion

Micro-ESR for Airborne Soot Measurement

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Summary

- Direct, in-situ measurement of airborne soot in vehicle exhaust.
- Minimum detectable concentration is 3 mg/m^3
- No accumulation necessary.
- Adequate sensitivity for 2012 OBD-II requirement.

Micro-ESR™

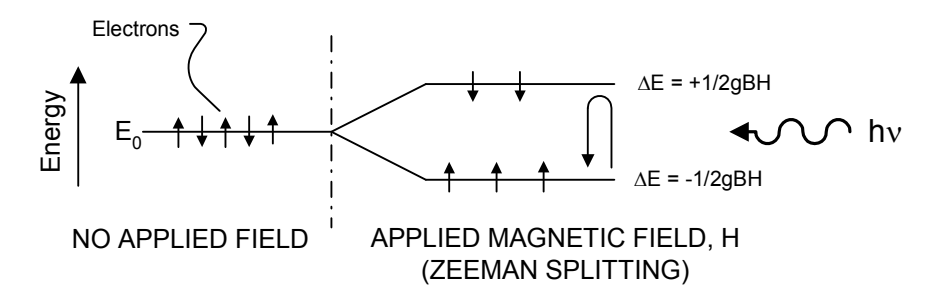
Conventional ESR

- Weight ~200kg+
- Cost ~$250k
- Size: XXL

- Housing is machined & nickel-plated steel.
- Fluid connections are 7/16”-20 JIC fittings.
- Electrical connection is CAN bus or USB. (Other options available).
- 2.25” DIA x 1.25” Tall
- Weight <1kg.

Micro-ESR Technology

- **ESR Principle:**



  - Excite resonant transitions between spin up and spin down state at a given magnetic field.
  - $h\nu = gBH$

- **Example: Oil Breakdown**

  $RH \rightarrow R\bullet$ (free radical) + $H\bullet$

  $RH + O_2 \rightarrow R\bullet$ (free radical) + $HO_2\bullet$

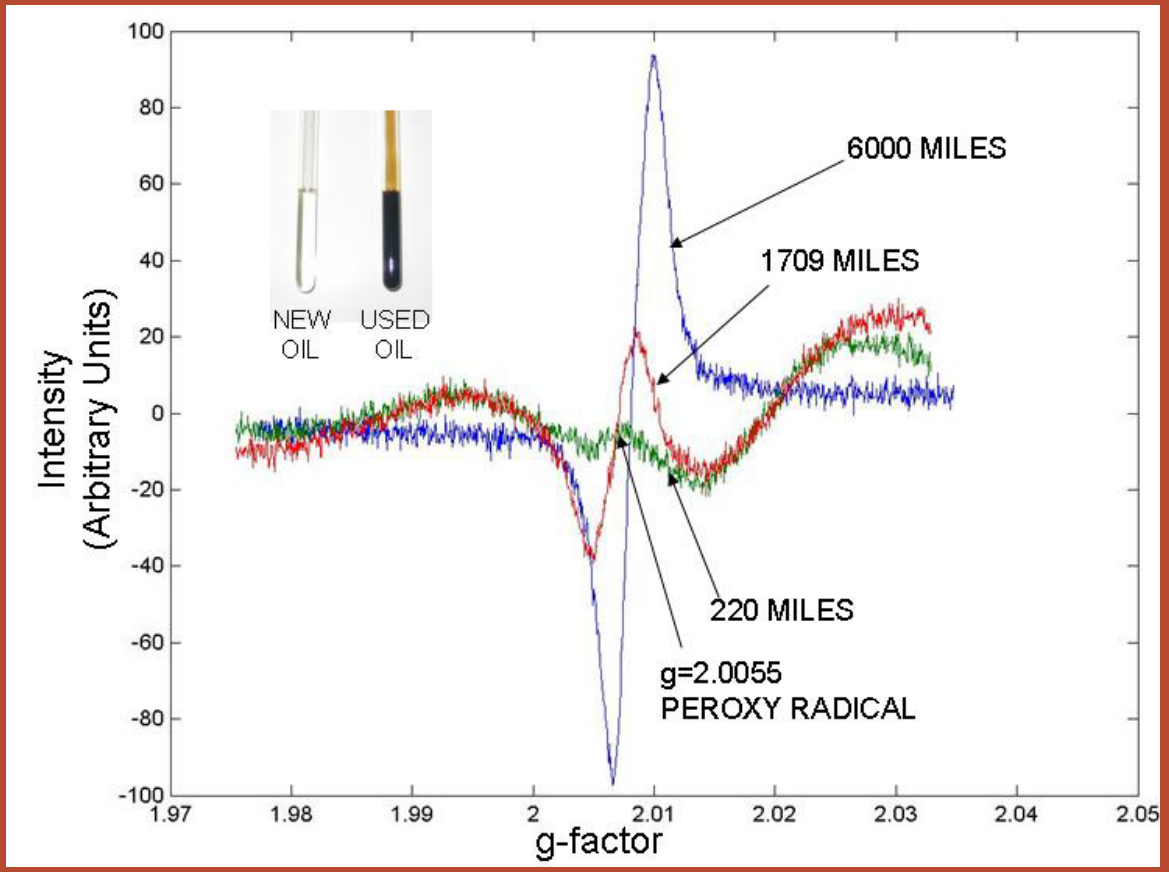
  The chain reaction then propagates as:

  $R\bullet + O_2 \rightarrow RO_2\bullet$ (peroxy radical)

  $RO_2\bullet + R'H \rightarrow ROOH$ (hydroperoxide) + $R'\bullet$

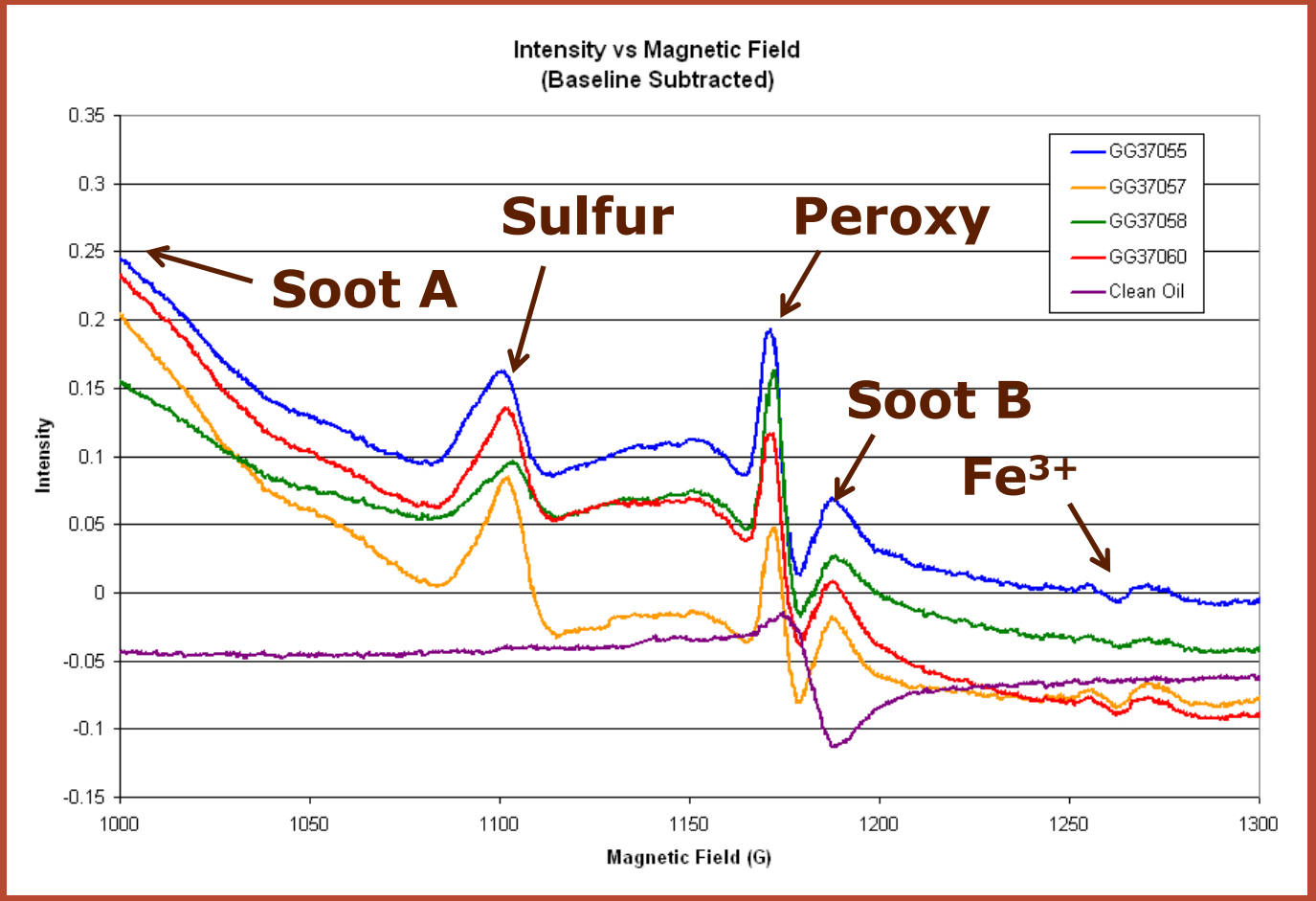
Example of Micro-ESR

Engine Oil Breakdown and Peroxy Radical Formation



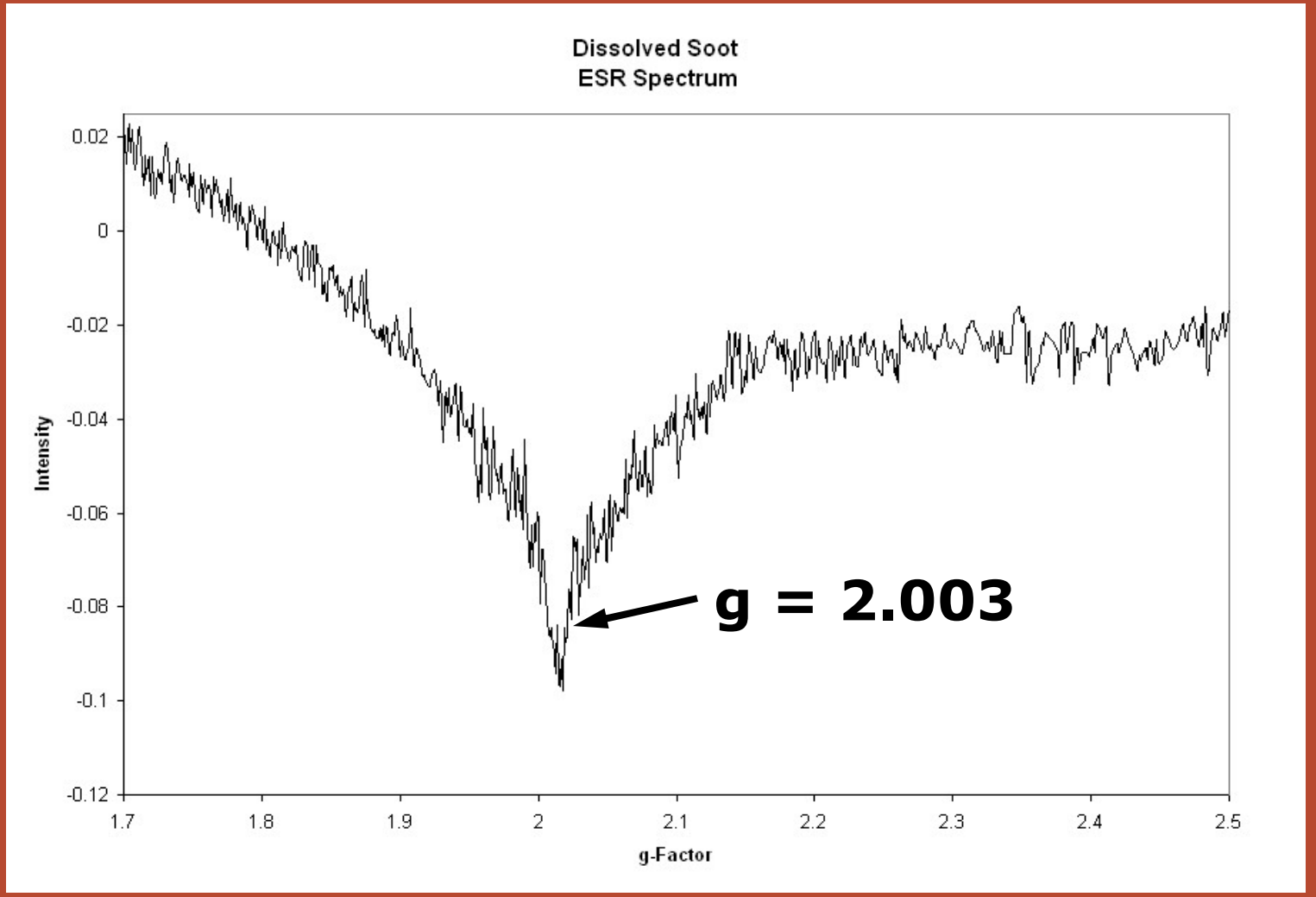
Measured increase in peroxy radical formation with mileage.

Marine Oil Example



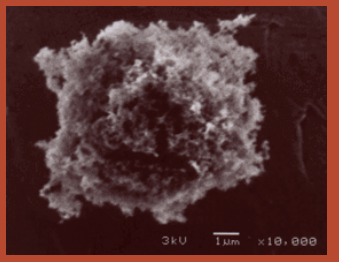
Contaminants in Marine Lubricating Oil

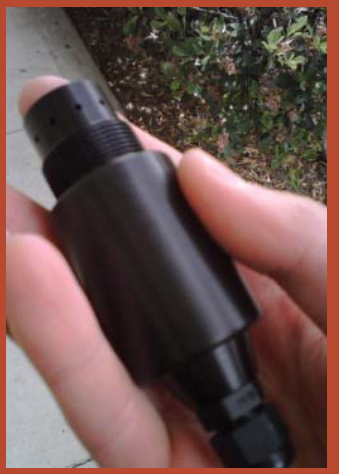
Soot in Oil


Dissolved Soot
ESR Spectrum
Intensity
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
g-Factor
g = 2.003

Soot

- Airborne soot is the No. 2 contributor to global warming (CO_2 is No. 1) and contributes directly to an elevated risk of lung cancer, acute bronchitis and asthma.
- Soot is a byproduct of inefficient combustion of hydrocarbons (coal, diesel, etc.).
- The EPA implemented new regulations to reduce airborne soot by 90% starting 2007.
- The EU also regulates soot emissions from diesel vehicles and is moving towards stricter regulation similar to the US by 2010 (Euro V).
- OBD II requirement to monitor onboard emissions control devices for soot and NO_x by 2012.





Soot Sensor Competitors

- **Optical**
  - **Attenuation**
  - **Scattering**
  - **Optical systems are expensive and rapidly fouled in the exhaust.**

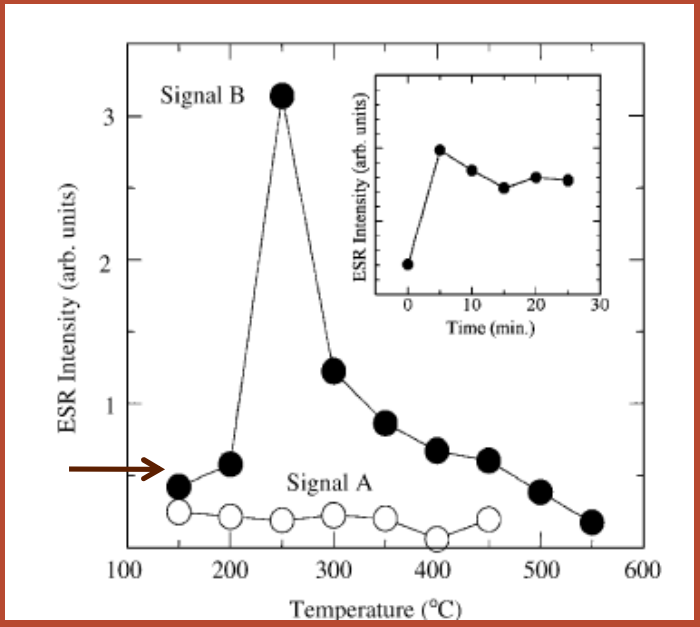
- **Spark Gap**
  - **Erosion of electrode.**
  - **High voltage supply required.**

- **Quartz Resonator**
  - **Not real-time (accumulate & release).**
  - **Nonspecific.**

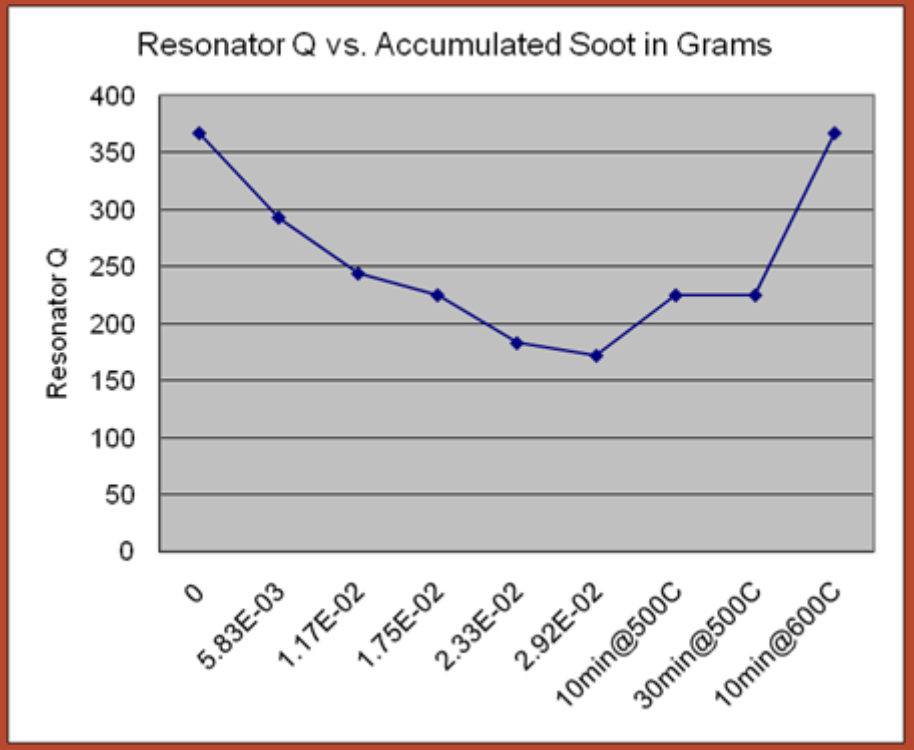
- **Capacitor**
  - **Requires accumulation.**
  - **Cannot operate above 600^{o}C.**

Micro-ESR Soot Sensor Advantages

- **Linear**
- **Stable**
  Quantum Mechanical ESR resonance is temperature invariant.
- **Specific**
  ONLY Carbon free radical can be detected (in this configuration).



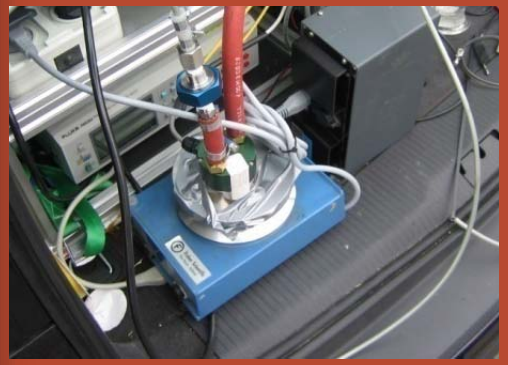
Accumulate and Oxidize



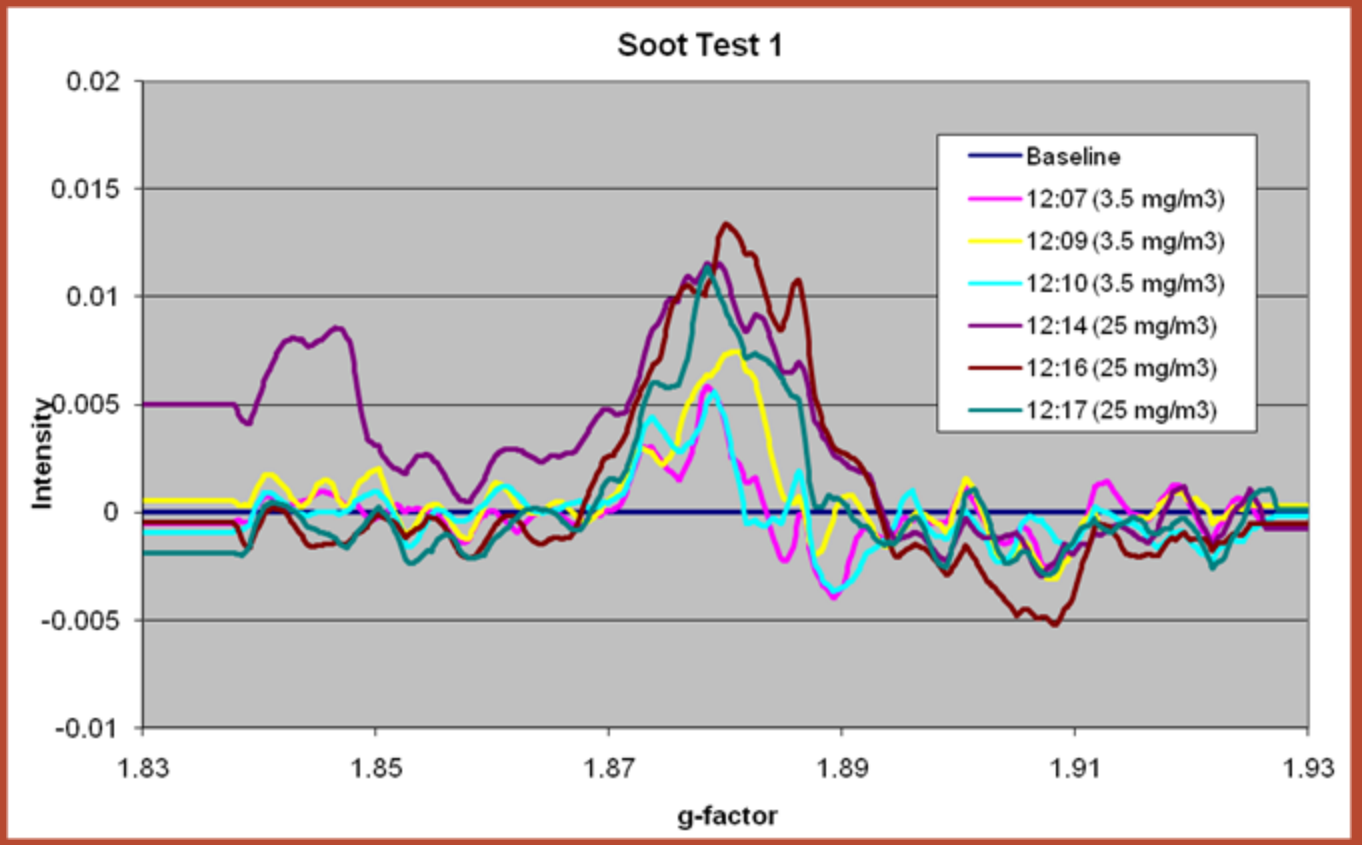
- Soot is conductive and can de-tune the RF cavity as it accumulates.
- Heating will oxidize the soot and restore the cavity resonance.

Testing

- Sensor mounted on a 2004 Opel Vectra 2.2L diesel without emissions controls.
- Particulates level in exhaust measured by a MAHA MPM-4 LLSP particulates meter.
- Vehicle was tested at idle and various load conditions which produced steady-state exhaust soot concentrations from 3 mg/m^3 to 200 mg/m^3.

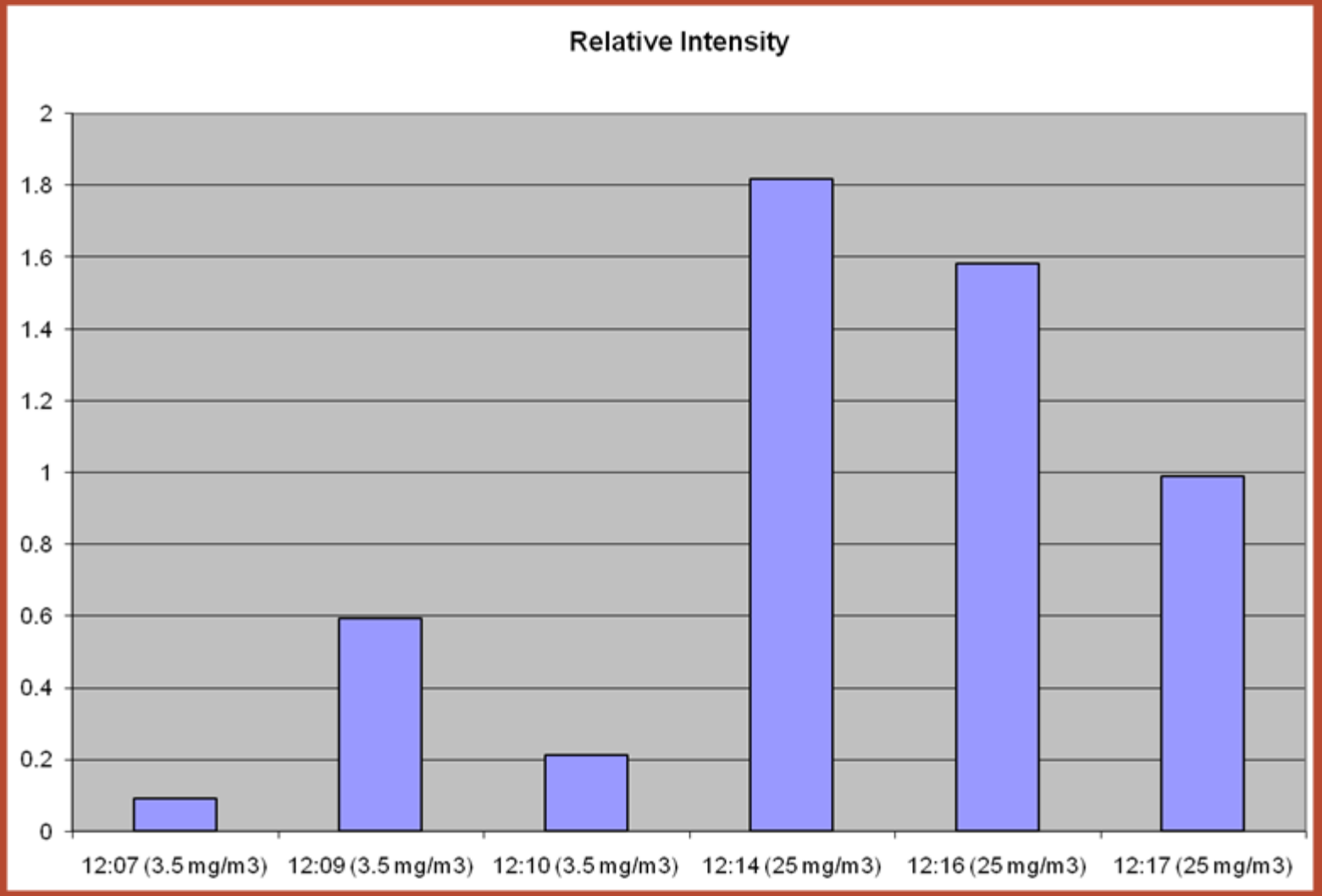


Test Results



- Integrate area under resonant peak to obtain concentration.

Test Results



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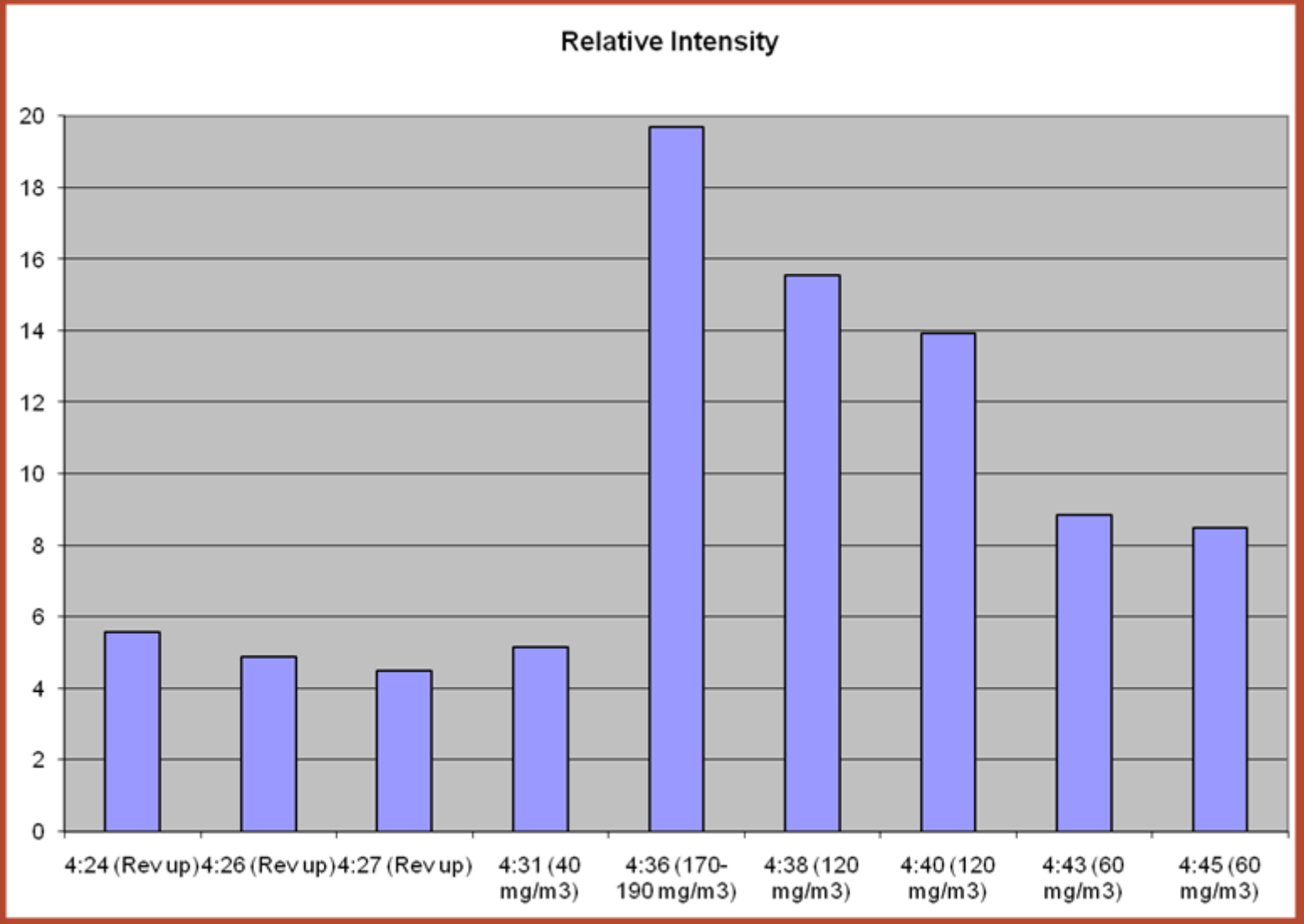

Technical Contributors

Dr. Chris White: 9 years of RF design experience. Developed Micro-ESR technology, solid-state atomic clock, tunable RF filters and VCOs.

Dr. James White: 10 years of MEMS & sensor design experience. Responsible for Micro-ESR packaging and manufacturing processes, and marketing.

Colin Elliott: Electrical engineer, circuit designer and software guru.

Paul Gennissen, Tim Tiek and Johan Haas:
Conducted in-vehicle tests at Sensata's facility in Almelo, NL.

US Army:
Funding for the development of Micro-ESR was provided by US Army TACOM (Warren) through an SBIR Phase II award.

Sensor Competitors

ON-LINE

Micro-ESR™

Dielectric

Viscosity

OFF-LINE

Particle Counters

FTIR

Metals Analysis (XRF)