# Effect of Fuel and Lube Oil Sulfur on the Performance of a Diesel Exhaust Gas Continuously Regenerating Trap

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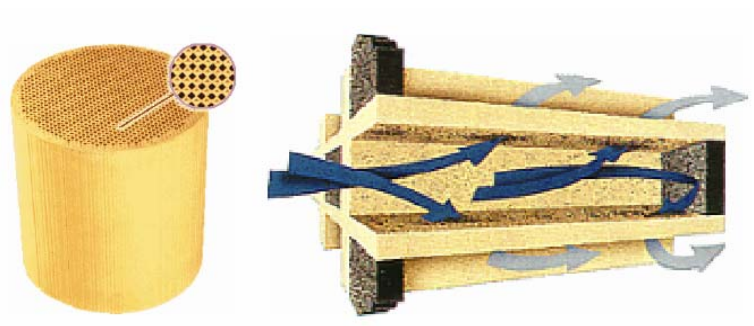
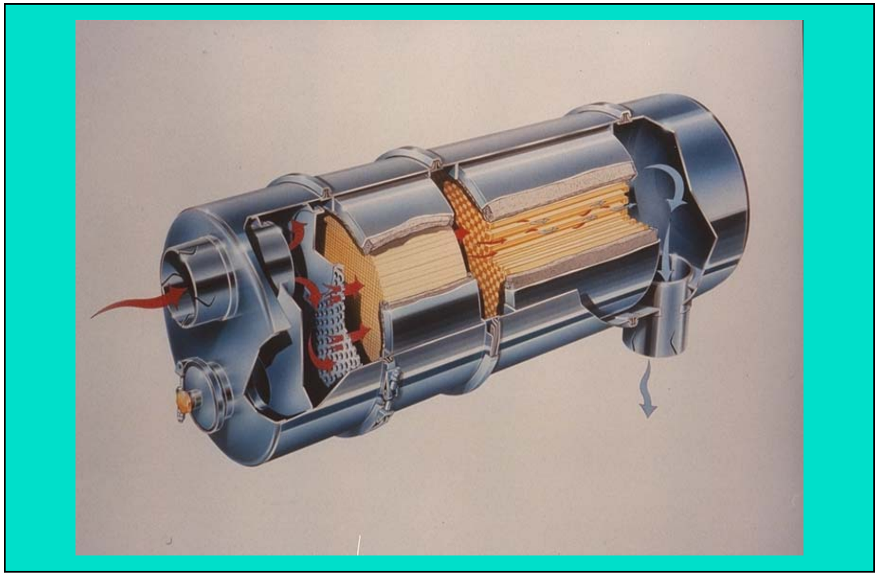
# Particle removal by exhaust filters



Figures courtesy Corning and Johnson-Matthey



- Most PM filtration systems being considered for 2007 are the wall flow type shown on the left. Without regeneration to oxidize soot these devices quickly plug.
- Catalyzed filtration systems like the J-M CRT® shown on the right reduce regeneration temperature by producing $NO_2$ from exhaust NO in an oxidizing catalyst upstream of filter
- The catalyst also converts $SO_2$ to $SO_3$ at higher temperatures
- The J-M CCRT® has a catalyzed washcoat on the filter as well to further reduce regeneration temperature
- A CRT followed by a sulfur trap was also tested

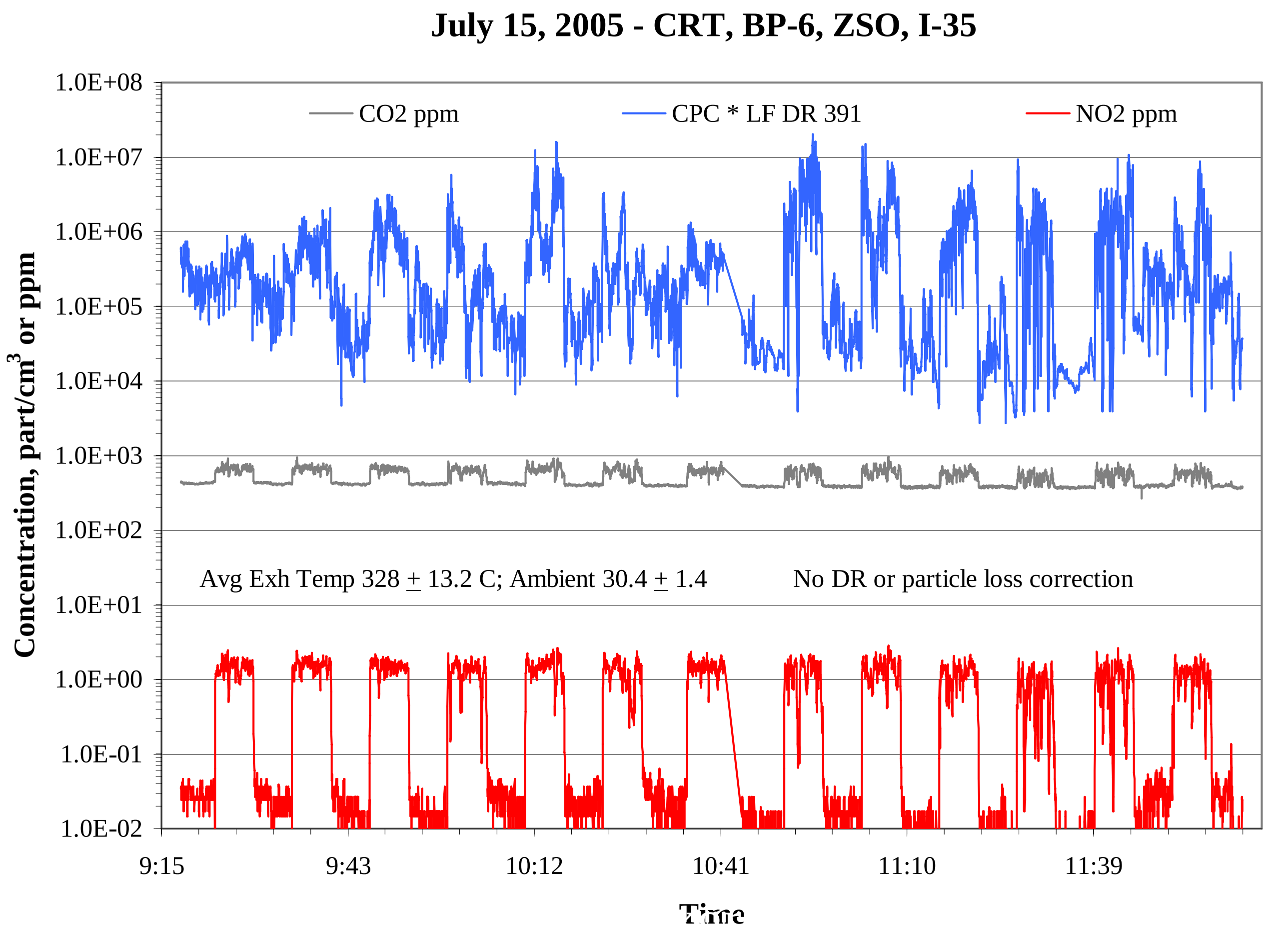
# Summary

- Analysis of 5 years of on-road particle measurements to determine influence of fuel, lubricating oil, trap type and trap age on nanoparticle emissions measured downstream of a heavy-duty vehicle operated under real-world highway cruise conditions**
- Under on-road cruise conditions, the only particles found downstream of a CRT are mainly sulfuric acid nucleation mode particles*
  - Strong dependence on exhaust temperature
  - These particles constitute little particle mass
  - Storage and release of sulfates on catalyst substrate appears to play an important role

*Grose, M., et al., “Chemical and Physical Properties of Ultrafine Diesel Exhaust Particles Sampled Downstream of a Catalytic Trap,” Environ. Sci. Technol.; 2006; 40(17) pp 5502 – 5507.
**Kittelson, D., et al., Effect of Fuel and Lube Oil Sulfur on the Performance of a Diesel Exhaust Gas Continuously Regenerating Trap, to be submitted to JAS.

# UMN Mobile Emissions Laboratory (MEL)

# How We Sample



# Test conditions for on-road filter evaluations

- Tests run with J-M CRT, CCRT, and CRTS
  - CRT consist of oxidizing catalyst plus wall flow filter
  - CCRT consist of oxidizing catalyst plus catalyzed wall flow filter
  - The CRTS consists of a CRT plus a sulfur trap
- 105 kph cruise on Minnesota rural freeway
  - Load and exhaust temperature varied with grade, headwind, tailwind
  - Exhaust T – 240 to 380 C

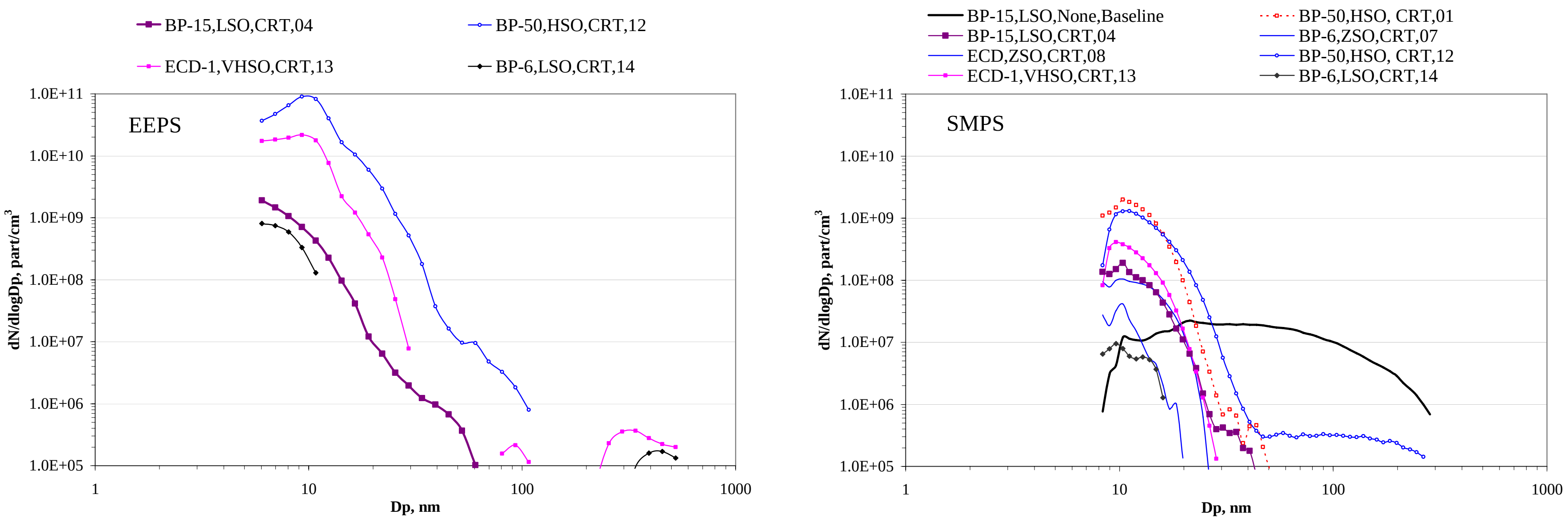
# Test Condition – 105 + 8 km/hr

| Trial | Fuel | Oil | Aftertreatment | Dilution ratio | |
|---|---|---|---|---|---|
| | | | | Avg | Std |
| Baseline | BP-15 | LSO | None | 477 | 91 |
| Trial 01 | BP-50 | HSO | CRT | 431 | 74 |
| Trial 02 | BP-15 | LSO | CCRT | 429 | 56 |
| Trial 03 | BP-15 | LSO | CRT + S-Trap | 340 | 33 |
| Trial 04 | BP-15 | LSO | CRT | 507 | 69 |
| Trial 05 | BP-15 | LSO | CRT + S-Trap | 406 | 24 |
| Trial 06 | BP-15 | LSO | CCRT | 400 | 48 |
| Trial 07 | BP-6 | ZSO | CRT | 381 | 60 |
| Trial 08 | ECD | ZSO | CRT | 473 | 75 |
| Trial 09 | BP-6 | HSO | CRT | 379 | 39 |
| Trial 10 | BP-50 | ZSO | CRT + S-Trap | 416 | 52 |
| Trial 11 | BP-50 | HSO | CRT + S-Trap | 362 | 40 |
| Trial 12 | BP-50 | HSO | CRT | 385 | 21 |
| Trial 13 | ECD-1 | VHSO | CRT | 413 | 41 |
| Trial 14 | BP-6 | LSO | CRT | 516 | 89 |

| Season | Trial | Fuel | Fuel S, ppm | Oil | Oil S, % |
|---|---|---|---|---|---|
| Fall 02 | -5 | BP-15 | 15 | HSO | 0.261 |
| Fall 02 | -4 | BP-50 | 45 | HSO | 0.261 |
| Summer 03 | -3 | BP-15 | 15 | HSO | 0.261 |
| Summer 03 | -2 | BP-15 | 15 | LSO | 0.126 |
| Summer 03 | -1 | BP-15 | 15 | LSO | 0.126 |
| Summer 03 | 1 | BP-50 | 45 | HSO | 0.261 |
| Summer 04 | 4 | BP-15 | 15 | LSO | 0.126 |
| Summer 05 | 7 | BP-6 | 4 | ZSO | 0.042 |
| Summer 05 | 8 | ECD | 6 | ZSO | 0.042 |
| Summer 05 | 9 | BP-6 | 4 | HSO | 0.261 |
| Summer 06 | 12 | BP-50 | 45 | HSO | 0.261 |
| Summer 06 | 13 | ECD-1 | 6 | VHSO | 0.619 |
| Summer 06 | 14 | BP-6 | 4 | LSO | 0.142 |

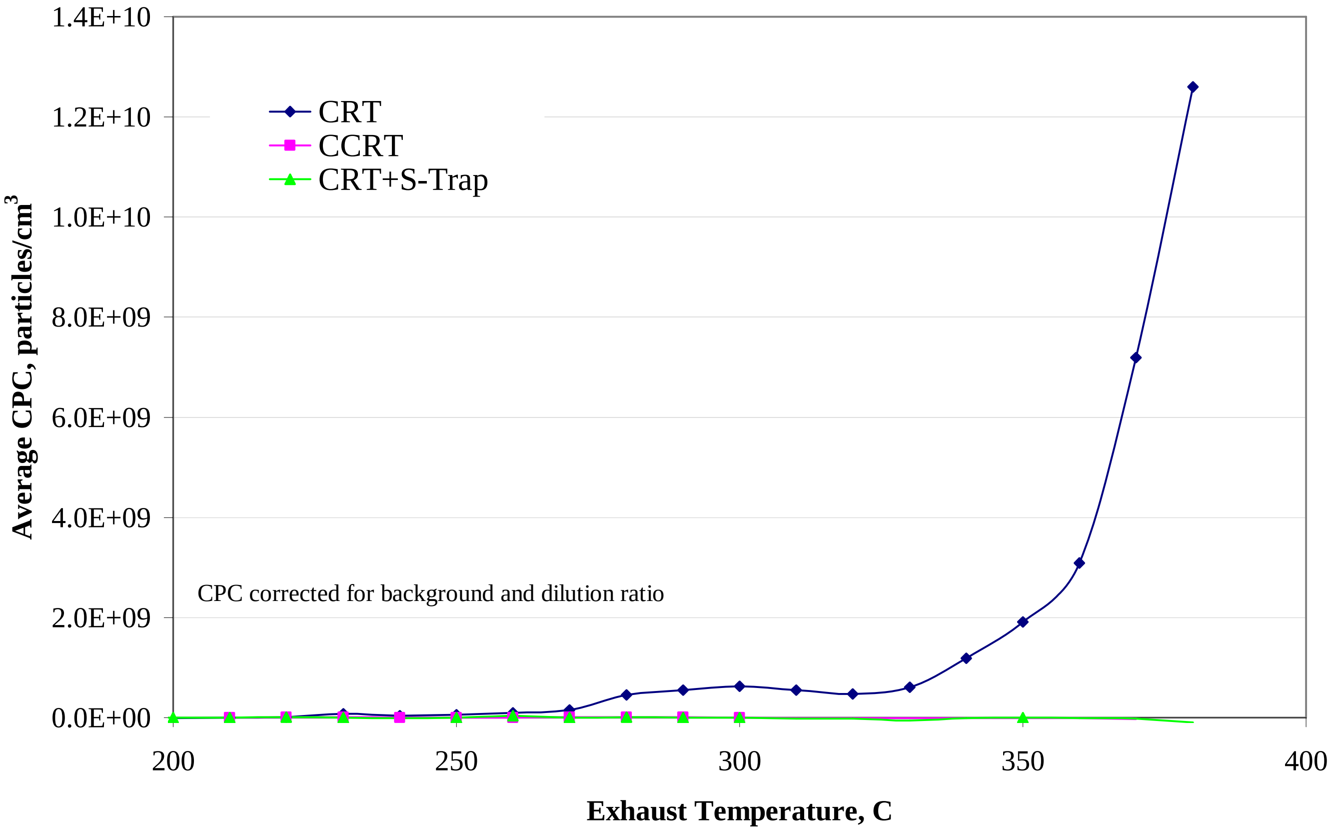
| Trial | Fuel | Oil | Aftertreatment | Number of repetitions | Number of plume samples | Number of background samples | Number of SMPS background scans | Nuimber of plume SMPS scans |
|---|---|---|---|---|---|---|---|---|
| Baseline | BP-15 | LSO | None | 26 | 7877 | 14974 | 146 | 74 |
| Trial 01 | BP-50 | HSO | CRT | 28 | 8622 | 17896 | 160 | 80 |
| Trial 02 | BP-15 | LSO | CCRT | 72 | 22453 | 47314 | 433 | 214 |
| Trial 03 | BP-15 | LSO | CRT + S-Trap | 33 | 10361 | 20490 | 192 | 98 |
| Trial 04 | BP-15 | LSO | CRT | 57 | 17215 | 35184 | 350 | 169 |
| Trial 05 | BP-15 | LSO | CRT + S-Trap | 45 | 14436 | 30823 | 277 | 135 |
| Trial 06 | BP-15 | LSO | CCRT | 37 | 11615 | 23124 | 217 | 111 |
| Trial 07 | BP-6 | ZSO | CRT | 66 | 20943 | 44492 | 406 | 197 |
| Trial 08 | ECD | ZSO | CRT | 38 | 12163 | 24831 | 229 | 113 |
| Trial 09 | BP-6 | HSO | CRT | 43 | 13882 | 26373 | 239 | 128 |
| Trial 10 | BP-50 | ZSO | CRT + S-Trap | 41 | 13168 | 28891 | 264 | 121 |
| Trial 11 | BP-50 | HSO | CRT + S-Trap | 60 | 18910 | 39326 | 358 | 178 |
| Trial 12 | BP-50 | HSO | CRT | 39 | 14456 | 29056 | 221 | 114 |
| Trial 13 | ECD-1 | VHSO | CRT | 40 | 14833 | 30386 | 239 | 119 |
| Trial 14 | BP-6 | LSO | CRT | 37 | 13091 | 26498 | 210 | 105 |

# SMPS and EEPS Size Distributions - CRT



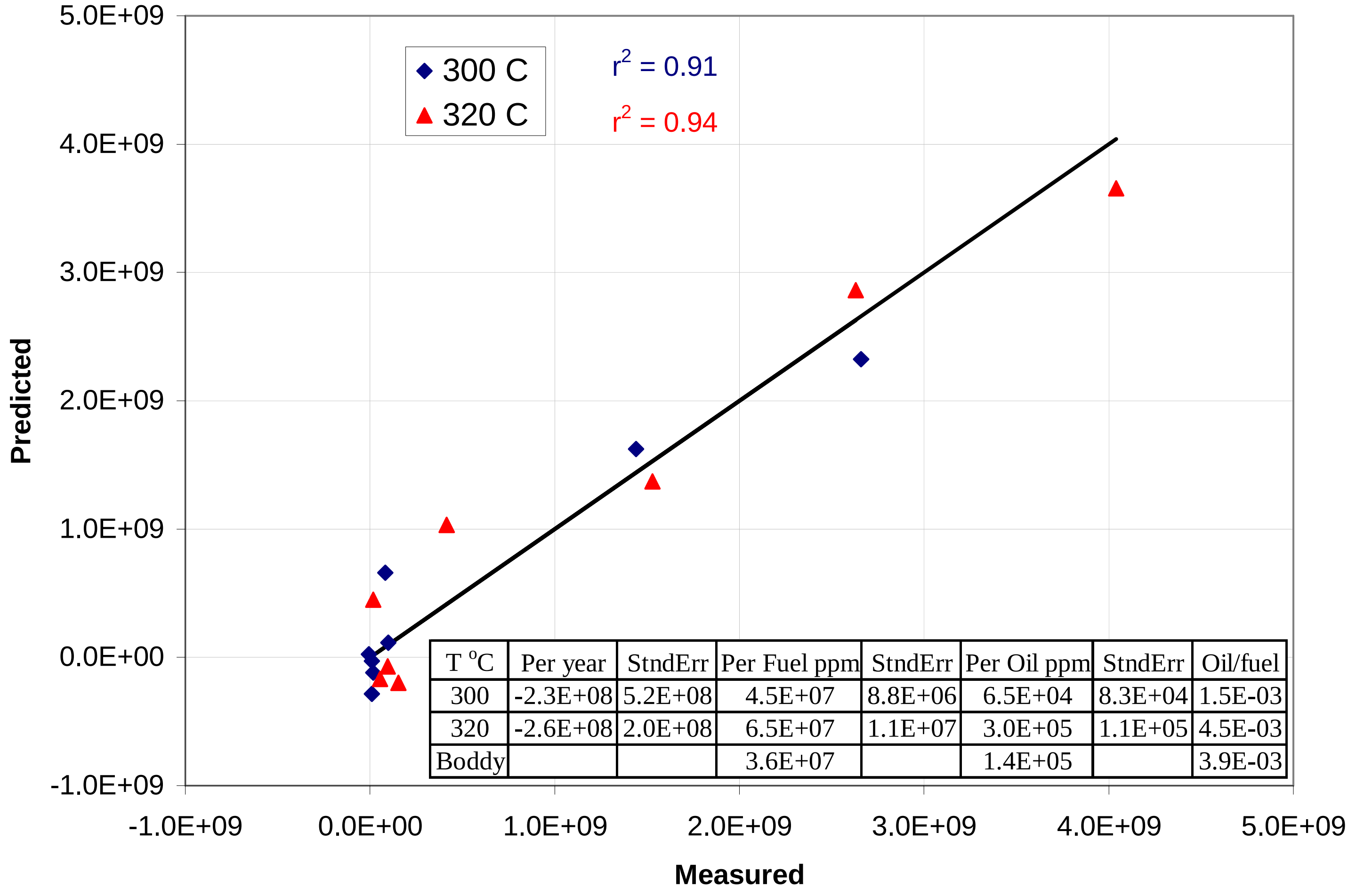

Note the much greater response of the EEPS to small particles under these transient conditions. The EEPS tracks well with the CPC on total number

# Relationship Between Particle Concentration And Exhaust Temperature – CRT, CCRT, CRT + S-trap




- Averaging all tests shows the differences between the CRT and CCRT and CRT + S-trap.
- Data shown are for all runs regardless of fuel and lube

# Correlate number emissions with age, fuel S, and oil S at constant binned T



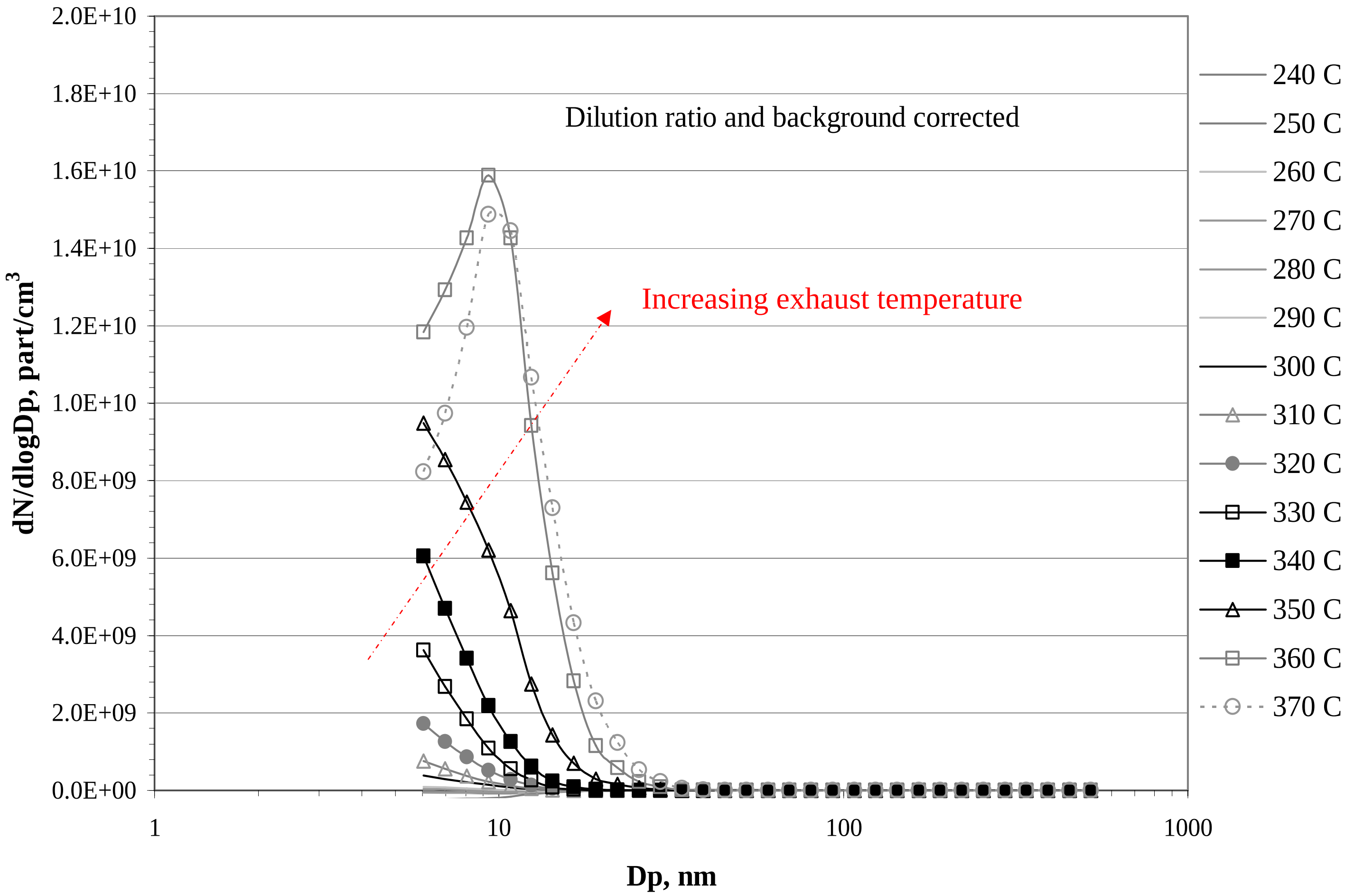

| T °C | Per year | StndErr | Per Fuel ppm | StndErr | Per Oil ppm | StndErr | Oil/fuel |
|---|---|---|---|---|---|---|---|
| 300 | -2.3E+08 | 5.2E+08 | 4.5E+07 | 8.8E+06 | 6.5E+04 | 8.3E+04 | 1.5E-03 |
| 320 | -2.6E+08 | 2.0E+08 | 6.5E+07 | 1.1E+07 | 3.0E+05 | 1.1E+05 | 4.5E-03 |
| Boddy | | | 3.6E+07 | | 1.4E+05 | | 3.9E-03 |

# Conclusions - 1

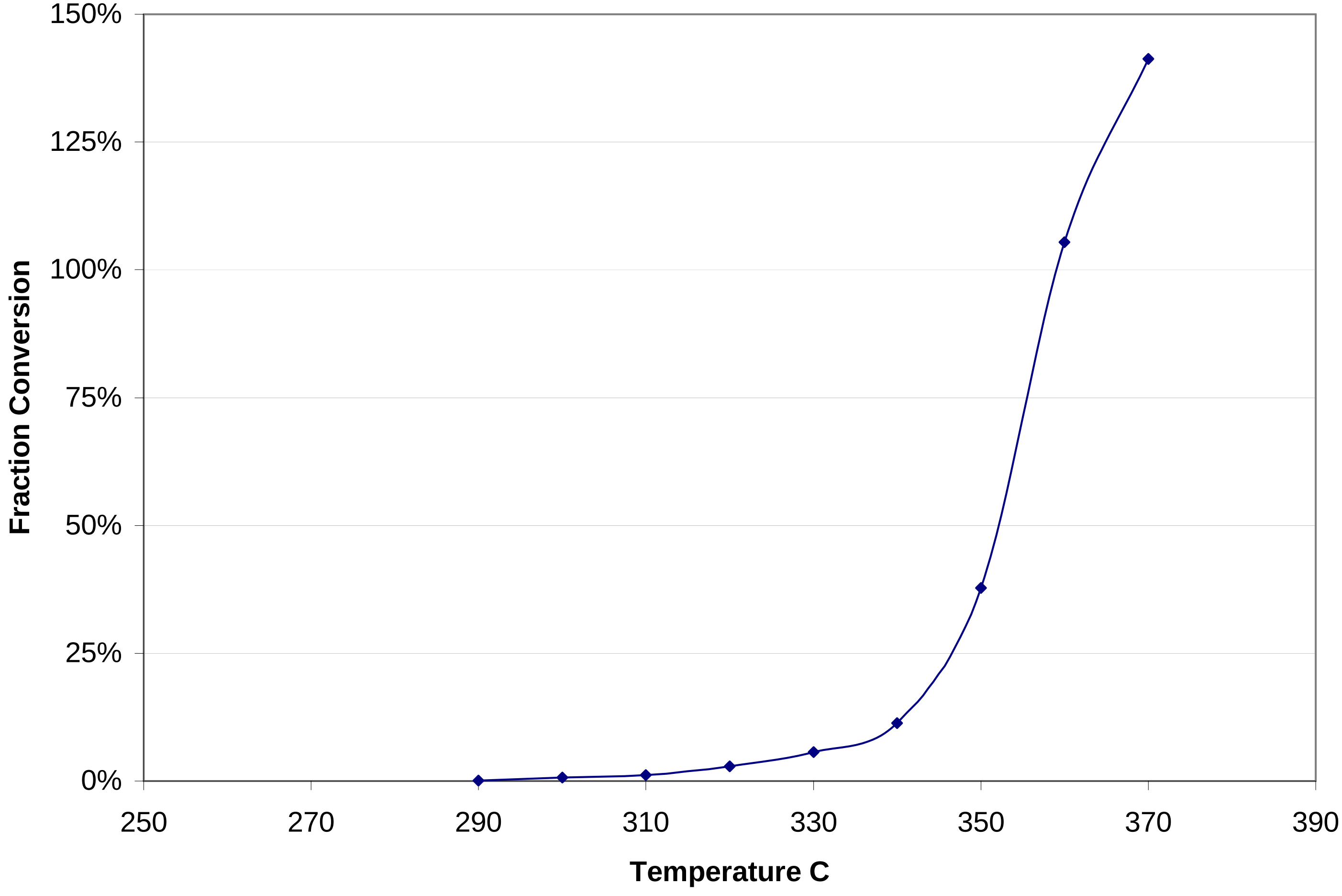
- Nucleation mode particle formation by the CRT is strongly temperature dependent, but neither the CCRT nor the CRT plus S trap form particles detectable above background at any temperature in the range examined
- The formation of nucleation mode particles by the CRT is proportional to fuel S, oil S, but decreases with catalyst age.
  - For the conditions tested a 10 ppm S fuel would be expected to produce from 4 to 7 x $10^8$ particles/$cm^3$
  - Particle formation per unit sulfur in the lube oil ranges from 0.15 - 0.45% of that per unit sulfur in the fuel.
    - For the conditions tested, the oil consumption of the Volvo is in the 0.05 - 0.15% of fuel consumption range. This suggest that S in the lube oil that is consumed is more effective at producing nuclei mode particles than the S in the fuel
    - For the conditions tested a 3000 ppm S lube oil would be expected to form as many particles as 4.5 to 13.5 ppm S fuel
- Other oil components may play a role, this is being examined by BP/Castrol

# Storage and release effects

# Nearly all particles downstream of CRT were in nucleation mode and strongly temperature dependent



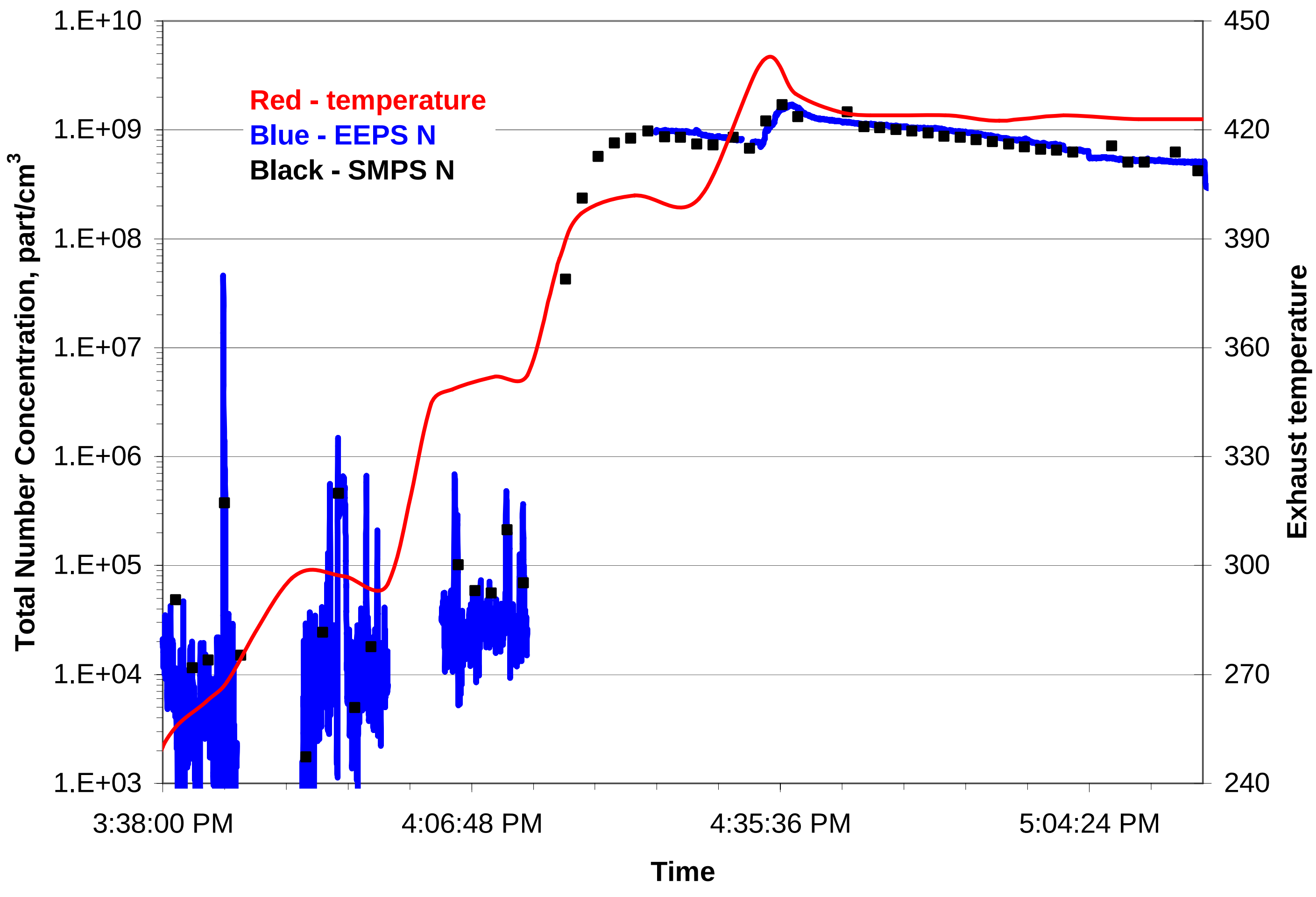
# Here nucleation mode measurements have been converted to sulfur mass (as sulfate) and compared to compared to sulfur available in exhaust



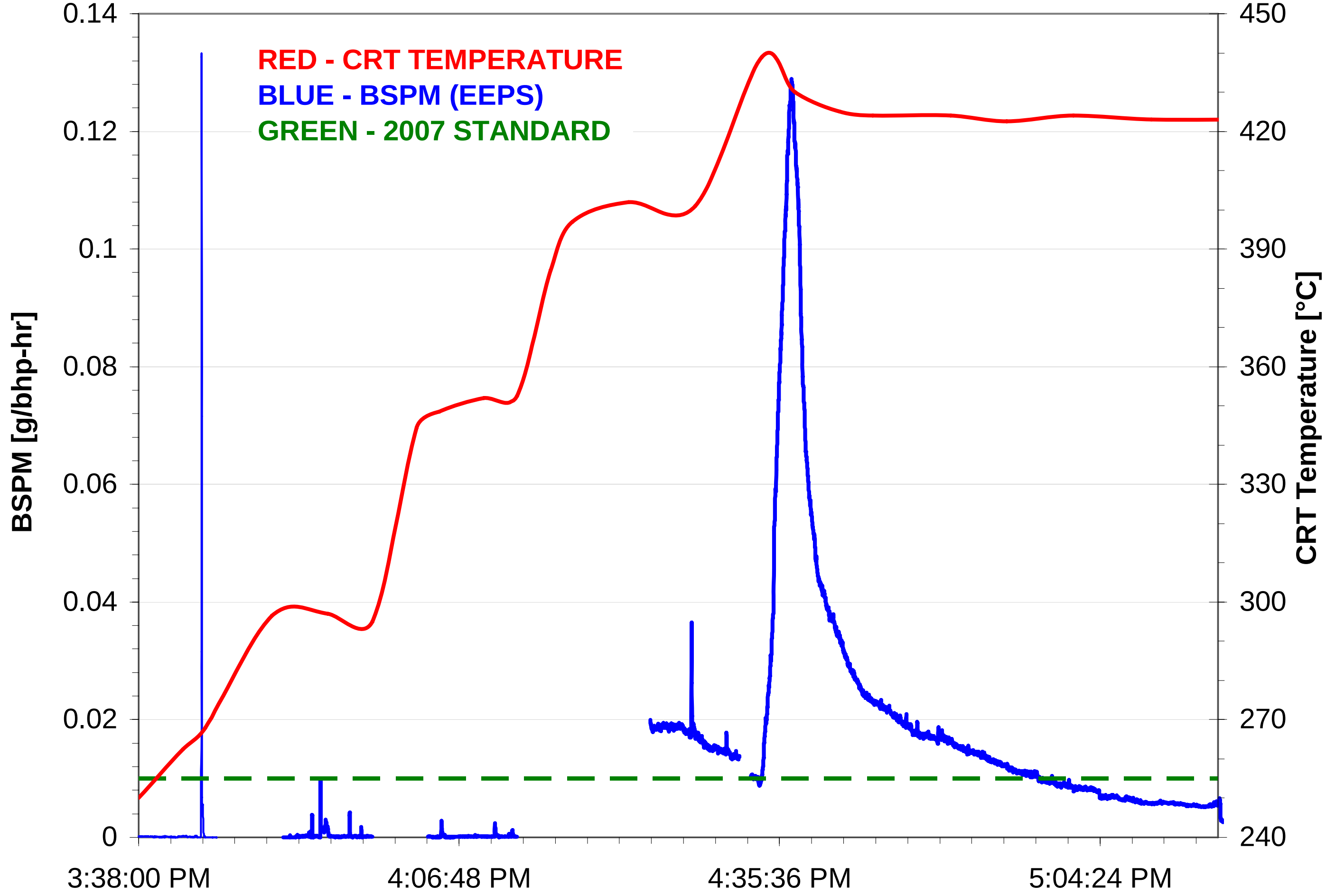
# Storage and release experiments

- On-road test indicate that stored sulfate is released at higher exhaust temperatures
- Lab tests done to confirm this
  - New CRTs tested in lab with zero S fuel and ultra low S lube oil – no nucleation mode formation at any temperature
  - **Used CRTs from on-road tests installed on lab engine and tests with zero S fuel and ultra low S lube oil repeated**
    - **1600 rpm**
    - **Vary load to vary exhaust T**
    - **Significant nucleation mode formation as temperature approaches 400 C**

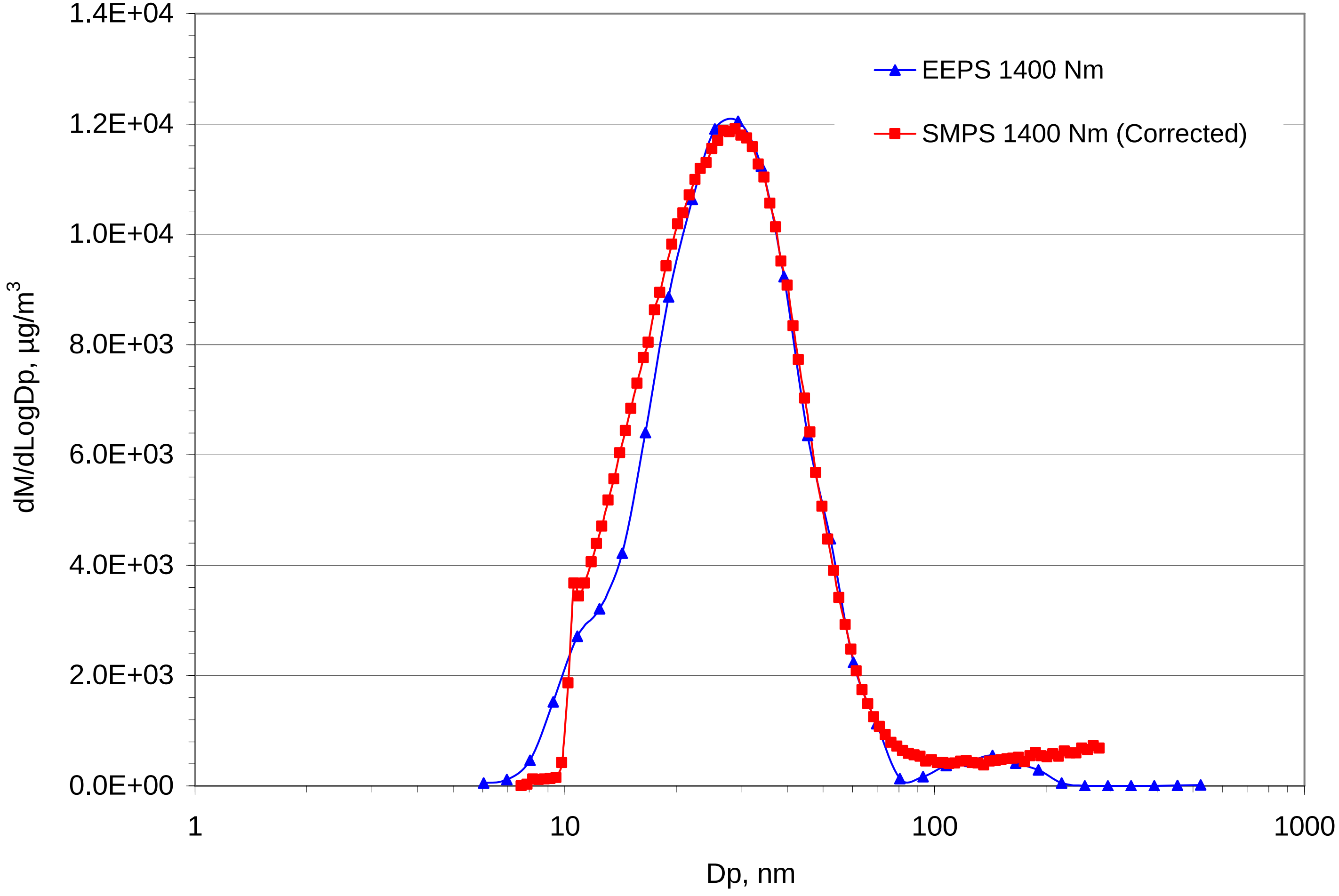
# Sulfate release experiment – number measurements



# Sulfate release – mass emission rates



# Size distribution observed near peak temperature



# Conclusions 2

- Zero S fuel eliminates nucleation mode formation with clean CRT
- It appears that in normal operation with ULSD sulfate is stored in the CRT catalyst at temperatures below about 350 C
- This material is released at higher exhaust temperatures
- This could lead to unexpected emissions for some operating cycles in passive systems
- It is likely that active regeneration would remove stored material

# Contributors

- W. F. Watts, J. P. Johnson, J. Swanson, U of M
- C. Thorne, C. McCann, M. Payne, S. Goodier, C. Warrens, H. Preston, BP / Castrol
- U. Zink, D. Pickles, Corning
- C. Goersmann, M. V. Twigg, A. P. Walker, Johnson-Matthey
- R. Boddy, BP consultant

# Summary SMPS Statistics

| Trial | Fuel | Oil | Aftertreatment | Dilution ratio | | CPC, part/cm$^3$ | | SMPS, part/cm$^3$ | | N/V | CPC/SMPS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Avg | Std | Avg | Std | Avg | Std | | |
| Baseline | BP-15 | LSO | None | 477 | 91 | 2.06E+07 | 1.20E+07 | 1.86E+07 | 6.21E+06 | 3.5E+03 | 1.10 |
| Trial 01 | BP-50 | HSO | CRT | 431 | 74 | 2.68E+09 | 5.02E+08 | 4.32E+08 | 2.79E+08 | 1.8E+06 | 6.20 |
| Trial 02 | BP-15 | LSO | CCRT | 429 | 56 | -5.79E+06 | 1.43E+07 | -2.11E+05 | 1.42E+05 | -1.7E+04 | 27.46 |
| Trial 03 | BP-15 | LSO | CRT + S-Trap | 340 | 33 | 1.33E+07 | 4.17E+07 | -9.32E+05 | 1.35E+06 | 7.1E+03 | -14.31 |
| Trial 04 | BP-15 | LSO | CRT | 507 | 69 | 5.43E+08 | 1.85E+08 | 3.75E+07 | 1.62E+08 | -1.4E+05 | 14.48 |
| Trial 05 | BP-15 | LSO | CRT + S-Trap | 406 | 24 | -7.02E+07 | 1.13E+08 | -7.65E+05 | 6.04E+05 | 7.5E+04 | 91.79 |
| Trial 06 | BP-15 | LSO | CCRT | 400 | 48 | -8.22E+06 | 1.62E+07 | -1.25E+06 | 2.71E+06 | 7.3E+03 | 6.58 |
| Trial 07 | BP-6 | ZSO | CRT | 381 | 60 | 3.88E+08 | 1.75E+08 | 2.88E+07 | 3.57E+07 | -2.3E+05 | 13.50 |
| Trial 08 | ECD | ZSO | CRT | 473 | 75 | 1.31E+08 | 1.25E+08 | 4.75E+06 | 9.55E+06 | -3.3E+04 | 27.65 |
| Trial 09 | BP-6 | HSO | CRT | 379 | 39 | 1.04E+08 | 6.06E+07 | 2.75E+06 | 8.78E+06 | -1.8E+04 | 37.72 |
| Trial 10 | BP-50 | ZSO | CRT + S-Trap | 416 | 52 | -1.08E+07 | 6.53E+07 | -1.12E+06 | 1.39E+06 | 6.0E+03 | 9.63 |
| Trial 11 | BP-50 | HSO | CRT + S-Trap | 362 | 40 | -1.55E+07 | 1.87E+07 | -1.62E+06 | 2.11E+06 | 9.5E+03 | 9.58 |
| Trial 12 | BP-50 | HSO | CRT | 385 | 21 | 2.17E+09 | 3.14E+08 | 3.16E+08 | 1.47E+08 | 4.2E+05 | 6.87 |
| Trial 13 | ECD-1 | VHSO | CRT | 413 | 41 | 1.23E+09 | 2.80E+08 | 7.97E+07 | 7.03E+09 | 1.8E+06 | 15.50 |
| Trial 14 | BP-6 | LSO | CRT | 516 | 89 | 1.55E+08 | 7.28E+07 | 1.16E+06 | 5.95E+05 | -4.7E+03 | 134.08 |