Steps towards a certification measurement approach for Aircraft PM emissions

15th ETH-Conference on Combustion Generated Nanoparticles
June 29th 2011, Theo Rindlisbacher, Swiss Civil Aviation Authority (FOCA)

Emissions from aircraft gas turbines are presently regulated[1] for emissions of oxides of nitrogen (NO and NO2), carbon monoxide, total unburned hydrocarbons, carbonaceous particulates (soot) as correlated to **visible smoke.** Suppression of visible smoke has been successful, however with increasing knowledge about health and climate effects of extremely small soot particles and condensed volatile material, aviation regulators started research projects to investigate aircraft gas turbine exhaust with respect to nanoparticle emissions. Unlike piston gasoline and diesel engines, gas turbines work on a continuous combustion process, mostly resulting in a stable combustion efficiency around 99.999% above idle. In general, soot number concentrations may peak at lower geometrical mean diameter compared to vehicle diesel engines (at around 20nm or even lower). Carbonaceous particles make up the most stable fraction of the exhaust aerosol. Volatile aerosols are mainly formed downstream and depend sensitively on ambient environmental conditions, the sampling conditions and the fuel used. Normally, the volatile mode is highest at engine idle conditions.
Findings and knowledge about combustion generated nanoparticles as shared during the annual meetings in Zurich have largely contributed to regulatory steps, taken at ICAO CAEP[2] in November 2009: The Committee decided to evaluate and document sampling and measurement methodologies for aircraft engine **non-volatile PM mass and number** emissions and to develop an aircraft engine based metric and methodology for application as a non-volatile PM emissions certification requirement[3] for new engine types. The control of particles in the range of D = 10 -100 nm is becoming a requirement. ICAO CAEP delegated the development of the measurement system and methodology to SAE-E31 (Society of Automotive Engineers, Aircraft Emissions). The goal is the production of an Aerospace Recommended Practice (ARP) for the measurement of aircraft engine non-volatile PM mass and number emissions. As the ARP requires a complete validation, it is expected to be finalized around 2013, also depending on the available funding. The ARP will then be translated into an ICAO standard and recommended practice of ICAO Annex 16, Volume II, which will have to be approved by CAEP, most likely in 2016.
A particle emissions measurement for aircraft gas turbines, which is qualitatively good and robust enough for application in an engine certification process, is particularly demanding in many aspects. As the main goal of aircraft engines is to accelerate large quantities of air, the whole engine environment is extremely energy loaded. The generated force “just by blowing air” from a large engine can easily equal the weight of 30 tons. Apart from massive forces, probes near the engine exit plane must withstand temperatures of up to 800°C. Furthermore, the engine exhaust diameter is so large that a technically complicated process is needed to get a so called representative sample, as emission concentrations are not uniform across the exhaust. Costs associated with engine testing are particularly high. A fuel consumption of 10 tons per hour is not unusual during a large engine test.
At first sight, downstream plume measurement could be considered beneficial to avoid some of the measurement problems near the engine exit plane. However, for a certification methodology, too much variability was introduced with this measurement approach. For PM measurement, there are additional problems for a certification measurement if the samples are taken downstream, like getting deposits from the tunnel, as tunnels normally have porous structures for noise reduction. During engine operation, everything in the tunnel is vibrating. At downstream measurements a large amount of practically uncontrollable ambient air is

[1] International Civil Aviation Organisation ICAO Annex 16, Volume II
[2] CAEP = ICAO Committee on Aviation Environmental Protection
[333] A certification requirement is a standardized methodology for measurement and reporting. It is useful to track engine emissions and to compare different technologies. It has the potential for developing limit values and a corresponding emissions standard.

mixed with combustion air before the sample enters the probe.
For a certification methodology, the regulators finally decided to work on a system, which is capable of measuring gaseous pollutants and PM emissions in parallel, using the sampling rake, the defined position behind the engine exit plane and the temperature gradient as specified in current ICAO Annex 16 with addition of a maximum residence time. After the probe system, the sampling line is split into the existing line and a tightly specified separate sampling system for the PM measurements. Development work has been delegated to the aircraft emission experts of the Society of Automotive Engineers (SAE-E31). The E-31 Committee produced a system concept proposal by the end of 2010, which has been successfully tested on three occasions, since then. The PM concept drawing is shown in the presentation. The system works with an ejector-dilutor placed as near as physically possible to the engine, Inlet pressure has to be controlled to accommodate for the different ram pressures produced by the engine. Lines, temperatures and flow rates to the instruments are specified. There is a controlled flow make-up to the instruments in order to reduce the residence time in the long sampling lines.
Just a month ago, the Swiss Federal Office for Civil Aviation finalized the installation of the first in the world sampling system for regular and continued testing of system components, instrumentation and operability behind large aircraft engines. This PM system test site is installed at the SR Technics Engine Maintenance Facility at Zurich Airport. The system makes use of the engine test schedules that SR Technics runs to release the engine for service after maintenance. It offers the opportunity for testing behind large engines without having to pay for engine running time. The system also comprises gas analysis, which runs in parallel to the PM system. A major part of the installation consists of a single point probe which can be vertically lowered remotely controlled into the exhaust stream of the tested engines with a precision of +-2mm.
The goal of SAE-E31 is to produce a first draft aerospace recommended practice (ARP) until the end of this year. Meeting the goal will largely depend on test progress in international cooperation and respective funding. Currently respective roadmaps are put together. They will be discussed at the next ICAO CAEP Emissions Technical Meeting mid July 2011.
One major issues is the selection of a lower cut-point for the particle number measurement, as the PMP cut-off limit is considered too high. This requires further testing of VPR systems and number-size instrumentation suited for the measurement of aircraft engine non-volatile particle emissions. Another issue is the selection of the measurement principles for fast mass (black carbon mass) measurements. Aviation regulators are open for continued collaboration with instrument manufacturers in order to solve the major issues in a timely manner.
Finally, validation exercises with system comparisons amongst the aircraft engine manufacturers will have to be made.
Current belief amongst the active aviation regulators (EASA, FAA, USEPA, FOCA) is, that the original target for having an ICAO PM certification requirement ready by 2013 cannot be met. But it is envisaged to bring the first PM mass and number standard for aviation into force by 2016.

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Swiss Federal Office for Civil Aviation FOCA

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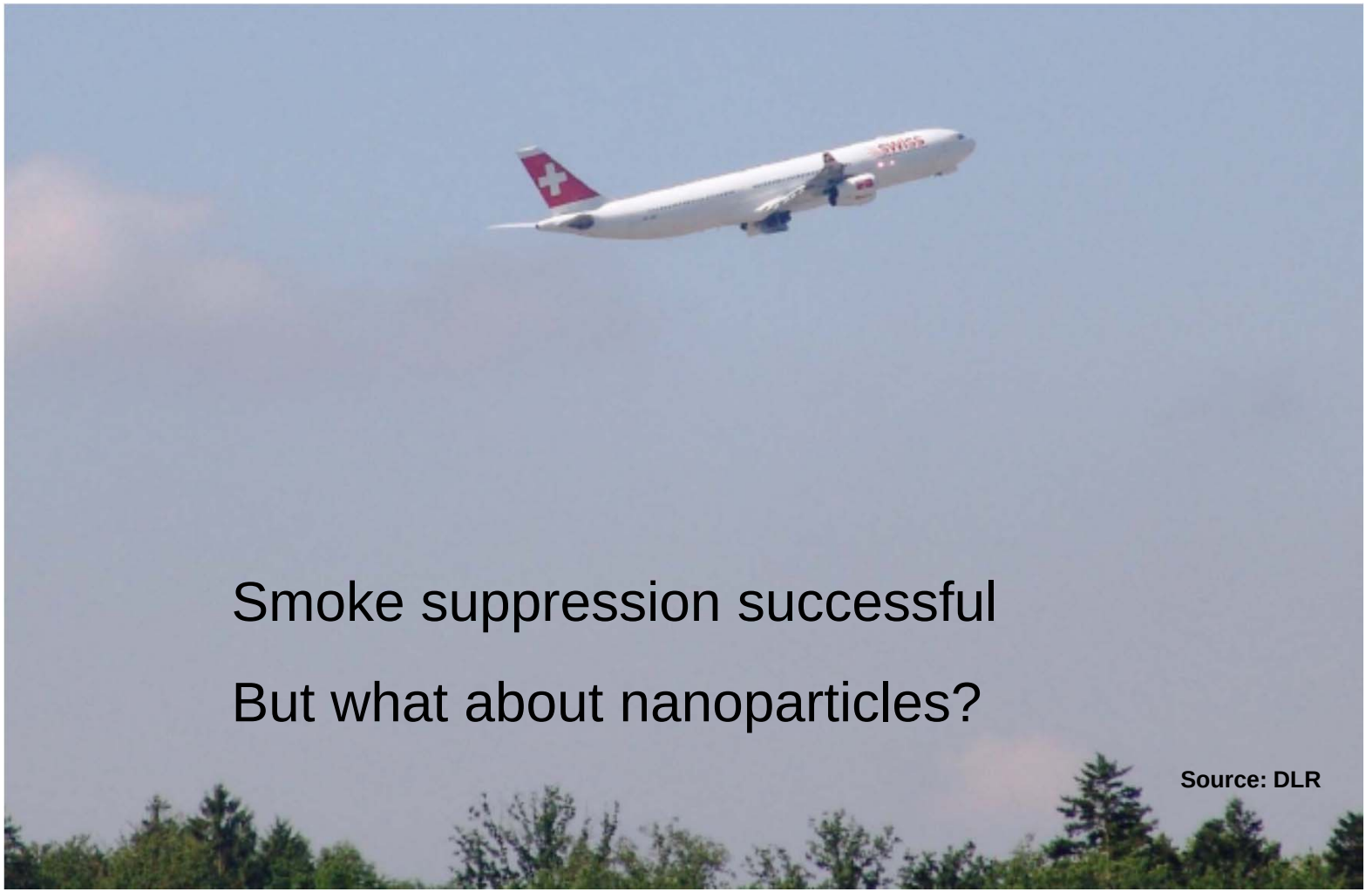
History…

Source: DLR

The Smoke Number



Current regulation (ICAO Annex 16 Vol. II)

Emissions from aircraft gas turbines are presently regulated for emissions of:

- Oxides of nitrogen (NO and NO2)
- Carbon monoxide
- Total unburned hydrocarbons
- Carbonaceous particulates (soot) as correlated to **visible smoke.**

Regulatory step forward in 2009

- **ICAO Committee on Aviation Environmental Protection (CAEP)** decides to work on the following remits with a target date 2013:
- Evaluate and document sampling and measurement methodologies for aircraft engine **non-volatile PM mass and number** emissions.
- Develop an aircraft engine based metric and methodology for application as a **non-volatile PM emissions certification requirement for new engine types.**

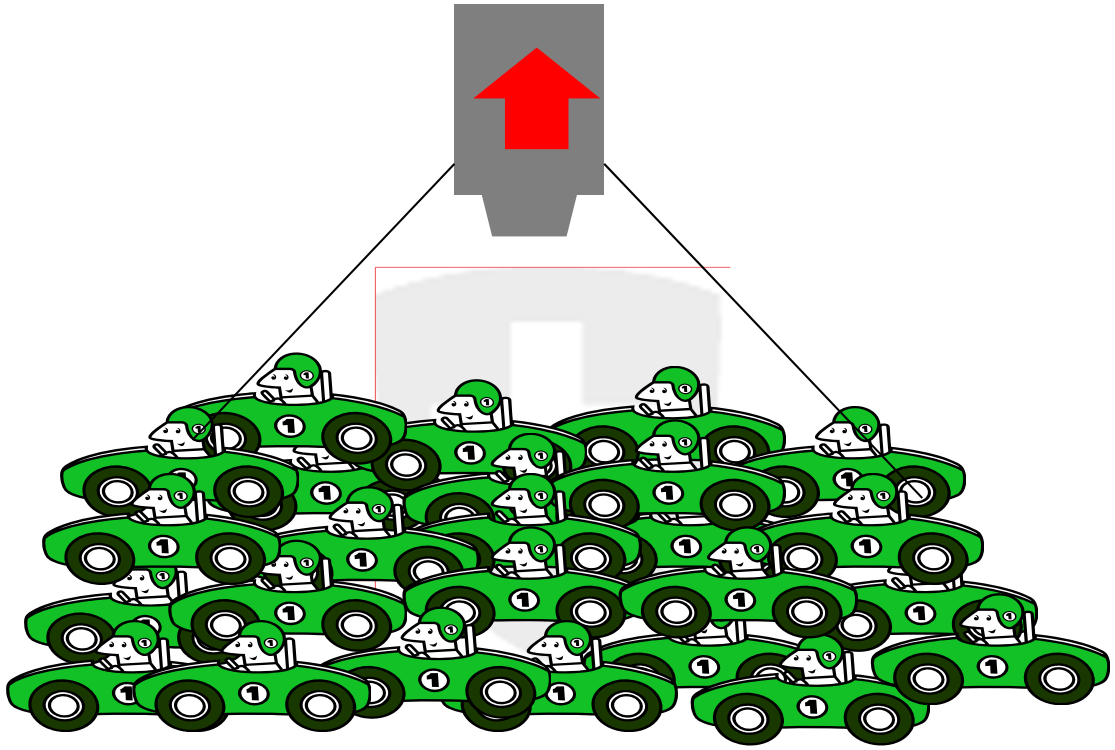
→ Control of non-volatile particles in the range of D = 10 -100 nm is desired as a requirement.

Aircraft gas turbine PM

Aircraft gas turbine PM summary

- Aircraft gas turbines work on a continuous combustion process (unlike piston / diesel engines)
- **Geometrical mean diameter of soot** may peak at **around 20nm or even lower** (also depending on sampling system…)
- Carbonaceous particles make up the most stable fraction of the exhaust aerosol.
- The volatile nanoparticle mode is highly variable and depends strongly on the sampling conditions and the fuel used. Normally highest at engine idle conditions.

Large engine specials



- Extremely harsh environment for measurements near the engine
- Can not take an engine to a laboratory

Large engine specials

- In the engine core exit (combustion air exit), temperatures from 400 to **650°C are not unusual**
- The engine **core often has a large diameter** with sometimes inhomogenous emission concentrations

→ **A single point probe and one position is not sufficient**

Large engine specials

- **A fuel consumption of 10 tons per hour** is not unusal for large engines during high thrust operation

Testing aircraft gas turbines is extremely expensive

→ Minimise certification cost by combining existing emission certification for gaseous pollutants and smoke with PM measurement

→ Fast response instruments needed (e.g. filter gravimetric for PM mass no option)

Downstream measurements?

Downstream measurements?

Not for certification:

- Bypass background air introduces large variability,
- inhomogenuous mixing issues,
- CO2 measurement critical,
- In a test cell environment, at downstream locations: collection of deposits from a large exhaust tunnel takes place,
- Would mean separate engine runs for gas and PM emission certification

(list not exhaustive)

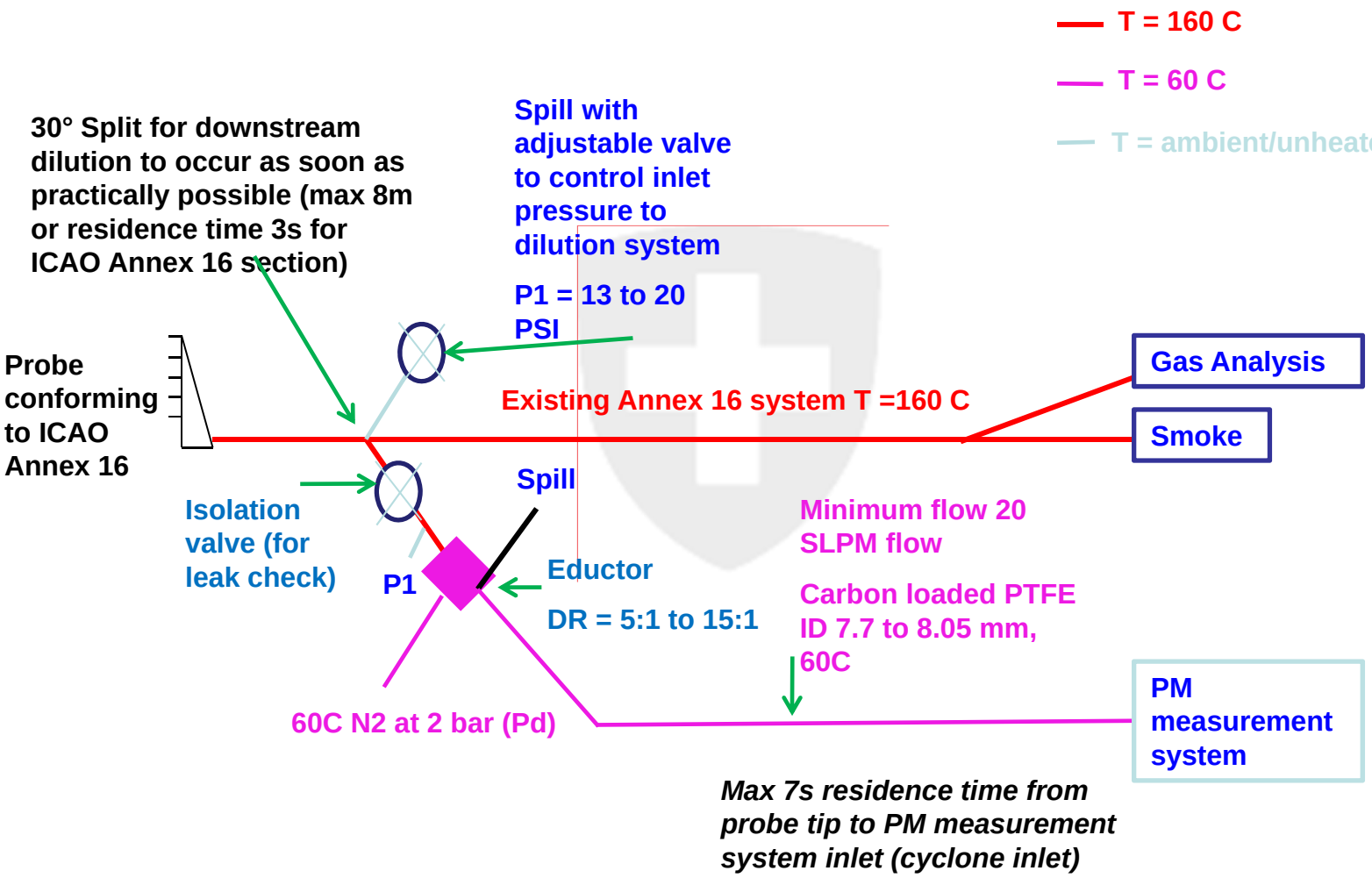
Prototype system concept developed by SAE-E31

- ICAO CAEP delegated the development of the measurement system and methodology to **SAE-E31 (Society of Automotive Engineers, Aircraft Emissions**)

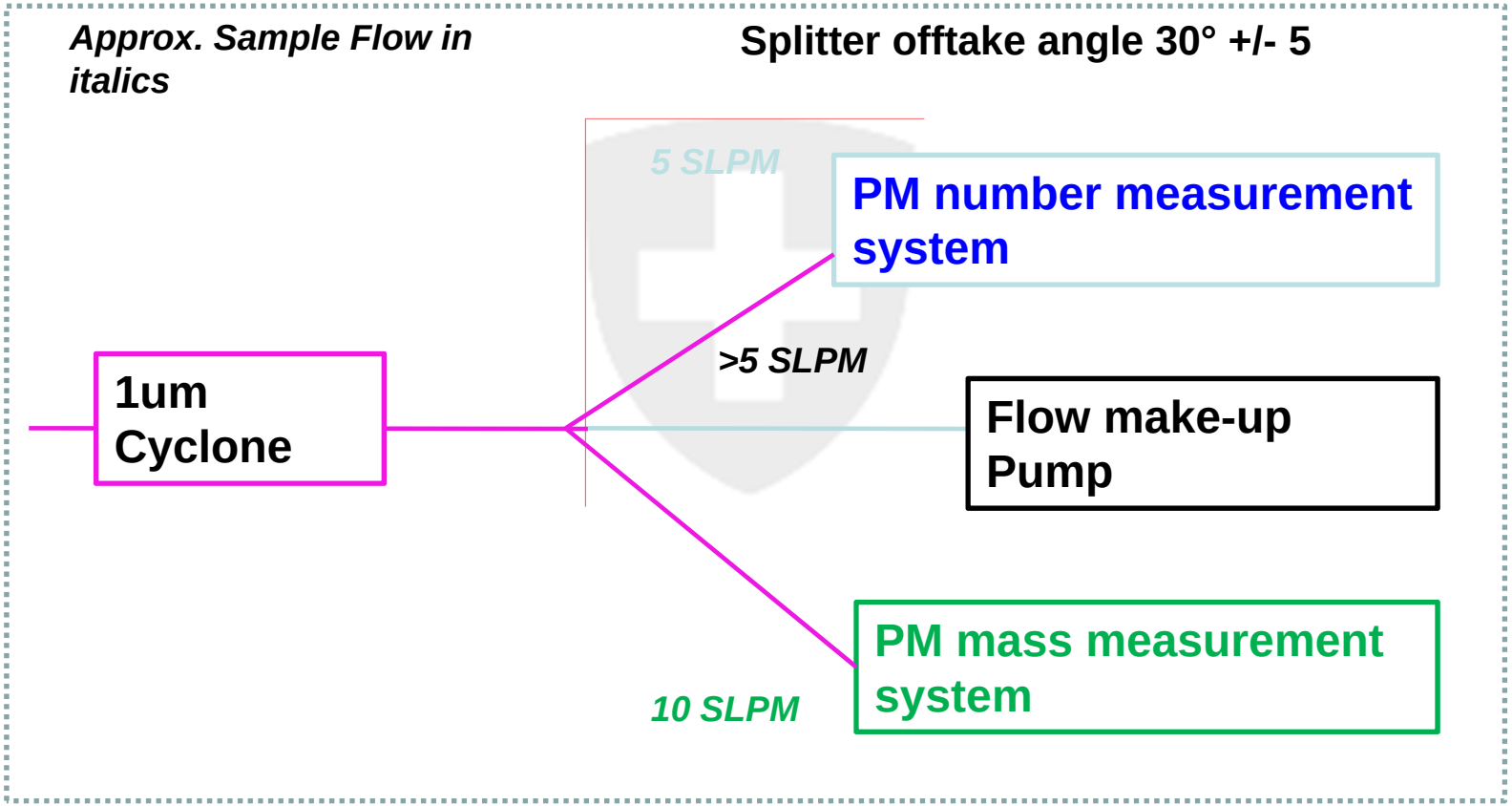
STRONG SYSTEM STANDARDISATION

CAEP = Committee on Aviation Environmental Protection

SAE-E-31 Sampling System Concept Proposal



SAE E-31 PM measurement system



Instruments

Mass instruments under investigation (adaptations, standard operating procedures, calibration):

- Artium LII → BC
- Thermo Scientific 5012 (Super-)MAAP → BC
- thermo-optical, carbon burn-off → EC, OC
- AVL Photoacoustic → BC

Number instruments:

- CNC (for certification)
- (fast) sizing instruments for investigations
- Special Issue: Lower cut-off curve and Volatile Particle Remover (VPR). Taking PMP system as a start

Does the system proposal work?

Successful test of concept

- at Rolls-Royce, UK, in engine test cell, November 2010
- during AFFEX II (alternative fuel experiment) campaign in the US in April 2011

Last month: **System prototype, installed in Zurich** thanks to

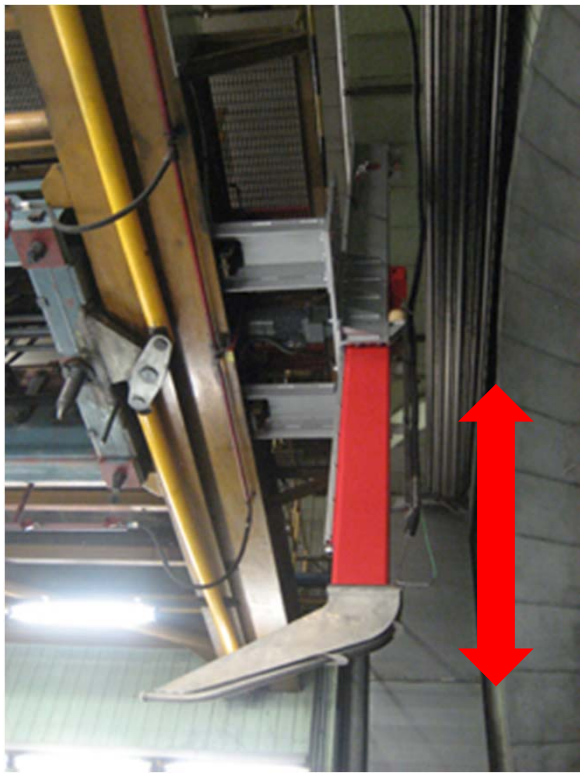
SR Technics

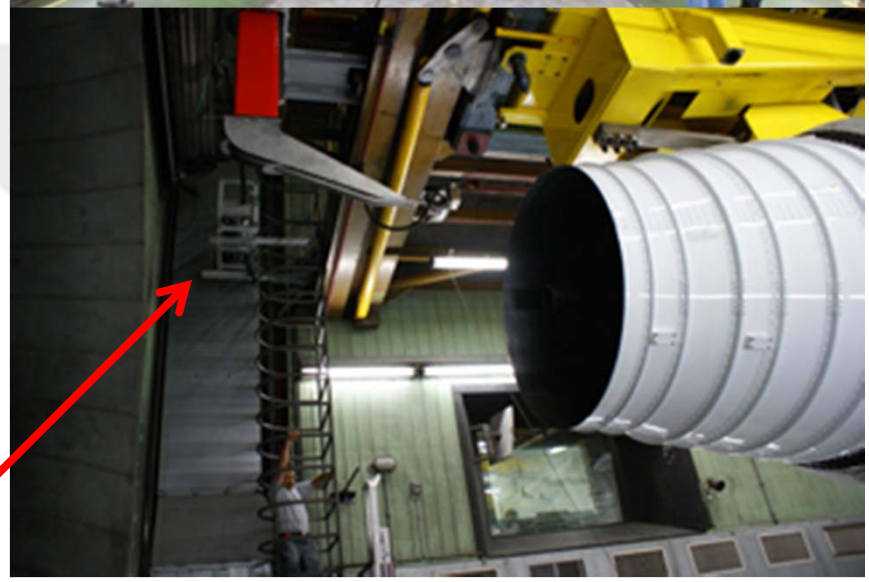
Maintenance facility, Zurich Airport

The **SR Technics PM System Test Site** is the first in the world, which is permanently installed for continuous testing behind large engines, open to all contributors

Access and support provided by Swiss FOCA and SR Technics.

SR Tech PM System Test Site: The probe

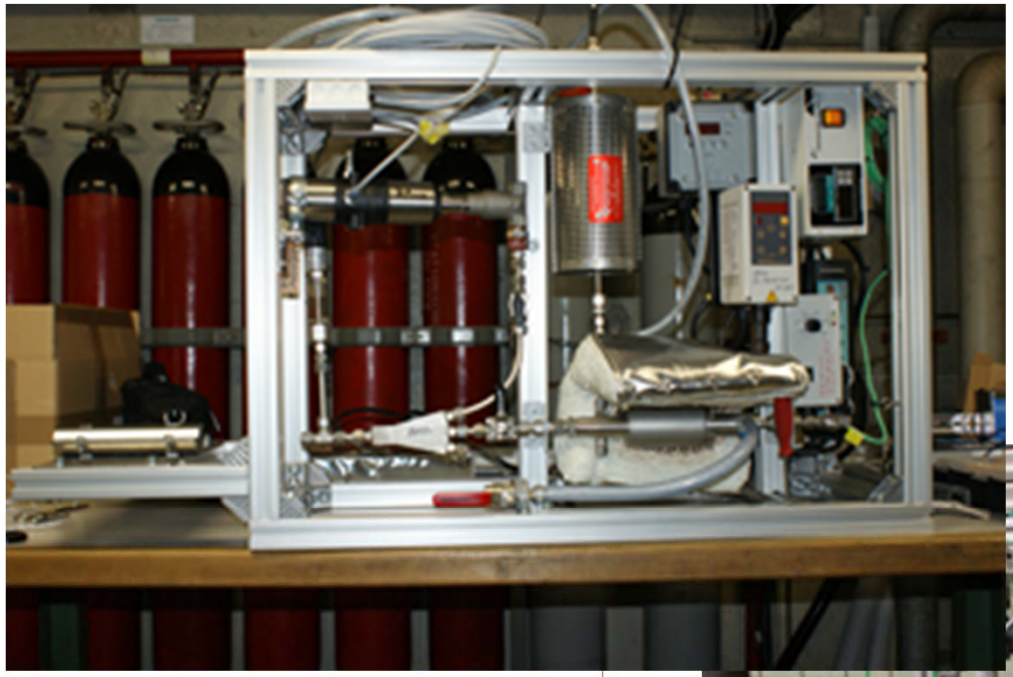




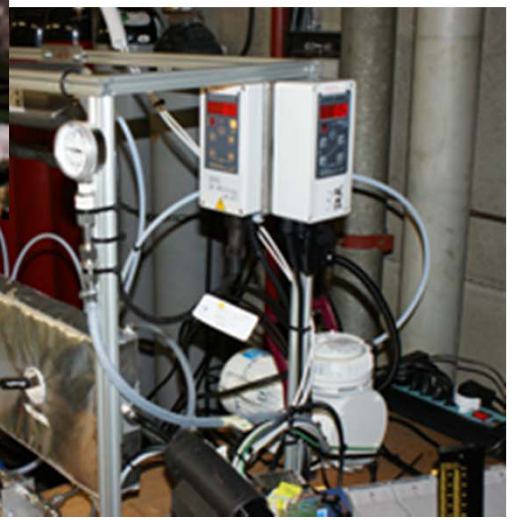
Industrial product with a mass of 1 ton

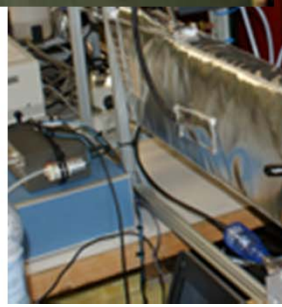
See next page

First flow splitter and dilution stage



Second flow splitter to instrument & flow make-up





Issues with instrumentation

- Which mass instrument(s) best suited?
- Number instrument:
- CNC will operate in single count mode
- Pragmatic approach to move forward, building on the extensive research under PMP:
- CNC counting efficiency will be D50 at 23nm, D90 at 40nm (PMP)
- CNC calibration will utilize ISO 27891 guidelines
- When the ability to use a lower non-volatile cut point is experimentally verified , then the specification will be revised to the appropriate lower cut point counting efficiency curve

Next steps

SAE-E31 Roadmap development

- List of Issues, Timeline, Test plans, Costs…
- Drafting of **Aerospace Recommended Practice**

Continued coordination among the active regulators

EASA

(European Aviation Safety Agency)

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

FOCA

(Swiss Federal Office for Civil Aviation)

FAA

(US Federal Aviation Administration)

US EPA

(US Environmental Protection Agency)

ICAO CAEP Emissions Technical Meeting 18th July 2011

- Roadmap discussion and decisions

SR Technics PM System Test Site operation

Contact for coordination of test & research projects:

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

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- Provider of engine test cell, engineering, engines and engine running

SR Technics

- Probe system development and builder

Martin Brunner GmbH
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- First system test activity, provision of hot dilution VPR, fast sizing and CNC instrumentation

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft


Thank You for your attention