STACK TESTING
DETERMINING POLLUTANTS ACCURATELY

Depending on the method employed, measuring an engine's exhaust gas emissions can lead to varying results. Therefore, stack tests need to be performed as carefully and as precisely as possible.

There are several different test methods that may be performed to measure the engine's exhaust gas emissions. Every method has its advantages and disadvantages, however different methods can lead to different results for the same pollutant being measured. On the following pages, the stack testing process is analysed in regards to the procedures required and the factors to be considered from the engine side. In addition, a guideline is provided to help ensure that the results of a stack test are valid and not impacted by either engine malfunctions or errors in the testing process.

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ABSTRACT

// Throughout the world, emission legislations are becoming more common. To meet the more stringent emission standards for diesel engines, many different exhaust gas optimization methods are being utilized. Although we already have a lot of these regulations worldwide, we see an increasing number of so called "local air boards" that have additional requirements regarding emissions or immissions. These requirements differ on the one side at the limits for certain emissions, on the other side which kind of emissions are taken into account.

Diesel genset owners/operators are often required to provide exhaust gas emissions information to the local permitting authorities regarding their diesel engines. For MTU diesel engines, this information is made available by the "Emission Data Sheets."

// Many times the local permitting authority is looking to verify the emissions from the engine match the reported emission values provided by the manufacturer. Otherwise, the wanted effect against air pollution may not take place. Local air boards are requiring various testing methods to verify engine emissions. In the USA and many other countries stack testing of an in-use engine is the preferred method to validate the manufacturer's statements.

// Stack testing is most commonly performed by placing probes in the stack following an approved and defined procedure, e.g. EPA Reference Test Method 5 or 202 for particulate (PM) measurement. The EPA Reference Test Methods define everything from the position of the probe within the stack to the Quality Assurance Quality Control (QAQC) methods to be utilized.

// There are several different test methods that may be performed to measure the engine's exhaust gas emissions. Every method has its advantages and disadvantages, however different methods can lead to different results for the same pollutant being measured. This variability may be the result of:

- The method in which the emissions are measured. For example, particle emissions can be of different sizes. Some test methods measure almost all particles, some measure only particles of a specific size and greater, and some measure only dry particles. MTU's experience and testing has determined that in the field

exhaust gas emissions measurements of particulate matter following EPA Method 202 are generally not comparable with the measurement results obtained from emissions measurement equipment as described in 40 CFR part 1065.

- Reliability and repeatability of the test method. In field test equipment can be hard to handle, and small mistakes can lead to a large deviation in the results. Other methods were not designed to measure the low level of emissions from today's cleaner engines.

In an effort to assist the customer in dealing with these difficulties, MTU provides this White Paper. Its goal is to deliver the following:

- an overview of the procedures required for stack testing,
- a definition of the factors to be considered from engine side,
- a guideline to ensure the results of a stack test are valid and not impacted by either engine malfunctions or errors in the testing process.

If you have any further questions or suggestions, please feel free to contact your local sales engineer.

REQUIREMENTS REGARDING TEST EQUIPMENT

// Most stack tests for Particulate Matter in the United States are done according to EPA Methods 5 and 202. The test equipment must be suitable for these methods to produce valid results.

// Before scheduling a stack test, clarify all testing requirements and test methods e.g. Particle emissions. This information is important for determining the proper test equipment for the required test methods and estimated emission concentrations is utilized. . Avoid using equipment with minimum or maximum measurement ranges near the expected emission range for the compound being tested. For example, if stack test equipment can be used to measure particle emissions between 2000 g/h and 100 g/h, ensure the tolerances are low throughout the entire test range. A tolerance of ± 10 g/h has little influence at 1200 g/h, however diesel engine particle emissions may be as low as

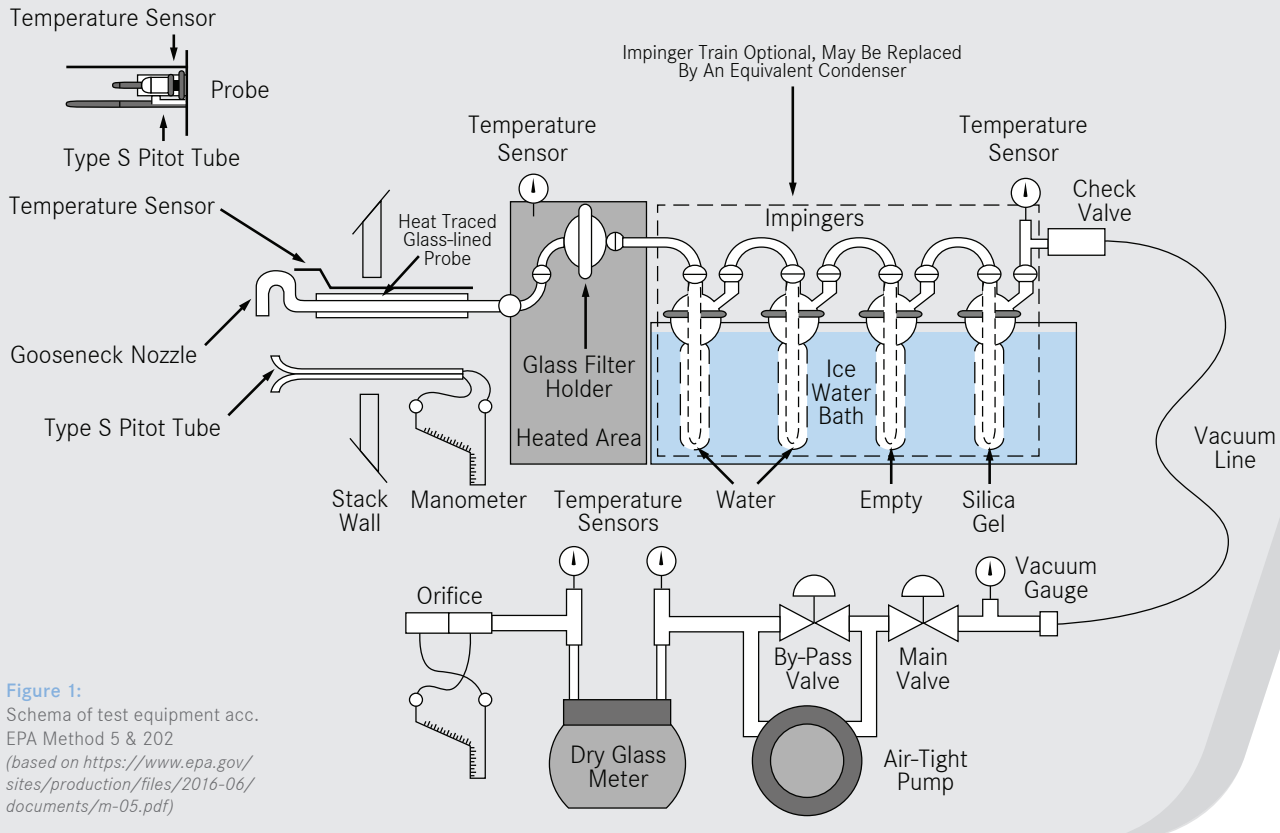

Figure 1:
Schema of test equipment acc. EPA Method 5 & 202
(based on https://www.epa.gov/sites/production/files/2016-06/documents/m-05.pdf)

110 g/h. At this concentration a ± 10 g/h tolerance results in a 10% margin of error.

STACK TEST PREPARATION

General Points

// A well designed stack test ensures reliable results. Testing should be designed to minimize the amount of time the Genset is out of service. To achieve this goal, please consider the following items prior to testing:

- **Equipment:** Can it be brought safely on site? Is lifting equipment required to get equipment and testing personnel near the stack? It is recommended that the genset be run under load in the weeks prior to testing to ensure everything is in working order when the testing team arrives.
- **Engine Load Requirements:** Can the required load be applied to the Genset? Is a load bank needed? A constant and stable load is required for a successful stack test. Often, this can't be realized by electric consumers installed on site.
- **Timeline:** A stack test is very time consuming, 6-7 hours per engine is not unusual
- **Effects on surrounding areas:** Some authorities prohibit the usage of Gensets at certain times (nights, periods of poor air quality, etc.)
- **Fuel quality and quantity:** Take into account the engine will run for several hours at full load. Fuel consumption for the duration of testing should be calculated with an appropriate buffer to ensure an adequate fuel supply will be available for testing. Also, ensure the fuel is of a sufficient quality. Aging fuel may be a problem and can lead to clogging of fuel filters. A fuel sample should be taken for analysis purposes.
- **Costs:** Certainly cost is a factor in selecting the stack testing company. It is not recommend to sacrifice the quality of the equipment or experience of the testing personnel in favor of lower cost. In many cases the fuel costs account for a significant portion of the overall testing cost. An experienced testing team with well-maintained equipment will minimize the chance that a test will require repeating. Additionally, an experienced testing team may have a better understanding of test methods that ensure a fast and accurate stack test is completed.

Required Information

// In preparation of the stack test, it is useful to have the following information on hand:

- Test method: What test methods are mandated by the authority?
- Stack diameter and height: This is important information for the testing company and will ensure that they have the proper equipment and probes when they arrive. Additionally, the stack test company will need to know the location and size of all available test ports.
- Engine serial number: If any questions arise during the stack test this is helpful information when you need to get in contact with After Sales/Application
- Maximum applicable load: Please consider that most gensets are unable to operate the engine at 100% mechanical power due to limited generator power. This is also important to understand when comparing the test results with the emission data sheets.

Equipment

// The testing company will bring the required test equipment. Additional equipment may be required to measure other parameters (fuel flow meters). A list of all equipment used during the test should be generated and should include any relevant calibration or service dates for each piece of equipment. Ensure to provide access to power for the test equipment. The power requirements of the equipment should be discussed prior to the test crew arriving.

// Please note that in some cases the ECU (Engine Control Unit) offers calculated values only, e.g. fuel consumption. For this reason, MTU Friedrichshafen recommends:

- The usage of a calibrated fuel flow meter.
- Recalculation of engine power from electrical power output.
- Recording of the exhaust gas temperature on the same point where the emission sample is collected.

Stabilization Run

// During low load operation, oil, unburned fuel etc. accumulates in the exhaust pipes. To minimize the influence of this material on the test results, it is important to ensure this material is removed from the stack prior to beginning any testing.

// A stabilization run is recommended to ensure the stacks are clean. A stabilization run consists of two hours of continuous operation at maximum load. The stabilization run will ensure the oil/unburned fuel gets burned prior to testing. Ideally the stack test will begin immediately following the stabilization run so there is no need to reduce load or shut the engine down.

PERFORMING THE STACK TEST

Ambient Conditions

// The ambient conditions at the time of testing have a significant influence on the result. Standard ambient conditions are the basis for the engine to fulfill the not-to-exceed values of the data sheet. Important conditions to record include:

- Air pressure, temperature and humidity. These parameters must be recorded near the air intake of the engine. Many times a testing company records from the internet a one time reading obtained from a nearby weather station. These values are not sufficient. It is important to obtain real measurements on site during the testing. During a stable weather situation, these parameters should be measured on site at least every 30 minutes, starting at the beginning of testing. If weather conditions are changing rapidly, the ambient conditions should be recorded more frequently.
- Altitude. Altitude also has an influence on the emissions and must be accounted for when evaluating the test results.
- Air intake depression/exhaust gas back pressure. These two parameters influence the power output of the engine. If

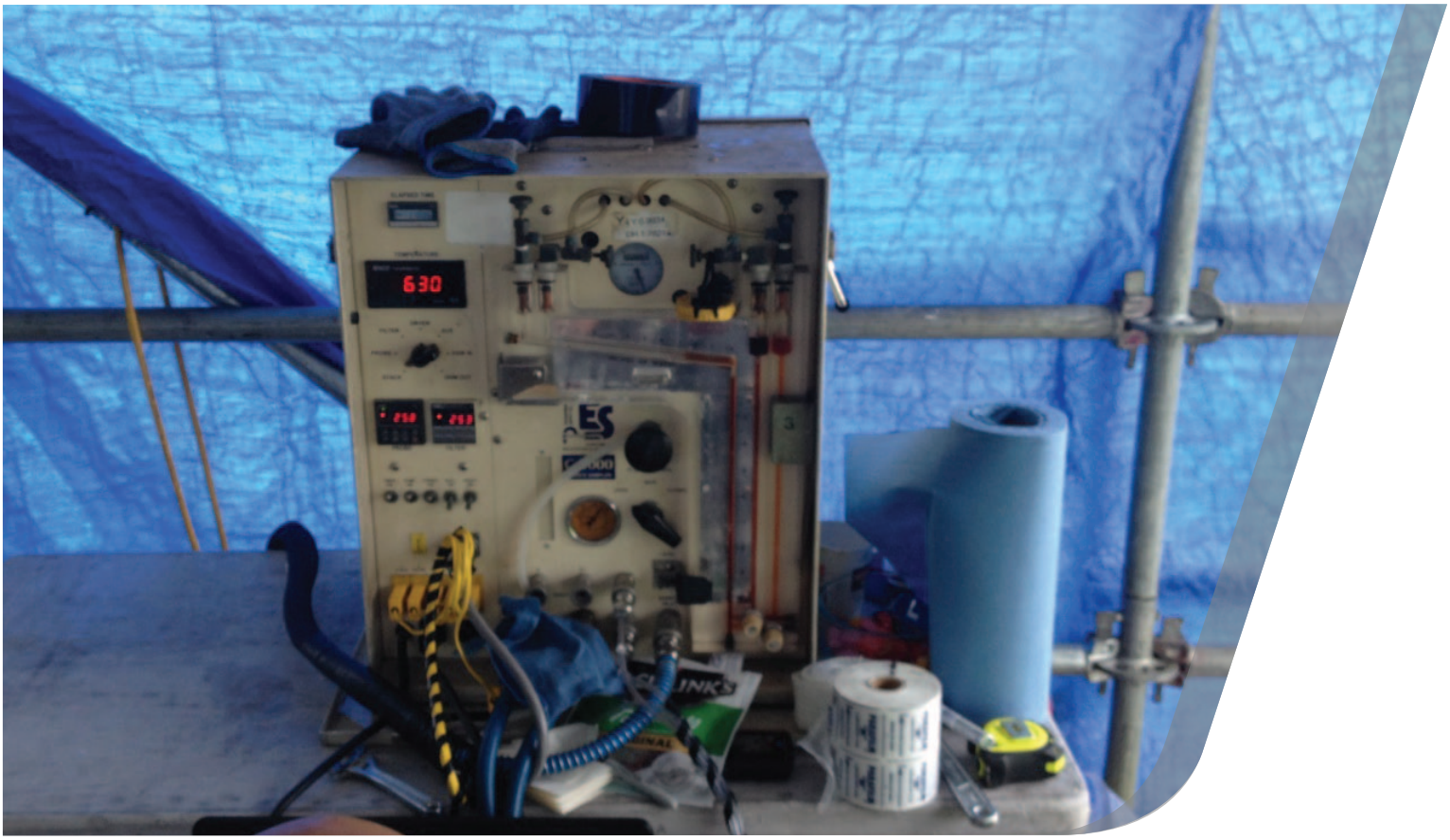

Figure 2:
Typical Equipment for Stack tests
acc. EPA Method 5 & 202

the engine loses power due to these factors, use the values on the emission data sheet according to the absolute power output and not the percentage value.

- Air mass ratio “Q” from the ECU as an indicator of lack of oxygen. Air mass ratio should be recorded with DiaSys. A list of other recommended parameters to be recorded during the test is provided in Appendix B.

Fuels and Lubricants

// The fuels and lubricants used will also have an influence on the results of the stack test. Refer to the emission data sheet provided by MTU for the type of fuel used during factory emission testing (e.g. fuel according to EN590 or US EPA 40CFR89 & coolant and lubricant according MTU Fuels and Lubricants Specification)

// The fuels and lubricants used must meet the requirements of the Fuels and Lubricants Specification provided by MTU. If there is any uncertainty about the quality and specifications of the fuel and lubricants used during testing, a sample of the fuel and engine lubricant should be collected and analyzed.

Engine Operation

// Emission values improve with time as the engine nears steady-state conditions.. Emission values provided on the MTU emission data sheet were collected with the engine at steady-state conditions.

// If engine loads are adjusted during the stack test, the engine should be allowed to run a minimum of 10 minutes at the new load point to reach steady-state conditions prior to starting emission testing.

// If the engine has been subjected to a higher number of cold starts it should be run forat least 30 minutesto reach steady state conditions.

Performing the Test

// The stacking testing company should have a solid knowledge of the test methods and testing equipment, however from time to time mistakes

are made. The following points are the most significant deviations observed in the field and are meant to help someone not familiar with stack testing have a general idea of what to look for. There may be exceptions to items listed below. Identify and document any deviations from the test plan and always discuss this with the person performing the stack test, if something looks different than mentioned below.

// Sampling and velocity measurements must be performed at a site at least eight stack diameters downstream and two stack diameters upstream from any flow disturbance (e.g. elbows).

// The number of traverse points is dependent on the stack diameter (see Fig. 3). For circular stacks:

- 12 points for a stack diameter greater than 0.61 meters/24 in.
- 8 points for a stack diameter between 0.30 and 0.61 meters/12 and 24 in.

// The total testing time/time per port depends on many factors, e.g. stack diameter, exhaust gas flow, expected quantity of particulate and condensable. The longer the test, the more reliable the results, but also the greater the time and the expense. Discuss testing time with the stack test company prior to testing. EPA mandates a minimum time of 1 hour per run and 30 minutes per port.

// The sampling time per traverse point should always be the same. For example, for a one hour test on a stack with diameter of 0.45 meters/18 in., a sample time of 3:45 min. per traverse point is required: eight traverse points required for test; each stack has two ports; one hour test; 30 minutes per port; 3:45 per traverse position.

It is important that the position of the probe meets the regulatory requirements. Different stack test companies use different methods to ensure the right position. Document how the stack test company ensures that the probe is at the right position for the right time.

// The pitot tube should be aligned perpendicular in the exhaust flow. Document how the stack test company ensures that the pitot tube is correctly aligned, e.g. by a water-level.

// The sample probe for collecting carbon dioxide and the oxygen samples must be placed in centroid of the stack. The probe for determining particulate should be placed in the ports according the stack traverse points. The port not in use must remain closed and the port in use for the probe should be sealed as much as feasible to prevent introducing fresh air into the exhaust stream. The probe must not make contact with any portion of the stack at any time. Also it should be avoided that the probe is bumped on the inside of the stack. The ports must be cleaned prior to testing to remove any soot or other contaminates.

// The EPA recommends a pre-test leak check of the particulate probe assembly. The post-test leak check is mandatory following each sampling run and must be done according EPA method.

// The filters should be removed from the filter-impinger in a clean area protected from wind to prevent contamination of the filter from airborne particles.

// After each run, the probe must be cleaned with acetone and a nylon brush. This must be done until the acetone comes out clean.

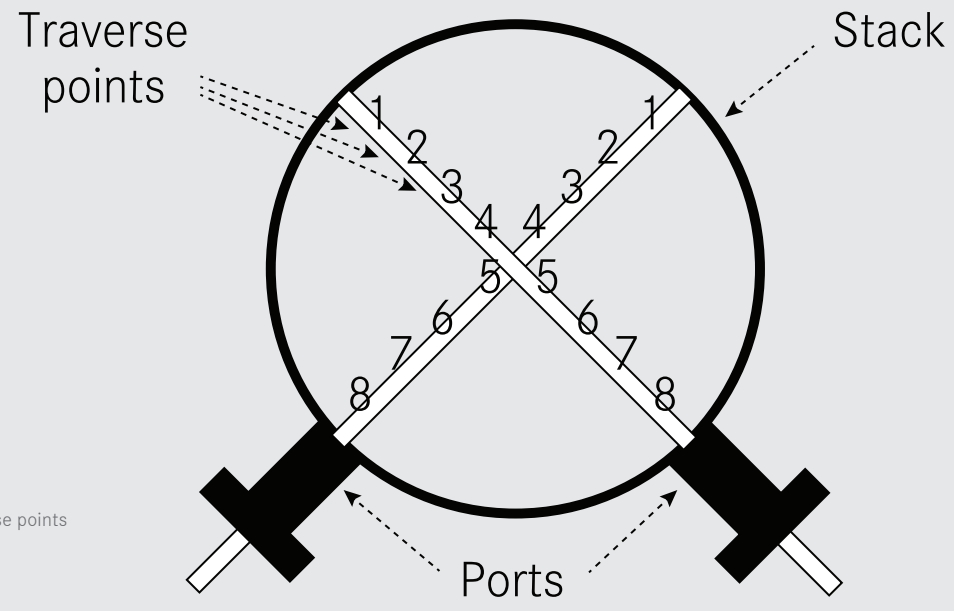

Figure 3:
Example of traverse points in Stack <24 in.

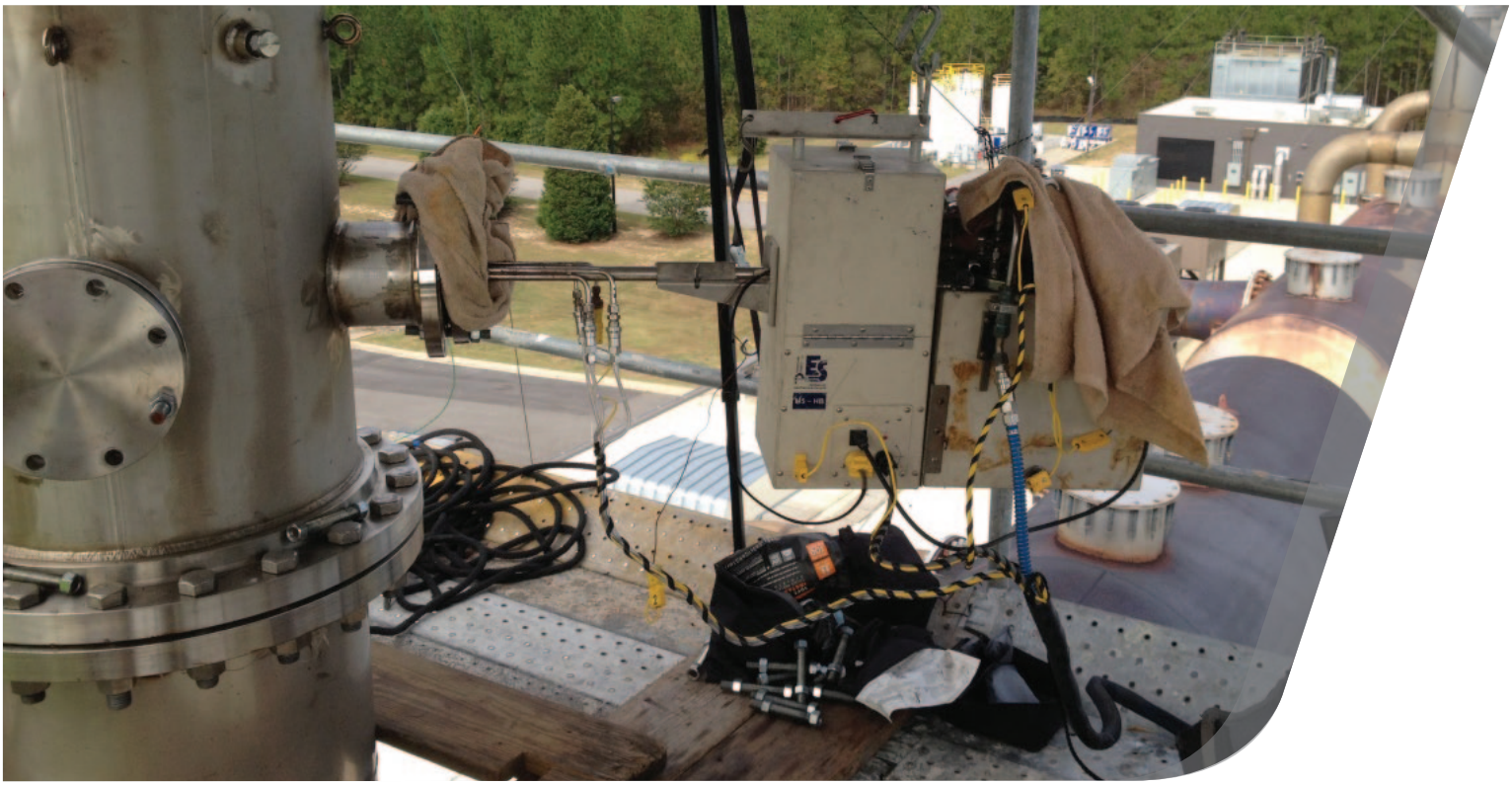

Figure 4:
Probe aligned in stack

Checking the Test Results

// The results of the each test should be checked regardless if the test passed or failed. When the engine runs without problems and the recorded Diasys values imply no instability, you should have the values and results of the stack test should not fluctuate by more than around five percent. Large fluctuations in the data could indicate improper equipment handling. A check list is provided in Appendix A to help determine if all steps and processes have been completed.

For Testing:

- How are the particle filters conditioned
- and weighted (before and after sampling)?
- Filters and equipment need to fit to each other otherwise leakage can occur
- Filters need to be installed flat and not wavy
- How are the filters handled (in separate containers, which are in an extra box to prevent moisture from the air)?
- Where is the connection of the PM measurement device in the exhaust pipe?
- Design of the exhaust pipe before measurement point (e.g. after elbow is not good)
- Measurement points always same distance from engine and last bend in exhaust line
- Measurement in laminar flow (measurement position)
- Use same nozzle for all measurements
- Fixed probe positions across stack diameter
- Probe in line with flow
- Measure exhaust gas mass for each measurement
- Fixed duration of measurement
- Maintain boundary conditions
- Exhaust gas from nearby engines might influence results

HINTS TO CHECK RESULTS

- ✓ Are the results, e.g. particle emission, steady during the test?
- ✓ Are the results reproducible?
- ✓ Are the protocols completed?
- ✓ Was a fuel used according to fuels and lubricants Specification?
- ✓ Are the boundary conditions (weather etc.) listed in the report?

CONCLUSION

The results of a stack test depend on many influences and factors. Therefore, it is very important to perform the test as carefully and precisely as possible. If you encounter unforeseen problems, please feel free to contact your local MTU Sales Engineer.

APPENDIX A: CHECK LISTS

PREPARATION

	YES	NO
Stack diameter known by stack test performing company		
Position for stack test is performed at a site at least eight stack diameters downstream and two stack diameters upstream from any flow disturbance		
Stabilization run needed		
Fuel and engine oil is according the MTU Fuels and Lubricants Specification		
Particle limit corresponding to mechanical power, not electrical power		
Wind-shielded and clean area nearby available for replacing and sealing the filters		
Lights or similar is available if the stack test takes longer than planned		
Ports are mounted at the recommended position and are accessible		
Your HS&E department is informed about the stack test		
All persons needed on site have access to this area, including instructions		
Measuring time per port is discussed and agreed		
Are the particle filters conditioned and weighted before sampling?		

STACK TEST RUN

	YES	NO
Stabilization run done on the engine		
Ports/stack are clean of soot etc.		
Time per port/test run is according to the agreement		
Filters fit in the test equipment		
Leakage tests are done and fulfilled at least after each run		
Filters are taken in or out of the measurement equipment in a clean and wind-shielded area		
Filters are handled correctly in separate containers, which are in an extra box to prevent moist from the air		
Same nozzle diameter is used for all tests		
Probe is perpendicular to the exhaust gas flow		
Exhaust gas from nearby engines doesn't influence the test		
Positioning of the probe is comprehensible		
Ambient conditions are recorded several times during the stack test		
Notes are taken in a professional way, e.g. lists or in a notebook		
Unused port is closed, airflow through open port is minimized		
Probe is handled with care, nozzle is not dragged through port etc.		
Probe is cleaned correctly with acetone and a nylon brush, acetone comes out clean after last flush		
Connection points in the test equipment are not open during the test unless needed. In this case, they are cleaned before reconnecting		

AFTER THE STACK TEST

	YES	NO
Are the results of the single test runs comparable to each other?		
Are the boundary and ambient conditions considered in the results?		
Is the test method, date etc. mentioned on the report?		
When the stack test failed, are the possible causes on engine side (see appendix B) checked?		
Are the results from test run to test run stable? E.g. fluctuating residual oxygen is an indicator for leakages in the equipment. Also, particle emissions varying from run to run are untypical and may be a sign of too short test run time.		
Was the fuel according the MTU Fuels and Lubricants Specification?		
Are the protocols complete?		

APPENDIX B: ENGINE PARAMETERS FOR RECORDING

1_0100_001_P_Lube_Oil_after_Filter
1_0101_001_P_Coolant_
1_0102 001_P_Fuel_
1_0103_001_P_Charge_Air
1_0104_001_P_HD__Common_Rail_
1_0106_001_P_CrankCase
1_0109_001_P_Lube_Oil_before_Filter
1_0120_001_T_Coolant
1_0121_001_T_Charge_Air
1_0122 001_T_Fuel
1_0124_001_T_Coolant_InterCooler
1_0125_001_T_Lube_Oil
1_1020_506_BOI_Main_Injection
1_1020_601_Main_Fuel_Mass_per_Cycle
1_1075_042_Max__Torque_LDA
1_1075_046_Max__Torque_DBR_corrected_
1_1075_052_Torque_Limit_Corr___Q_Air_
1_1075_056_Max__Torque_MCR_corrected_
1_1075_061_Charge_Air_Mass
1_1075_065_Torque_Limitation_Code
1_1100_503_BOI_Norm
1_1100_504_BOI_Hot_Engine
1_1100_505_BOI_Cold_Engine
1_1100_506_Norm_Air_Mass
1_1300_100_P_Railfuel_Demand__Map_
1_2500_044_Engine_Speed__ECU_
1_8009_002_ECU_Operating_Hours
1_8009_003_ECU_Operating_Minutes
2_1000_048_Maximum_Requested_Torque
2_1000_049_Requested_Torque
2_8009_015_Fail_Code

These parameters are good to be collected additionally:

1_0108_001_P_Ambient_Air
1_1005_012_Engine_Power
1_1020_554_Injector_Drift_PW_Correction
1_1075_041_Max__Torque_DBR_at_Rated_Power
1_1075_054_Max__Torque_MCR_at_Rated_Power
1_1100_512_AirMassRatio_Trans__Norm_filt
1_1100_515_Injector_Drift_BOI_Correction
1_1100_516_Steady_State_BOI_Correction
1_1100_517_Delta_BOI_Correction
1_1300_105_Number_of_active_Cylinders

Photo credits: MTU Onsite Energy.

APPENDIX C: POSSIBLE ENGINE MALFUNCTIONS THAT COULD HAVE AN EFFECT ON PARTICULATE EMISSIONS

Wrong injection timing and/or rail pressure

- Broken, blocked or worn out nozzle
- Malfunction of high pressure pump and/or pressure valve
- Blocked fuel filters
- Low battery voltage
- Wrong high pressure sensor

Air-related issues

- Blocked air filters
- Turbo charger malfunction
- Malfunction of charge air cooler might lead to high charge air temperature
- Loss of charge air pressure
- Blocked silencer
- Air leakages at engine (e.g. charge air pipes)
- Blocked air pipes

Crank case ventilation system

Crank case ventilation system without filter elements (oil before turbocharger, low crank case pressure)

Additional possible causes

- Wrong valve adjustment
- Leaking gasket at cylinder head

APPENDIX D: TERMS AND DEFINITIONS

DiaSys: An MTU specific tool to record various engine parameters during operation and to communicate and change engine parameters on the ECU.

ECU: Engine Control Unit

Port: An opening in the stack that should easily be closed if not needed, even when the engine runs. It must be closed during the stack test when not needed.

Probe: The probe for particle measurement consists of the pitot probe and a hook probe for collecting the exhaust gas.

Stack Test: An exhaust gas measurement performed directly at the stack / exhaust pipe. This is an in-use test method for particles, NOx etc. Two ports are required attached to the stack in a 90° angle, in which the probe is put into. A second probe is stacked into the port through an additional hole. A stack test usually takes three test runs, the results are averaged.

Test run: A test run consists of two measurements, one per port. A test run takes at least 1 hour according EPA regulatory.

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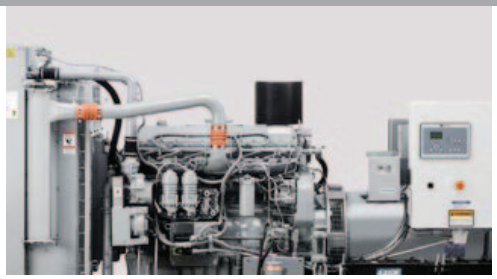

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