Investigation of gaseous ammonia for NOx control by SCR on an experimental basis

Master Thesis in Energy Technology

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Preface

I started this journey seeking out the one thing so frightening, it was banned by local authorities, feared by the wealthiest ship owners, and locked away in thick steel bunkers. Hazardous, yet appealing, with a huge potential for both disaster and greatness: Anhydrous ammonia!

The title "Investigation of gaseous ammonia for NO_x control by SCR on an experimental basis" refers to my master's thesis in Energy Technology, a project that investigates the possibility of using anhydrous ammonia as a reducing agent for marine SCR operations. The thesis was written to fulfill the graduation requirements of the study Energy Technology at the University of Bergen and Bergen University College.

I want to thank Lars Magne Nerheim for the inspiring idea for this topic - a topic I find very exciting and relevant. A topic I would gladly contribute to, and a great motivator to work towards a goal to change the future for the better. A technology that can relieve the strain on the environment in the long transaction phase from conventional fuels to renewable energy sources.

I would like to thank Peter Edgar Koch and Lars Magne Nerheim for the support and supervising throughout the project, the beneficial discussions and valuable inputs, Harald Moen and Odd Eirik Smistad for helping with the manufacturing of parts and construction of the system. I would also like to thank MECMAR, Yara and MAN Diesel & Turbo for providing information about SCR-systems related to the marine field.

Thank you for reading my thesis.

Bergen, August 14, 2016

Vitaliya Makoveyenko

Abstract

My dissertation argues which of the two reducing agents, urea or pure ammonia, is better suited for reducing NO_x emissions in Marine SCR applications. While the question might seem straight forward, there are several upsides and downsides to them both. What proves a challenge with marine diesel engines are the low exhaust gas temperatures, making it a brain twister to reduce NO_x across varying engine loads by any respectable amount. Still, theoretically, pure ammonia should be able to do this, or?

To put this claim to the test, a micro scale SCR system is designed and built by a team of competent individuals, including myself. A series of NO_x reduction tests are then carried out under conditions similar to a diesel SCR process, using gaseous ammonia as reducing agent.

While results are varying it is confirmed that pure ammonia does indeed perform well at low temperatures. NO_x reduction rates are impressive considering the system is not optimized with regard to dimensioning. Results are presentative but with potential for improvement.

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Nomenclature

ABS	American Bureau of Shipping
ASDS	Ammonia Storage and Delivery System
CI-engine	Compression-ignition engine
DNV GL	Det Norske Veritas (Norway) and Germanscher Lloyd (Germany)
ECAs	Emission Control Areas
EPA	Environmental Protection Agency
HFO	Heavy Fuel Oil
IACCSEA	The International Association for the Catalytic Control of Emissions to Air
IMO	International Maritime Organization
LR	Lloyd's Register Marine
MARPOL	International Convention for the Prevention of Pollution from Ships, 1973 "MARPOL" is short for marine pollution
NOx	Nitrogen Oxides (NO + NO_2)
SCR	Selective Catalytic Reduction
SOx	Sulphur Oxides
USCG	United States Coast Guard

Introduction

Today's mentality and tendencies to make energy sustainable and less harmful for human health and the environment get us to promote an image of a "clean engine". Diesel engines, with characteristics of superior fuel economy, excellent performance, good acoustics as well as low exhaust emissions, are steadily increasing market shares. The diesel's main challenge, however, in terms of sustainability is the abnormally high NO_x emissions. Advanced technologies such as common-rail, turbocharging, cooled EGR as well as sophisticated control algorithms have helped to reduce engine-out emissions, but NOx reduction-scaling by engine-only modifications is not enough to meet the stringent Euro and Tier standards.

Practice shows that exhaust aftertreatment systems have better NO_x reduction capabilities than any other technology. Currently, SCR is the only NO_x reduction method single handedly capable of meeting the upcoming standards beyond 2016.

With anhydrous ammonia as reducing agent NO_x can be removed from the diesel exhaust gas nearly completely and hence, full scale efficiency of SCR can be extracted. Instead, because of HSE risks, urea is used which does not have the same potential as pure ammonia.

Excellent NO_x reduction capabilities by ammonia are already proven and steadily getting implemented in high-speed engines, typically for vehicles. Ammonia-SCR for marine applications is not yet explored to its full potential, prevented by HSE and challenges with low temperature exhaust gas, especially at part load.

The master thesis will examine SCR technology with ammonia as reducing agent aimed at marine applications. A micro-scale SCR-system is build where reduction rates, as a function of temperature will be tested and analyzed. Results will serve as a foundation for further work towards bigger scale testing related to the marine field.

Problem statement

Rules and regulation for operating at sea have over the last decades been strictly enforced. The most recent regulation issued on 1 January 2016 required a further reduction of NO_x by 76% up from the previous tier, Tier II. Due to increased international focus on emissions, regulation will no doubt tighten even further on a global scale and even more so in the future. So far the 2016 regulations only apply to newer vessels, which poses a significant challenge when designing ships after 1 January. Some of the previous engines for meeting the Tier II regulations were compliant by themselves, however, meeting the new Tier III standards will require additional solutions such as exhaust gas aftertreatment systems.

There are several measures that may be relevant to reduce the strain on the environment from ships such as low Nitrogen-containing fuels – LNG and Biogas, which are prioritized by the Norwegian Ship-owners' Association. Other solutions are Fuel cells and fuel cell hybrid systems. The challenge with these methods however, is limited infrastructure. SCR on the other hand has the potential to solve the NO_x emission problem for all fuel types and a series of other challenges.

SCR is an aftertreatment system which cleanses NO_x from the engine exhaust by mixing it with ammonia. The reaction, which takes place on a molecular level, reduces the NO_x particles to harmless levels of Nitrogen and water. It is a proven technology, compact and commonly used in hundreds of vessels, both on propulsion and auxiliary engines.

SCR can achieve NO_x reduction by up to 99% provided ideal exhaust gas temperatures. Maximum effectiveness is obtained by using pure ammonia as a reducing agent, either in liquid or gas form. Today's ships however, use a diluted solution of ammonia called urea. SCR reactions by urea require a certain temperature for the reaction to take place. Because of this, diesel engine emissions under lean conditions can be problematic. Mainly because the efficiency under part load can result in particularly low exhaust gas temperatures.

Because the required temperatures are not met at low loads, the SCR system is usually turned off. In some cases, ship-owners install engines with preheating functions to keep the exhaust gas temperature constant even at low loads, which result in extra expenses.

Pure ammonia SCR has been given low priority due to HSE concerns, skepticism and restrictions from local authorities some places. Still, at least 2 enterprises worldwide have commercialized the technology, the Danish company Amminex for vehicles and the Norwegian company MECMAR for marine applications.

Available data on ammonia SCR for marine applications is close to non-existent. This thesis will therefore explore the potential of gaseous ammonia as a reducing agent for marine applications at different loads and temperatures. Gaseous ammonia will allow for a higher reduction rate compared to conventional urea over a wider temperature range, as well as reduced weight and size of the system, injection unit complexity, let alone overall system costs.

Objectives

The aim of this master thesis is to improve the understanding of catalyst performance, especially in regard to anhydrous ammonia as reducing agent. An experimental method is chosen which involves projecting and constructing a microscale ammonia-SCR test-system in order to survey the NO_x conversion efficiency with anhydrous ammonia as a reducing agent.

This includes:

- Looking into catalyst physics and chemistry on a theoretical level
- Looking into the differences of ammonia-SCR compared to urea-SCR
- Exploring the challenges and advantages with ammonia-SCR
- Designing, dimensioning and building the ammonia-SCR microscale system
- Monitoring NO_x reduction rates and gas temperatures

The thesis is further divided into four parts for easier navigating. Each part covers a different aspect of Selective Catalyst Reduction.

Part 1 gives an introduction to NO_x, NO_x formation and emissions. The NO_x -reduction methods available today, and an overview of the legislation demanding these methods.

Part 2 offers the history of SCR with a typical SCR-system setup, illustrating the components. Further describing ammonia as a reducing agent with an in depth explanation of the "magic" that happens inside the catalyst. The factors that influence it, the challenges associated with marine SCR and the research already conducted on marine SCR as of today.

Part 3 compares the two reducing agents of interest in regard to physical properties, safety, storage and transportation.

Part 4 is the practical part where tests are run to replicate an ammonia SCR process in a micro scale system built in this project. The tests are conducted in the laboratory facilities of Bergen university college.

Literature review

There is a manageable amount of information in research papers about pure ammonia as reducing agents in marine SCR applications. Neither enterprises who have commercialized ammonia based SCR are willing to share their achievements. There are, however, some papers with comparisons from the economical and HSE point of view from pure ammonia SCR against other ammonia-containing reducing agents:

- The paper "Optimization of Ammonia Source for SCR Applications" by R. Salib and R. Keeth presents a technical and economic comparison of three alternative sources of ammonia for an SCR installation: anhydrous, aqueous and urea-derived ammonia.

- The paper “Comparison of Urea-Based Ammonia to Liquid Ammonia Systems for NO_x Reduction Applications” by Jeffery E. Fisher, compares risk assessment, consumption and cost of anhydrous, aqueous and urea-derived ammonia.

The content of these papers are discussed in the Part III of this thesis.

Part I. Background

Ships are a huge contributor to bad air quality due to high NO_x emission levels both while operating at sea and while docked. It is estimated that global transport makes up 30% of global anthropogenic NO_x emissions, with shipping accounting for 5% - 7% [1]. Due to raised worldwide awareness of the marine industry's contribution to exhaust emissions, the international marine transportation sector is facing increasingly tighter regulations to curb air pollution.

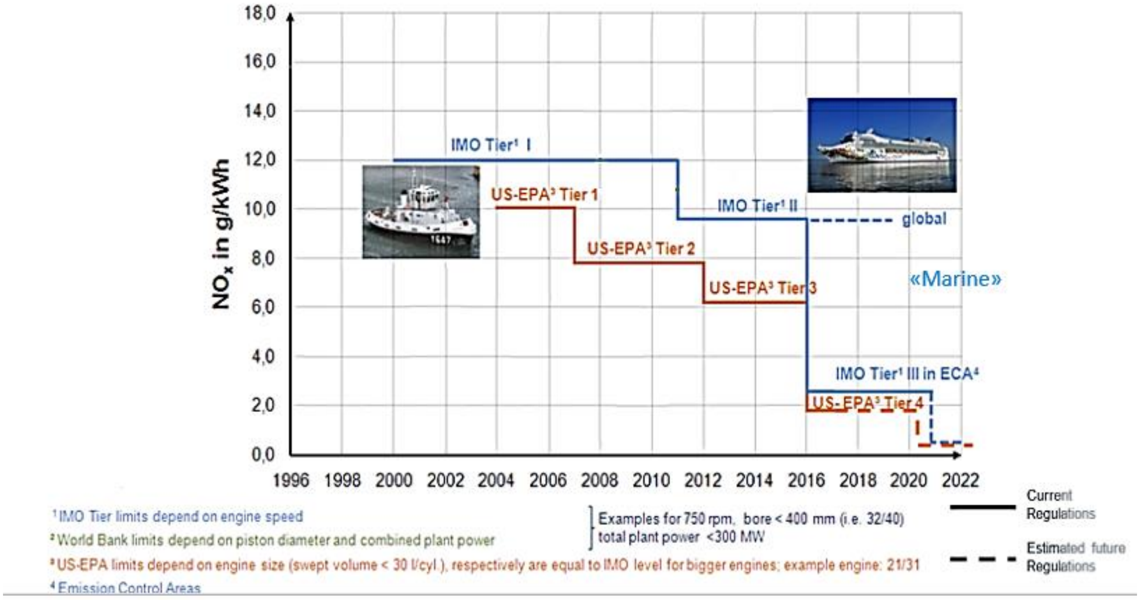


Figure 1 - Development of NOx restrictions [2]

Various methods for reducing emission have been developed in recent years through research and development by engine manufacturers and specialized companies. Ship-owners and ship manufacturers are constantly on the lookout for high efficient technology to handle NO_x emissions while also lowering other costs. With its superior return in both economic and environmental benefits, SCR (Selective Catalytic Reduction) is claimed the most promising solution according to classification companies (DVN, Lloyd). SCR is a widely used technology for all types and sizes of diesel engines. Compared to the others, it's a very effective measure, which enables diesel engines to comply with the latest statutory emission limits. SCR diesel catalysts do not only relieve the strain on the environment, but cut fuel consumption, toll charges and tax rates as well.

Selective Catalytic Reduction is a method placed in the aftertreatment category, as it cleanses the exhaust independently of possible pre- and internal treatments, highlighted red in Figure 2 - NOx Emissions Control alternatives.

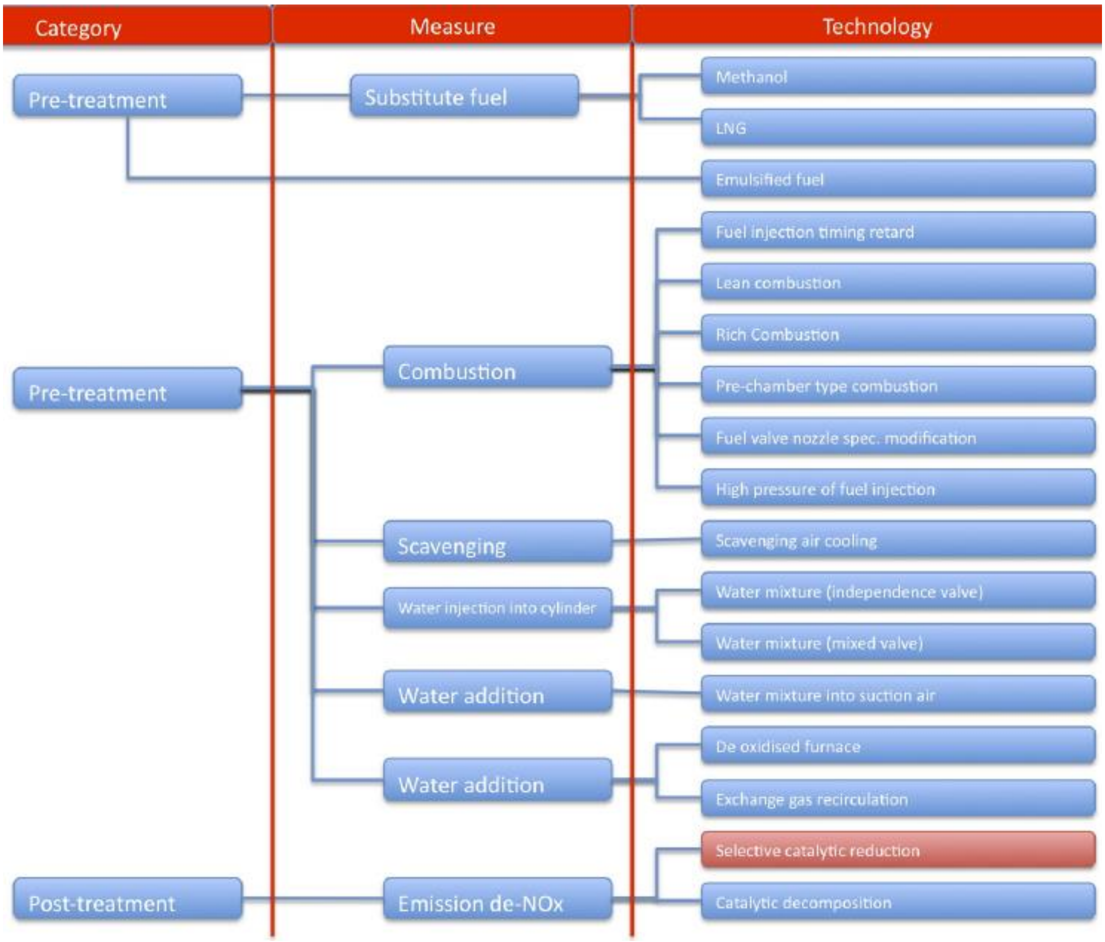


Figure 2 - NOx Emissions Control alternatives [Edraw]

The important matter of discussion is further optimization of the SCR process, which can be done by varying system parameters, including catalyst type and reducing agent. The latter one is the matter of focus in this thesis. Urea solutions are the commonly used reagent in SCR applications today and is namely ammonia, derived from a urea-based liquid. Pure, or anhydrous, ammonia on the other hand are the cheapest sources of ammonia, and has the potential of being the most cost-effective and beneficial options considering capital, operating and maintenance aspects. The strongest argument for using pure ammonia as a reducing agent in marine SCR is its efficiency at low exhaust temperatures. It allows for expanding the SCR operating temperature range which is beneficial for engines operating at part load. But there are unavoidable downsides of pure ammonia as reducing agents in form of risk management and mitigation to be taken into account as well. Pure ammonia is hence a trade-off subject for many and each.

NO_x emissions from ships

Emissions from marine diesel engines generally consist of nitrogen, oxygen, carbon dioxide and water vapor. Smaller amounts of carbon monoxide, oxides of sulphur and nitrogen, and particulate matter are also present and are the ones which should be reduced because of their harmful effects.

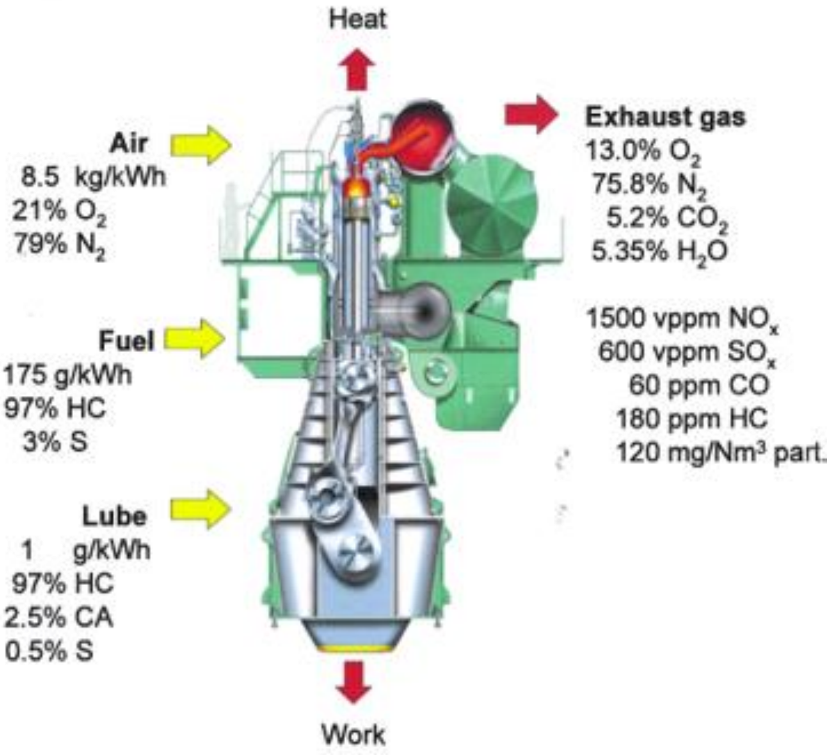


Figure 3 - Emissions from an engine process (Low-speed 2-stroke diesel engine) [3]

As shown in Figure 3 - Emissions from an engine process (Low-speed 2-stroke diesel engine) the major pollutants are NO_x and SO_x. In this thesis only NO_x reduction methods are discussed.

NO_x Emission formation in Diesel Engines

NOx compounds

Nitrogen Oxides are a family of poisonous, highly reactive gases, which are formed when fuel is burned at high temperatures, such as in a combustion process. The NO_x family contains five substances, but in the “engine world”, NO_x is a generic term for mainly NO and NO_2 as they are the two main components formed. NO_x is a pollutant which causes a wide variety of adverse health and environmental problems: NO_x gases react in the atmosphere forming smog and acid rain and it is central to the formation of fine particles (PM) and ground level ozone, as well as contributing to nutrient overload that deteriorates water quality.

Nitrogen is normally an inert gas, but during combustion of fossil fuels at temperatures above 1100°C the nitrogen in the air is no longer inactive and will react with oxygen to form oxides of nitrogen. In heating applications operating at these temperatures, the majority of the NO_x in the exhaust gas is in the form of nitric oxide (NO) and nitrogen dioxide (NO2) in somewhat smaller quantities, usually 95% and 5% respectively. As opposed to nitrogen dioxide, nitric oxide is not considered hazardous to health at typical ambient concentrations. However, the tendency of NO to get further oxidized to NO_2, a harmful combustion product, attracts more attention to NO_x emissions [4].

The mechanisms of NOx formation

There are three generally accepted mechanisms for NO_x formation; Thermal NO_x, prompt NO_x, and fuel NO_x.

The largest emission contributor is the extended "Zeldovich"-mechanism, proposed by Russian scientist Zeldovich in 1946, presented by the following reactions.

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

The mechanism was later extended to include a third reaction:

$$N + OH \rightarrow NO + H$$

According to the Zeldovich equations, NO is generated from the limit of available oxygen at temperatures above 1100°C. Zeldovich- mechanism is often considered to be dominating as an automotive diesel engine can typically not avoid high temperature regions in its entire operational range. NO_x formed by high temperature reactions is called "Thermal NO_x" [5].

There are also 2 other, non-dominant NO_x formation mechanisms: "Prompt NO_x" and "Fuel NO_x":

- *"Prompt NOx"* is formed by the relatively rapid reaction between intermediate species in the rich zones of the flame (reaction between atmospheric nitrogen and radicals in the air) at a lower temperature range. This is a very complicated mechanism consisting of hundreds of reactions and dozens of species. The levels of prompt NO_x are generally very low, so it is usually only of interest for the most exacting emission targets [6].
- *"Fuel NOx"* comes from nitrogen containing fuels (e.g., coal, diesel) and is created in a similar way Prompt NO_x is formed. Fuel NO_x is however formed by the direct oxidation of nitrogen-containing organic compounds contained in the fuel [6].

NOx formation in diesel engines

There are three conditions required for NO_x to form:

- Combustion temperatures higher than 1100°C

  *The temperature dependency is exponential, e.g. NO formation rate can increase by a factor of 10 for every 373°C rise in temperature.

- N_2 (N) present in oxidation-rich environment
- Excess O_2

A diesel engine combustion process, as well as other lean-engines, form the perfect environment for NO_x formation as they run with excess oxygen under normal operation. That is because excess air in CI-engines increase the likelihood of nearly all injected fuel to react with oxygen molecules and being burnt up, which give better SI engine efficiency. Unreacted oxygen in the cylinder will be wasted. This is done so that the alternative, wasting unreacted fuel instead, will not happen. “Wasted” oxygen reacts with N_2, which initially is quite unreactive under normal conditions, but under high temperature and pressure form oxides [5] [7].

NO_x forms during two of four phases of the CI-engine operation cycle - combustion and expansion. Liquid fuel is injected into the compressed charge at the end of the compression stroke, evaporating and mixing with the hot air before igniting due to the high temperatures of the compressed gases in the cylinder. Combustion occurring during the “premixed” combustion period creates an extremely thin (in the order of 0.1mm) flame reaction zone and residence time within this zone is short. As more fuel is injected, the combustion is controlled by the rate of diffusion of air into the flame or evaporated fuel particles into air. NO forms both in the propagated flame front and in the post flame gases.

The diffusion combustion process in direct-injection diesel engines is, by its nature, inhomogeneous. Non-uniform fuel – air mixture prevails throughout the entire combustion period, so very rich to pure zones can be found locally. During such an inhomogeneous combustion, there is and always will be some regions where combustion takes place at conditions favorable for NO_x formation. Once nitrogen species have been formed, the charge cools down so rapidly that the reverse reaction becomes impossible [8].

Conceptual model for the diffusion combustion period has been proposed by Dec [9] and this provides a simplified way to describe the process. Dec’s model is shown in a schematic in Figure 4 – “Real” Combustion in an optical access engine and Quasi-Steady Diesel Combustion plume together with a picture of a “real” combustion in an optical access engine.

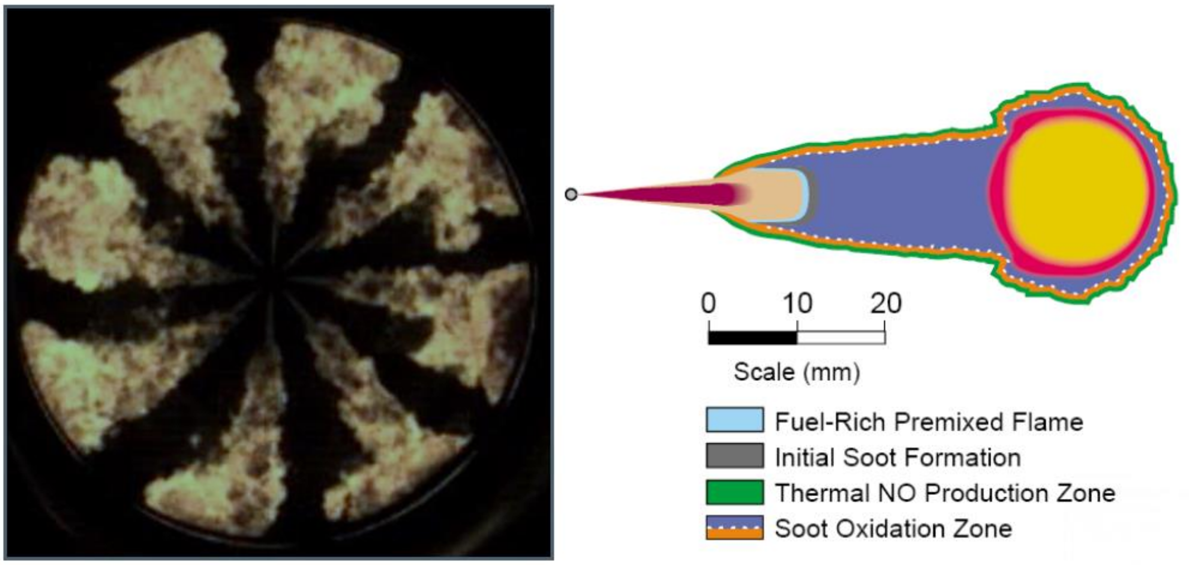


Figure 4 – "Real" Combustion in an optical access engine and Quasi-Steady Diesel Combustion plume [9]

The green region in Figure 4 – "Real" Combustion in an optical access engine and Quasi-Steady Diesel Combustion plume is where most NO is formed - in the flame front where the air/fuel mixture is approximately stoichiometric and the flame is as hottest. NO_x is also formed in SI engines but since these are operated without excess air, they can take care of the emissions relatively easy with a three-way catalytic converter. This is not possible in the diesel engine where overall air excess is necessary to achieve acceptable combustion efficiency.

NO$_x$ Technical Code

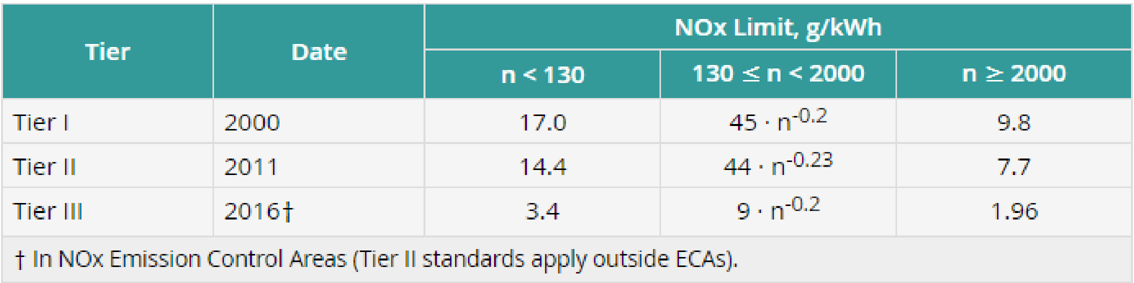
Shipping is largely an international industry where regulations are developed and adopted in the International Maritime Organization (IMO) and the EU. The IMO is an agency of the United Nations which has been formed to promote maritime safety and became active in 1958.

IMO ship pollution rules are contained in the “International Convention on the Prevention of Pollution from Ships”, known as MARPOL 73/78. MARPOL is divided into Annexes according to various categories of pollutants, each of which deals with the regulation of a particular group of ship emissions. MARPOL Annex VI deal with the prevention of air pollution from ships and sets limits for NO$_x$ and SO$_x$ emissions from ship exhausts, as well as prohibits deliberate emissions of ozone depleting substances [10].

Annex VI is further subdivided into Tiers, which currently control NO$_x$ emission levels - the IMO emission standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/III standards were introduced by Annex VI amendments adopted in 2008, also called the NO$_x$ Technical Code 2008.

The NO$_x$ control requirements of Annex VI apply to installed marine diesel engine of over 130 kW output power with the exceptions of lifeboat engines or emergency generators.

Different levels (Tiers) of control apply based on the ship construction date. Within any particular Tier the actual limit value is determined from the engine’s rated speed (the engine maximum operating speed (n, rpm)) as shown in Table 1 - MARPOL Annex VI NOx Emission Limits and presented graphically in Figure 5 - MARPOL Annex VI NOx Emissions Limits [10] [11]:



Tier	Date	NOx Limit, g/kWh		
		$n < 130$	$130 \leq n < 2000$	$n \geq 2000$
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96

† In NOx Emission Control Areas (Tier II standards apply outside ECAs).

Table 1 - MARPOL Annex VI NOx Emission Limits [10]

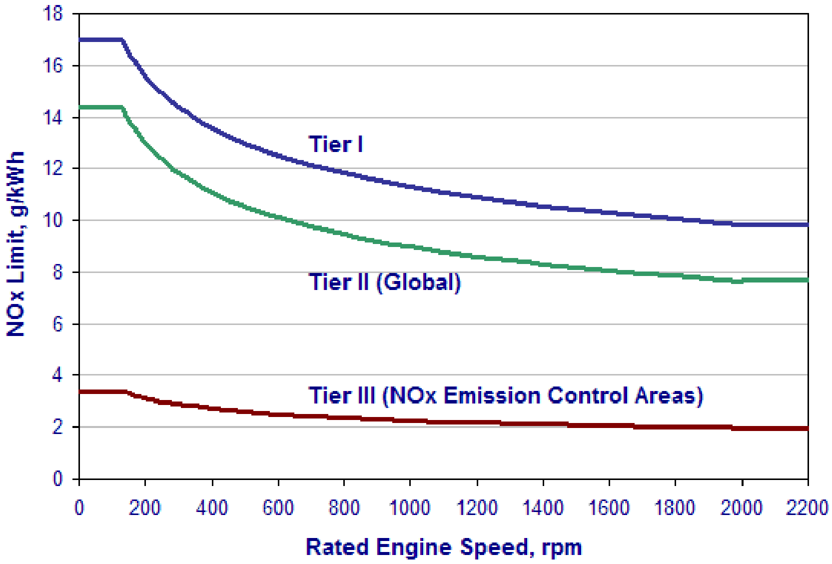


Figure 5 - MARPOL Annex VI NOx Emissions Limits [10]

The Tier III standards apply to ships with keel-laying on or after the date of adoption (1st January 2016) and to ships operating within current existing Emission Control Areas (ECAs) for NO_x, which are:

- North American ECA, including most of US and Canadian coast (NO_x & SO_x, 2010/2012).
- US Caribbean ECA, including Puerto Rico and the US Virgin Islands (NO_x & SO_x, 2011/2014).

Outside the Emission control areas, the Tier I and II standards apply, globally.

Figure 6 - Emissions Control Areas [4]

The penalties for failing to comply with NO_x Tier III follow the same principles as other instances of non-compliance with the MARPOL Annex VI, and will vary according to the severity. The United States Coast Guard (USCG) has indicated that the penalties for failing to comply with NO_x Tier III will be $25,000 per violation [12].

Local NO_x Emission controlling measures

Although NO_x Emission Control Areas (NECA's) apply in several countries, they are not all bound by the same rules. Depending on the country, NO_x restrictions may vary. This thesis will mention local NO_x restriction related to just 2 countries, Norway and Sweden, taken as examples.

North American NECA and United States Caribbean Sea NECA, currently use the IMO Tier III NO_x emission standard for marine diesel engines installed on new ships constructed on or after 1 January 2016. Per definition, this grants ships older than 2016 a free pass when sailing in these waters.

Norway introduced a tax for ship engines above 750kW. As of 1 January 2007 the rate was set at NOK 15 per kilo NO_x emitted. The tax applies to ships operating within Norwegian waters, regardless of nationality or the vessels production year, with the exception of ships in international traffic between Norwegian and foreign ports.

For domestic emissions between Norwegian ports, an agreement between 15 business organizations and the Ministry of the Environment was approved by the ESA (Efta Surveillance Authority) in 2008. Affiliated enterprises replace the governments NO_x tax by paying NOK 4 per kilo to the NO_x fund instead. In return these enterprises have to commit themselves to investigate investments required to reduce NO_x and to report back to the board of the fund.

In Sweden NO_x fees were introduced 1 January 2005 which were based on the gross tonnage (GT) of the vessel. The basic rates were following:

- SEK 1.80 (€0.18) per GT for passenger ships
- SEK 2.05 (€0.20) for oil tankers
- SEK 2.05 (€0.20) for other types of ships
- SEK 0.80 (€0,08) for Cruise ships

On top of this rate, vessels were charged an additional SEK 0.70 (€0.07) per GT unless they use fuels containing less than a percentage of sulphur. Vessels that hold a NO_x reduction certificate i.e. vessels that have a SCR system installed receive a reduced GT tax depending on the NO_x level reduction. Starting at an emission level of 6g/kWh to less than 0,5g/kWh, in which case the vessel is totally exempted from GT taxes.

From 1 January 2015 the Swedish Maritime Administration (SMA) issued new regulations regarding fees for port calls. The number of calls that are subject to fairway dues are limited to five per calendar month for passenger and cruise vessels and two per month for other vessels [13].

NO_x reduction methods

To go from the current NO_x Tier II limits to the NO_x Tier III limits as defined in IMO MARPOL Annex VI regulation 13, NO_x emissions must be reduced by approximately 75%. The available technologies for compliance with the IMO NO_x Tier III limits currently include [4]:

- Selective catalytic reduction (SCR) systems
  - This is the most widely used method for reducing NO_x from an engine's exhaust gas.
- Exhaust gas recirculation (EGR)
  - Recirculation of the exhaust gas back into the engine's combustion process. It's a competitive option for NO_x compliance.
- Alternative fuels such as liquefied natural gas (LNG).

  - Dual fuel engines (DF)/pure gas engines

  But at the same time, according to Lloyd's Register Group Services Ltd., "Some gas engines (particularly those operating on the Otto cycle and using spark ignition) can meet the Tier III emission limit, however not all gas engines (particular those operating on the Diesel cycle with oil pilot fuel) offer Tier III compliance." [14]

Technologies that don't have NO_x emission like batteries and fuel cells are not a part of the regulation.

According to DNV GL, which is currently working with customers on approving their different solutions for complying with the IMO NO_x Tier III requirements, SCR is the leading solution [12].

Wärtsilä has rated NO_x reduction measures in the following scale Figure 7 - NOx Reduction Technologies **Feil! Fant ikke referansekilden.**, where only two methods show sufficient reduction potential to comply with Tier III:

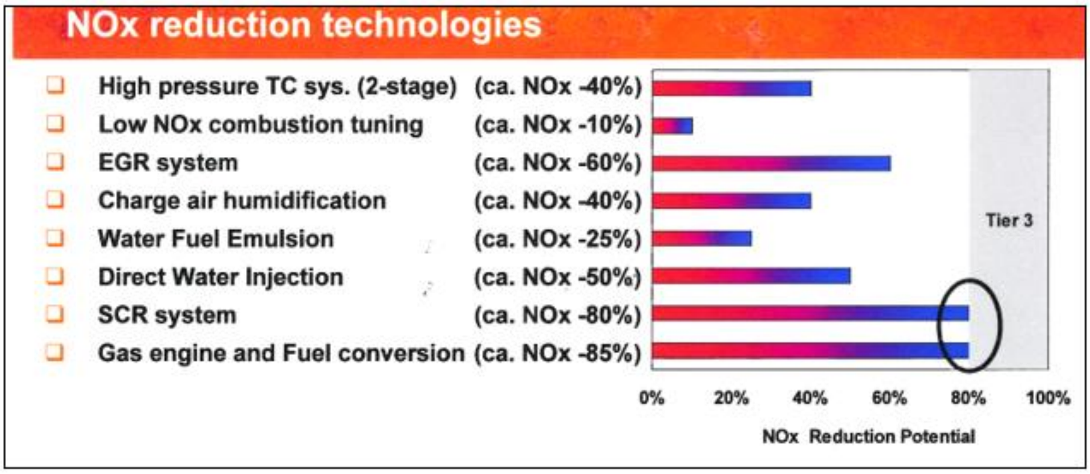


Figure 7 - NOx Reduction Technologies [15]

Part II. SCR System Overview

History

The first Selective catalytic reduction of NO_x was patented in the United States by the Engelhard Corporation in 1957, using ammonia as reducing agent. It was originally developed to reduce NO_x emissions in utility and industrial boilers. The first SCR technology implementation took place in Japan in the late 1970s applied in thermal power plants, followed by widespread application in Europe and USA since the mid-1980s. SCR applications included coal-fired cogeneration plants, gas turbines, plant and refinery heaters and boilers in the chemical processing industry, furnaces, coke ovens, municipal waste plants and incinerators. The list of fuels used in these applications include industrial gases, natural gas, crude oil, light or heavy oil, and pulverized coal.

The first SCR units aboard vessels were installed in 1989 and 1990 on two Korean 30,000 metric ton carriers. Both ships were powered by MAN B&W 2-stroke 8 MW diesel engines. The ships were equipped with ammonia SCR systems designed for 92% NO_x reduction. Commercial SCR systems have also been installed on ferries. In 1992 the ferry “Aurora of Helsingborg” that shuttled between Sweden and Denmark was equipped with a urea SCR system. Since then, and prior year 2013, SCR systems have been installed on over 500 marine vessels. Numbers have most likely spiked near the release of Tier III since Yara alone claims to have over 1300 installations worldwide as of 2016 [16].

Development of SCR implementation is shown in Figure 8 - Total number of vessels with SCR installations prior 2013 prior 2013, presented by the International Association for Catalytic Control of Ship Emissions to Air, IACCSEA. Compiled using the knowledge and experience of IACCSEA member organizations (Yara, Johnson Matthey, Hitachi Zosen, Ibiden, Haldo Topsoe and Cormetech) [17]. In all these applications ammonia is derived from urea solutions that are injected into the exhaust gas where hydrolyses occur, forming ammonia and carbon dioxide.

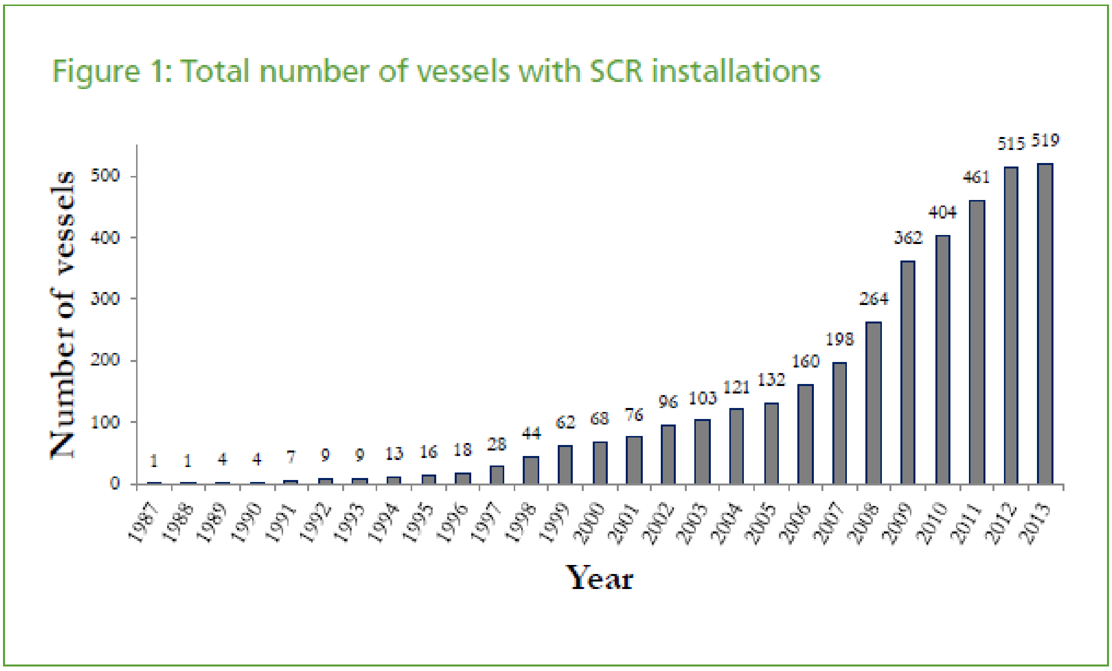


Figure 8 - Total number of vessels with SCR installations prior 2013 [17]

In Figure 9 – Share of various types of vessels with SCR , ship types and their respective shares in percentages gives an overview of SCR installations. Over half the ships using SCR are of the category carriers, including tankers, bulkers and container ships classified as carriers.

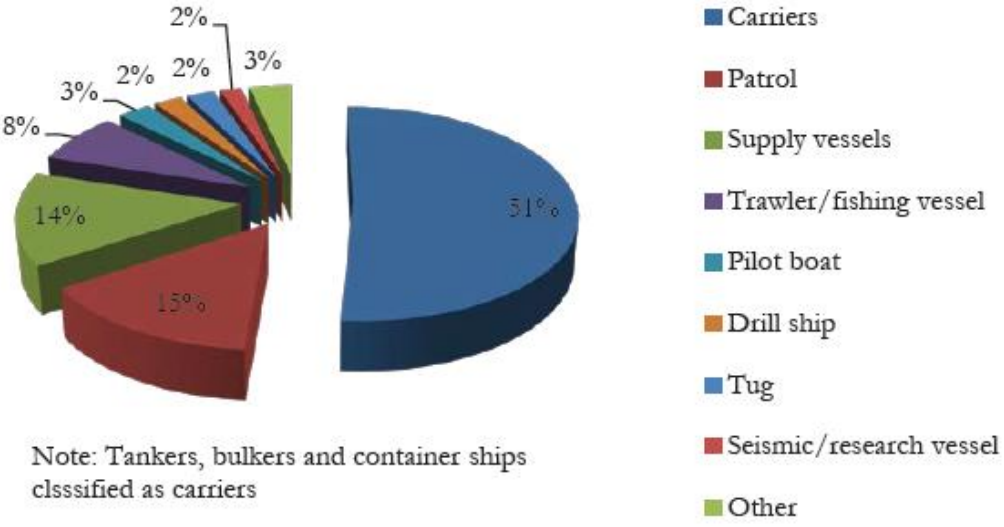


Figure 9 – Share of various types of vessels with SCR [17]

Selective Catalyst Reduction (SCR) general description

SCR is a method that reduces NO_x in the exhaust gas into two harmless, natural components - pure nitrogen (N2) and water vapor (H2O) [18]. This is done by adding a reducing agent like urea or ammonia to the exhaust gas flow. The exhaust gas and ammonia mixes to a more uniform gas and passes through the channels of the SCR catalyst where NO_x is neutralized by a chemical reaction between the two components.

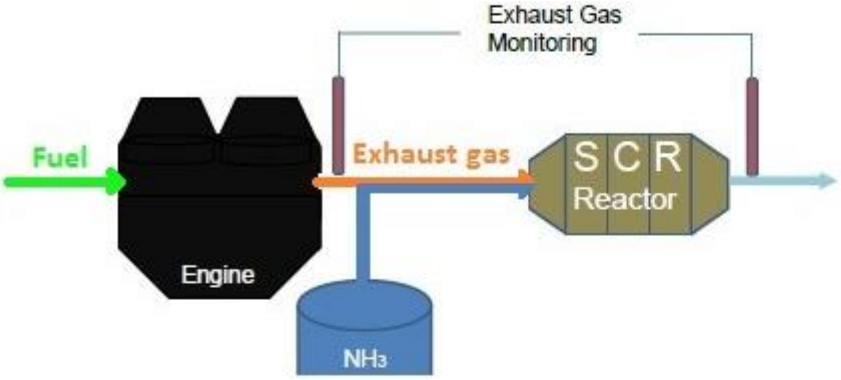


Figure 10 - Schematic of an engine/SCR system [1]

When the combustion products of a ships engine exit the chambers, the content of the hot exhaust gas includes NO_x, SO_x and particulate matter. The concentrations of these and other gases can be predicted, knowing the fuel and engine conditions, or determined more accurately via monitoring. The difference between the actual NO_x concentration and the desired limit determines the amount of reducing agent needed.

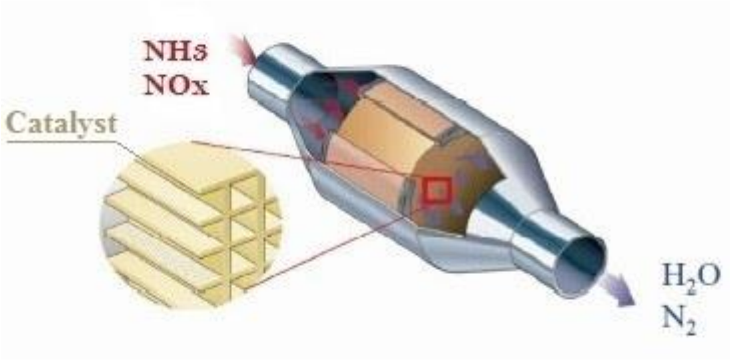


Figure 11 - Schematic of a SCR reactor with the catalyst exposed [19]

A catalyst is a component that increases the rate of a chemical reaction while not consuming the catalyst itself in the process. In a SCR system, the catalyst is located inside the SCR reactor where the NO_x reduction reaction takes place. Funneling the mixed gas flow through the catalysts channels allows for a larger contact area, exposing more of the mixed gas to the catalytic component, and increasing the efficiency of the reaction [18].

Reducing agents

Ammonia is the main reactant of the SCR system. It is a colorless gas with a characteristic, pungent, choking odor. Ammonia is about half as dense as air and is exceedingly soluble in water. As an example, one volume of water will dissolve 1000 volumes of ammonia gas at Standard Temperature and Pressure. Ammonia boils at -33.4°C and freezes at -77.7°C. Ammonia’s impacts and characteristics will be discussed later in this thesis [20].

There are two forms of ammonia used in SCR systems:

(1) anhydrous ammonia, gaseous or liquid

(2) aqueous ammonia

(3) aqueous urea, e.g. AdBlue

The word "anhydrous" is used for ammonia in its pure form, e.g. without water. Pure ammonia can appear in both liquid or gaseous form. Anhydrous ammonia is highly toxic, hazardous, and requires thick-shell, pressurized storage tanks and piping due to its high vapor pressure. Aqueous ammonia, e.g. ammonia with added water or diluted in water, $NH_3 \cdot H_2O$, is less hazardous and easier to handle.

Urea is another ammonia based reductant, and the most common reducing agent of all ammonia based SCR-systems nowadays. Urea, H_2N-CO-NH_2, is a solid compound made of ammonia and carbon dioxide, which is further diluted in water to achieve aqueous state for usage simplicity, H_2N-CO-NH_2 + H_2O. It has many other commercial applications, for example fertilizer [21].

There is a reason why urea and aqueous ammonia are preferred above anhydrous ammonia – the latter one is extremely toxic and difficult to safely store and transport. It is volatile and poisonous for human health, but needs no further conversion to operate within a SCR system, and supposedly give excellent SCR-performance of up to 100% reduction with a set of additional advantages as well. It is the most cost effective and efficient reagent because no additional equipment is required to convert it for use. Less volume of the reagent is needed due to its pure state. Anhydrous ammonia is stored under pressure (5-10 bar) or stored at atmospheric pressure if kept t -33°C [21].

Aqueous ammonia and urea must be vaporized in order to be used, but it substantially safer to store and transport than anhydrous ammonia. For example, a typical industrial grade ammonia, containing about 27% ammonia and 73% water by weight, has nearly atmospheric vapor pressure at normal temperatures and can be safely transported [22]. While being safer, they both require conversion to ammonia through thermal decomposition in order to operate as an effective reductant.

SCR-reactions

In the SCR catalyst, NO and NO_2 react selectively with NH_3 as reducing agent. The overall reactions taking place in the reactor are the adsorption-desorption equilibrium of ammonia and the reactions between NH_3 and the NO_3 species, expressed in equation (2.1) - (2.4), where NH_3^* designates the ammonia adsorbed on a catalytic site [23]. Equations (2.1) - (2.4) represent desirable reactions which reduce NO_x to elemental nitrogen in the SCR-reactor.

$$NH_3 \leftrightarrow NH_3^* \qquad (2.1)$$

$$4NO + 4NH_3^* + O_2 \rightarrow 4N_2 + 6H_2O \qquad (2.2)$$

$$3NO_2 + 4NH_3^* \rightarrow 3.5N_2 + 3H_2O \qquad (2.3)$$

$$NO + NO_2 + 2NH_3^* \rightarrow 2N_2 + 3H_2O \qquad (2.4)$$

The reaction in equation (2.2) is called the standard SCR reaction which represents the dominant reaction mechanism; the reaction in equation (2.3) is the slow SCR reaction, and the reaction in equation (2.4) is referred to as the fast SCR reaction. The standard SCR reaction occurs at temperatures above 200°C, however, the reaction rate is significantly faster for higher temperatures [24].

The fast SCR reaction is favored by an equimolar mixture of NO and NO_2, and the reaction occurs at temperatures as low as 140-170 ◦C [24]. Thus, the effect of NO_2 in the exhaust gas has higher significance at low temperatures due to the low reaction rate of the standard SCR reaction at low temperatures. According to [25] and [24] the NO comprise above 90% of the NO_x in the exhaust gas, and therefore, actions have to be taken if the optimal 1:1 NO:NO_2 ratio is desired, favoring the fast SCR reaction. Thus, one way to improve the reaction rate at low temperatures is by increasing the amount of NO_2 in the exhaust gas. This can be done by the use of an oxidation catalyst placed upstream the SCR catalyst. Furthermore, the oxidation of NO to NO_2 has been reported to occur over iron exchanged zeolites following the reaction given in equation (2.5) [26].

$$2NO + O_2 \rightarrow 2NO_2 \qquad (2.5)$$

The slow SCR reaction occurs at temperatures above 275°C if excess NO_2 is present [24].

All the reactions presented above are the same for all ammonia containing reducing agents.

Besides the reduction reactions, there can be several unwanted side reactions occurring which are presented in Attachment 1. Some of them are discussed later in Part II.

Catalyst types and materials

The two most common catalyst designs for SCR are honeycomb and plate. Both designs are named after their structure as displayed in Figure 12 - Catalyst structures.

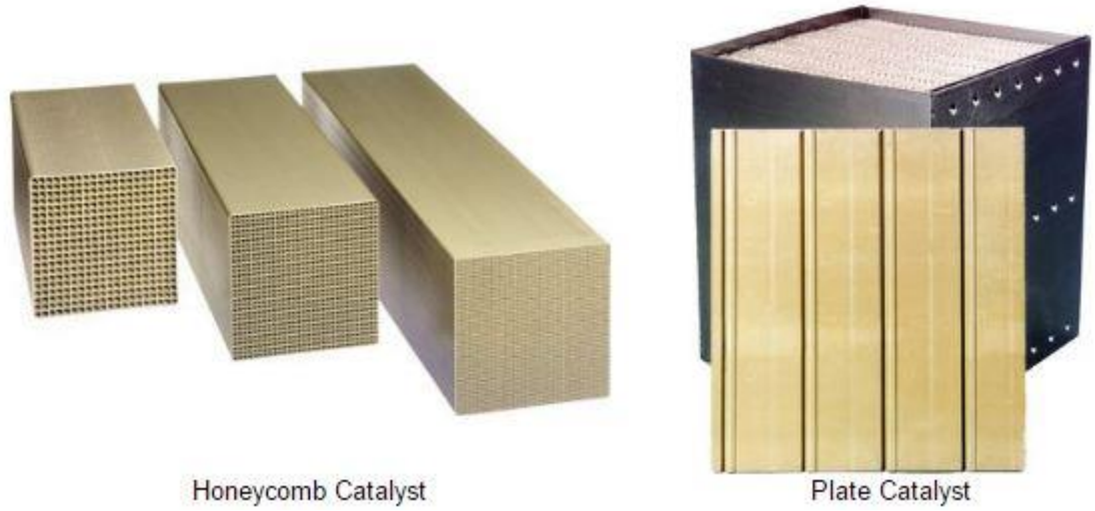


Figure 12 - Catalyst structures - [27]

Honeycomb catalysts are better suited for mobile applications due to their compact design, and offer the benefit of a larger surface area compared to plate catalysts. The compact design however results in a higher pressure drop across the catalyst layers [27].

Another consideration when choosing catalyst type is materials. Catalyst materials may vary depending on the desired performance. Various materials react differently to temperature and fuels, so choosing the right type of catalyst is crucial for an optimal SCR reaction. For marine SCR the honeycomb is typically composed of a ceramic material as a carrier, mixed with an active catalytic component. Base metals such as vanadium, molybdenum and tungsten are often used. Even though these materials lack thermal durability, they are capable of handling the temperature ranges for marine SCR, in addition to being less expensive than the high thermal durability materials such as zeolites. This type of honeycomb is called "Homogenously Extruded". The alternative, although less common today, is a "coated" version, where the honeycomb is dipped in a liquid, active catalytic component. The honeycomb is then dried and calcined [28].

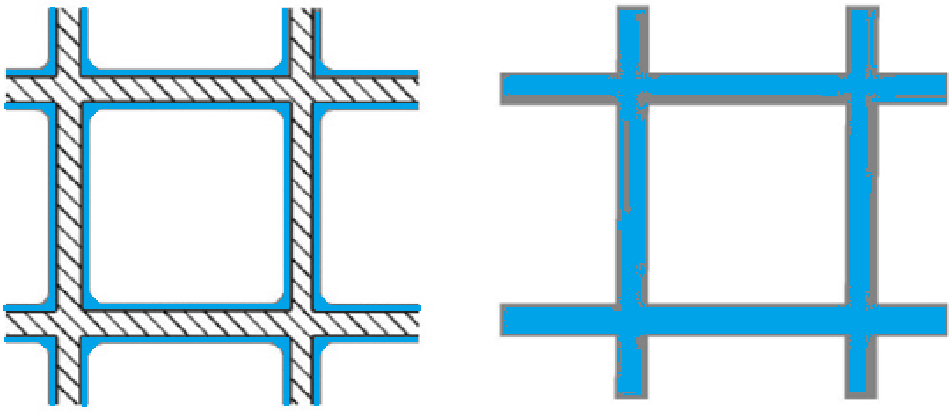


Figure 13 – Catalyst formulation: a) Wash-coated Honeycomb and b) Homogenously Extruded Honeycomb

As displayed in Figure 13 – Catalyst formulation: a) Wash-coated Honeycomb and b) Homogenously Extruded Honeycomb, the coated honeycomb has a slightly smaller surface area due to the coating occupying space in the canals. In terms of "active material per volume", it is less effective than its counterpart, meaning it has to be larger to maintain the same rate of NO_x conversion as the Homogenously Extruded version [29].

Marine SCR

Installing or retro-fitting a ship with SCR technology is a rather expensive investment. In addition to the cost itself the system also requires a sizable SCR, a premixing system, an injection system, and a storage unit for the reagent. Further considerations are the size of the system, setup depending on engine type and whether to use urea, anhydrous ammonia or gaseous ammonia as reducing agent.

The obvious difference for marine applications are the huge engines compared to automobiles. Slower, more energy efficient engines with lower combustion temperatures that directly affect the exhaust gas temperature. This is the main problem with marine applications which represents a challenge for an efficient SCR reaction to take place. In addition, the fuels used for marine engines contain sulphur which can contaminate the catalyst. These differences pose additional challenges. The technology cannot simply be copied from automobiles to marine vessels. Further complications are space and weight. Due to the share mass of marine engines the SCR systems has to be scaled to match and handle the exhaust output [30]

By operating type criteria, all ship engines are divided into 2-stroke and 4-stroke, which are further allocated into the general engine types: slow speed, medium speed and high speed engines. The following table shows the engine classifications based on information from MAN Diesel (pers. comm., Flemming Bak, 2009) and Winther (2008). Fuel types used for a specific engine category and average life time is given in Table 2 - Estimated main engine type and fuel type for ship engines in the present inventory [32, pp. 86-111] [31].

Engine type	Engine size [kW]	Engine type	Fuel type	Engine life time [years]
4-stroke	≤ 1000	High-speed	Diesel	10
	1000 - 4000	Medium-speed	Diesel	30
	≥ 4000	Medium-speed	HFO	30
2-stroke		Low-speed	HFO	30

Table 2 - Estimated main engine type and fuel type for ship engines in the present inventory [31] [32, pp. 86-111]

The average Specific Fuel Consumption (SFC) factors for slow-, medium- and high-speed engines, as a function of engine production year are shown in Figure 14 - Average sfc factors for marine engines for the inventory years 2000-2020 (g/kWh) (Danish Environmental Protection Agency, 2009), for the inventory years 2000-2020. All fuel consumption data are based on the engine specific fuel consumption data from several engine manufacturers (pers. comm. Hans Otto Kristensen, DTU, 2009).

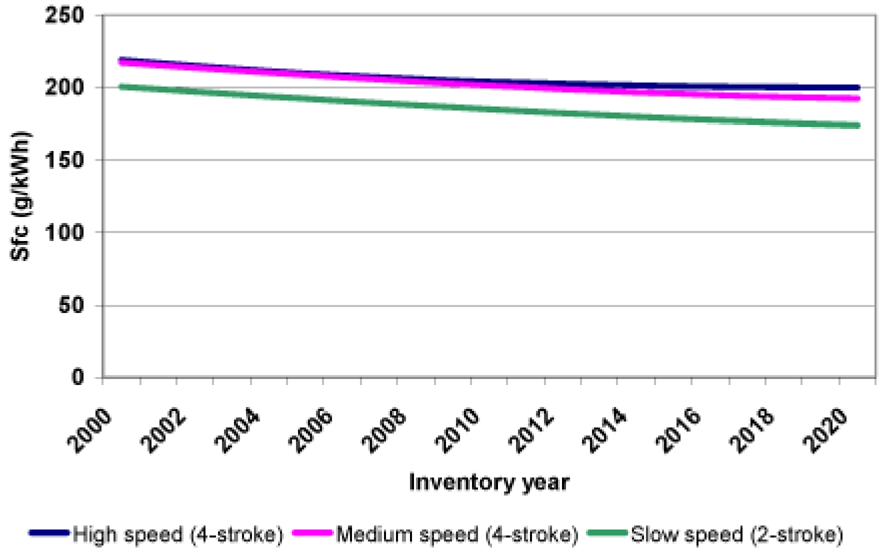


Figure 14 - Average sfc factors for marine engines for the inventory years 2000-2020 (g/kWh) (Danish Environmental Protection Agency, 2009)

The estimated emission factors for the engine production years 2006-2020 are shown in Figure 15 - NOx emission factors for ship engines built from 2006 onwards (g/kWh).

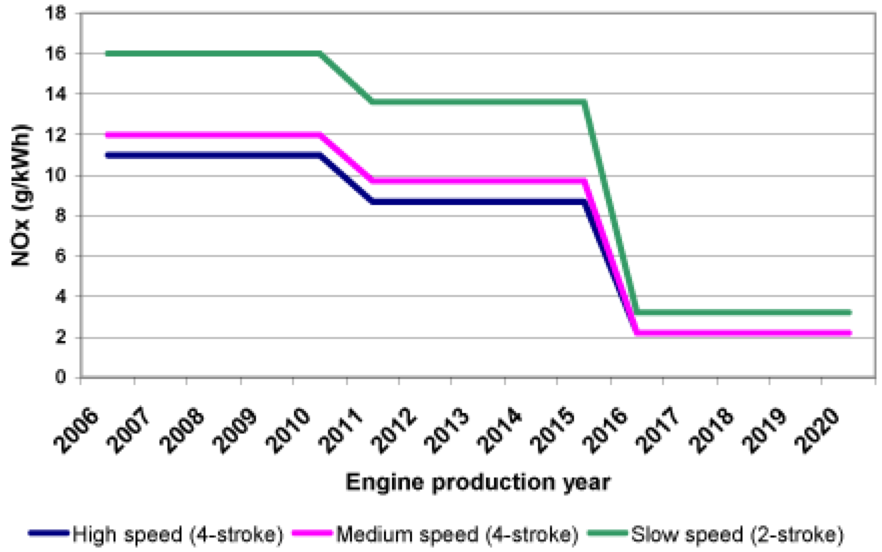


Figure 15 - NOx emission factors for ship engines built from 2006 onwards (g/kWh) [31]

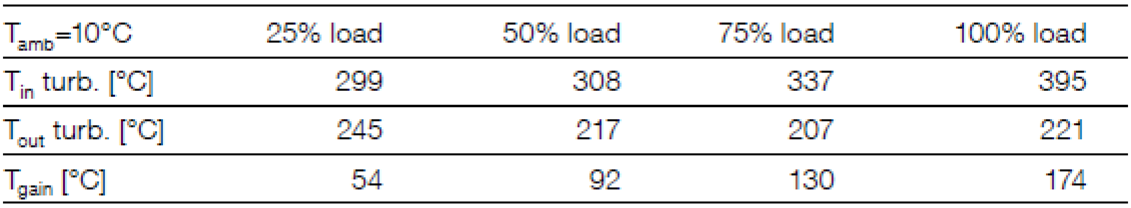
One advantage of using pure ammonia as a reducing agent is the reduced fuel consumption. The NO_x reaction itself becomes more effective which directly affects the fuel consumption. Generally, consumption and emission factors in g/kWh are directly proportional and dependent on engine type, fuel type and engine production year.

For engines, the residence time of the combustion and the high temperatures is what determine the amount of NO_x produced. These factors vary depending on engine size, type and load, which again affects the exhaust gas temperature. This is the main factor for a successful NO_x reduction process. The exhaust gas temperature has to be sufficient at the catalyst inlet for an effective reaction to occur. In the case of larger engines, like high energy efficient 2-stroke engines, the exhaust gas temperature after the turbocharger is often too low to support trouble free SCR, (230-260°C).

These problems can however be worked around with clever engineering. The exhaust gas temperature should ideally be around 330-350°C at the SCR inlet when the engine is operated on HFO and using urea as reducing agent. This can be done by using a burner to heat the exhaust gas or by placing the SCR on the high pressure side of the turbine. Temperatures can then be increased by 50 to 175° C depending on the engine load.

These actions might not be necessary when using pure ammonia, either in gas or liquid form, as it allows NO_x reduction at lower temperatures. Exactly which temperatures apply for pure ammonia-SCR is the matter of investigations in the experimental part of this thesis. Despite this, the solution of placing the SCR on the high pressure side of the turbocharger is discussed further.

Table 3 - Temperatures before and after the turbine based on MAN B&W's, 6S50ME-C engine . reveals that even though the SCR-reactor is placed in front of the turbine, the exhaust gas temperature is still too low at loads below approximately 50%.



T_{amb}=10°C	25% load	50% load	75% load	100% load
T_{in} turb. [°C]	299	308	337	395
T_{out} turb. [°C]	245	217	207	221
T_{gain} [°C]	54	92	130	174

Table 3 - Temperatures before and after the turbine based on MAN B&W's, 6S50ME-C engine [33].

A suitable solution for the problem is to introduce a "low load method" which can be done by installing a cylinder bypass valve. The valve will be able to bypass some of the intake air directly to the turbo charger, thus reducing the mass of air through the cylinders which will further increase the exhaust gas temperature.

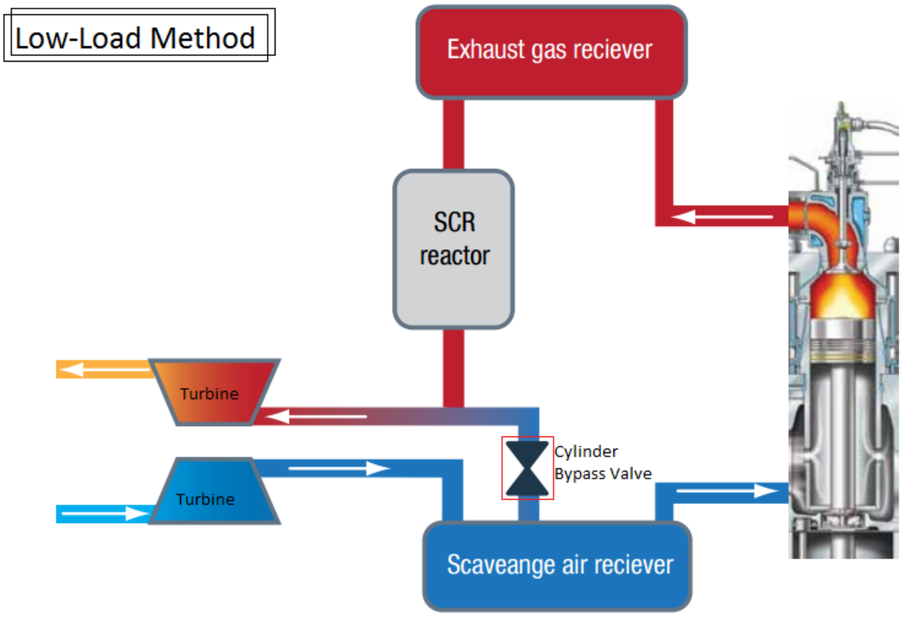


Figure 16 - Low-load method to increase exhaust gas temperatures [33]

Placing the SCR before the turbine has its downsides as well. The energy balance between the engine and the turbocharger is directly affected. To ensure sufficient energy to the turbine, some of the exhaust gas must be bypassed directly to the turbocharger during engine start-up and acceleration. This also means that it might be necessary to bypass the turbine during de-acceleration of the engine, as the energy level of the exhaust gas form the SCR is too high.

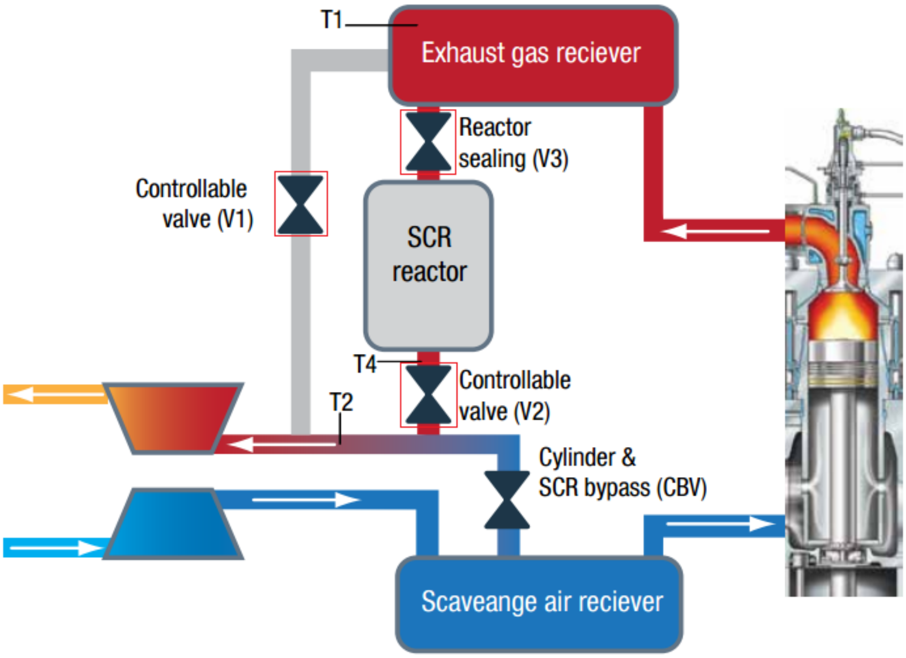


Figure 17 - Overview of bypass valves [33]

While meeting the Tier III restrictions are possible for the marine industry today, the technology can still be matured. From the above example the SCR system is quite advanced. The number of components and programming needed to make it work could just as well be the weak point of the system. Furthermore, at engine loads below 50%, the system allows for a complete bypass of the exhaust gas during de-accelerating, defeating the purpose of the system all together [33].

Challenges with SCR operations at low temperatures

Below are some of the known challenges with SCR at low temperatures:

1) Fuels with a high sulphur content may cause ammonium sulphate formation. NH_3 combines with SO_3 to form $(NH_4)_2SO_4$ and NH_4HSO_4, Equation (1) and (2), which deposit on and foul the catalyst, piping and equipment. At low exhaust temperatures, generally below 250°C, the fouling by ammonium sulphate may lead to a deactivation of the SCR catalyst.

   (1) $NH_3 + SO_3 + H_2O \rightarrow NH_4HSO_4$

   (2) $2NH_3 + SO_3 + H_2O \rightarrow (NH_4)_2SO_4$

Illustrated in the graph below are the minimum temperatures required to prevent ammonia sulphate formation in relation to the sulphur content in fuels.

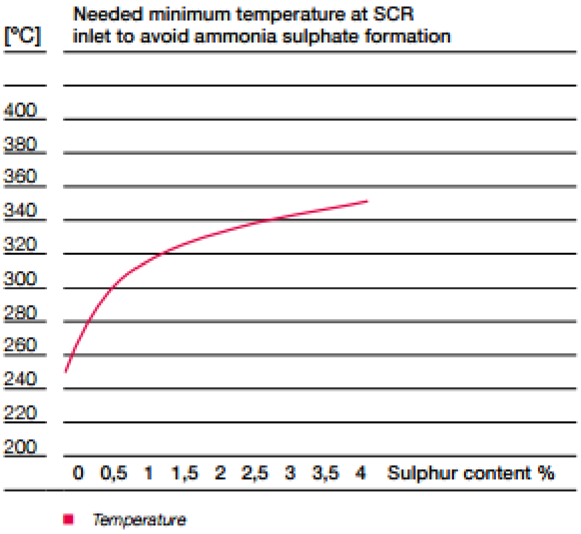
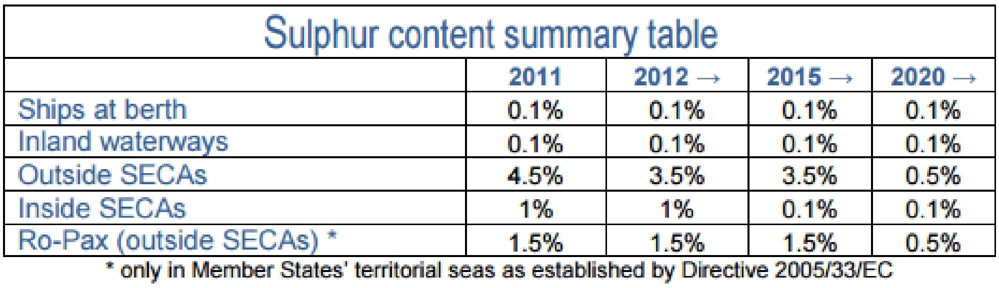


Figure 18 - Generic representation of minimum temperature needed to avoid ammonia sulphate formation [34]

This can be seen as a conservative depiction as actual critical conditions are system dependent.

The limits for sulphur content in marine fuels are designated by IMO as follows [34], where values for 2020 are under review:



Sulphur content summary table				
	2011	2012 →	2015 →	2020 →
Ships at berth	0.1%	0.1%	0.1%	0.1%
Inland waterways	0.1%	0.1%	0.1%	0.1%
Outside SECAs	4.5%	3.5%	3.5%	0.5%
Inside SECAs	1%	1%	0.1%	0.1%
Ro-Pax (outside SECAs) *	1.5%	1.5%	1.5%	0.5%

* only in Member States' territorial seas as established by Directive 2005/33/EC

Table 4 - Sulphur content limits in marine fuels [34]

2) Ammonia can also react with NO_2 producing explosive ammonium nitrate (NH_4NO_3), Equation (3). This reaction, due to its negative temperature coefficient, occurs at low temperatures, below about 100-200°C. Ammonium nitrate may deposit in solid or liquid form in the pores of the catalyst, leading to its temporary deactivation [35].

   $$(3)\ 2NH_3 + 2NO_2 + H_2O \rightarrow NH_4NO_3 + NH_4NO_2$$

   Ammonium nitrate formation can be avoided by making sure that the temperature never falls below 200°C. The tendency of NH_4NO_3 formation can also be minimized by supplying less than the precise amount of NH_3 necessary for the stoichiometric reaction with NO_x (1 to 1 mole ratio) into the gas stream.

3) Normally, NO_2 concentrations in most flue gases, including diesel exhaust, are low. In some diesel SCR systems, NO_2 levels are purposely increased to enhance NO_x conversion at low temperatures. In case the NO_2 content has been increased to exceed the NO level in the feed gas, N_2O formation pathways are also possible, as shown in Equation (4) and (5) [35].

   $$(4)\ 8NO_2 + 6NH_3 \rightarrow 7N_2O + 9H_2O$$

   $$(5)\ 4O_2 + 4NH_3 + O_2 \rightarrow 4N_2O + 6H_2O$$

Commercial use of ammonia-SCR

As mentioned earlier, pure ammonia as a reducing agent have been met with skepticism, HSE concerns and in some areas banned by local authorities. Yet, at least 2 enterprises have commercialized ammonia SCR technology still – The Danish company Amminex for automotive applications, and the Norwegian company MECMAR for marine applications.

Amminex

Amminex AS is a pioneer company to implement pure ammonia SCR in vehicles. They have recently come up with a new emission technology called ASDS (Ammonia Storage and Delivery System), which sets a new industry benchmark by enabling significantly higher NO_x

reduction rates for busses, trucks and passenger cars than any other known technology. Amminex ASDS technology first became commercialized with the Copenhagen ASDS™ buss-retrofit project started in June 2015.

The reductant used in ASDS is pure ammonia which is bound in a solid material named AdAmmine. It allows for safe storing and transportation of ammonia in big quantities and at high density. The carrier material is a salt, originally magnesium chloride (SrCl2), depicted below [36]. A block of AdAmmine holds approximately 450 g ammonia per liter solid AdAmmine [37]. When bounded in soled, ammonia is safely stored and storage is of compact size.

Figure 19 - AdAmmine cubes [36]

The AdAmmine cubes are delivered in a cartridge system, combined with a unit for dosing and a controlling unit for operating the system. The AdAmmine gradually releases ammonia while heated. ASDS one- and two-cartridge systems are presented in Figure 20 - ASDS one- and two-cartridge systems

Figure 20 - ASDS one- and two-cartridge systems [36]

Advantages of Amminex ASDS technology are:

- Each AdAmmine cartridge can be refilled hundreds of times and is 100% recyclable
- Safe to transport: AdAmmine cartridges are classified as non-hazardous goods by UN

- No expiration date
- Easy to handle: the cartridges can easily be exchanges or refilled – just like a propane bottle
- Reliable system: deposit problems in liquid systems are eliminated
- Reduced operating-cost, down-time and maintenance
- Fuel efficiency can be increased by up to 4%
- Short mixing line, hence exhaust line pressure drop is low
- Additionally, EGR and thermal management can be avoided, with the result of less complex engine architecture
- ASDS enables effective NO_x conversion even at low exhaust temperatures. It is fully effective for cold climate operation and start-up. According to Amminex, the use of gas eliminates the risk of freezing.

The Amminex system offers direct and accurate dosing of pure ammonia gas directly into the SCR catalyst with no risk of deposits or corrosion in the exhaust line. It is a robust system with a simple exhaust interface which eliminates the use of expensive injectors.

Amminex has successfully retrofitted its ASDS™ solution on 300 buses operating in Copenhagen. Online emissions data transmitted from the buses show NO_x conversion of 95 - 99% [38]. ASDS is fully compliable with not only Euro VI legislation [36].

Amminex confirms the efficiency of pure ammonia reduction and takes SCR development to the next stage. Replication of identical systems on a bigger scale, by applying it to the marine sector is theoretically possible, but practically not favorable, because of the weight and space occupation issues of AdAmmine. Ammonia in liquid or gas form will retain all the listed advantages, but new HSE measures would have to be considered for AdAmmine.

Mecmar

Mecmar AS is a Norwegian company, offering the Marine market complete exhaust gas systems for mainly speed boats, yachts and military ships. Here, the focus lies on light, compact and environmental friendly exhaust gas system designs.

The Mecmar Exhaust System solutions incorporate the following options:

- Standard Sea Water Injection.
- Integrated Selective Catalytic Reduction with the standard system.
- Integrated Exhaust Gas Economizers with either or both the previous two options.

According to Bergens Tidene from 02nd of march 2011, Mecmar's system is able to take away about 80 percent of the NOx gases using seawater and urea as reducing agent in SCR-unit [39]. But as MECMAR's strategy of keeping the status of "pioneering company" make them to constantly seek new ways of improving the benefits of the proven systems of Water Injection and SCR, the anhydrous ammonia as reducing agent for marine SCR systems became an optional and truly advised choice.

By using ammonia, facilities can be built smaller and boats become lighter, entailing following benefits as even lower NO_x emissions, lower fuel consumption and lower consumption of reducing agent. For shipping companies, there is much to save. In addition, such a system makes ships compliable with the strictest Tier III of 2016 [40].

It took, however, several years of negotiation with local authorities about allowing ammonia storage aboard ships, before SCR technology with ammonia as reducing agent have got commercialized.

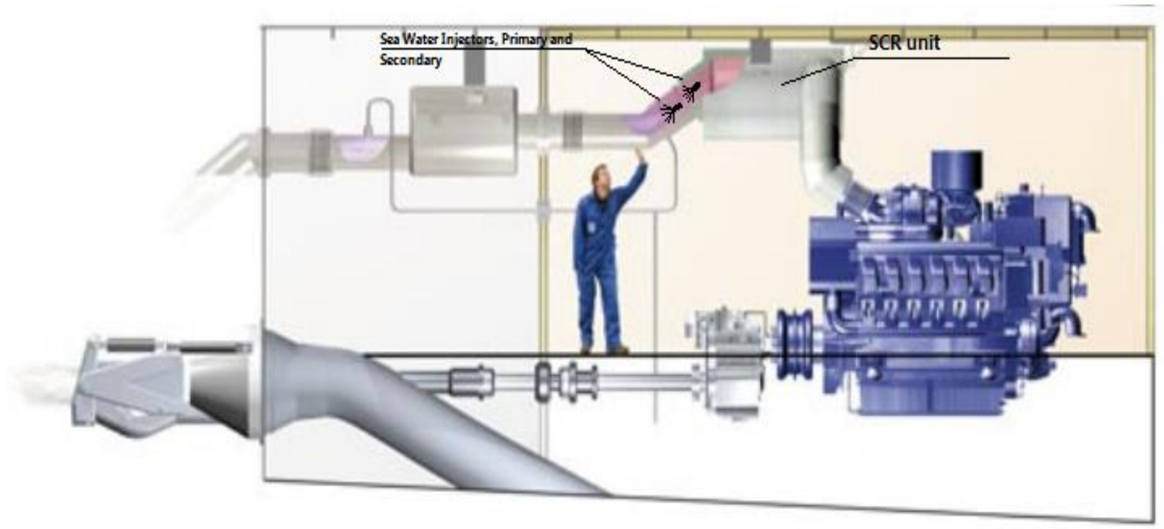


Figure 21 - Marine Diesel Engine Installation [40]

Due to this master thesis, Mecmar has shared one example of reconstructing Exhaust Gas System to SCR system with ammonia as reducing medium and Sea Water Injection in exhaust stream. The purpose of reconstruction is reducing NOx emissions from 9.8 g / kWh (IMO Tier I) to 2,0g / kWh (IMO Tier III). For a particular installation, 220 liters ammonia needed for two engines each of 2.4 MW, 10 hours running at 90 percent engine load. The specific consumption of ammonia needed is 0.00293 kg / kWh. The lowest temperature for full SCR performance using ammonia for marine applications is 280 ° C. According to Mecmar, such SCR system can be used for all engine sizes.

As a result of such Exhaust Gas System manipulation, the weight of the existing Exhaust System is reduced from 3290 kg to 2720 kg. Mecmar are also practicing partial substituting stainless steel titanium.

<u>Other enterprises</u>

In addition to *Mecmar* and *Amminex*, several other companies were contacted to gather facts about today's market solutions for SCR.

Due to the uncertain nature of several sources of information, *MAN Diesel & Turbo Norge AS* was contacted to verify actual NO_x rates for urea, and regulations for 2016.

The *NOx fund* and *Sjøfartsdirektoratet* were contacted for an up to date statistics of ships having a SCR system installed.

IACCSEA was contacted for the same reasons mentioned above, only on a global scale.

Contacted *Yara* to better understand the difference between stationary and mobile solutions and verify actual NO_x rates for NOxCare 40.

Contacted *Cummings Emission Solutions* regarding the challenges with urea dosing and what factors to consider when dosing.

Unfortunately, not all of the companies were willing to share specific information.

Part III. Urea VS Ammonia

It is convenient to know the difference between reagents used in marine SCR and automotive SCR, as well as the differences between the reagents themselves.

For the automotive market a typical urea solution of a 32,5% is used, referred to as AdBlue or AUS-32,5%. For the marine industry the optimal ammonia content in reducing agent is about 40%, referred to as NOxCare 40% [22]. The 32,5% solution can still be used for marine applications, though it is less effective.

The advantage of AdBlue is its low freezing point at -11°C, while the marine solution has a freezing point of 0°C. However, on board a vessel the storage unit for urea is usually located inside the ships atmosphere, in an environment never exposed to temperatures below 0°C. Thus a 40% solution yields better economy for vessels because it allows for more reagent and less water to be stored [22].

Advantages and disadvantages

Urea advantages [41]:

- Urea is stable, non-volatile, non-explosive and non-flammable which makes it less hazardous then pure ammonia.
- As a result, it poses less risk on the workplace and doesn't require special training like ammonia.
- Urea can be safely stored, transported and handled without the need for specific training.

Urea disadvantages [41]:

- Urea is less effective than ammonia as the urea need to be converted to ammonia prior to the NO_x reduction process.
- There is an increased probability of fouling and corrosion in equipment downstream of the injection point
- Urea can lead to additional nitrous monoxide or carbon monoxide emissions (poisonous gasses).
- The freezing point depends on the concentration: at 40% the freezing point is 0°C, at 32,5% the freezing point is -11°C
- Leakages of urea solution leads to white salt precipitates giving an ageing look to your equipment.
- CO2 emissions as a by-product derived from urea under decomposition process in catalyst.

- If Urea blended with hard water is used for operation, it may cause scaling and clogging of the NO_x reduction system.

Anhydrous ammonia advantages [42]:

- Anhydrous ammonia is the pure state of the reagent, and thus it provides the highest efficiency.
- Has a lower transportation cost due to its concentration and takes up less storage space.
- Reduced likelihood of contamination and corrosion downstream from the injection point.
- Less formation of nitrous monoxide and carbon monoxide.
- Gives higher NOx reduction, hence allow lower fuel consumption.
- The use of gaseous ammonia eliminates the risk of freezing

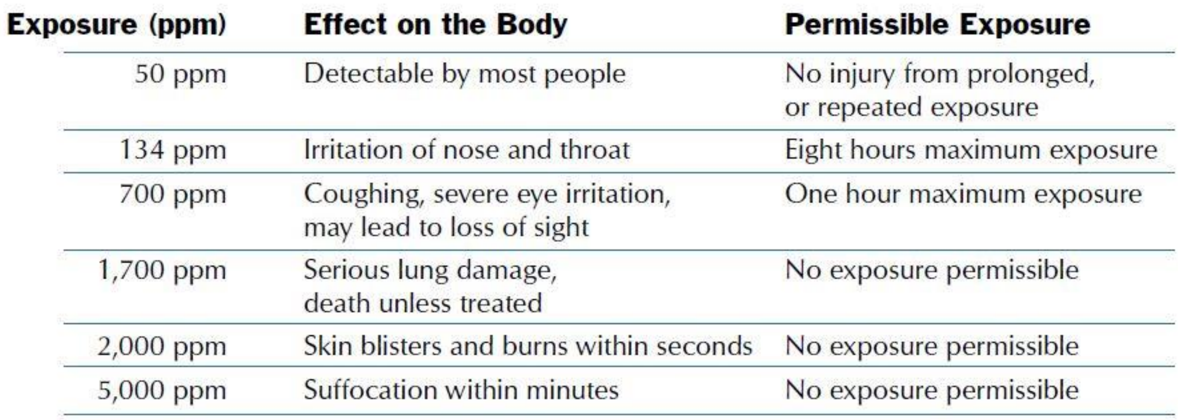
Anhydrous ammonia disadvantages [42]:

- Requires special training to handle properly.
- Hazardous, toxic and requires thick-shell, pressurized storage tanks due to its high vapour pressure.

Safety

Gaseous ammonia: The risks

Ammonia is classified as a hazardous substance. At standard temperature and pressure conditions ammonia will appear as a colourless gas with a very characteristic odor. At concentrations of only 50 ppm the gas is detectable by the human nose, and usually enough to drive people away from an area. At concentrations above 5000 ppm, exposure will disable a person so that escape is impossible and death will follow within minutes [43]. The effects of ammonia exposure can be viewed in Table 5.



Exposure (ppm)	Effect on the Body	Permissible Exposure
50 ppm	Detectable by most people	No injury from prolonged, or repeated exposure
134 ppm	Irritation of nose and throat	Eight hours maximum exposure
700 ppm	Coughing, severe eye irritation, may lead to loss of sight	One hour maximum exposure
1,700 ppm	Serious lung damage, death unless treated	No exposure permissible
2,000 ppm	Skin blisters and burns within seconds	No exposure permissible
5,000 ppm	Suffocation within minutes	No exposure permissible

Table 5 – Exposure level and effects on human body [43]

Most accidents with gaseous ammonia occur due to improper procedures, careless or untrained personnel, or faulty equipment. Protective equipment is required by law wherever pure ammonia is handled, whether in gas or liquid phase.

In order to safely store anhydrous ammonia, the substance must be cooled or compressed to a liquid state to prevent vaporization. Because of the temperature/pressure difference ammonia will cause freeze burns to skin if directly exposed from the tank or even freeze clothing to the body. The caustic nature of the substance will form an alkali if it comes in contact with water, which chemically burns body tissue. This process can only be treated by more water which will dilute the concentration.

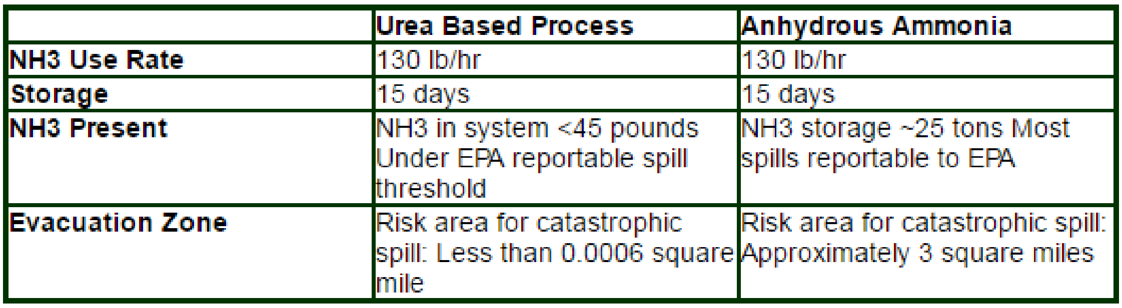
Pure ammonia is typically not considered a flammable substance since the temperature of ignition is 849°C.

Risk Assessment and cost comparison

Both anhydrous ammonia and water based solutions are viable options for SCR, and they both have their advantages and disadvantages. While safety is the main advantage of one, efficiency is the backbone of the other.

For many reasons, safely dealing with pure ammonia is certainly a challenge. The substance has been neglected all along in regard to commercial use, and suffers from not getting the same attention as its counterpart. While scientists have been working on making Urea more effective, they might just as well have been working on making ammonia more safe.

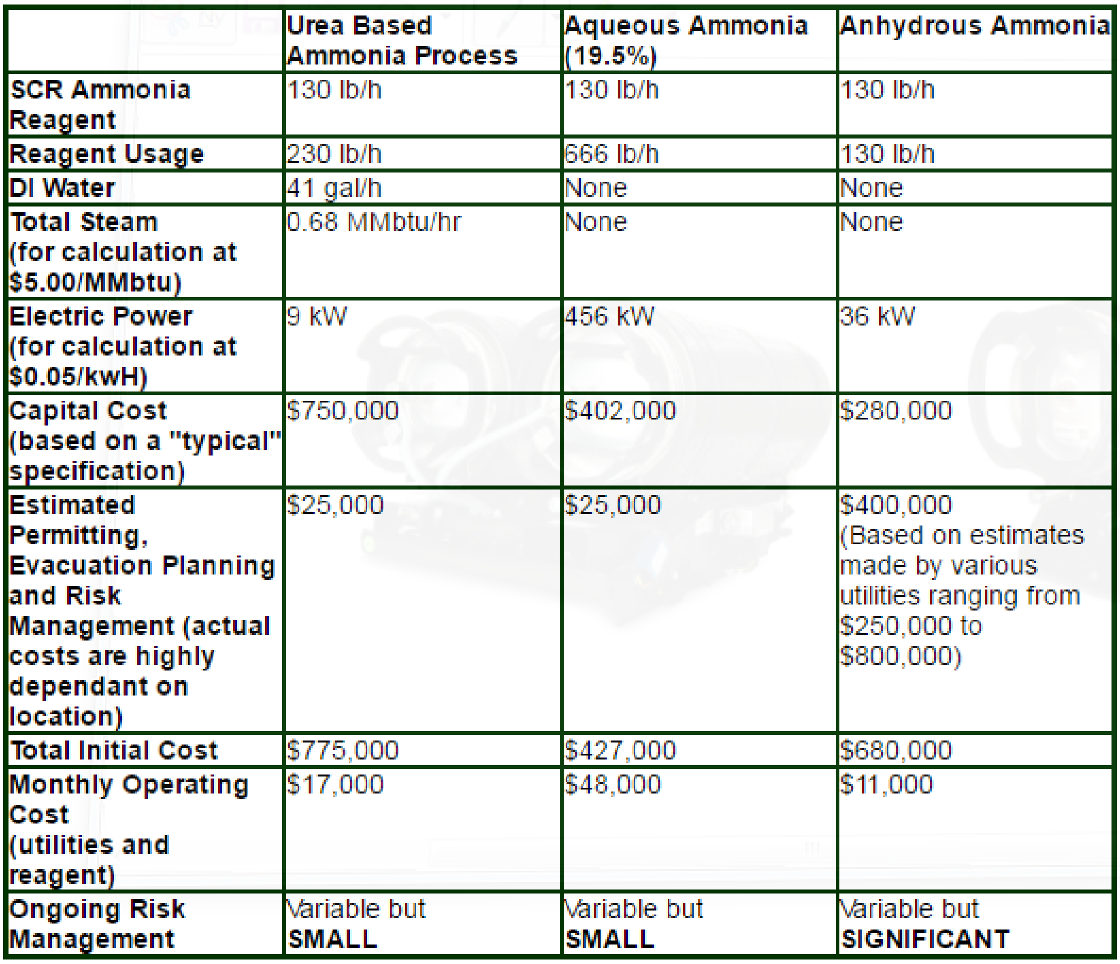
The article “Comparison of Urea-Based Ammonia to Liquid Ammonia Systems for NO_x Reduction Applications” compares the risk image of a typical urea-based ammonia system to an anhydrous ammonia system.



	Urea Based Process	Anhydrous Ammonia
NH3 Use Rate	130 lb/hr	130 lb/hr
Storage	15 days	15 days
NH3 Present	NH3 in system <45 pounds Under EPA reportable spill threshold	NH3 storage ~25 tons Most spills reportable to EPA
Evacuation Zone	Risk area for catastrophic spill: Less than 0.0006 square mile	Risk area for catastrophic spill: Approximately 3 square miles

Table 6 - Risk analysis for urea-based ammonia system to an anhydrous ammonia system [44]

Further considerations are the total cost of a SCR system. The table below compares the cost of a typical urea-based ammonia system to an anhydrous ammonia system for an average SCR application [44]:



	Urea Based Ammonia Process	Aqueous Ammonia (19.5%)	Anhydrous Ammonia
SCR Ammonia Reagent	130 lb/h	130 lb/h	130 lb/h
Reagent Usage	230 lb/h	666 lb/h	130 lb/h
DI Water	41 gal/h	None	None
Total Steam (for calculation at $5.00/MMbtu)	0.68 MMbtu/hr	None	None
Electric Power (for calculation at $0.05/kwH)	9 kW	456 kW	36 kW
Capital Cost (based on a "typical" specification)	$750,000	$402,000	$280,000
Estimated Permitting, Evacuation Planning and Risk Management (actual costs are highly dependant on location)	$25,000	$25,000	$400,000 (Based on estimates made by various utilities ranging from $250,000 to $800,000)
Total Initial Cost	$775,000	$427,000	$680,000
Monthly Operating Cost (utilities and reagent)	$17,000	$48,000	$11,000
Ongoing Risk Management	Variable but **SMALL**	Variable but **SMALL**	Variable but **SIGNIFICANT**

Table 7 - Cost analysis of a typical urea-based ammonia system to an anhydrous ammonia system [44]

From a HSE perspective it becomes clear that anhydrous ammonia is a dangerous substance in most regards. Table 6 reveals that a potential accident involving pure ammonia would in all scenarios be more severe than with Urea.

Cost wise, pure ammonia proves the cheaper option, both in regard to initial cost and monthly operating costs, in addition to being more efficient and convenient for weight purposes.

Comparison is based on Wahlco's typical designs and experience, so comparison preceding in Table 6 - Risk analysis for urea-based ammonia system to an anhydrous ammonia system and Table 7 - Cost analysis of a typical urea-based ammonia system to an anhydrous ammonia system is to be count as fair representative.

Storing and transportation of anhydrous ammonia

Challenges with storing anhydrous ammonia

Currently there are no guidelines for storing large quantities of anhydrous ammonia on ships because it has rarely or never been done before. In agriculture pure ammonia is used as a fertilizer and stored in large tanks. Even here, under stationary conditions, restrictions are strict. To fit a storage system on a vessel would require further safety measures and barriers. A worst case scenario on a ship would most likely result in the demise of the whole crew, while on the mainland, storage areas are usually not occupied by people. Furthermore, they can be avoided or evacuated if necessary.

Considerations for marine applications:

On-shore tanks are usually mounted on a solid foundation. For marine applications a whole new angle has to be approached. How will ammonia behave if stirred by rough seas for hours? How will the tanks hold up? Considering tanks are usually filled to 85% to account for expansion, the shifting weight inside could become a problem. The reagent in its concentrated form would take up less space on a ship, however, the crew would have to be trained in handling, transporting and storing the reagent.

Safety measures for vessels:

- Double pipes, which allows for leakage detection between the pipes rather than direct exposure to the atmosphere
- Safety equipment; gas masks, protective suits, gloves, goggles, rubber boots
- Trained personnel
- Double hulled tanks. Ammonia tank enclosed in a strong outer shell, with absorption material (Amminex) and sensors between the two tanks
- Locate the catalyst closer to the engine or insulate the exhaust piping to the catalyst housing
- Expansion Chambers

Expansion Chambers (for liquid service), Expansion chamber are a necessary component of any liquid ammonia line. Due to ammonia's large coefficient of expansion, any liquid that is trapped in the pipeline could expand rapidly and burst the pipe should the temperature of the room increase. Expansion chambers provide pressure relief to avoid such a leak. They consist of a rupture disc and holder assembly, a pressure switch and an expansion chamber. The rupture disc is designed to burst should the pressure in the pipeline exceed safe limits, and the gas will expand into the expansion chamber, thus relieving the pressure. The pressure switch is for indication that the disc has burst. The volume of the expansion chamber should cover at least 20% of the volume of pipeline it is to protect [45] [43] [46].

Part IV. Experimental

Micro lab

This part of the thesis describes the design, building and testing phases of the miniature version of a marine diesel exhaust gas system with a built in SCR-reactor. The purpose of the system is to replicate a marine SCR process on a smaller scale for easier testing. The SCR-micro system is built in the laboratory facilities of Bergen University College.

Experiments are performed in a micro-scale test system fitted with a commercial, extruded honeycomb monolith. Tests are performed in the temperature ranges of 250-300°C feeding NH_3 and NO in the presence of oxygen in synthetic air. The thermal evolvement of NO and O_2 is continuously monitored by the 2 different emission Gas Analyzers, HORIBA PG-300 and Testo 350. The relationship between temperature and catalyst conversion efficiency is monitored.

Simplified exhaust gas and lab setup

The working medium is an approximation of exhaust gas, containing only NO out of all the diesel exhaust gas components, mixed with synthetic air corresponding to a value of lambda 2.

Simplifications and limitations are listed below:

- Moisture is always present in diesel exhaust and other flue gases. To obtain valid results, water vapour should always be present in laboratory gas tests of SCR processes and in process modelling. In this experiment the system is simplified and runs with dry synthetic air.
- Limited to one catalyst type
- The test results achieved in this report are presentative but cannot be relied upon 100%. The relation between exhaust gas and reduction rates will always differ from an actual process to a laboratory process.
- Several limitations were discovered during the construction of the system, and during testing. These are mentioned in the “Results” section.

Designing the SCR setup

Simulated exhaust gases

When designing the SCR setup several air mixtures were considered. By using a synthetic air mixture of 88% N_2 and 12% O_2 as sweep gas, the concentration would correspond to a Lambda value of 2 which is typical for diesel exhaust. It was decided to exclude all exhaust gas components (CO_2, HC and PM) but NO_x. In addition, NO_2 was eliminated in the exhaust sample because of the originally low concentrations in diesel exhaust. Furthermore, NO_2 can cause additional reactions in a SCR process which make the chemistry more complex, creating several pathways listed in Attachment 1.

Because the highest oven setting in this project is 600°C, NO_2 formation can be excluded as it cannot form at these temperatures.

Since the goal is to link the lab results to marine SCR applications, NO_x ppm values were set for a typical marine diesel engine with the following concentrations:

- Before the SCR-reactor: between 1000 and 1500 ppm NO_x (NO)
- After the SCR-reactor: between 100 and 250 ppm. These are desired values after reduction.

In the experiments, values within a given range of 1000-1500 ppm before the reactor are acceptable.

SCR-system test setup

When composing the bottled air mixture, NO cannot simply be mixed with air due to the formation of NO_2 during the mixing process, according to the gas supplier Yara Praxair AS. A possible solution is to keep the two gases in separate bottles and introduce them in one stream just before the oven.

Another solution is to introduce NO as well as NH_3 into the already hot sweep gas after the oven. However, because of the micro scale, the NO and NH_3 amounts needed are too small for any dosing equipment to pick up. To solve this, NO and NH_3 is diluted with N_2 to create a flowrate sufficient enough to register in a measuring device. The solution causes no unwanted bi-products.

Eventually, a total of 3 different gas compositions are chosen:

1. 88% N_2 and 12% O_2 - 50 liter
2. 3% NO mixed with N_2 - 10 liter
3. 3% NH_3 mixed with N_2 - 10 liter

To view the order confirmation paper please see Attachment 2.

Component placement in the system is illustrated below. Full version can be seen in Attachment 3.

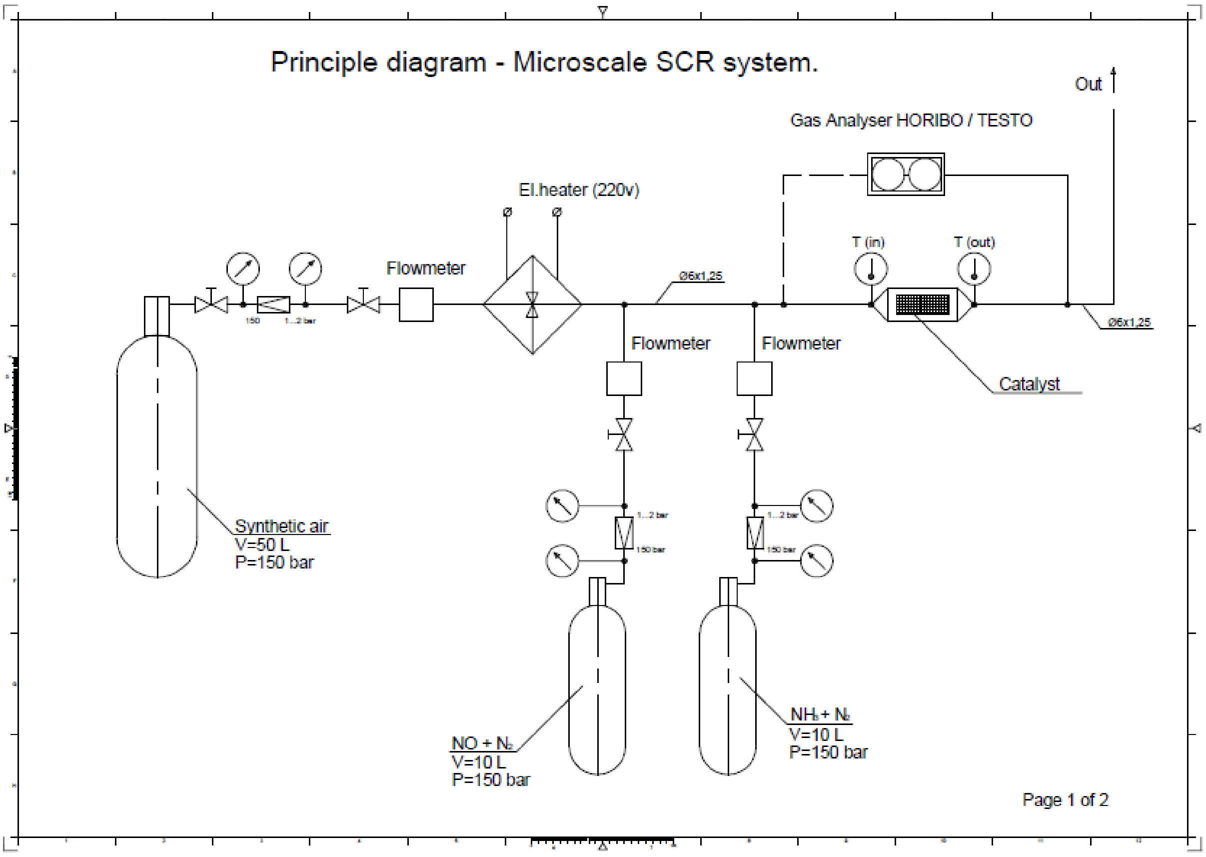


Figure 22 - Principle diagram for Microscale SCR-setup

For preheating the exhaust gas, a spiral tube is placed inside the muffle oven. The spiral length will guarantee the required residence time for an efficient temperature rise in the exhaust gas.

Temperature will be measured right before and after the SCR-reactor.

The thermal evolvement of NO and O_2 throughout the experiments will be continuously monitored by 2 different emission gas analyzers, the HORIBA PG-300 and Testo 350. Only one of the analyzers are in use at any one time. They are first used to adjust NO concentration before the catalyst and then to measure the final gas composition after the SCR-reactor.

NO_x components will be measured in parts per million (ppm). Ppm is a dimensionless quantity, a ratio of 2 quantities of the same unit. One ppm is equal to 1/1000000 of a whole. [47]:

$1ppm = 1/1000000 = 0.000001 = 1\times10^{-6}$.

In percent: $1ppm = 0.0001\%$

Measuring system

For an efficient urea reaction to take place, temperatures are typically between 300-400°C. Ideally a temperature of 350°C is preferred in the reactor as a baseline for all testing with gaseous ammonia as reducing agent. The temperature will gradually be reduced to study the effects on the performance of the catalyst.

There are 3 separate gases participating in the micro-scale SCR tests, flowing into each other. The following criteria must be met for the flows to be approved:

1) The main flow of synthetic air is combined with the NO flow after the heating unit, giving a NO concentration of 1000-1500 ppm.
2) NH_3 is further added to the Air/NO stream in the same amount as the NO flow. The micro scale SCR-system is thus supposed to operate with stoichiometric NH_3/NO_x ratio, which is about 1 for any SCR system: 1 mole NH_3 is needed for each mole NO according to the dominant SCR reaction:

   $$(SCR): \qquad 4\,NO + 4\,NH_3 + \,O_2 \,\rightarrow 4N_2 + 6H_2O$$

   A SCR process requires precise control of the ammonia injection rate. Balanced injection is necessary in order to avoid unacceptably low NO_x conversions if insufficient ammonia is injected. Or the release of undesirable ammonia, so called ammonia slip, to the atmosphere when too much ammonia is added to the process. Laboratory test of the SCR micro-system are planned to operate with excess ammonia rather than a shortage, and does not worry about ammonia slip.

NO/NH_3 compositions combined are supposed to make up about 5% of the total stream each.

A graphical distribution between the gases in the flow is displayed in Figure 23 - Distribution between gases in the SCR-micro scale test system**Feil! Fant ikke referansekilden.**:

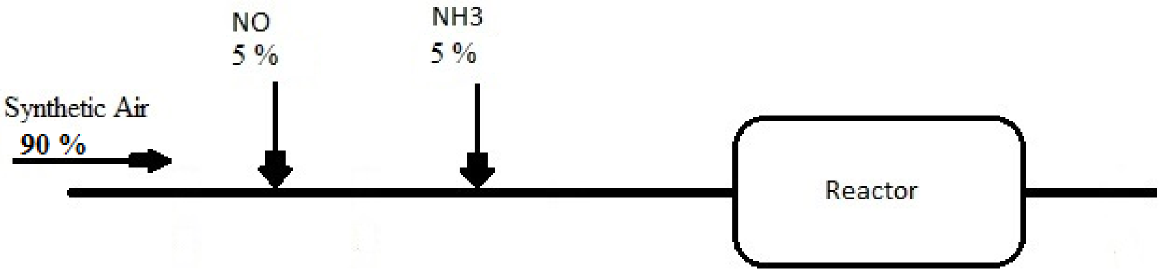


Figure 23 - Distribution between gases in the SCR-micro scale test system

PEMS-Instrumentation

HORIBA

Figure 24 - Portable Gas Analyzer HORIBA [50]

The HORIBA PG-300 is a Portable Stack Gas Analyzer. It can measure up to five separate gas components simultaneously: sulfur dioxide SO_2, carbon monoxide CO, methane CH_4, ozone O_2 and Nitrogen Oxides NO_x in the air. The analyzer is compact and lightweight, with robust side guards to protect the unit from shock and physical damage. It is suitable for long-term measurements in tough environments such as gas turbines, boilers, and incinerator facilities, and is also well suited for study of the catalysts, and control of process gas [48].

The HORIBA PG-300 combines several air pollution monitoring systems, which are based on the cross-flow modulation methods. Cross-flow modulation is an analytical technique which uses the sample gas to be measured for certain components along with a zero gas, identical to the sample gas except that these components have been removed. These gases are alternately introduced to the same measurement cell, and the difference between them is output as an alternating signal. Clean air is fed into the sample cell in between each batch of sample gas so the cell remains clean, which ensure extremely accurate and stable measurement.

Detection methods are:

1) The NO_x analysis unit uses a Cross-flow modulation chemiluminescence detection method;
2) The SO_2, CO, and CH_4 units use a Cross-flow modulation Non-dispersive infrared (NDIR) absorption method;
3) CO_2 unit uses standard Non-dispersive infrared (NDIR) absorption method;
4) The O_2 unit uses zirconia method, galvanic method, and paramagnetic method

The HORIBA PG-300 does not measure NO_2 and NO separately, but NO_x gathered. NO_2 and other nitrogen oxides in the air are converted to NO using a pre-processing device (NO_x converter), and then measured using the CLD method. A method that detects the light given off when NO reacts with O_3 (Ozone). The output of Nitrogen Oxides is displayed as “NO” units by the HORIBA [49].

For information about accuracy, reputability, dimensions, ranges, please see Attachment 4 or literature source [50].

HORIBA requires calibration each time it is started up. Calibration procedure is explained in details in the Introduction to the “Practical Part – NO Reduction Experiments”.

Testo 350

The Testo 350 is a practical, portable, easy-to-use emission analyzer for a variety of applications, including flue gas purification systems.

The Testo 350 contains up to six sensors, which allows for measuring up to six different parameters simultaneously, like O_2, CO, NO_x, NO, NO_2, SO_2, CO_2, C_xH_y and H_2S. Figure 25 - Testo 350 Portable Emission Analyzer illustrates components for the Testo 350.

Figure 25 - Testo 350 Portable Emission Analyzer [51]

The Testo 350 use electrochemical sensors which measure flue gas constituents through the principle of ion selective potentiometry. The sensor contains an electrolytic matrix that is designed for a specific gas to be detected, that's why one sensor for one gas.

Flue gas enters the sensor and chemically reacts (oxidation or reduction) on the electrode releasing electrically charged particles (ions). This reaction generates current which is proportional to the concentration of gas present. The output is converted into the concentration unit, typically ppm or percent. Sensors can be easily swapped-out or changed. Replacement sensors are supplied by Testo, pre-calibrated and ready for installation [51].

In addition to measuring gas, the Testo 350 also perform integrated pressure measurements, ΔP, velocity, flow and mass emissions calculations (with Pitot tube), and is equipped with a continuous temperature compensation system to ensure accuracy. For more information about Testo 350 specifications please see Attachment 5.

Volume flow control

Figure 26 - Sho-Rate™ 1350 flowmeter [52]

3 flowmeters of the type BROOKS GT-1350 are ordered from Process Partner AS for controlling the flow from all three gas sources. The flowmeters are equipped with an optional needle valve which will substitute the injection nozzle and needle valve on the reducers, which are fitted to each of the gas flask.

By operating principle, GT-1350 is a variable area flowmeter or simply a rotameter. A rotameter consists of a tapered tube, typically made of glass with a 'floater', which is pushed up by the drag force of the flow and pulled down by gravity. The position of the floater is a measure of the flowrate, which can be read on a scale.

GT-1350 flowmeters withstand high pressures and corrosive gases. Fitted with Borosilicate glass they are also resistant to thermal shock. [52]

This type of flowmeter provides an accuracy of 5% and a repeatability of 0.25%. For datasheets and technical information please see Attachment 6.

Carbolite Furnace

The heating module used in this project is an electric muffle furnace, equipped with a ceramic fiber chamber and operates within a temperature range of 0 - 600°C.

Figure 27 - Laboratory Carbolite Furnace

The heating chamber is insulated with vacuum-formed low thermal mass insulation to provide maximum energy efficiency.

The furnace has a double skin construction with air convection, which provides a low outer skin temperature. A vertical counterbalanced door mechanism keeps the hot door insulation away from the operator when the door is opened. A safety switch disconnects the power when the door is opened [53].

The control module is situated below the door. Temperature is controlled by an Eurotherm 91 digital controller with full PID action and digital temperature display of both preset and actual values. Temperature is measured by thermocouples of the type K [54].

Temperature indicator

The Fluke 2176A is a portable multipoint digital thermometer with the measurement range from -200°C to +778°C. The Fluke 2176A allows for several temperature sensors to operate simultaneously and independently. The measuring principle is a thermocouple. A thermocouple is comprised of at least two metals joined together to form two junctions. One is connected to the body whose temperature is to be measured; this is the hot or measuring junction. The other junction is connected to a body of known temperature; this is the cold or reference junction. Therefore, the thermocouple measures unknown temperature of the body with reference to the known temperature of the other body.

Figure 28 - FLUK Multipoint Digital Thermometer

Thermometer is powered by either line voltage or an external battery pack. [55]. For other relevant specifications please see Attachment 7.

Main components

Reactor

The micro-reactor is designed specifically for the current SCR system, based on the catalyst dimensions using the following specifications:

- The reactor room is rectangular with dimensions 28x28x55 mm, providing just enough room to fit a catalyst. $L_{reactor} = 55$ mm
- The transition from the stream pipe to the reactor is a divergent duct downstream, and convergent duct upstream. The intersecting duct is square in cross section at the one end and circular at the other end.

The easiest way to produce such a tiny reactor is by milling two identical half-parts:

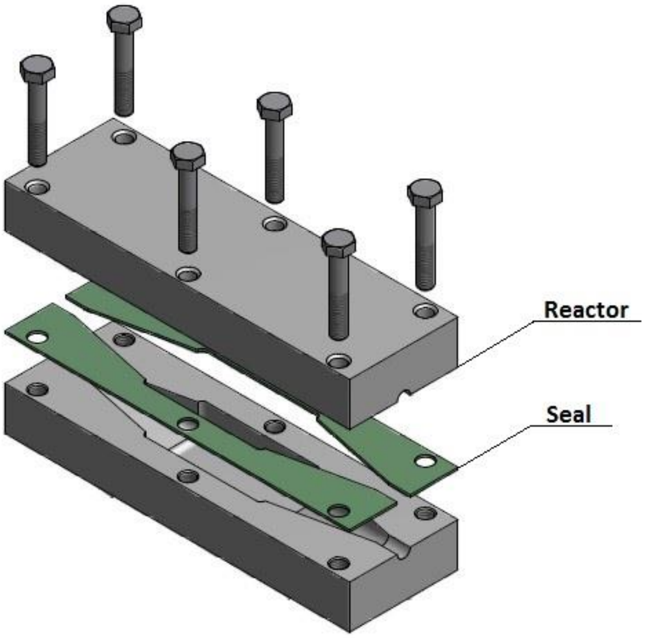


Figure 29 - SCR reactor 3D-model

- The two halves are connected by 6 bolts of the type M6
- The reactor material is Carbon steel
- The seal is visualized as one consistent layer but is in reality made up completely from exhaust paste

3D model of the SCR reactor can be found in Attachment 8.

Optimal nozzle/duct shape

To ensure that the catalyst is at its most efficient, the best possible distribution of flow is desired during expansion of the exhaust gas. The ratio of the inlet cross-section area of the nozzle, to the exit plane area, is mainly what determines how efficient the gas is converted into linear velocity during expansion. The exit angle of the nozzle needs to be as small as possible in order to minimize the chances of separation problems at low exit pressures.

According to Omkar N. Deshpande, Venturi Nozzles show minimum delta pressure at 12 degrees of convergence and achieves its optimality at a low angle of divergence (12 degrees) [56].

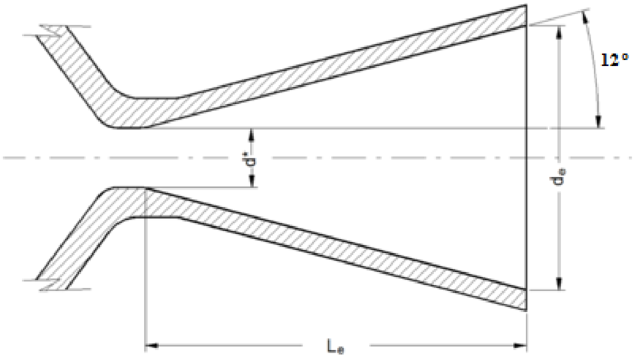


Figure 30 - Duct with the cone shape and half-angle of 12°

The micro-reactor is thus constructed with tilt angles of 12°.

Catalyst

The catalyst used in this experiment is of a similar type as the BASF Catalyst O-4 85 – a typical honeycomb catalyst for marine SCR systems. Other manufacturers are Haldor Topsoe or Ibiden/Ceram.

The catalyst for this project was donated by the German company H+H Umwelt- und Industrietechnik, a leader in Marine Selective Catalytic Reduction (SCR) Technology, which uses a.o. BASF’s catalysts in installations they provide - NOxCare SCR Marine. The catalyst monolith is displayed in Figure 32 - BASF Catalyst O-4 85.

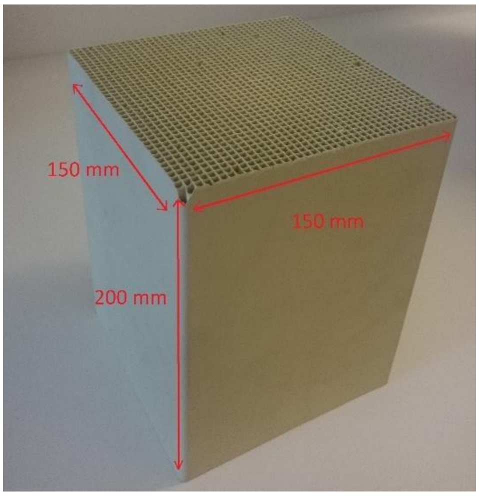


Figure 32 - BASF Catalyst O-4 85

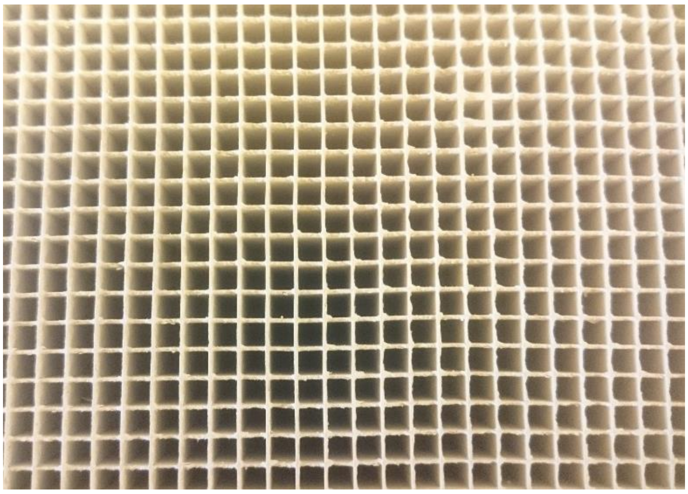
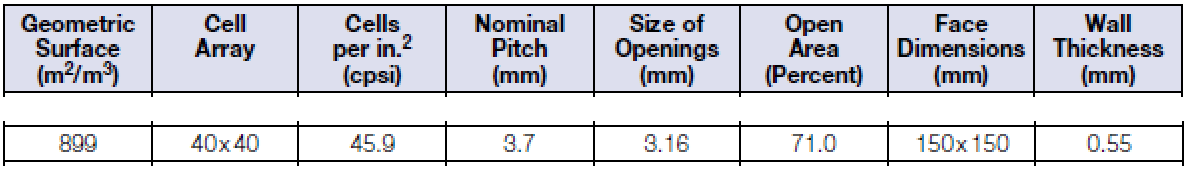


Figure 31 - Honeycomb structure of BASF Catalyst O-4 85

Honeycomb dimension specifications for BASF Catalyst O4-85 are as follows [57]:



Geometric Surface (m^2/m^3)	Cell Array	Cells per in.^{2} (cpsi)	Nominal Pitch (mm)	Size of Openings (mm)	Open Area (Percent)	Face Dimensions (mm)	Wall Thickness (mm)
899	40x40	45.9	3.7	3.16	71.0	150x150	0.55

Table 8 - Technical data for BASF Catalyst O4-85

BASF Catalyst O4-85 is a homogeneous extruded honeycomb catalyst, which is composed of a mixture of several oxides: titanium oxide, tungsten oxide and vanadium pentoxide. The necessary mechanical strength is achieved by adding glass fibers. The concentration of catalytically active Vanadium Oxide (V_2O_5) is variable – it is tailored to the actual flue gas composition and performance requirements for each application. The catalyst used in this project contains 1,25% V_2O_5.

In contrast to wash-coated catalysts, homogeneous catalytic material is exceptionally durable and deliver the same high performance under all operating conditions [58].

Other components

1) Fittings: cutting ring fittings, T-junctions, reducers (Swagelok)
2) 6 mm stainless steel pipes and 6 mm plastic tubes
3) Ventilation hood
4) Reducers: DruVa, AGA, Yara
5) Insulation: fiberglass bandage, aluminum foil

Catalyst sizing

The size of the catalyst determines the degree of reduction efficiency. A properly sized catalyst has the efficiency level to comply with the engines operating limit.

Parameters

Several factors influence the degree of NOx conversion in a SCR catalyst using ammonia as reductant. They are:

1) Temperature
2) Space velocity
3) NO to NO_2 ratio
4) Availability of NH_3

For any combination of catalyst formulation and substrate, the variables of temperature and space velocity are the essential parameters to manipulate as they effect the performance of catalyst [46].

Temperature effects

Temperature provides the energy for chemical reaction, and the space velocity sets the amount of time that a molecule comes in contact with the active sites of the catalytic material as it passes through the catalysts cells. The reaction is initiated by the exhaust gas itself, but the performance will vary depending on the temperature it holds.

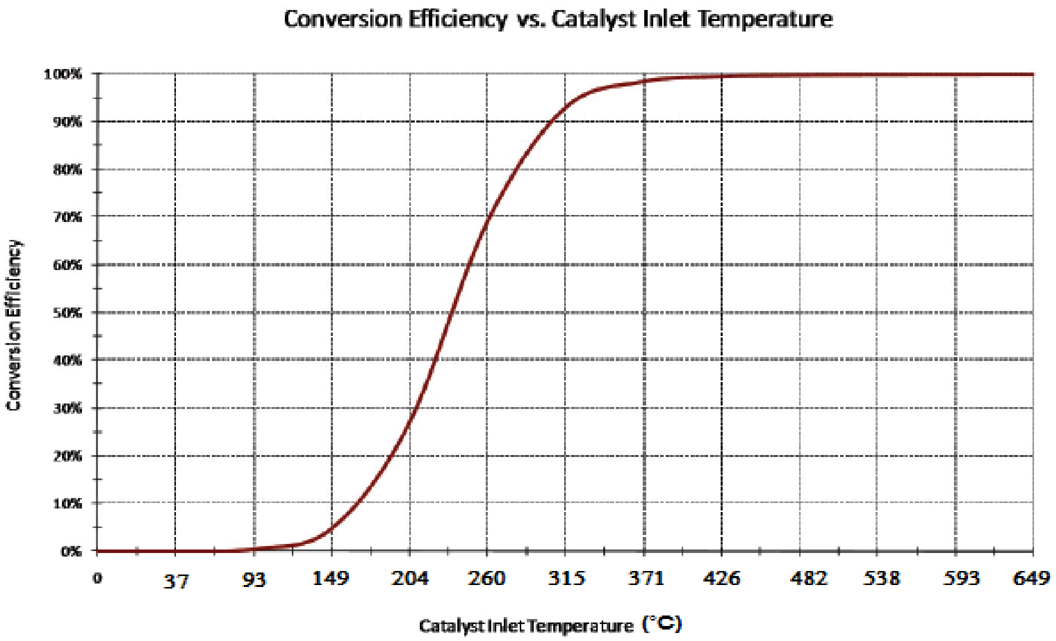


Figure 33 - Conversion efficiency vs catalyst inlet temperature [46]

Each catalyst has its own unique light-off curve for a given set of parameters as a specific catalyst formulation, substrate cell pattern, space velocity. The light-off curve shows the change in catalyst performance vs. temperature. This curve varies with regards to catalyst composition and reducing medium [46].

Space velocity

Space velocity is a term which describes the fraction of a second that it takes a segment of exhaust gas to pass from the catalyst’s inlet face to its outlet face. In general, the higher the residence time the higher conversion.

The mathematical definition of the Space Velocity is as follows:

$$Space\ velocity = \frac{Exhaust\ Flow}{Catalyst\ Volume}$$

with hr^{-1} as the unit of measure. Residence time in seconds can then be found by dividing 3600 seconds/hour by Space velocity value. Because of the unit, space velocity is often called Gas Hourly Space Velocity, GHSV [46].

Space velocity is a function of temperature and conversion efficiency. The figure below presents space velocity functions graphically:

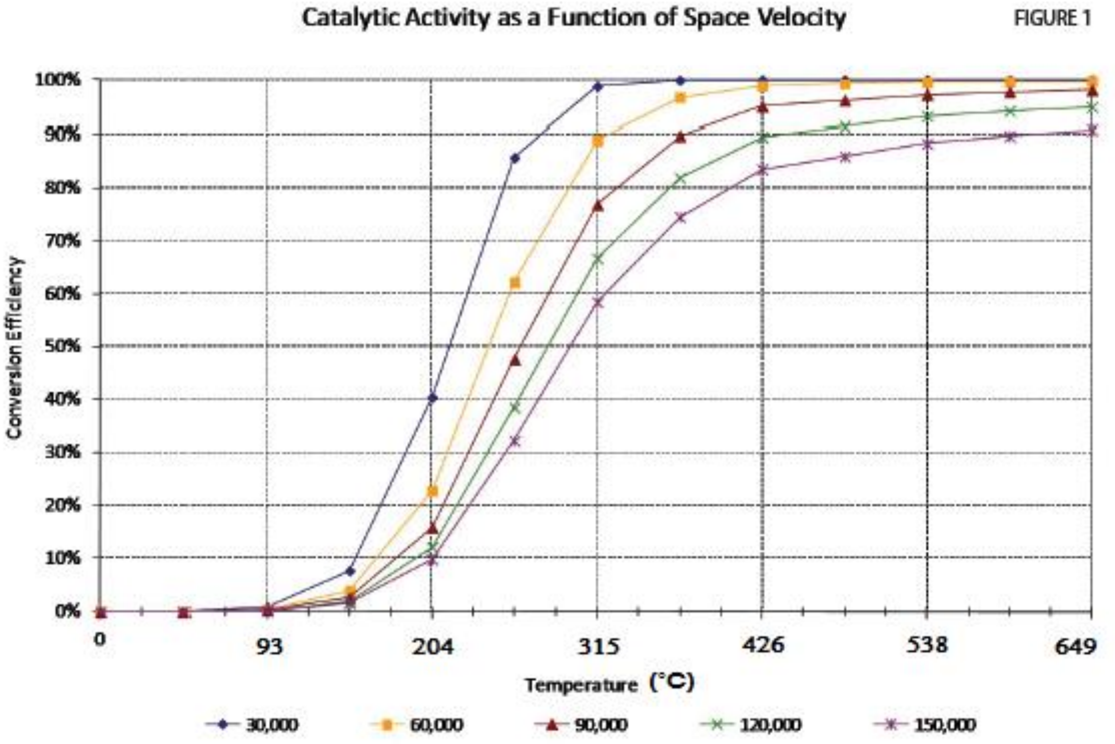


Figure 34 - Catalytic Activity as a Function of Space Velocity [46]

As shown in the graph, performance and space velocity have an inverse relationship: as the space velocity increases, the performance of the catalyst decreases. If the space velocity increases, the exhaust flow rate has to increase too. Therefore, the amount of time that a compound has to move from the gas stream to the surface of the catalyst decreases. These statements are applicable for the fixed catalyst volume.

NO to NO_2 ratio

Depending on the $NO:NO_2$ ratio, different reduction reactions occur, and according to Ciardelli et al. [59], the highest conversions are obtained at a $NO:NO_2$ ratio of 1:1, which corresponds to the stoichiometry of the fast SCR reaction. The lower temperature limit, above which NO_x reduction occurs, depends strongly on the $NO:NO_2$ ratio. Thus, for $NO:NO_2$ ratio of 1:1 the lower temperature limit is 140-170 °C in comparison to an exhaust gas with only NO present, where the lower temperature limit for NO_x reduction is 200°C [59]. Furthermore, the upper temperature limit for NO_x reduction is caused by the oxidation of ammonia which occurs at temperatures above 400°C in the reaction:

$$4\,NH_3 + 5\,O_2 \rightarrow 4\,NO + 6\,H_2O$$

Ammonia coverage

The ammonia used in the reduction of NO_x, is initially absorbed in the catalyst. The amount of absorbed ammonia is referred to as the ammonia coverage. Several factors influence the ammonia coverage, with the most important listed below [60]:

1. Catalyst material
2. Temperature
3. Presence of other adsorbates

The catalyst material is of importance, as zeolite can have a higher coverage than Vanadium-based catalysts [61]. Furthermore, the ammonia storage potential is highly temperature dependent. At low temperatures large amounts of ammonia can be stored, however, the ammonia storage potential decreases significantly with increasing temperature. Between 200°C and 300°C, and at temperatures above 350°C hardly any ammonia is stored in the vanadium and zeolite catalyst, respectively [61]. Thus, temperature ramps in the catalyst bed can lead to significant ammonia slip.

Other compounds, such as H_2O, can also be absorbed into the catalyst, thereby influencing the adsorption of NH_3.

Catalyst sizing – Full scale

When sizing a catalyst for an engine, the first parameters to consider is Conversion Efficiency% (CE%) for a compound based on the raw emissions from the engine and the limits of the operating permit [46].

$$CE\% = \left(1 - \frac{Permit\ Limit}{Raw\ Emissions}\right) * 100\%$$

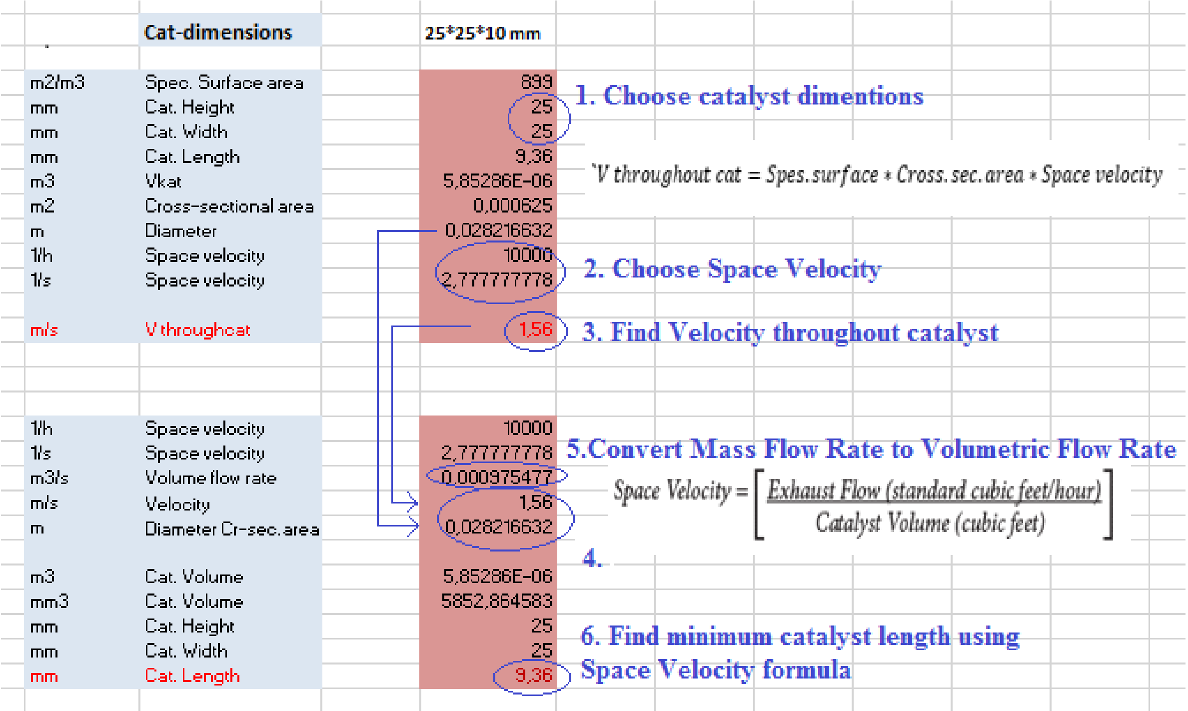
The sufficient space velocity is then to be determined, which will yield the specific conversion efficiency for the temperature of the exhaust gas at the inlet face of the catalyst.

As the exhaust gas include several compounds that have different operating permit limits, the space velocity is normally selected according to the component with the highest performance requirements and which is the hardest to convert [46].

Once the space velocity is determined, the size of the catalyst (the catalyst volume) can be calculated using the exhaust flow rate and the space velocity equation. John W. Robinson states in the paper "Understanding Catalysts. A Handbook for the User" that a safety factor is necessary to allow for flow blockages inside the housing and to allow some loss of performance due to ashing or other deactivation mechanisms. So the final size of the catalyst will be slightly larger than the calculation yields.

Catalyst sizing – Micro scale

Calculations performed in this section are highlighted to define the catalyst parameters and the flow profile of synthetic air, NO and NH_3. The screenshots of the dimensioning spreadsheets below and on the following pages explain the approach step by step, followed by detailed calculations.



	Cat-dimensions	25*25*10 mm
m2/m3	Spec. Surface area	899
mm	Cat. Height	25
mm	Cat. Width	25
mm	Cat. Length	9,36
m3	Vkat	5,85286E-06
m2	Cross-sectional area	0,000625
m	Diameter	0,028216632
1/h	Space velocity	10000
1/s	Space velocity	2,777777778
m/s	V throughcat	1,56
1/h	Space velocity	10000
1/s	Space velocity	2,777777778
m3/s	Volume flow rate	0,000975477
m/s	Velocity	1,56
m	Diameter Cr-sec. area	0,028216632
m3	Cat. Volume	5,85286E-06
mm3	Cat. Volume	5852,864583
mm	Cat. Height	25
mm	Cat. Width	25
mm	Cat. Length	9,36

1. Choose catalyst dimentions

$$V\ throughout\ cat = Spes.surface * Cross.sec.area * Space\ velocity$$

2. Choose Space Velocity

3. Find Velocity throughout catalyst

5.Convert Mass Flow Rate to Volumetric Flow Rate

$$Space\ Velocity = \left[\frac{Exhaust\ Flow\ (standard\ cubic\ feet/hour)}{Catalyst\ Volume\ (cubic\ feet)}\right]$$

4.

6. Find minimum catalyst length using Space Velocity formula

Table 9 - Excel Sheets

1) Catalyst cross section area parameters, height and width, are set to:

25 mm x 25 mm

which fits perfectly in the SCR-reactor. The catalyst height and width is an assumption and a baseline for the rest of the calculations.

2) Choosing a Space Velocity value:

   The relation between the exhaust gas flow rate and the normal hourly space velocity (catalyst bed - $Nm^3/h/m^3$), has direct influence on the conversion ratio. Space velocity for the current application is assumed 10 000 hr^{-1}. This value is chosen based on the Figure 34 - Catalytic Activity as a Function of Space Velocity , where a space velocity of 30 000 hr^{-1} gives the highest reduction rate at low temperatures compared to all other curves of higher space velocity. A space velocity of 10 000 hr^{-1} is supposed to insure a safety margin to compensate for errors while dimensioning.

3) Velocity throughout the catalyst can be determined using the following equation:

   $$'V\ throughout\ cat = Spes\ surface \times Cross\sec\ area \times Space\ velocity$$

   Where:

   - Specific Surface is a Geometric Surface (m^2/m^3) of the Honeycomb with Cell Array 40x40 mm, **Feil! Fant ikke referansekilden.**. The Geometric surface value given is 899 m^2/m^3.
   - Space Velocity in 1/h is converted to 1/s: $10\ 000\frac{l}{h} = \frac{10\ 000}{3600}\ \frac{1}{s} = 2{,}77778\ \frac{1}{s}$

   Velocity throughout the catalyst is then calculated:

   $$V\ throughout\ catalyst =\ 899\frac{m^2}{m^3}\ \cdot 0{,}000625\ m^2\ \cdot 2{,}77778\ \frac{1}{s}$$

   $$V\ throughout\ catalyst = 1{,}56\ \frac{m}{s}$$

4) Converting the cross sectional area of the catalyst from a quadratic shape to a circular shape to define the diameter of the circular cross sectional area. This is necessary for further use in Flowrate Equation.

   The cross section area of 0,000625 m^2 gives a diameter of 0,02821 m.

5) Calculating exhaust flow rate on Volumetric basis:

   $$\dot{Q} = v\ \cdot A$$

Where, v is velocity and A is a cross-sectional area of the catalyst:

$$\dot{Q} = 1{,}56\ \frac{m}{s} \cdot \left(\frac{\pi \cdot 0{,}02821^2}{4}\right) m^2 = 0{,}000975 \frac{m^3}{s}$$

6) Finding minimum catalyst length by using the space velocity equation:

$$Space\ Velocity = \left[\frac{Exhaust\ flow\ (standard\ cubic\ feet/hour)}{Space\ Velocity\ (cubic\ feet)}\right]$$

$$Catalyst\ Volume = \frac{Exhaust\ Flow}{Space\ Velocity} = \frac{0{,}000975\ \frac{m^3}{s} \cdot 60\ s}{10\ 000\ \frac{1}{h}} = 5{,}85 \cdot 10^{-6} m^3$$

$$= 5850{,}0\ mm^3$$

$$Length = \frac{Catalyst\ Volume}{Cross\ sectional\ Area}$$

$$Length = \frac{5850{,}0\ mm^3}{(25 * 25)\ mm^2} = 9{,}36\ mm$$

7) Defining Flow Rate of the feed gas to the reactor.

It is important to mention that when dealing with compressible fluids, as in the case with synthetic air and NO/NH_3 gases, density has to be taken into account as gas density varies significantly with temperature. For incompressible fluids the Continuity Equation would be enough, but for a compressible flow, multiple relations of parameters would have to be applied. In a compressible flow at ordinary densities and high velocities, a more basic parameter is the Mach number, and, in some cases, Reynolds number. At very low densities other factors must be considered, which are not covered by ordinary bachelor or master courses, unless specified in fluid dynamics [62, pp. 133-140].

Fluid dynamic applications with compressible fluids as working medium are complex systems, where simplifying assumptions are necessary. They are:

- It is assumed that the flow is steady
- The flow is one-dimensional
- Velocity gradients within a cross section are neglected
- Friction is restricted to wall shear
- Gravitation effects are negligible
- Mechanical potential is negligible
- The fluid is an ideal gas of constant specific heat [62, pp. 133-140].

A flowrate was attempted calculated several times without success, resulting in an abnormally high flowrate value. For this reason, a reasonable assumption is made, and a value of 700 l/h is chosen as a baseline.

From the calculations the following values are presented:

- Catalyst: 25 mm / 25 mm / 9,36 mm
- Flow rate: 700 l/h

The effective catalyst length needs to be an absolute minimum of 9,36 mm. However, it is always best to account for possible margins of error, so a length of 34 mm is chosen instead.

8) The share of each gas in the total feed flow of 700l/h is presented in the Table 10 - Calculations of NO and NH3 flowrates. Meaning that NO+N_2 and NH_3+N_2 will compose 5% of the main stream each.

	Flow share	Component share %	Component share l/h	Component share of total flow of 700 l/h
NO	NO+N_2 total	NO % flask	NO flow	NO % total
	35 l/h = 5%	0,03	0,70 l/h	0,1%

NH_3	NH_3+N_2 total	NH_3 % flask	NH_3 flow	NH_3 % total
	35 l/h = 5%	0,03	0,70 l/h	0,1%

O_2	Synt. Air	O_2 % flask	O_2 flow	O_2 % total
	630 l/h = 90%	0,13	81,90 l/h	11,7%

Table 10 - Calculations of NO and NH3 flowrates

From the above chart a flowrate of 700 l/h consists of:

O_2 = 630 l/h

NO+N_2 = 35 l/h

NH_3+N_2 = 35 l/h

It provides that, for each 0,117 % O_2 present, it is added 0,001% NO and 0,001% NH_3. The rest is simply inert N_2 gas.

Preliminary system design considerations

Muffle oven testing

Purpose:

- To test the muffle oven
- To test the heating conditions through the muffle oven for different air flowrates
- To establish the ovens heating capacity by comparing the temperature inside the oven, flowrates, and the temperature of the gas exiting the oven
- To test the muffle ovens heating capabilities over a given pipe length with a given airflow

Instruments:

- Air flow meter: 4 – 50 l/min
- Muffle oven
- Pipes: $D_{outer} = 6\,mm$, $D_{inner} = 3{,}5\,mm,\ h = 1{,}35\,mm\ (wall\ thickness)$, stainless steel
- Temperature sensor
- Isolation material

Working medium:

- Pressurised air

Description:

The muffle oven is heated to T_{oven}=500°C, before air with a flowrate of 100 l/h is blown through it. The air exits the oven in a pipe length running 30 cm outward from the oven Figure 35 - Muffle oven test. The pipe length is fitted with a temperature sensor at the end to monitor the temperature of the airflow. The temperature registered with the above conditions is

$T_{pipe\ exit}$=35°C.

Results show that, higher flowrates give higher temperatures at the sensors location. This is contradicting logic to what is expected, but can be explained by the heat loss along the pipe length. At higher flowrates the warm air has less time to cool before reaching the temperature sensor, and thus higher temperatures are registered.

Tests are conducted both with and without isolation on the pipe length. The tests with isolation give higher and more stable temperatures.

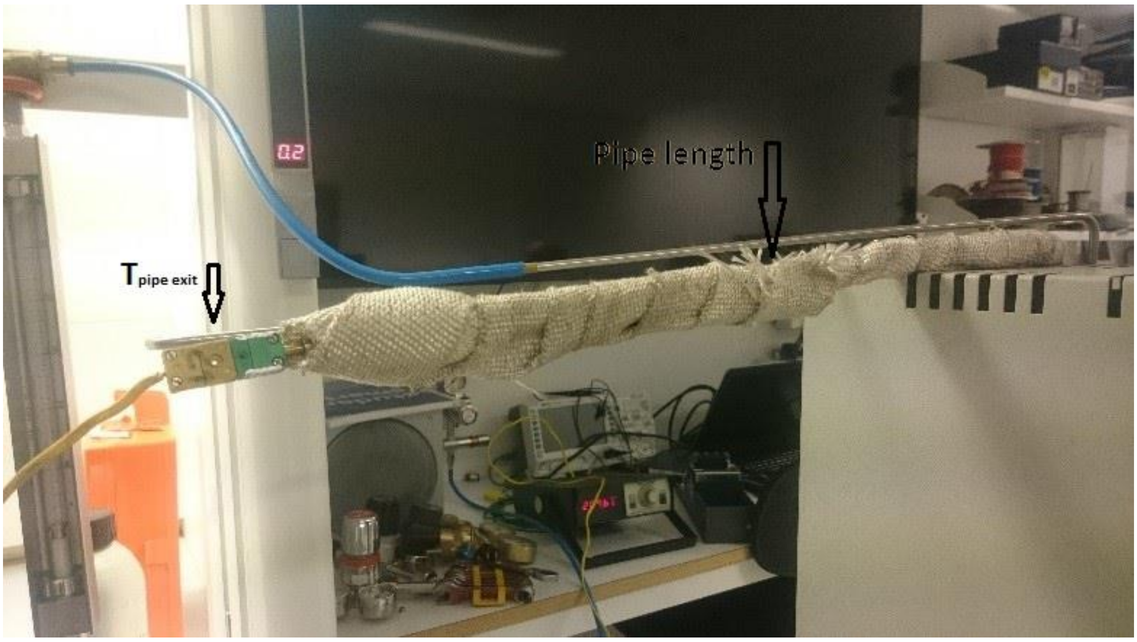


Figure 35 - Muffle oven test

Results:

Test nr	Flow Rate [l/min]	Flow Rate [l/h]	Pressure	T_{oven} [°C]	$T_{pipe\ exit}$ [°C]	Isolation
1	10	600	1	400	195	No
2	15	900	1	400	240	No
3	13	780	0,5 – 0,8	400	275 - 280	No
4	16	960	2 bar	400	275	Yes
5	20	1200	2 bar	400	300 - 320	Yes

Remarks:

- A pressure loss over the flowmeter is registered
- Higher flowrates give higher temperatures
- Isolation is required to avoid heat loss

Conclusion:

- The spiral tube inside the oven is sufficient to get the desired temperatures at high flowrates
- With a flowrate of 780 l/h, the air is sufficiently heated if isolation is present

System setup

The system built for this project is a micro scale version of a marine diesel exhaust gas system with a built in SCR-reactor. The purpose of the system is to replicate a marine SCR process on a smaller scale for easier testing. The system is built from blueprints produced earlier in this thesis, figure/picture xx. The system design is the result of teamwork between student, mentor and other involved parties from Bergen University College. The construction process is described in detail below.

1. SCR-reactor preparations:

- The catalyst with dimensions 25 /25 /34 mm is placed inside the reactor.

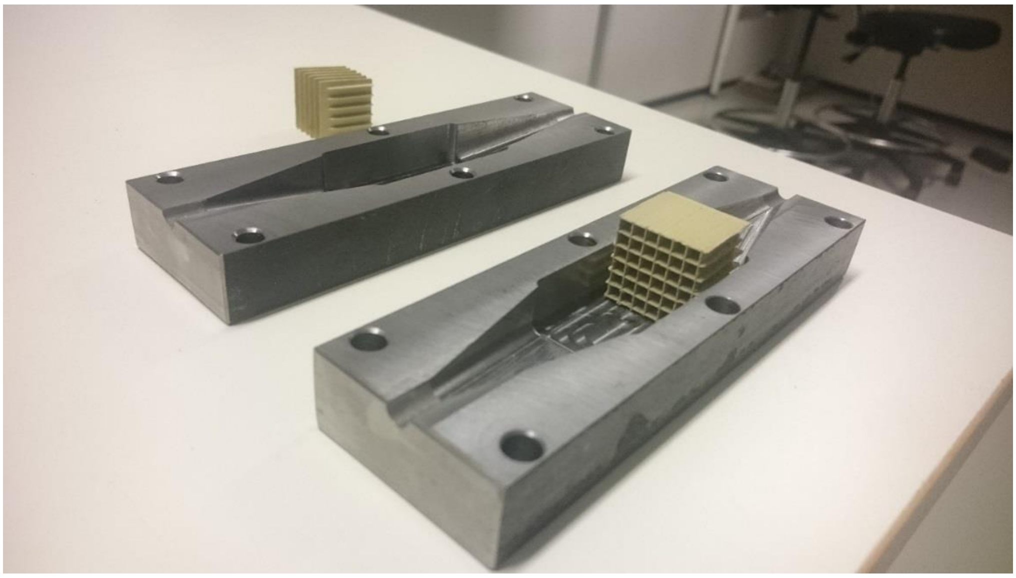


Figure 36 - SCR-micro reactor with catalyst

- The reactor is bolted shut and sealed with thermal paste before put in the oven to hardened at slowly increasing temperatures, reaching 500°C in the duration of an hour.

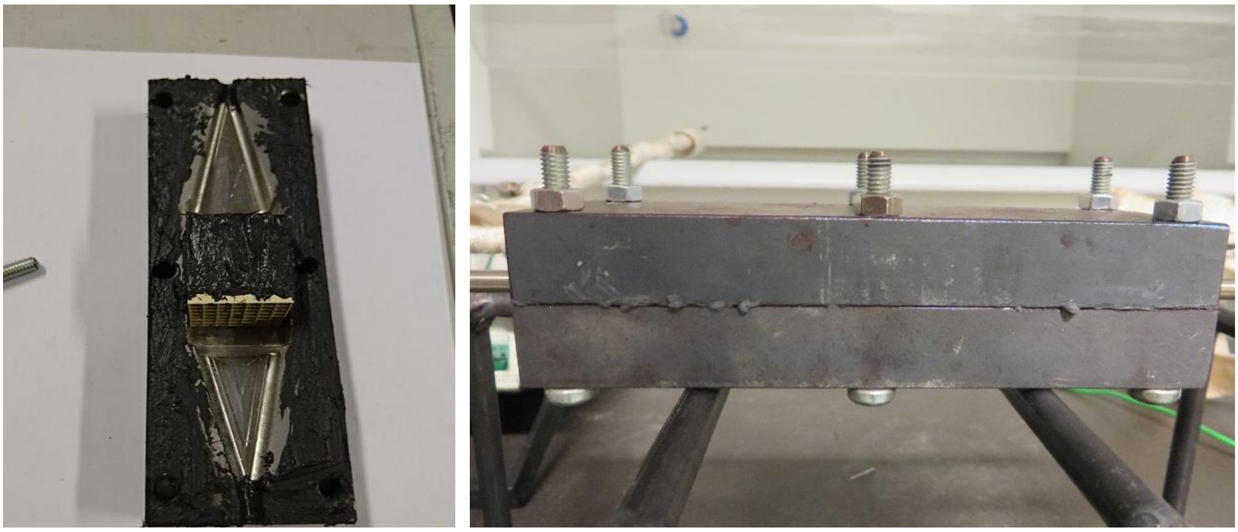


Figure 37 - Sealed SCR- reactor, before hardening and after hardening

The reactor is then ready to be connected to the rest of the system

2. The system has two temperature sensors, the first one is placed at the reactor inlet and is referred to as T_{inlet}. The second one is placed at the reactor outlet and is referred to as T_{outlet}.

Figure 38 - Temperature sensors coupled at reactor inlet and outlet

3. To keep the reactor level with the rest of the system, a support structure is constructed to serve as a foundation for the reactor to rest upon. With minimum surface area the reactor only rests upon two bars. It is displayed at Figure 38 - Temperature sensors coupled at reactor inlet and outlet.
4. A similar solution is constructed for the flowmeters to keep them levelled with the system and locked in a vertical position.

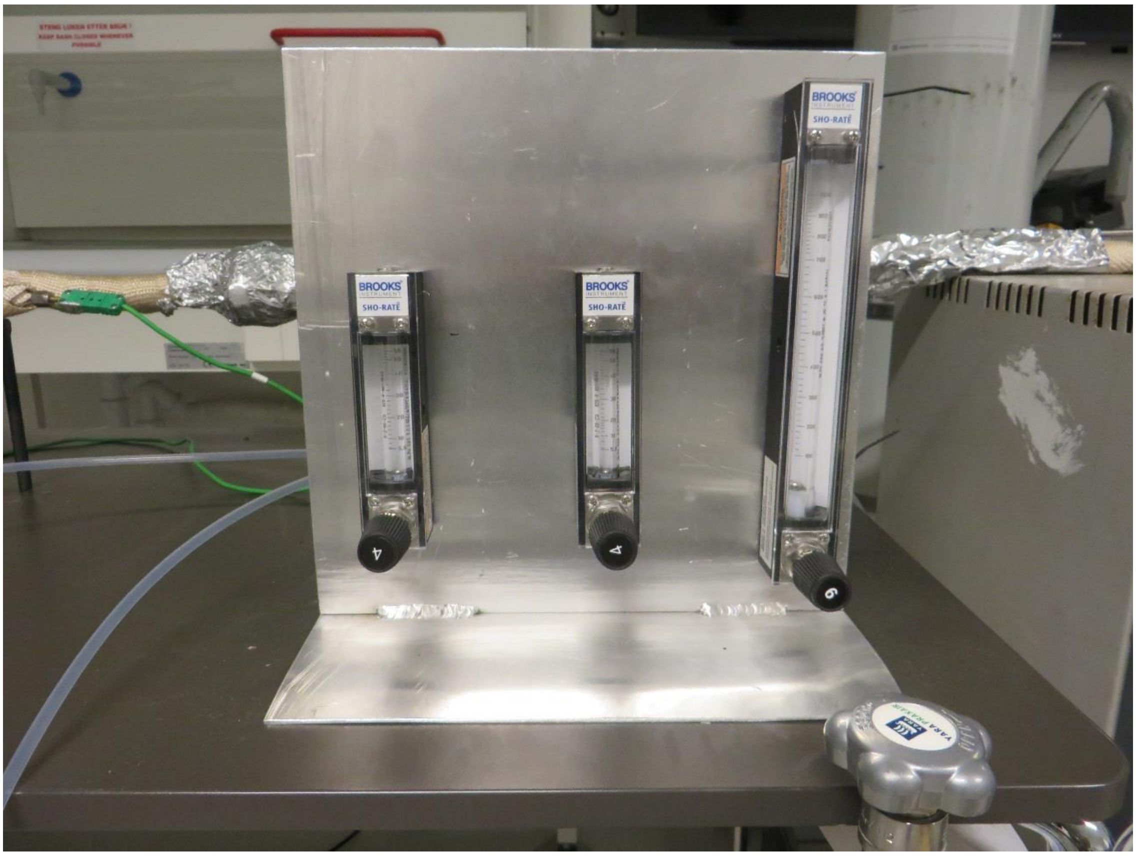


Figure 39 - Flowmeter stand

5. All the parts in the system are fitted together by couplings supplied by “Swagelok”.

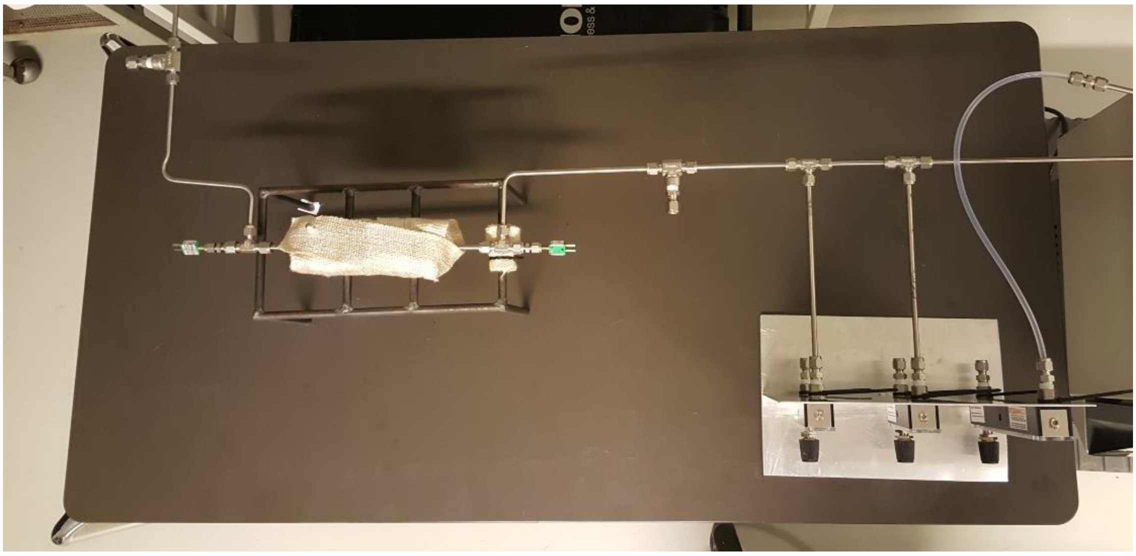


Figure 40 - SCR-system coupled together

6. Three separate flasks containing Synthetic air, NO and NH_3 are connected to each of the flowmeters. Picture xx illustrates the flow patterns in the system. Gases are supplied by Yara Praxair AS.

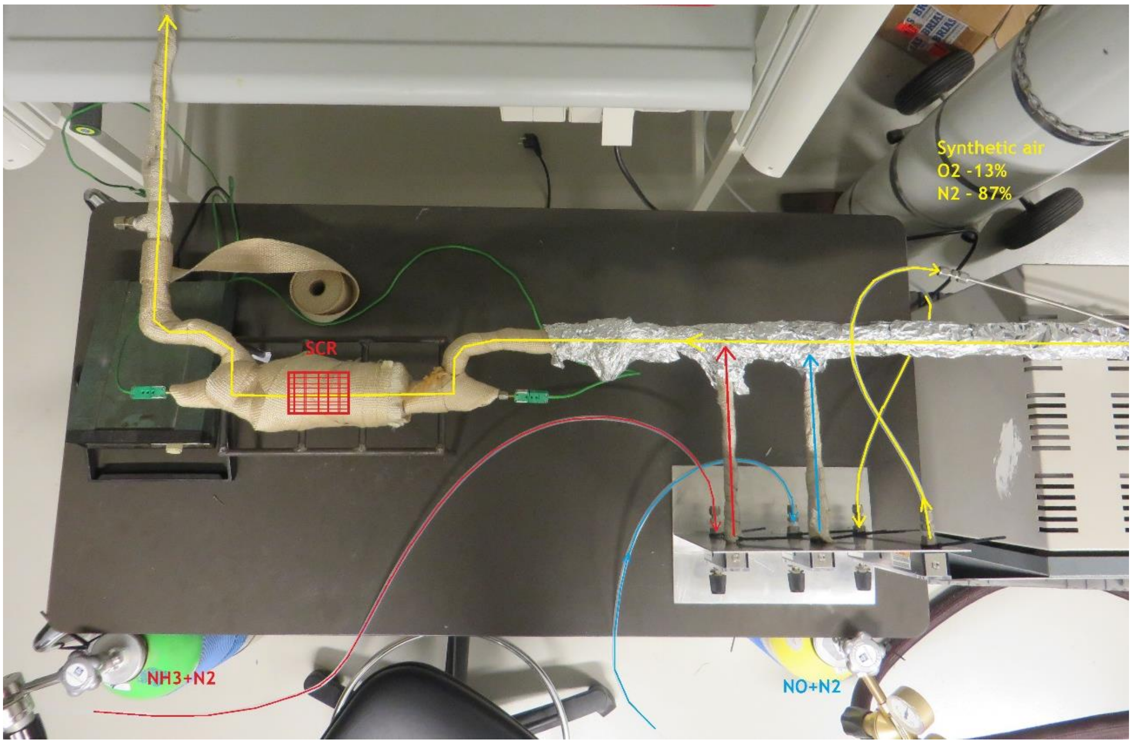


Figure 41 - Flow patterns in the system

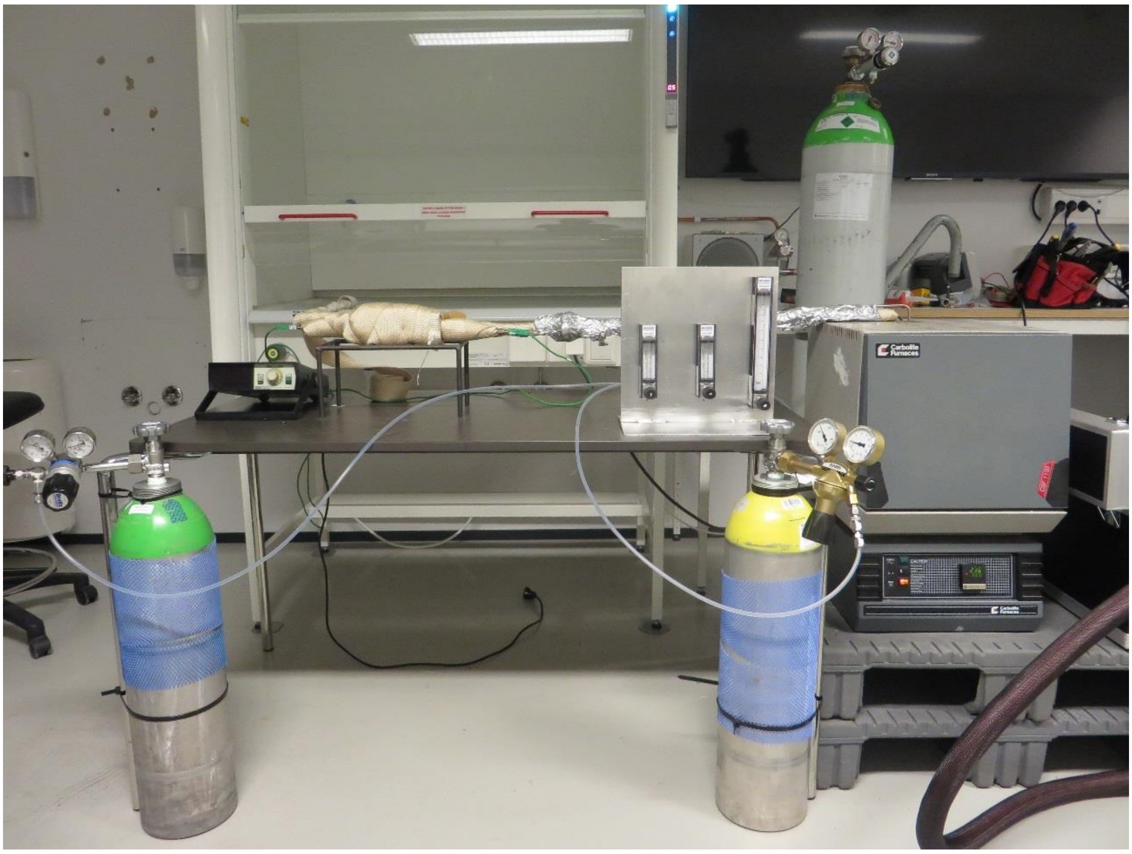


Figure 42 - Gas flasks connected to the SCR-system

7. The systems carrier pipe is made out of stainless steel with the following dimensions: D_{outer} =6 mm and D_{inner} =3,5 mm. Flexible plastic pipes are used at the connection

points where the flow is still cool, typically where the flasks are connected to the flowmeters.

8. The reactor, along with the rest of the system is isolated with a single layer of thick fiberglass bandage.

System tests

As with any new system, functional tests are carried out for a number of reasons for the given SCR micro-lab. The system has to be modified and optimized for its purpose, along with being safe to operate. The main goal is to build a system which will operate under as close conditions to the marine SCR-process as possible. As a result, a number of tests are carried out:

- Leakage tests
- Heat tests
- Pressure tests

1.*The Leakage* tests can be viewed in Attachment 9. The test covers the process of putting the reactor together, the process of choosing a suitable thermal paste for sealing it, and furthermore testing it for leaks.

Conclusion: The best suited thermal paste for this project is the Exhaust repair paste. Out of several possible candidates it performs best within the temperature ranges of this project while not expanding and causing risk to the honeycomb structure inside the reactor.

2.*The Heat test* can be viewed in Attachment 9. Several heat tests are carried out to map the system thermally with the purpose of identifying sources of heat loss.

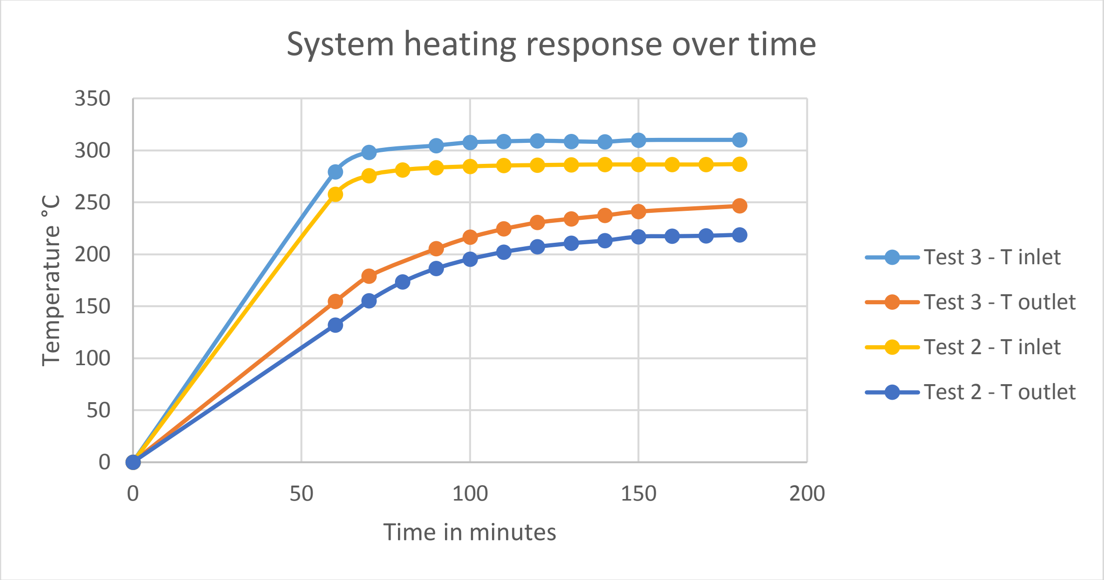


Figure 43 - Heat test 2 and 3 plotted together

It was concluded that:

- Higher flowrates give higher system temperatures

- A high oven setting (above 500°C) is required for a sufficient reactor temperature due to the heat loss in the system. A loss of roughly 50% from the oven to the reactor is registered.
- Isolation is affecting the thermal capability of the system from one test to another as improvements are made. Results from Test 2 and Test 3 with the same oven setting of 500°C and different isolation are plotted on to the Figure 43 - Heat test 2 and 3 plotted together to illustrate thermal improvement.
- The best isolation proved to be 3 layers of fibreglass bandage wrapped with an outer layer of aluminium foil, referred as Test 3. Test 2 was performed without aluminium foil.

3. The Pressure test can be viewed in Attachment 9. Pressure tests are conducted to map the pressure drop in the system to eliminate the possibility of pressure loss affecting temperatures.

Conclusion*:* Even though the originally, significant pressure loss is reduced by half, the temperature difference between T_{inlet} and T_{outlet} is nearly unaffected. The conclusion is that the temperature is not affected by the pressured drops.

Practical part – NO reduction experiments

This practical part contains several NO-reduction experiments using NH_3 as reducing agent, with a varying sets of parameters.

Purpose:

- To examine NO_x-reduction rate by conducting tests using different parameters
- To examine how reduction rate varies with temperature
- To present the results graphically
- To analyse chain of error, limitations, uncertainties and inaccuracy

NO_x -experiment material list:

- Muffle type furnace
- 3x gas flasks with:
  - Synthetic air
  - NO + N2 mixture
  - NH3+ N2 mixture

- Pressurized air
- 3x flowmeters
- 2x temperature sensors
- Thermometer
- Reactor
- Catalyst with dimensions 28/28/34 mm
- HORIBA
- Testo
- Madur PGD-100

Measuring method and calibration:

Both the Horiba and Testo are used to measure NO-concentrations in the flow during NOx-reduction tests. The Horiba is used in the first lab test, while the Testo is used in all of the following tests – the reason is explained further in the rapport.

Unlike the Horiba, the Testo does not need pre-calibration as it uses cartridges for each separate gas, while the Horiba needs to be calibrated for each use every time it is turned on. Calibration papers can be found in Attachment 4.

The Horiba can be programmed to measure 5 separate gasses and needs to be calibrated against each one of them. The calibration method is as follows:

1. Using N_2 as sample gas to calibrate $O_{2} =$450 ppm with Calibration gas $N_{2} =$ 0 ppm
2. Sample gas with SO_2, CO and CO_2 calibrates each of these gases respectively
3. NO sample gas for NO calibration
4. The O_2 concentration is referenced against the O_2 concentration in air. A value of 20,38 is obtained which is slightly low as air contains 20,95% O_2.
5. The calibration process is repeated and the end result is a 20,90% O_2 concentration which is used throughout the tests where the HORIBA is used for measuring.

Before the sample gas from the system can be measured by the HORIBA or the Testo it has to be cooled down by the Madur PGD-100. The latter one prepares gas samples for the co-operating gas analyzer by removing dust, salts particles and condensate, so the sample is dry and clean, and not least cooled [63].

Lab Experiment 1

Conditions:

The system is pre-heated to the desired temperatures using the same procedure as in the heat tests. The only difference is that the pressurized air is replaced with synthetic air after the heating process, but before testing starts. The synthetic air is the working medium for the NO_x -reduction tests. The parameters for the experiment are listed below:

- System pressure 2 bar.
- A steady flowrate of 900 l/h which is maintained throughout the experiment while monitoring flowmeters and adjusting for errors.
- Muffle oven temperature between 400- 460°C
- Reactor temperature is assumed to be the average of T_{inlet} and T_{outlet} at any one point.

During the heating process the following temperature development is observed:

- T_{inlet} stagnates at 228°C after 1,5 hours
- T_{outlet} is still climbing 2,5 hours into the experiment, with a 5°C climb in the last 30 minutes, but stagnates at 178°C.
- ΔT =50 °C

Testing is scheduled to start using the given temperatures after 2,5 hours of heating, but at the last minute an error is detected in the calibration values. The HORIBA's O_2 levels appear to be fluctuating between 20,90% to 21,10%. The oxygen levels are re-calibrated to a steady value of 20,78%. Because this is a minor deviation of 0,17%, testing continues as planned.

To monitor NO concentrations in the system the HORIBA is attached to the T-connection in front of the reactor. Similarly, for NO values after the reactor the HORBIA is attached to the T-connection behind the reactor. The HORIBA can only be plugged into one point at same the time. So it has to be moved during testing to take reading at both locations. Because of this there is a small temperature loss when changing between the two points, as can be seen under "Conditions 1 and 2" in Figure 44 - Placement of T-junction to connect measuring equipment before and after SCR-reactor.

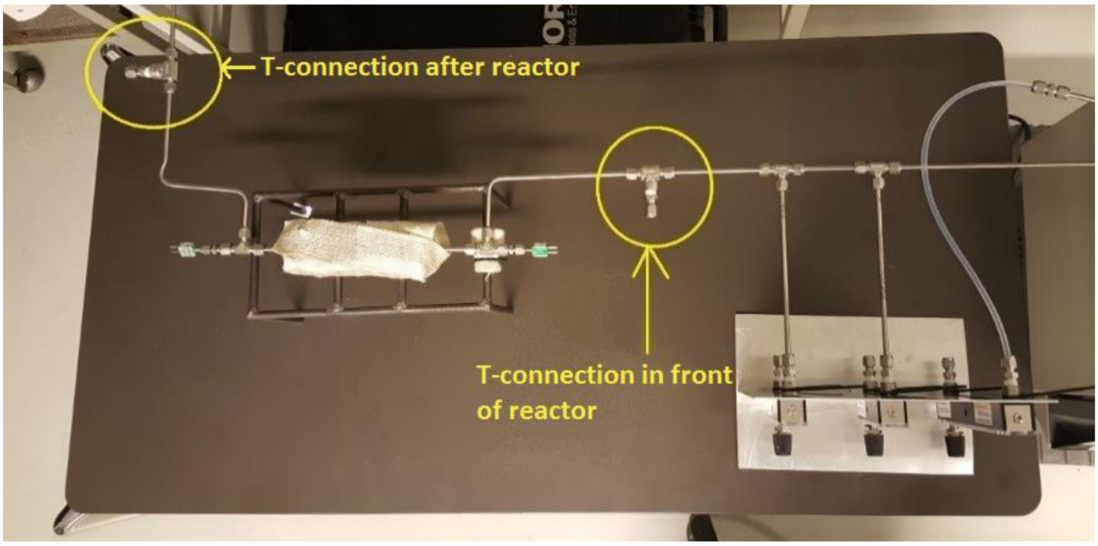


Figure 44 - Placement of T-junction to connect measuring equipment before and after SCR-reactor

The test is divided into 3 conditions where each has its own set of parameters.

Displayed as "(Air flow /NO flow /NH_3 flow) l/h — T_{inlet} / T_{outlet}".

Condition 1: (900 /38 /38) l/h — T_{inlet} = 228,0°C / T_{outlet} = 178,0°C

Condition 2: (900 /50 /50) l/h — T_{inlet} = 222,6°C / T_{outlet} = 175,6°C

Condition 3: (900 /50 /50) l/h — T_{inlet} = 255,2°C / T_{outlet} = 190,0°C

As displayed above, the ratio between NO and NH_3 is consistently 1:1 throughout the tests.

Procedure:

For each setup the NO-concentration in front of the reactor is measured and registered. The HORIBA is then connected to the other side of the reactor to compare [NO ppm] values before and after the catalyst to determine NO-reduction rate.

Results and observations:

- Starting with the parameters in condition 1, it is observed that the NO-reduction rate steadily increases within 1-2 minutes while holding the same temperature. T_{inlet}=228°C, with a NO- reduction rate climbing from 11% to 14%. This indicates a change in the reduction rate at the same temperature, which makes little sense.
- To examine this further, the composition of the flow is slightly altered to the parameters in condition 2. It is observed that the NO-concentration in front of the reactor is less than from the previous result, despite adding more NO to the flow.
- Small break, then condition 3
- Furthermore, the HORIBA flow drops from 0,5 to 0,4 l/min.

Conclusion:

Test results are confusing and not in accordance with the theoretical expectations. The results can be viewed in Table 11 - Data collected in Experiment 1. The testing is aborted at this point and the HORIBA is examined.

	Setup 1				Setup 2					Setup 3
	in	out	out	out	in	out	out	out	out	in
T_{inlet}	228	231,6	231,6	234,7	222,6	227,8	229	246,6	254	255,2
T_{outlet}	178	180	180	183,2	175,6	177,4	179,2	185,6	189,2	190
T_{oven}	400	400	400	400	400	400	400	459	460	460
Flow air [l/h]	900	900	900	900	900	900	900	900	900	900
Flow NO [l/h]	38	38	38	38	50	50	50	50	50	50
Flow NH_3 [l/h]	38	38	38	38	50	50	50	50	50	50
NOx [ppm]	1160	1035	1004	931	969	865	850	761	730	872
O_2 [%vol]	12,47	12,59	12,63	12,70	12,77	12,73	12,73	12,76	12,78	12,83
CO_2 [%vol]	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
CO [ppm]	0	0	0	0	0	0	0	-1	-1	-1
SO_2 [ppm]	9,6	6,3	6,4	5,5	0,2	-0,5	-0,2	-1,2	-1,6	-1,6
Flow HORBA [l/min]	0,5	0,5		0,5	0,4	0,4	0,4	0,4	0,4	0,4
Reduction rate NO [%]	0	11		20	0	11	12	21	25	0

Table 11 - Data collected in Experiment 1

Because of the strange results the HORIBA is re-calibrated, but without success. It shows a NO concentration of 225 ppm rather than the supposed 450 ppm measured against the sample gas from the NO flask. The HORIBA is connected to the mixed gas bottle, containing CO_2, CO and SO_2 which show that some values drop below zero, for example the SO_2 concentration is -271 ppm. Due to these circumstances the results cannot be considered valid.

HORIBA troubleshooting:

While unsuccessful in fixing the HORIBA, assistance came from the HORIBA supplier "Håkon Rygh AS" who quote:

"We assume that this is caused by a plugging of the exhaust tubes. Sometimes a white powder occurs when having too much NH3 in the sampling gas. This white powder could plug the tubes and especially the T-piece where the two exhaust tubes (red colored tubes) are coming together. In a first step please check those tubes and T-piece and clean them if necessary."

The HORIBA is opened and the "red colored tubes" inside are examined. A white powder is indeed clogging the tubes, confirming the suppliers statement.

Figure 45 - Clogged intake tubes of HORIBA

The clogged tubes can explain the deviation in the readings. The powder is assumed to be Ammonium Sulfite, a solid product from the reaction between gaseous ammonia and sulphur dioxide (SO_2) [64].

$$2NH_3 + SO_2 + H_2O \rightarrow (NH_4)_2SO_3$$

But sulfur dioxide is not used in any aspects of this project. So where is it coming from? The answer is found in the intake hose of the HORIBA. It turns out this particular HORIBA unit was used to measure actual exhaust shortly before this project. The hose contains traces of soot and sulphur and is showing small traces of SO_2 ppm in the gas throughout the test. After the HORIBA was cleaned of the ammonium sulfite powder, a new successful calibration was taken. However, after 5-10 minutes of measuring, traces of SO_2 reappeared. The HORIBA requires service and is not used any further in this project. Instead the Testo is used throughout the remainder of the project.

Lab Experiment 2

Previous testing reveals a significant temperature difference between T_{inlet} and T_{outlet}. Because of this there is an uncertainty regarding the temperature in the centre of the reactor. To get a more accurate reading a temperature sensor needs to be placed inside the reactor itself to monitor the actual temperature of the reaction.

To do this the reactor is taken apart and a hole is drilled through the top plate to fit a sensor as shown in picture xx. While the reactor is open the catalyst honeycomb is also replaced with a fresh block of the same size and length – 25 /25 /34 mm. The used honeycomb smells strongly of ammonia, the walls are thinner and the appearance is bleached as show in Figure 46 - New catalyst on the left side and used catalyst on the right side..

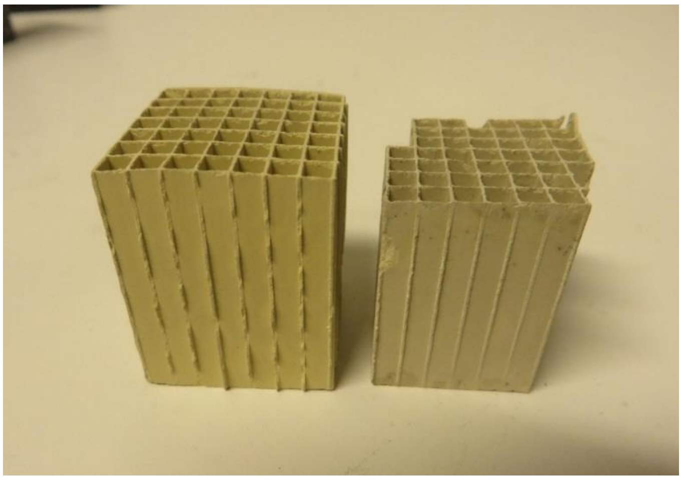


Figure 46 - New catalyst on the left side and used catalyst on the right side.

The reactor is then sealed with exhaust paste and hardened inside a muffle oven at slowly increasing temperatures, reaching 500°C in the duration of an hour. The reactor is then cooled before being isolated with 3 layers of fiberglass bandage topped off with aluminium foil.

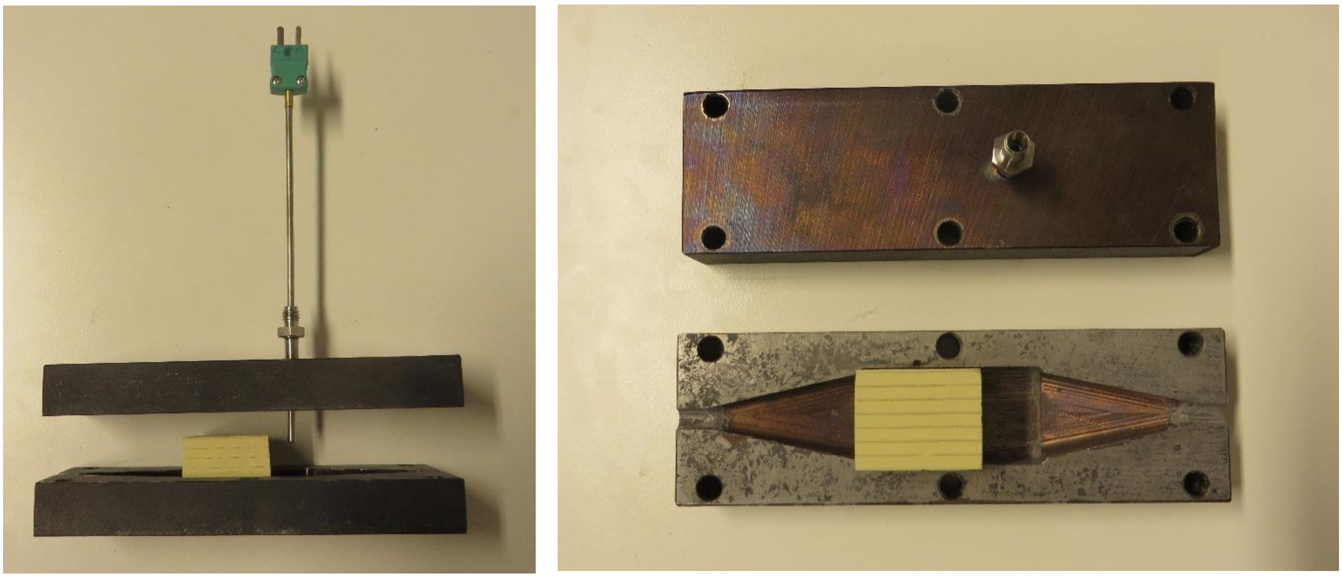


Figure 47 - Temperature sensor installed in the reactor before the catalyst, upstream

Conditions:

Lab Experiment 2 can now commence, but before testing starts the system is pre-heated for 3 hours using pressurized air. The pressurized air is then replaced with the synthetic air for the purpose of NO-reduction testing under the following conditions:

- System pressure 2 bar
- Flowrate of 900 -1000 l/h
- Muffle oven temperature 600°C
- T_{inlet} = 344°C
- $T_{reactor}$ 268°C
- T_{outlet} = 240°C

The data collected during Lab Experiment 2 is divided into groups, sorted after its purpose and thus Lab Experiment 2 is subdivided into “4 tests”. All the tests are carried out on the same date, one after another due to the limited supply of synthetic air and the time consuming task of heating the system.

All the data collected during test 2, 3 and 4, is recorded with a Testo rather than the HORIBA, which is fitted to the pipe length after the reactor. Instead of moving the Testo back and forth between the T-connections like the HORIBA earlier, the Testo remains stationary. NO-concentrations are measured by running NO through the system without any ammonia. This way a baseline can be established and ammonia is then mixed with the flow and run through the system afterwards.

It was initially planned to use between 1000 and 1500 ppm NO before adding NH_3. The values within this region are acceptable for starting conditions. Only NO is measured and not NO_x. The reason for this is that the HORIBA measures all NO_x values as one, while the Testo uses cartridges for each separate gas. Furthermore, it is assumed that the operating temperatures are not sufficient for NO_2 to form, and thus NO_2 is neglected in these tests.

Test 1

Conditions:

- Muffle oven temperature 600°C
- 1000 l/h synthetic air
- 35 l/h NO+N2
- 35 l/h NH3+N2
- gas mixture NO-concentration, 1025 ppm
- Note: NH_3 is gradually increased from 0 to 100%

Results and observations:

NH_3 is gradually injected into the Synthetic-air/NO mixture while monitoring the effects on the NO reduction process. The NH_3 values 0 l/h to 35 l/h correspond to 0 -100% NH_3 injection.

Flow Synthetic air [l/h]	1000					
Flow NO [l/h]	35					
Flow NH_3 [l/h]	35					
NH_3 [l/h]	0	10	20	30	35	35
NH_3 [%]	0	29	57	86	100	100
NO ppm	1025	873	784	733	708	701
NO reduction %	0	15	24	28	31	32
$T_{reactor}$	298,6	299,6	299,6	300,4	301	305

Table 12 - Data selected from Test 1 in Experiment 2

The test shows and confirms that max NO reduction is achieved by adding an equal amount of ammonia and NO to the flow. In this test 31% NO reduction was achieved at $T_{reactor}$=301°C.

The reduction rate seems to be increasing with temperature. The results are graphically displayed in Figure 48 - NO concentration at variable NH3 injection rate.

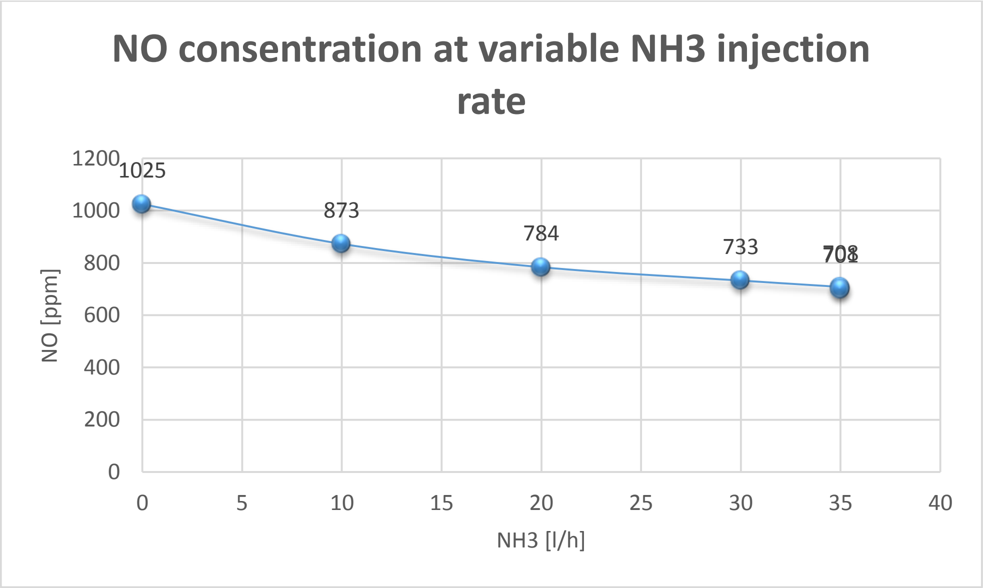


Figure 48 - NO concentration at variable NH3 injection rate

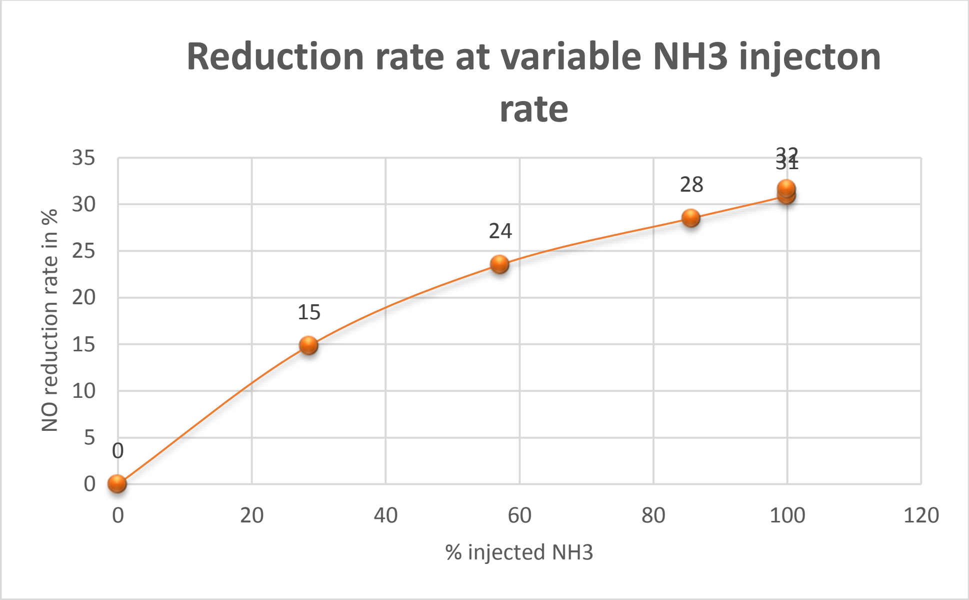


Figure 49 - Reduction rate at variable NH3 injection rate

Test 2

Conditions:

- Muffle oven temperature 600°C
- 900 l/h synthetic air
- 37 l/h NO+N2
- 37 l/h NH_3+N2
- gas mixture NO-concentration, 1180 ppm
- Note: NH_3 supply is constant throughout the test

Results and observations:

The amount of NH_3 injected is equal to the NO flowrate and remains unchanged during the whole test. NO-reduction data is collected over the temperature range of 268-298°C and is presented in the Table 13 - Data collected from Test 2 in Experiment 2.

Synthetic air [l/h]	900							
NO [l/h]	37							
NH_3 [l/h]	37							
NO ppm	906	894	883	862	849	849	839	831
NO reduction [%]	23	24	25	27	28	28	29	30
$T_{reactor}$ [°C]	268	270	272	274	276	278	280	282

NO ppm	828	825	825	817	814	810	802	798
NO reduction [%]	30	30	30	31	31	31	32	32

$T_{reactor}$ [°C]	284	286	288	290	292	294	296	298

Table 13 - Data collected from Test 2 in Experiment 2

The relation between NO-reduction rate and temperature for this experiment is presented graphically below.

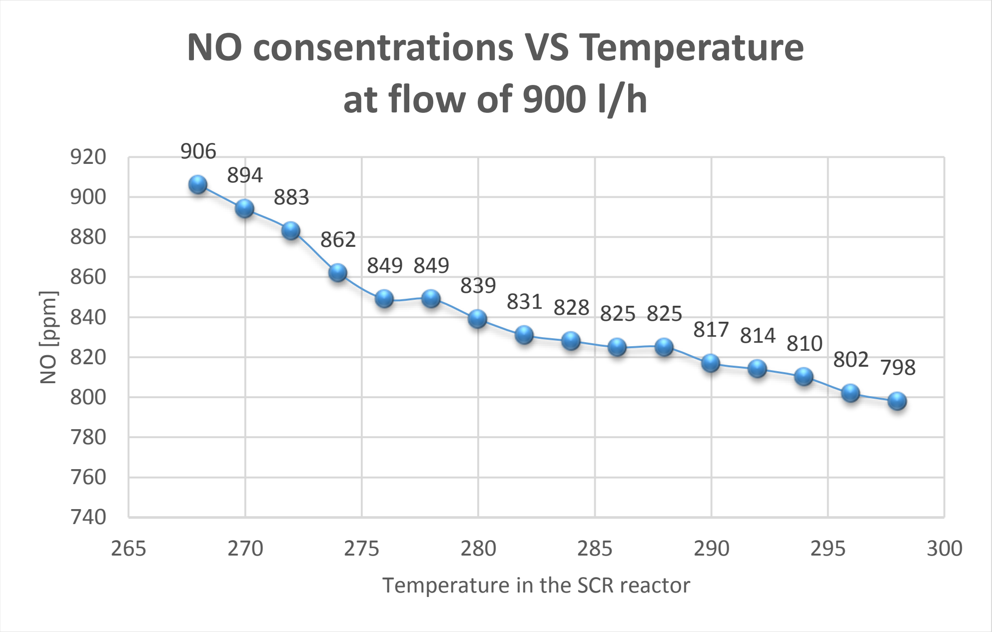


Figure 50 - NO concentration VS Temperature at flowrate 900 l/h

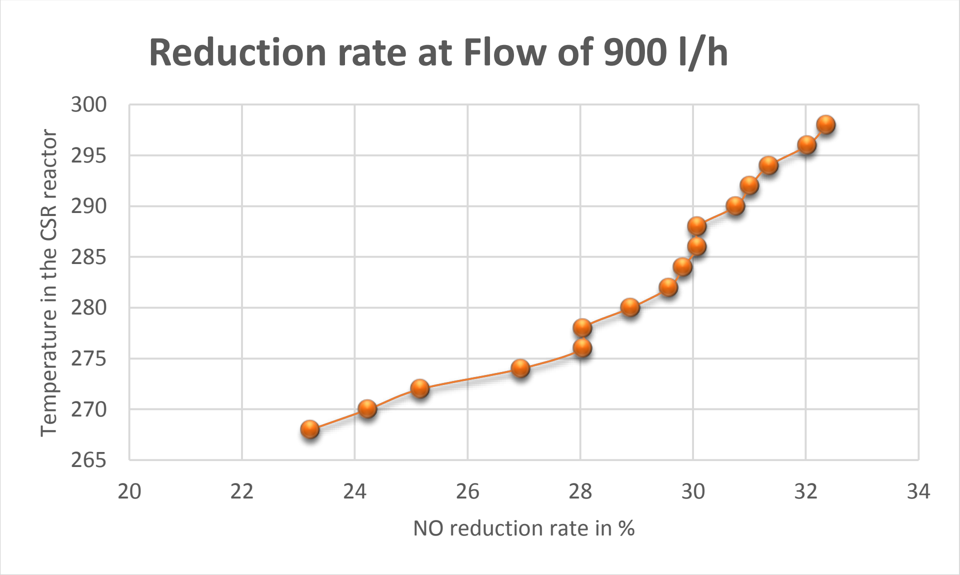


Figure 51 - Reduction rate at flowrate 900 l/h

As depicted in Figure 51 - Reduction rate at flowrate 900 l/h, NO-reduction rate increases with temperature. The reduction line is not “smooth” which is a result of manually adjusting the flowrate to compensate for gas expansion/compression, which lead to some inaccurate readings.

The following minimum and maximum reduction rates are registered:

- 23% reduction at $T_{reactor}$ =268°C
- 32% reduction at $T_{reactor}$ =298°C

$T_{reactor}$ =298°C is the max temperature achieved in the system with a flowrate of 900 l/h.

It is probably also important to note that testing is done while the system is slowly cooling. The results are registered from the highest temperature to the lowest, but are displayed in Table 13 - Data collected from Test 2 in Experiment 2 and Figure 51 - Reduction rate at flowrate 900 l/h in adverse order for simplicity reason.

Further, a trend-line is added to the data in Figure 51 - Reduction rate at flowrate 900 l/h, illustrated in Figure 52 - Trade line applied to NO conversion data from Test 2 in Experiment 2. A trend line, often referred to as a line of best fit, is a line that is used to represent the behavior of a set of data to determine if there is a certain pattern.

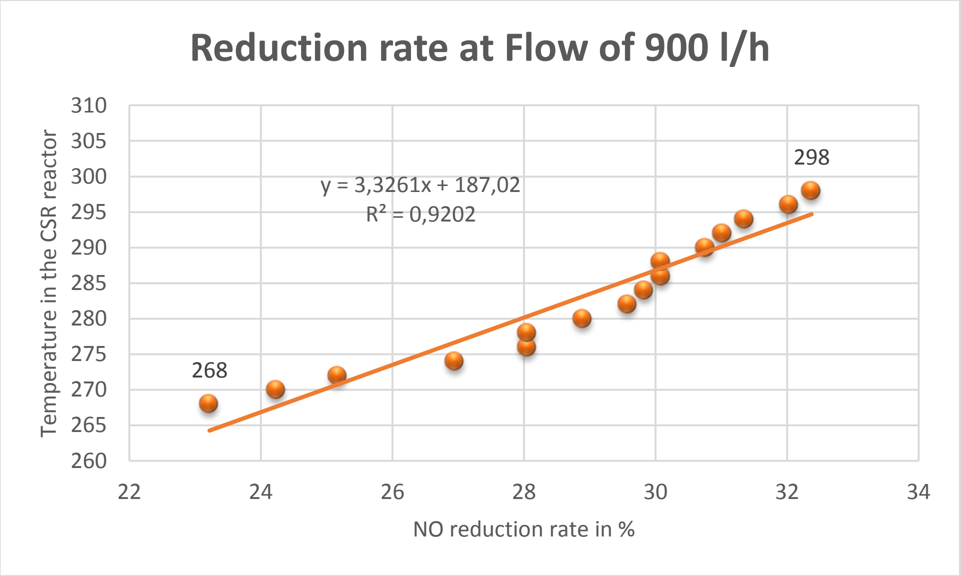


Figure 52 - Trade line applied to NO conversion data from Test 2 in Experiment 2

As can be seen from Figure 52 - Trade line applied to NO conversion data from Test 2 in Experiment 2, the test data set has high positive correlation with a R-squared value equal to 0,9202. The R value identifies how well the line fits for the given data set and how reliable the trend-line is. According to the trend-line definition, the line provides the most reliable approximation when R-squared value is at or near 1.

The slope coefficient of the line is calculated to approximately 3,3, which means that each 3,3°C temperature change in the SCR reactor corresponds to 1% change in NO_x reduction rate and vice versa. With other words, 0,303%

Test 3

<u>Conditions:</u>

- Muffle oven temperature 600°C

- 900 l/h synthetic air
- 37 l/h NO+N2
- 37 l/h NH_3+N2
- Gas mixture NO-concentration, 1180 ppm
- Note: Comparing results gathered during decreasing temperatures vs increasing temperatures

In test 2, results are gathered while the system temperature is dropping. In test 3 results are gathered while temperatures are climbing.

Results and observations:

By comparing the two tests, a small difference in the reduction rate is observed at the same thermal point, in a temperature window of 280-292°C. A difference of 9-26 ppm is noted. The ppm gap increases with temperature.

Measuring while temperature is decreasing	$T_{reactor}$	280	282	284	286	288	290	292
	NO ppm	839	831	828	825	825	817	814

Measuring while temperature is increasing	$T_{reactor}$	280	283	285,2	287,2	-	289,6	291,4
	NO ppm	830	821	810	803	-	792	788

Table 14 - Data collected from Test 3 in Experiment 2

This can be explained by the variation in the flowrate at the different thermal points. As mentioned in tests earlier, the flowrate changes with temperature: If the temperature climbs the flowrate decreases, and the other way around. Because of this the flowrate of all three gases are adjusted regularly throughout the experiments to a reference value of 900/37/37 l/h (Air/NO/NH_3). The Testo is not as accurate as the HORIBA either, and might also be a factor affecting the results.

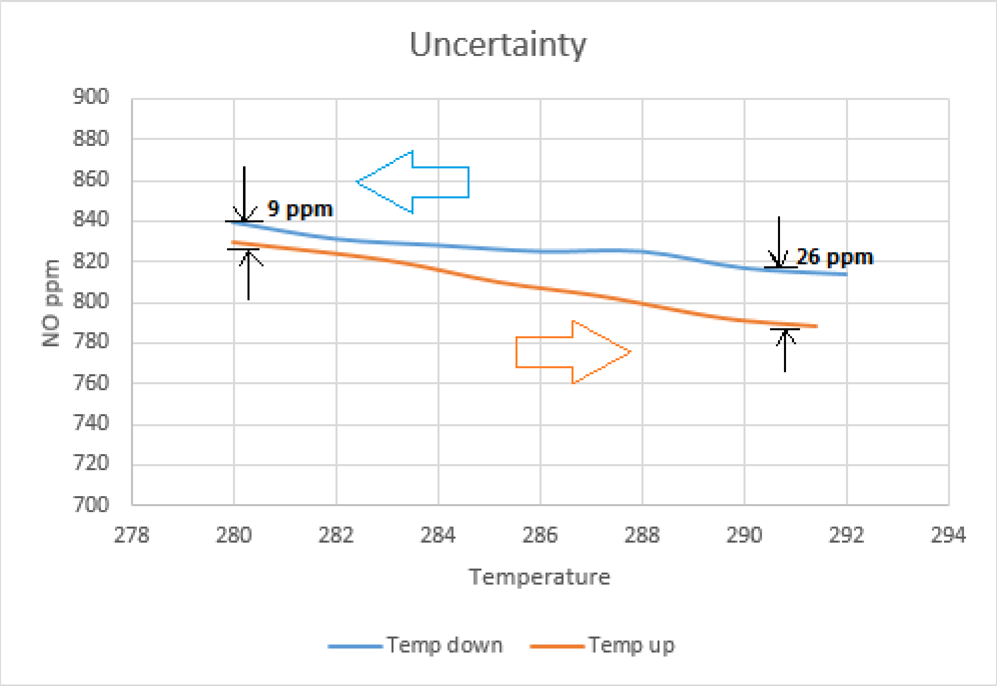


Figure 53 - Uncertainty

<u>Conclusion:</u>

- Because of the factors mentioned above the ppm gap is small enough to be neglected.
- NO-reduction rate increases with temperature

Errors

In retrospect, when the SCR-system is already dimensioned, built and all test are run, a critical error in calculations are discovered. The mistake is found in the formula for determining the catalysts volume and further catalyst length. All the calculations are given below, where the incorrect ones are shaded by a grey line, followed by the correct ones.

~~$Catalyst\ Volume = \frac{Exhaust\ Flow}{Space\ Velocity} = \frac{0{,}000975\ \frac{m^3}{s} \cdot \mathbf{60\ s}}{10\ 000\ \frac{1}{h}} = 5{,}85 \cdot 10^{-6} m^3$~~

~~$= 5850{,}0\ mm^3$~~

$$Catalyst\ Volume = \frac{Exhaust\ Flow}{Space\ Velocity} = \frac{0{,}000975\ \frac{m^3}{s} \cdot \mathbf{3600\ s}}{10\ 000\ \frac{1}{h}} = 0{,}000351\ m^3$$

$$= 351000\ mm^3$$

$$\cancel{Length = \frac{Catalyst\ Volume}{Cross\ sectional\ Area} = \frac{5850{,}0\ mm^3}{(25 * 25)\ mm^2} = 9{,}36\ mm}$$

$$Length = \frac{Catalyst\ Volume}{Cross\ sectional\ Area} = \frac{351000\ mm^3}{(25 * 25)\ mm^2} = 561{,}6\ mm$$

The gap between the originally calculated catalyst length and the corrected value is so huge, that it can have dramatic consequences on the test result. A catalyst size of approximately 70/ 70/ 70 mm should have been chosen with a catalyst volume of 351000 mm^2.

Results and Discussion

Summery for all test:

1) Max temperatures achieved in the system for all tests are:
    - T_{inlet} = 363,0°C
    - $T_{reactor}$ = 305,0°C
    - T_{outlet} = 278,8°C
2) Max temperature is achieved with a flowrate of 1000 l/h and an oven temperature of 600°C
3) Max NO reduction rate of 33% is registered at $T_{reactor}$ = 298°C. It is achieved with the following parameter set:
    - Muffle oven temperature 600°C
    - 900 l/h synthetic air
    - 37 l/h NO+N2
    - 37 l/h NH_3+N2
    - gas mixture NO-concentration - 1180 ppm

    The flow component share matrix is presented below and yields the total flow of 900 l/h:

	Flow share	Component share %	Component share l/h	Component share of total flow of 900 l/h
NO	NO+N_2 total	NO % flask	NO flow	NO % total
	37 l/h = 4,11%	0,03	1,11 l/h	0,123 %

NH_3	NH_3+N_2 total	NH_3 % flask	NH_3 flow	NH_3 % total
	37 l/h= 4,11%	0,03	1,11 l/h	0,123 %

O_2	Synt. Air	O_2 % flask	O_2 flow	O_2 % total
	826 l/h = 91,78%	0,13	107,38 l/h	11,93%

The O_2 / NO / NH_3 proportion is pretty close to theoretically evaluated values. NO concentration is within the reference window.

4) NO-reduction of 22% is registered at as low temperatures as 268°C. Compared to MECMAR's experience however, these results are far from optimal: MECMAR are claiming to have achieved 100% NO_x reduction at as low exhaust temperature as 280°C.

There are several uncertainties that could lead to the obtained test results. Some of the factors are accounted for while others are based on pure assumptions.

System restrictions and limitations occurring during testing:

a. *Thermal instability*. The temperature inside the reactor is almost half of that inside the oven, which indicates a lot of heat is lost over the pipe length from the oven to the reactor and partially from the reactor itself. As a result, a temperature of 600°C in the muffle oven gives a reactor temperature of 305°C. For this reason, flow rates need to be kept high to maintain temperature, (900-1000 l/h). Higher flowrates could have been used, but the flowmeters have an operating limit of 1000 l/h

b. *Muffle oven operation limits.* The highest temperature the muffle oven can deliver is 600 °C.

c. *Limited amount of synthetic air.* Another limiting factor is the amount of synthetic air available for testing. 50 liters of pressurized synthetic air at 150 bar corresponds to 11 laboratory hours if using flowrate of 700 l/h and 8 laboratory hours if using flowrate of 900 l/h. With the system responding poorly to temperature change, it is time-consuming to monitor reduction rates even with small temperature adjustments (within a temperature range of 250-300 °C). At temperatures close to 300°C, the system climbs only a few degrees every hour which is depleting the synthetic-air supply rapidly. This is considering that system preheating is done with pressurized air, not synthetic calibrated air. Because of the system's thermal instability, the only reasonable way to conduct tests are while the system temperatures are either climbing or sinking.

d. *Insufficiently sized catalyst.* An error in the theoretical calculations was discovered while analysing test data. Unfortunately, it was too late to do anything with the system as the testing phase is long past.

e. *Catalyst mesh.* The catalyst used for this project is originally intended for full scale SCR operations. The mesh might be too rough for a micro scale experiment like this. A finer mesh could possibly have improved reduction rates.

f. *Incorrect settings*: Because the system suffers from severe heat loss, the high flowrates are set to maintain the desired system temperatures rather than adjusted to fit the catalyst, resulting in reduction rates not optimized and test results.

Suggestions for future work

There are many aspects of the SCR-micro system that can be optimized. The system performed well considering a forced flowrate and a questionable catalyst, but has great potential for further improvements.

Following steps in further testing are advised:

1. For a more temperature stable system, the isolation can to be improved. This will allow for higher reactor temperatures along with less time spent heating the system.
2. If isolation is successfully improved, the following can further be examined:
    a. Increasing size of the catalyst in accordance with calculations corrected for errors.
    b. Varying flowrates, configured for the catalyst rather than the system.
    c. Increasing the amount of catalytic material. Using the same flowrate for comparison simplicity.
    d. Using the theoretical estimations initially intended for the system.
3. Different catalysts can be tested to see how the NO-reduction rate is affected. There are several different catalysts with different compositions, active components, space velocity, structure and mesh (pore density).
4. It is preferable to perform tests at either climbing or sinking temperatures for a more precise comparison, not both simultaneously.
5. It is preferable to monitor NO_2 and NO development separately as NO_2 concentrations can explain catalyst behaviour in some cases.
6. Different reducing agents can be tested, such as gaseous ammonia, urea-solutions and Amminex ASDS technology for mapping improvement range.
7. A measuring device can be fitted to check the NH_3 concentration after the reactor to get an indication of how much has reacted and for controlling ammonia slip.

It is important to remember the golden rules: “change only one parameter at the time” and “normalize collected data to referenced oxygen concentrations, if O_2 amounts vary from test to test”. The last rule applies to combustion related applications.

Conclusion

Pure ammonia as a reducing agent in marine SCR applications is an interesting idea, especially since todays urea solutions are unable to reduce NO_x at low exhaust gas temperatures. Leaving a gap for emissions to run freely when engines are operating at to low loads for urea to handle.

Investigating the possibilities of using anhydrous ammonia instead, by illuminating the subject, could be an important milestone in promoting anhydrous ammonia as an alternative. This was one of the main motivators when researching and testing the substance, to document its efficiency at low exhaust gas temperatures as a solution to the emission problem.

Gaseous ammonia was tested in a lab facility to investigate its efficiency at low temperatures. While tests confirm that gaseous ammonia has potential to reduce NO_x at low exhaust gas temperatures, results are not conclusive. Mainly because the SCR system is a micro scale version built for the purpose of this thesis. The matter of downsizing a full scale system is a challenging one. As a result, the system is not optimized or properly dimensioned. Due to time restrictions only the smallest of adjustments were possible. The system is still a well-designed construction capable of replicating marine SCR processes for testing purposes.

The thesis also spotlights the fact that ammonia has already been commercialised for marine SCR despite the reputation it has for being hazardous in regards to HSE. And it is, very hazardous, but it takes a pioneer to break the ice before the realization is made, that it can be done. That perhaps it was possible all along, and that perhaps anhydrous ammonia deserves a little more attention than it has gotten so far.

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Attachments

Attachment 1 – SCR Reactions

Attachment 2 – Gas Specifications in Order Confirmation

Attachment 3 - Principle diagram for Microscale SCR-setup

Attachment 4 – HORIBA PG-300 Data Sheet and Calibration Paper

Attachment 5 – Testo 350 Data Sheet and Calibration Paper

Attachment 6 – Flowmeter BROOKS GT-1350 Data Sheet

Attachment 7 – Fluk 2176A Data Sheet

Attachment 8 – SCR-MicroReactor, 2D model and 3D model. Reactor dimensions.

Attachment 9 – System tests

Attachment 1 – SCR Reactions

Attachment 1 - SCR reactions

Information in this attachment is quoted from the DieselNet Thechnology Guide, Diesel Catalysts, Selective Catalytic Reduction of the author W. Addy Majewski, Copyright 2005.

Positive pathways

Chemical reactions, expressed by Equations (1) to (5), represent desirable reactions which reduce NOx to elemental nitrogen.

$$(1)\quad 6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O$$

$$(2)\quad 4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$(3)\quad 6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

$$(4)\quad 2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

$$(5)\quad NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$

Equation (2) represents the dominant reaction mechanism.

Equation (5) represents the fast SCR reaction. This reaction is responsible for the promotion of low temperature SCR by NO_2.

Normally, NO_2 concentrations in most flue gases, including diesel exhaust, are low. In diesel SCR systems, NO_2 levels are often purposely increased to enhance NOx conversion at low temperatures.

Negative pathways for NO_2

In case the NO_2 content has been increased to exceed the NO level in the feed gas, N_2O formation pathways are also possible, as shown in Equation (6) and (7):

$$(6)\quad 8\ NO_2 + 6\ NH_3 \rightarrow 7\ N_2O + 9\ H_2O$$

$$(7)\quad 4\ NO_2 + 4\ NH_3 + O_2 \rightarrow 4\ N_2O + 6\ H_2O$$

Undesirable processes occurring in SCR systems include several competitive, nonselective reactions with oxygen, which is abundant in the system. These reactions can either produce secondary emissions or, at best, unproductively consume ammonia. Partial oxidation of ammonia, given by Equations (8) and (9), may produce nitrous oxide (N_2O) or elemental nitrogen, respectively. Complete oxidation of ammonia, expressed by Equation (10), generates nitric oxide (NO).

$$(8)\quad 2NH_3 + 2O_2 \rightarrow N_2O + 3H_2O$$

$$(9)\quad 4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$$

$$(10)\quad 4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$$

Ammonia can also react with NO_2 producing explosive ammonium nitrate (NH_4NO_3), Equation (11). This reaction, due to its negative temperature coefficient, occurs at low temperatures, below about 100-200°C. Ammonium nitrate may deposit in solid or liquid form in the pores of the catalyst, leading to its temporary deactivation.

$$(11)\quad (11)2NH_3 + 2NO_2 + H_2O \rightarrow NH_4NO_3 + NH_4NO_2$$

Ammonium nitrate formation can be avoided by making sure that the temperature never falls below 200°C. The tendency of NH_4NO_3 formation can also be minimized by supplying into the gas stream less than the precise amount of NH_3 necessary for the stoichiometric reaction with NOx (1 to 1 mole ratio).

Negative pathways for SO_2

When the flue gas contains sulfur, as is the case with diesel exhaust, SO_2 can be oxidized to SO_3 with the following formation of H_2SO_4 upon reaction with H_2O. These reactions are the same as those occurring in the diesel oxidation catalyst. In another reaction, NH_3 combines with SO_3 to form $(NH_4)_2SO_4$ and NH_4HSO_4, Equation (12) and (13), which deposit on and foul the catalyst, as well as piping and equipment. At low exhaust temperatures, generally below 250°C, the fouling by ammonium sulfate may lead to a deactivation of the SCR catalyst.

$$(12)\quad NH_3 + SO_3 + H_2O \rightarrow NH_4HSO_4$$

$$(13)\quad 2NH_3 + SO_3 + H_2O \rightarrow (NH_4)_2SO_4$$

Attachment 2

Gas Specifications in Order Confirmation

YARAPRAXAIR

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0915 Oslo Norge
Email:
Kundeservice_Ypx@Praxair.com

Telefon
04277
Telefax
Internett:

Foretaksregisteret
NO 945 772 042 MVA
23 70 70 00
www.yarapraxair.no

Ordrebekreftelse

Kunde 110811	Leveringsadresse
Høgskolen i Bergen Inndalsveien 28 NO-5063 BERGEN	

Bestillings Dato		**Ordre Nummer**	76795016
Bestillings Ref.	NOA 3410 - Harald Moen	**Dokument Dato**	23.03.2016
Leverings Bet.	EXW	**Leverings Uke**	17.2016
Betalings Bet.	Netto pr. 30 dager	**Valuta**	NOK
Brutto Vekt	115 KG	**Netto Vekt**	KG

1 av 1

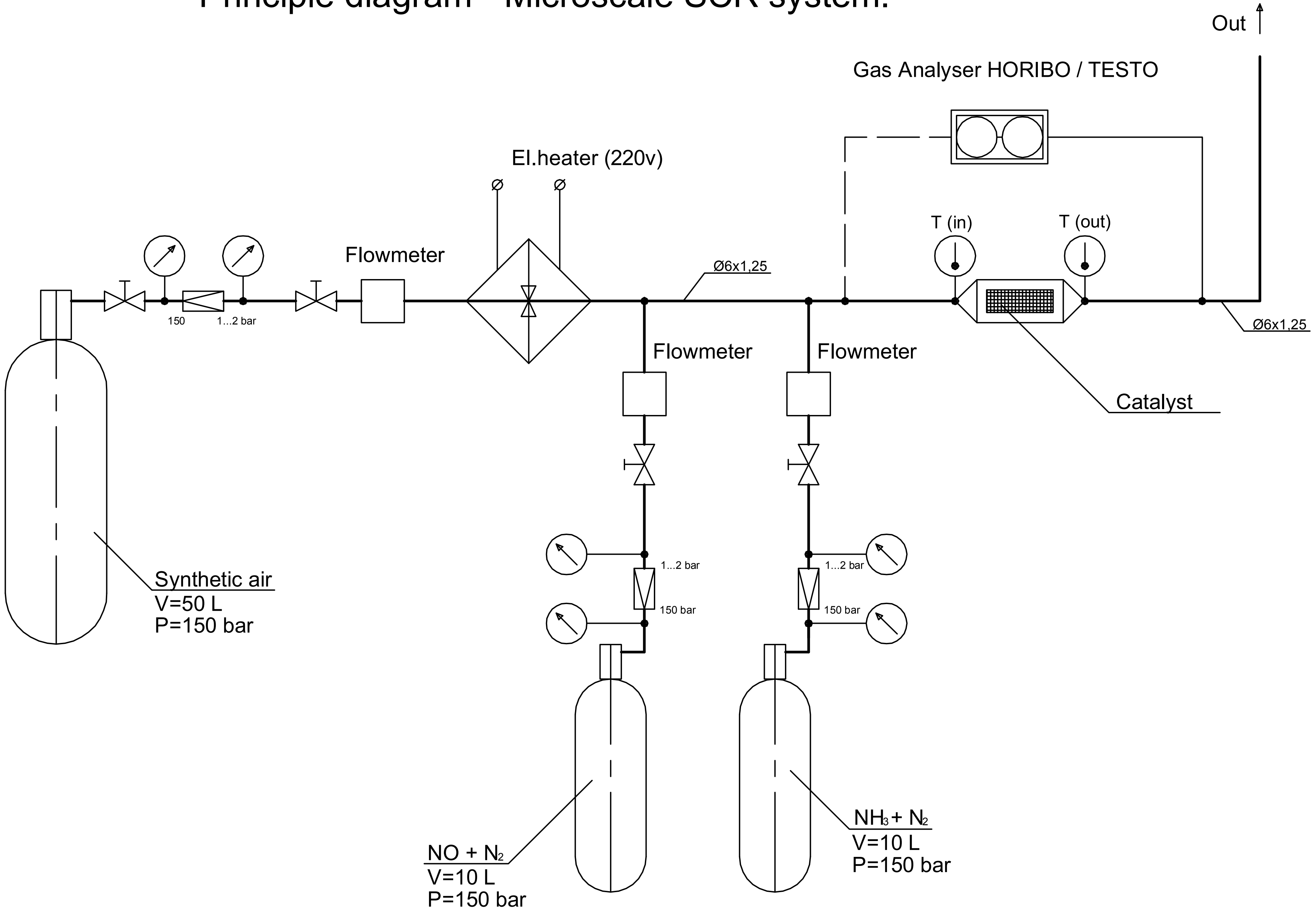
Pos	Art.nr Spesifikasjon	Antall	Enhets Pris	Beløp
	Ref. tilbud 27815			
0010	500063 -Kalibreringsgass O2 I N2 50 L Klasse 2 *13% Oksygen i Nitrogen* *Flaskeventil: DIN 477 No.10* *Standard fylletrykk: 150 bar* *SDS nr. RJ0006*	1 ST	4.632,00 per 1 ST	4.632,00
0020	500094 -NO Testgass 10 L Klasse 2 *3% NO i Nitrogen* *Flaskeventil: DIN 477 No.10* *Standard fylletrykk: 150 bar* *SDS nr. RJ1090*	1 ST	4.101,00 per 1 ST	4.101,00
0030	500099 -NH3 Testgass 10 L Klasse 2 *3% NH3 i Nitrogen* *Flaskeventil: DIN 477 No.10* *Standard fylletrykk: 150 bar* *SDS nr. RJ1091*	1 ST	4.101,00 per 1 ST	4.101,00
			Mva	3.208,50
			Øreavrunding	0,50
			Total Beløp	NOK **16.043,00**
	via F093 TESS Vest as avd Kokstad			

Levering i forhold til Yara Praxair's Alminnelige Forretningsvilkår
Sikkerhetsdatablader kan hentes på:
http://www.yarapraxair.no/ressurs-bibliotek/sikkerhetsdatablad
for Yara Praxair
Elin Bråtane

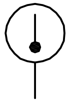
Attachment 3

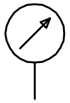
Principle diagram for Microscale SCR-setup

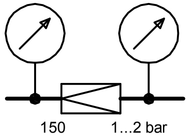
Principle diagram - Microscale SCR system.



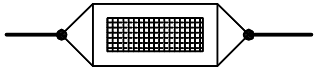
Symbol list

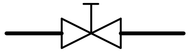

Termometer (Fluk 2176A)

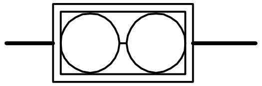

Manometer (AGA, Yara, DruVa)

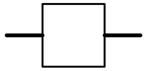


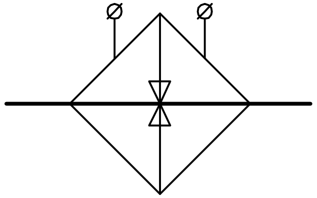
Reducer with manometers (AGA, Yara, DruVa)


SCR - Reactor


Check valve (Swagelok)


Gas Analyser HORIBO / TESTO


Flowmeter (BROOKS GT-1350)


El.heater (220v)
Carbolite Furnace Eurotherm 91

Attachment 4

HORIBA PG-300 Data Sheet and Calibration Paper

HORIBA
Process & Environmental

HORIBA celebrates its 60th anniversary in 2013.
One past, One future, One HORIBA

Portable Gas Analyzer

PG-300 Series

$NOx-SO_2-CO-CO_2-O_2-CH_4$

Precision analyses, anywhere.

ISO9001 JQA-0298
ISO14001 JQA-E-90039
OHSAS18001 JQA-OH0068
IMS
HORIBA Group is operating Integrated Management System

Measurement So Easy It's Almost Instinctive

Portable and lightweight with laboratory-level precision.

The New Possibilities of Gas Analysis Begin with "Precision Mobility"

For situations when you can only take measurements in the field, but you want the same precision that you get in the laboratory: Horiba presents the PG-300 Portable Gas Analyzer. The PG-300 offers the same accuracy and reliability of laboratory measurements in a portable and durable unit that is 20%lighter with a faster response time than existing models. With less warm up time required, high visibility touch screen, accuracy in measuring five crucial components in the field and the durability to facilitate mobile measurement, the PG-300 is the analyzer of the future.

Portable Gas Analyzer

PG-300 Series

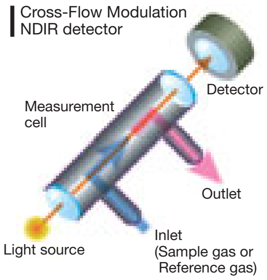
$NOx-SO_2-CO-CO_2-O_2-CH_4$

Functions Advanced measurement needs met with advanced functions.

- Cross-Flow Modulation type detector
- Capable of measuring methane (CH_4)
- Less warm-up time
- Timer Function
- Data management with Ethernet and LAN
- SO_2 reduced response time
- Multi languages and Certificates

Cross-Flow Modulation advanced efficiency of NDIR analysis

In PG-300, Cross-Flow Modulation is newly applied to SO_2, CO, and new CH_4 analyzers. With Cross-Flow Modulation NDIR method, sample gas and reference gas flow into a single measurement cell switching one by one, and it brings about advantages that no optical adjustment is required, the zero point is kept stable, and the sample cell remains clean and it reduces span drift. The equipments will be kept safe for a long time as well. Cross-Flow Modulation Chemiluminescence detection method is already introduced for NOx analyzer in previous model and has the same effects as aforesaid analyzers.



Capable of measuring methane (CH_4) for expanded options

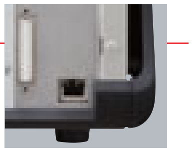
Improving on previous models, the new PG-300 is equipped with a methane (CH_4) analyzer that is ideally suited for many current and emerging applications such as biomass combustion.

CH_4 248.8
CH_4 235.6

Ethernet communication facilitates data management*1

Standard Ethernet interface for connection to LAN environment enables real-time data import.

Collecting data over LAN network*1



Following network connectivity on the PG-300, data uploads and status checking can be performed remotely over the network.

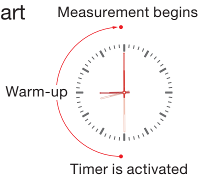
*1 Requires separate software.

Warm-up time has been signigicantly reduced

Reducing from 1 hour to 30 minute warm-up time , the PG-300 increases its readiness time for measurement.

Timer function enables automatic instrument start and sleep modes

For example, setting the PG-300's automatic start time 30 minutes ahead of when measurements are needed eliminates your need to wait for the instrument to warm up; it will be ready when you are. There is also a sleep mode that reduces power use when the unit is idle.



Reduced response time for SO_2 analyzer

The response time of the SO_2 analyzer is faster than on previous models, increasing the overall measurement performance.

Multi languages and Global certificates

<Languages>
English, Chinese, Korean, German, French, Russian, and Japanese
<Certificates> Acquired: TÜV(EU), China, Korea, Japan
To be acquired: MCERTS(UK), GOST(Russia)

Field × Lab

Rugged Lightweight Design

20% lighter than previous models, the PG-300 is your choice for portability. Side guards are available to prevent unexpected impacts during transport.
PG-300 provides full support for your field measurements and analyses.

Lightweight makes it easy to transport.

Easy Operation

Simple and intuitive, making it easy to operate in the lab or out in the field.

- SD™ memory card slot
- Screen capture function
- On screen guidance
- Color trend graph

Equipped with an SD™ memory card slot to enable data to be saved immediately

SD™ memory card slot accessed from the front of the instrument enables necessary data to be saved on the spot in the universal CSV format.

The SD™ card slot is located on the front of the unit for easy access. ▶

Screen capture function enables data to be saved immediately as a bitmap image onto the SD memory card.

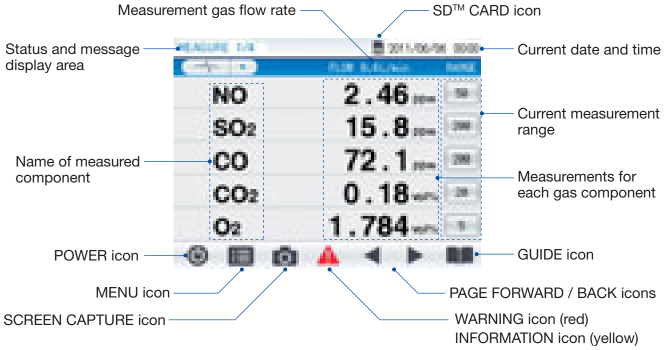
No paper or pen required - simply touch the SCREEN CAPTURE icon and a screen shot is stored in memory.

On screen guidance function allows you to confirm review operating procedures instantly

The simple guidance function provides assistance when you forget how to perform an operation. You can review regular operational procedures or important points right on the screen.

LCD touch screen improves ease of operation

All operations, including calibration, measurement and saving on-screen data, can be performed on the touch screen. The high visibility color display makes it easy to check the status.



Easy real time analysis using the color trend graph

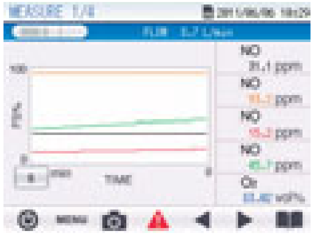
A convenient color trend graph function enables gas component trends as a function of time to be confirmed at a glance.

[Sample display screens]

When you press the GUIDE button...

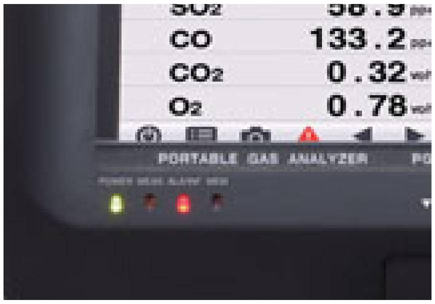
...and then the screen shows information that you can handle at the current operation.

[Color trend graph]



[Calibration screen]

Note: Calibration requires separately purchased calibration gas and pressure regulator.



- Front panel LED's clearly display unit status.

- Easy-to-operate unit yields precision analysis results.

- Color LCD touch screen with high visibility display.

- SD is a trade mark for SD-3C, LLC.

Analyzer Specifications

Type of Analyzers	2 component Analyzer		3 component Analyzer			4 component Analyzer	5 component Analyzer	2 component Analyzer	4 component Analyzer
Model	PG-320	PG-325	PG-330	PG-335	PG-337	PG-340	PG-350	PG-324	PG-344
Components Measured	CO/CO_2	NOx/O_2	$CO/CO_2/O_2$	$NOx/CO/O_2$	$NOx/SO_2/O_2$	$NOx/CO/CO_2/O_2$	$NOx/SO_2/CO/CO_2/O_2$	CH_4/CO_2	$CH_4/CO/CO_2/O_2$
Analysis Principle	NOx: Cross-Flow Modulation Chemiluminescence Detection Method SO_2,CO,CH_4 : Cross-Flow Modulation Non-Dispersive Infrared Absorption Method CO_2 : Non-Dispersive Infrared Absorption Method O_2* : Galvanic Method, Zirconia Method								
Ranges	NOx : 0-25/50/100/250/500/1000/2500 ppm SO_2 : 0-200/500/1000/3000 ppm CO : 0-200/500/1000/2000/5000 ppm CO_2 : 0-10/20/30 vol% O_2 : 0-5/10/25 vol%							CH_4 : 0-2000/5000 ppm CO : 0-2000/5000 ppm CO_2 : 0-5/10/20 vol% O_2 : 0-5/10/25 vol%	
Repeatability	±0.5% of Full scale (NOx : ≧ 100 ppm range / CO : ≧ 1000 ppm range) ±1.0% of Full scale (Except above)							±1.0% of Full scale	
Linearity	±2.0% of Full scale								
Drift	±1.0% of Full scale / day (For SO_2 analyzer only : ±2.0% of Full scale / day)							±1.0% of Full scale / day	
Response Time (T_{90})	Analyzers except SO_2 analyzer : 45 sec. or less (From sample inlet, response time setting of electrical system : 10 sec.) SO_2 analyzer : 180 sec. or less (From sample inlet, response time setting of electrical system : 10 sec.) Moving average selectable (10 or 30 sec.)								
Sample Gas Flow Rate	Approx. 0.5 L/min.								
Display	Measurement (3 or 4 digit display), range, flow rate, etc.								
Output	DC 4-20 mA (non-insulated) / Ethernet								
Warm-up Time	With 30 min. warm-up, ±2.0% of Full scale / 2 hours								
Data Saving	SD™/SDHC™ memory card								
Ambient Temperature	0□ to 40□ / 32°F to 104°F								
Ambient Humidity	85% R.H. or less								
Power	AC 100 V - 120 V, 220 V - 240 V								
Power Consumption	Approx. 160 VA in a steady state								
Outline	260 (W) x 520 (D) x 260 (H) mm 10.2" (W) x 20" (D) x 10.2" (H) (without side guards) 300 (W) x 520 (D) x 260 (H) mm 11.8" (W) x 20.5" (D) x 10.2" (H) (with side guards) (projections excluded)								
Mass	Approx. 13 kg to 15 kg / Approx. 29 lb to 33 lb								
Sample Gas Conditions	Temperature : Less than 40°C / 104°F, H_2O Content : Standard or less at ambient temperature, Dust : 0.1 g/m^3 or less, Pressure : ±0.98 kPa								

* Paramagnetic Method is available. Please contact Horiba representative in your area for the details.

- SD is a trade mark for SD-3C, LLC.
- TAKE GREAT CARE WHEN HANDLING SAMPLE GASES CONTAINING TOXIC OR FLAMMABLE GASES. TAKE MEASURES SUCH AS PROVIDING ADEQUATE VENTILATION, INSTALLING GAS DETECTORS, AND REMOVING IGNITION SOURCES IN THE WORKING AREA.
- THE PG-300 SERIES IS NOT EXPLOSION-PROOF. DO NOT USE THIS PRODUCT IN A HAZARDOUS LOCATION OR FOR MEASUREMENT OF SAMPLE GASES IN EXPLOSIVE ATMOSPHERES (MIXTURE OF A COMBUSTIBLE GAS AND AIR WITHIN THE FLAMMABILITY LIMITS). HORIBA, LTD. AND ITS AFFILIATES ARE NOT LIABLE FOR EMERGENCIES CAUSED BY LEAKAGE OR MISHANDLING OF SUCH GASES.

Standard Accessories

Part Name	Specifications	Quantity
Filter element	For reference line	24
Signal cable	For analog output (2 m) with connector	1
Power cord	2.5 m	1
Tube	ϕ6/ϕ4PTFE tube 0.12 m (for mist catcher short)	1
Tube	ϕ6/ϕ4PTFE tube 5 m (for sample)	1
Tube	ϕ9/ϕ5 Imron tube 5 m (for exhaust)	1
Tube	ϕ9/ϕ5 Imron tube 1 m (for drain discharge)	1
Joint	ϕ6 straight (for sample tube)	1
Cover	Dust cover (for storage)	1
SD™ memory card	512 MB	1
Galvanic O_2 cell	R22-A	1*

- Separate tubing and joint are required if a pretreatment unit is added.

* Differs depending on model.

Replacement parts

Replacement part intervals assume 8 hours of operation per day.
Replacement interval may be more frequent depending on measurement gas conditions and use conditions.

[Consumable Items]

Name	Replace Every (general guideline)	Notes
Mist catcher	3 months	MC-025
Scrubber	3 months	For reference line
Air filter element	2 weeks	For reference line

[Replacement Parts]

Name	Replace Every (general guideline)	Notes
Pump	1 year	Replace when broken
NOx converter catalyst	1 year	For NOx analyzer*
Zero gas purifier unit catalyst	1 year	*
Ozone generator	1 year	For NOx analyzer*
Deozonizer	1 year	For NOx analyzer*
CR2032 battery	5 years	For clock backup
Galvanic O_2 cell	1 year	Replace when broken*

* Differs depending on model

Options

Additional optional components expand the PG-300 portable analyzer capabilities.

Drain separator

Drain pot

Drain separator unit ▌Drain pot unit

When the gas sample includes moisture ranging from ambient temperature saturation to 40 °C saturation, a Drain Separator and Drain Pot are installed at the stage before the analyzer unit.

Drain separator unit / Drain pot unit specifications

Model		DS-300 (drain separator)	DP-300 (drain pot)
Sample conditions (at feed port)	Temperature	0□ to 40□ / 32°F to 104°F	
	Moisture	Ambient temperature saturation ~ 40□ / 104°F saturation	
	Dust	0.1 g/m^3 or less	
	Pressure	±0.98 kPa	±4.9 kPa

Electronic cooler unit

When the gas sample includes moisture exceeding 40 °C saturation, or when conducting continuous measurement (for five days or less), a thermoelectric cooler is installed at the stage before the analyzer unit. The electronic cooler unit can also accommodate low-temperature SO_2 measurements.

Electronic Cooler unit specifications

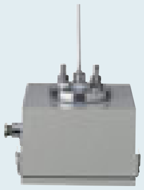
Model	PS-300
Material in contact with gas	Ti, SUS, PVC, PTFE, FKM, PVDF, PP, Glass
Inlet sample	Approx. 2 L/min
Dehumidify	15□ / 59°F saturated
Usable temperature	0□ to 40□ / 32°F to 104°F
Usable humidity	85% or less
Power	100/110/115/120/220/230/240 V AC, 50 Hz/60 Hz (depend on specifications)
Outline	260(W) x 375(D) x 235(H) mm / 10.2"(W) x 14.7"(D) x 9.2"(H) (except for protrusion)
Mass	Approx. 12kg / 26.46 lb
Sample gas condition	Temperature Ambient temperature; Dust: 0.1g/m^3 or less; Moisture: $H_2O \leqq 20$ vol%; Pressure: ±4.9 kPa (8 mm O.D./6 mm I.D. PTFE tube, within 50 m)

[Halogen scrubber] (optional)

The Halogen scrubber can be built into the electronic cooling unit as an option. It is used to prevent corrosion of the cells, tubes and other internal components when the gas analyzer is operated at waste incineration facilities or in other situations where the gas sample includes Cl_2.

Primary side filter probe

Either of two types may be selected depending on use.



Flue probe

Simple probe

Primary side filter probe specifications

Model		Simple probe	SE3 (flue probe)
Probe length (standard)		10 cm / 3.937"	1 m / 3'28"
Sample conditions (at feed port)	Temperature	0□ to 50□ / 32°F to 122°F*	0□ to 120□ / 32°F to 248°F
	Moisture	40 vol% or less	
	Dust	0.1 g/m^3 or less	
	Pressure	±2.94 kPa	

*At flange inlet

Note:

- Please contact Horiba if the analyzer will be used in environments in which the temperature exceeds 120 °C.
- Please contact Horiba in case of use under the environmental that the pressure condition is other than ±2.94 kPa.

Accessory

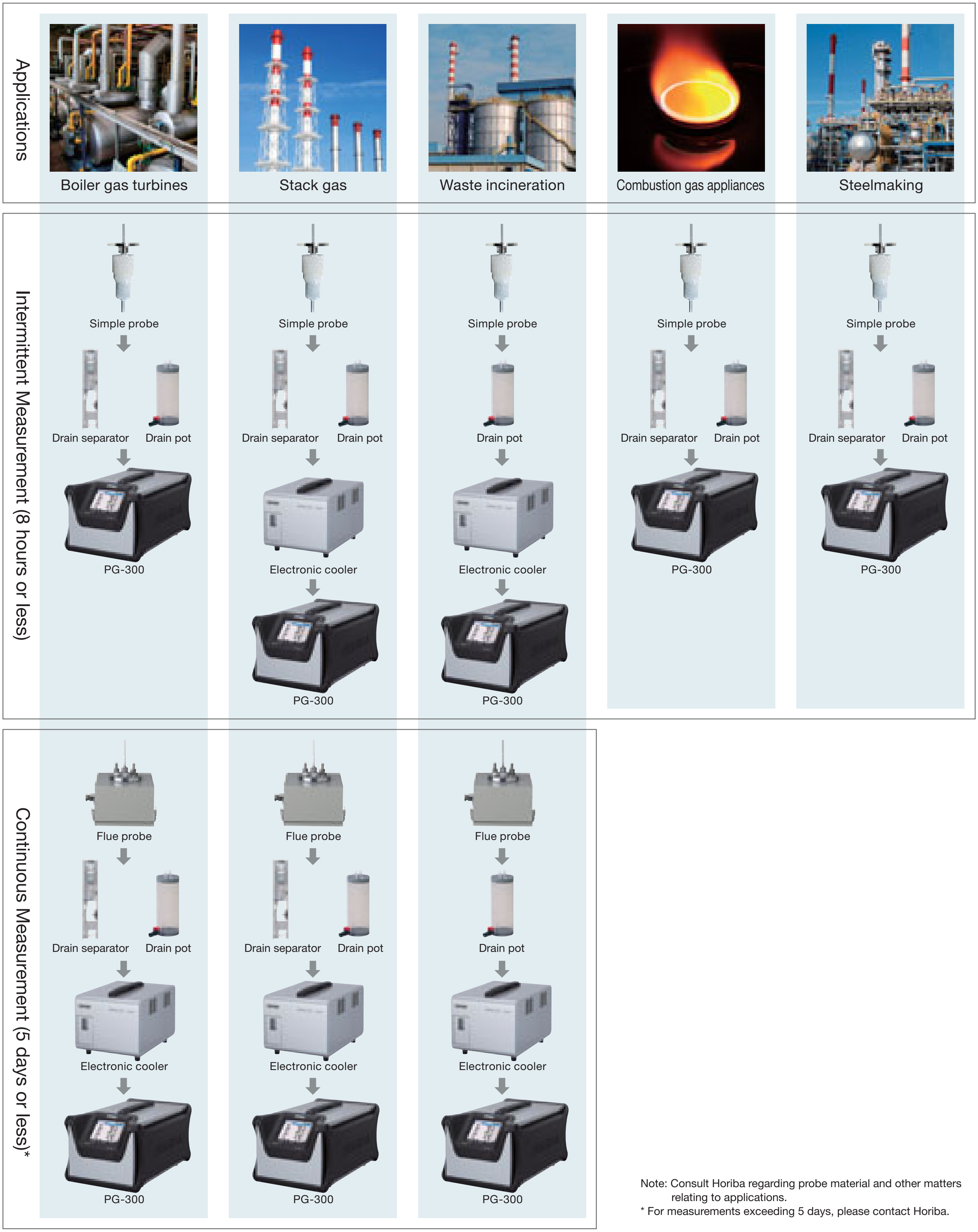
PG-300 Carrying Case

Specifications

Model	PG-300 Carrying Case
Outline	630 (W) x 492 (D) x 352 (H) mm 24.8" (W) x 19.3" (D) x 13.8" (H)
Mass	12kg / 26.4lb
Materials	Case: Polypropylene Interior: Ethylene foam
Equipments	Carry handle, casters, handles, etc.

Please select the ideal combination according to your needs.

Sample Preprocessing Unit (optional) Uses



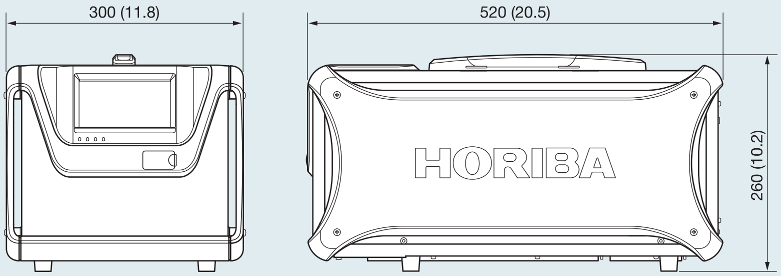
Applications	Boiler gas turbines	Stack gas	Waste incineration	Combustion gas appliances	Steelmaking
Intermittent Measurement (8 hours or less)	Simple probe ↓ Drain separator, Drain pot ↓ PG-300	Simple probe ↓ Drain separator, Drain pot ↓ Electronic cooler ↓ PG-300	Simple probe ↓ Drain pot ↓ Electronic cooler ↓ PG-300	Simple probe ↓ Drain separator, Drain pot ↓ PG-300	Simple probe ↓ Drain separator, Drain pot ↓ PG-300
Continuous Measurement (5 days or less)*	Flue probe ↓ Drain separator, Drain pot ↓ Electronic cooler ↓ PG-300	Flue probe ↓ Drain separator, Drain pot ↓ Electronic cooler ↓ PG-300	Flue probe ↓ Drain pot ↓ Electronic cooler ↓ PG-300		

Note: Consult Horiba regarding probe material and other matters relating to applications.

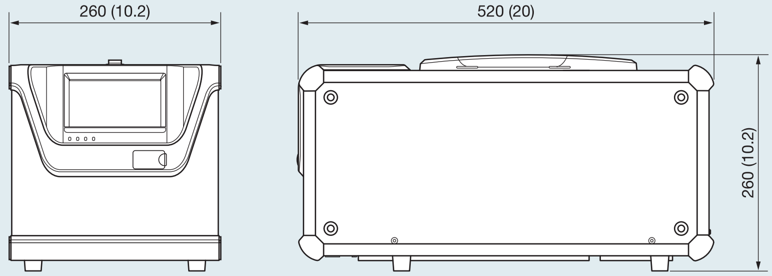
* For measurements exceeding 5 days, please contact Horiba.

External Dimensions Unit: mm (in)

- PG-300 Series Analyzer Unit



- PG-300 Series Analyzer Unit (Side guards excluded)



Please read the operation manual before using this product to assure safe and proper handling of the product.

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Bulletin:HRE-2879B

Printed in Japan TM-M(SK)53

HORIBA

検　査　票
TEST CERTIFICATE

当社の製品は、品質保証の国際規格ＩＳＯ　９００１の品質システム【審査機関：（財）日本品質保証機構（登録証No.ＪＱＡ－０２９８）】に従い生産されており、定められた作業標準及び検査規格に基づく適切な品質管理及び検査が行なわれ、結果は仕様を満足しております。

We certify that this product is thoroughly inspected and confirmed to meet all of its necessary criteria specified in Inspection Standard. HORIBA LTD is operating a Quality Management System which complies with all of the requirements of ISO 9001.(Certificate Number JQA-0298)

検査者
INSPECTOR
氏名：
NAME M. Fukai

検査責任者
SUPERVISOR
氏名：
NAME T. Toyonaka

HORIBA Ltd. Kyoto Japan
Quality Control Dept.
株式会社 堀場製作所
品質保証統括センター

Customer: Hakon Rygh

TEST REPORT

NO /SO_2 / CO / CO_2 / O_2 Analyzer, HORIBA PG 350E

Serial number:	7ADNV53F
Year of Construction:	28.05.2014
Ambient Air Pressure:	995hPa
Sample Flow Rate	0,5 l/min

NO Concentration	456,0 ppm
SO_2 Concentration	181,5 ppm
CO Concentration	900,0 ppm
CO_2 Concentration	8,95 vol%
O_2 Concentration	20,95 vol%

Calibration factor	NO	ZERO	0	Span	0,9734
Calibration factor	SO_2	ZERO	0	Span	1,0686
Calibration factor	CO	ZERO	0	Span	1,0159
Calibration factor	CO_2	ZERO	0	Span	0,9991
Calibration factor	O_2	ZERO	0	Span	0,9639

Test equipment	Reg. No.
Digital Multimeter	301320802
Digital Manometer, rel.	402320715
Digital Manometer, abs.	403320202

Quality Check ☒OK.

HORIBA Europe GmbH
18. Juli 2014
Quality Control

Date

42

QC Inspector

Signature

TEST REPORT

TRE00213A

A. Specifications

Model	PG-350E	
HGS No.	7ADNV53F	
Measuring Range	NOx	25/50/100/250/500/1000/2500 ppm
	SO$_2$	50/100/200/500 ppm
	CO	60/100/200/500/1000 ppm
	CO$_2$	10/20/30 vol%
	O$_2$	5/10/25 vol%
Power	AC 100～240V 50/60Hz	
Output	DC 4～20mA·LAN・RS-232C	

B. Test Results

1. Appearance and Construction ---------- Good

2. Function and Operation ---------- Good

3. Performance (Note: %FS means percentage of full scale.)

1) Repeatability ---------- Good

Parameter	NOx	SO$_2$	CO	CO$_2$		
Test range	25 ppm	50 ppm	60 ppm	10 vol%		
Deviation	±0.2 %FS	-0.2 %FS	±0.1 %FS	-0.1 %FS		
Criteria	within ±1.0%FS (within ±0.5%FS for higher conc. than 1000ppm of CO and 100ppm of NOx)					

2) Linearity ---------- Good

Parameter	NOx	SO$_2$	CO	CO$_2$		
Test range	2500 ppm	500 ppm	1000 ppm	30 vol%		
Deviation	-0.5 %FS	0.4 %FS	-0.9 %FS	0.3 %FS		
Criteria	within ±2.0%FS					

3) Drift ---------- Good

Parameter	NOx	SO$_2$	CO	CO$_2$		
Test range	25 ppm	50 ppm	60 ppm	10 vol%		
Zero (/day)	0.2 %FS	1.1 %FS	-0.3 %FS	-0.2 %FS		
Criteria	within ±1.0%FS/day (within ±3.0%FS/day for SO$_2$, within ±2.0%FS/day for CO)					
Span (/day)	-0.4 %FS	0.4 %FS	0.8 %FS	0.2 %FS		
Criteria	within ±1.0%FS/day (within ±3.0%FS/day for SO$_2$, within ±2.0%FS/day for CO)					

4) Response Time ---------- Good

Parameter	NOx	SO$_2$	CO	CO$_2$		
Test range	25 ppm	50 ppm	60 ppm	10 vol%		
Td	22 s	18 s	19 s	17 s		
T90	8 s	13 s	8 s	9 s		
Td+T90	30 s	31 s	27 s	26 s		
Criteria(Td+T90)	smaller than 45s from sample inlet (smaller than 180s for SO$_2$)					

5) Noise level (less than 1.0%FS p-p , less than 2.0%FS p-p for SO$_2$ and CO) ---------- Good

6) Interference with coexisting gas ---------- Good
(within ±2.0%FS, however higher conc. range than 200ppm for CO is within ±1.0%FS, lower conc. Range than 200ppm for SO$_2$ and CO is within ±4.0%FS and C$_3$H$_8$ interference on SO$_2$ is within ± 4ppm, and CH$_4$ interference on SO$_2$ measurement is within ±3.0%FS)

7) Supply Voltage Fluctuation ---------- Good

Parameter	NOx	SO$_2$	CO	CO$_2$		
Test range	25 ppm	50 ppm	60 ppm	10 vol%		
Influence	0.1 %FS	-0.1 %FS	-0.3 %FS	0.0 %FS		
Criteria	within ±1.0%FS by ±10% fluctuation from rating voltage					

4. Withstand voltage (AC1400V between AC and E terminals for 5 seconds) ---------- Good

5. Insulation Resistance(more than 5MΩwith DC1000V) ---------- 2000 MΩ ---------- Good

6. Leakage(less than 500Pa/5min. with 15kPa pressure) ---------- -200 Pa ---------- Good

7. NOx converter efficiency(more than 95%) ---------- 95.6 % ---------- Good

C. Overall Judgment ---------- Pass

Date : 28 May 2014

Inspected by : M. Fukai

Approved by : T. Toyonaka

Temperature 25 ℃ Humidity 55 %RH

Consignor
Scientific and Technical Gases Ltd
Units 1 & 2, Speedwell Road
Parkhouse Industrial Estate East
Newcastle-Under-Lyme
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F: +44 1782 564906

SPECIALISTS IN
• GAS MIXTURES •

Certificate of Composition S70516 - 1

N2 (5.0)

112DAN2N50

Customer : Hakon Rygh A.S
Order No. : B14070/AJ
Our Ref S70516
Nett Weight 0.12

Cylinder No. 33039
Cylinder Valve C10
Cylinder Size 112DA
Gross Wt (Kg) 1.5

Component	**Requested Values**	**Certified Values**
Nitrogen (5.0)	99.999 %	99.999 %

Pressure: 1000 psi Volume:1.55 ltr

Please note all units are in mol % and mixture accuracy

Relative Mixtures traceable to standards calibrated at the National Physical Laboratory, Teddington, Middlsesex, England. The UK National Physical Laboratory (NPL) Standards are internationally recognised and directly equivalent to the USA N.I.S.T Standards.

Certified by: Mark Whitmore

Manufactured Date: 11-Jun-2014

Valid until: 11-Jun-2017

UN1066 Nitrogen, compressed2.2

All Gas Mixtures that are quoted with a balance of Air contain 20.9% (+/-2%) Oxygen relative to the overall Gas Mixture

The gases contained in this cylinder are not breathing gases.
DO NOT INHALE

Consignor
Scientific and Technical Gases Ltd
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Newcastle-Under-Lyme
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F: +44 1782 564906

SPECIALISTS IN
• GAS MIXTURES •

Certificate of Composition S70517 - 1

450ppm NO // N2

112DANON-0450

Customer : Hakon Rygh A.S		Cylinder No.	022525
Order No. : B14070/AJ		Cylinder Valve	C10
Our Ref	S70517	Cylinder Size	112DA
Nett Weight	0.12	Gross Wt (Kg)	1.5

Component	Requested Values	Certified Values
Nitric Oxide	450 ppm	450 ppm
Nitrogen	Balance	Balance

Pressure: 1000 psi Volume:1.55 ltr

Please note all units are in mol % and mixture accuracy +/- 2%
Relative Mixtures traceable to standards calibrated at the National Physical Laboratory, Teddington, Middlsesex, England. The UK National Physical Laboratory (NPL) Standards are internationally recognised and directly equivalent to the USA N.I.S.T Standards.

Certified by: Frank Williams

Manufactured Date: 10-Jun-2014

Valid until: 10-Jun-2015

UN1956 Compressed Gas N.O.S.2.2

All Gas Mixtures that are quoted with a balance of Air contain 20.9% (+/-2%) Oxygen relative to the overall Gas Mixture

The gases contained in this cylinder are not breathing gases.
DO NOT INHALE

Consignor
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Parkhouse Industrial Estate East
Newcastle-Under-Lyme
Staffordshire, ST5 7RG. UK
T: +44 1782 566897
F: +44 1782 564906

Certificate of Composition S70513 - 1

112DA3GASN-0113 ***180ppm SO2, 900ppm CO, 4.5% CO2 // N2***

Customer : Hakon Rygh A.S
Customer Order No. : B14070/AJ
Batch Ref : S70513
Nett Weight (kg) 0.12

Cylinder No. 27984
Cylinder Valve C10
Cylinder Size 112DA
Gross Weight (kg) 1.5

Component	Requested Values	Certified Values
Sulphur Dioxide	180 ppm	180 ppm
Carbon Monoxide	900 ppm	903.4 ppm
Carbon Dioxide	4.5 %	4.51 %
Nitrogen	Balance	Balance

Pressure: 1000 psi Volume: 1.55 ltr

Please note all units are in mol % and mixture accuracy +/- 2%
Relative Mixtures traceable to standards calibrated at the National Physical Laboratory, Teddington, Middlsesex, England. The UK National Physical Laboratory (NPL) Standards are internationally recogonised and directly equivalent to the USA N.I.S.T Standards.

Certified by: Leon Dailey

Manufactured Date: 4-Jun-2014
Valid until: 4-Jun-2016
UN1956 Compressed Gas

All Gas Mixtures that are quoted with a balance of Air contain 20.9% (+/-2%) Oxygen relative to the overall Gas Mixture

The gases contained in this cylinder are not breathing gases.
DO NOT INHALE

Attachment 5

Testo 350 Data Sheet and Calibration Paper

We measure it. testo

testo 350.

For emission testing and combustion analysis.

Portable
Emission
Analyzer

The testo 350 Portable Emission Analyzer

The Standard for Emission Testing and Combustion Analysis

Whether you are testing for compliance or troubleshooting and tuning your combustion process, the testo 350 has everything you need. The **ultra-rugged construction**, coupled with a simple **intuitive operation,** and **innovative measurement technology,** sets the standard in emission testing and combustion analysis.

The 350's **housing, bump protection, and industrial connectors** enable it to **stand up to any field condition.** Simply click on the application icon and the analyzer automatically begins its setup process. The proper parameters, correct calculations, and real diagnostics are displayed in HD color.

The testo 350's **exclusive sensor design, patented gas paths, active sample conditioning, intelligent automatic data logging, and testing programs,** work together seamlessly providing a lightweight and simple-to-use emission monitoring solution.

Control Unit

Docked or remote operation via Bluetooth (up to 300 feet) or wired (up to 3,000 feet).

Bluetooth®

The testo 350 is built with rugged cam-lock connections and a simple USB interface.

Analyzer Box

Superior rugged construction.

Use it for testing:

EPA methods • CTM's - 030, 034 • ASTM - D6522 • State and Local Protocols

Unmatched Capability and Superior Testing Performance

Control Unit

Small in size, but big in capabilities

- Measurement interface provides a multitude of field configurations so testing is faster to set up and easier to perform
- Real-time color graphics
- Intuitive operation lets you view collected data in a graph or numeric values
- Use the control unit as your data storage device and download data to your computer at your convenience
- Push the fresh air button to purge instead of climbing a ladder to pull the probe
- Long-range (300 ft.) Bluetooth eliminates the need for long sample lines
- Integrated magnets for mounting to steel surfaces

Analyzer Box

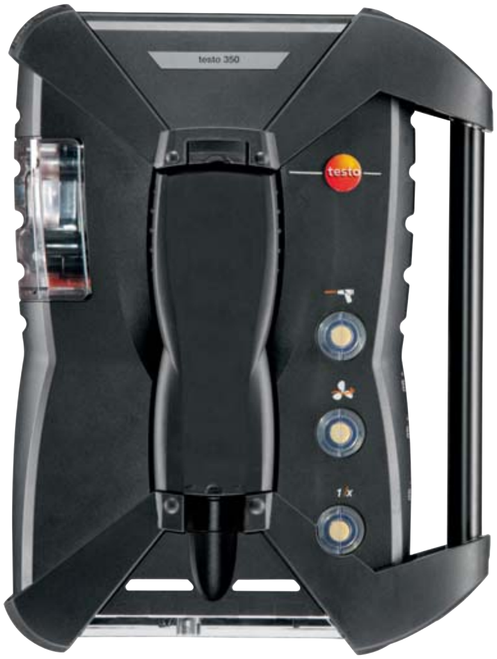
Where the measurement action begins

- Contains the pumps, sample conditioning, electronics, and up to six sensors
- Continuous sensor temperature monitoring for superior accuracy
- Thermoelectric (peltier) chiller (optional) conditions the gas sample as required by regulatory agencies.
- Protection in many forms, from rubber bumpers to components mounted in shock-resistant material

Measurement capabilities:

- O_2
- CO
- CO_{low}
- NOx
- CO_2
- NO
- NO_{low}
- NO_2
- SO_2
- H_2S
- HC
- Velocity
- Pressure
- And more...

Use the control unit of the testo 350 remotely from a comfortable location instead of up on the stack.



Control unit turned over and docked for safe transport.

Built for Superior Job Site Performance...

Proven technologies provide more testing versatility.

- Sensing technologies, such as electrochemical and infrared combined to offer **long-term measurement stability** and superior response.
- Digital sensors provide numerous site benefits, including:
  - Calibration history
  - Temperature compensation
  - Interference filter (ppm hours)
- **Advanced temperature monitoring** combined with new thermal control strategies result in unwavering results and confidence in the measurement.
- **Smarter diagnostics** provide more information. When testing conditions are not correct, detailed messages explain the reason and corrective action.

Designed for the job site with features to make testing easier.

- The **flow-controlled pump** and gas paths (built with non-reactive materials) **sets the standard in sampling**. No need to fumble with valves and flow meters because the 350 automatically corrects for positive or negative pressure. Combine these with sample hoses that utilize high-velocity sample transport and you get faster response and better sample integrity.
- The **thermoelectric** (Peltier-type) **sample conditioner** and peristaltic pump automatically removes moisture and provides a dry sample for more accurate results for **EPA testing & compliance**.
- The **dilution system** has proven to be essential in many applications where high concentrations are encountered. For example, the system ensures that CO measurements on rich burn engines are accurate and account for cross sensitive gases (H_2).

And Simple Field Service

The 350's design lets you perform routine service with plug and play convenience - no tools are needed. Simply click out the sensors, battery, or pumps - it's that simple.

Pump with Automatic Flow Control

Automatic flow control and high capacity (sample to 50 ft. away). Sampling pump gives you more power to maintain constant sample flow. No need to adjust valves and gauges. The pump will maintain flow rate for best sensor response and accuracy.

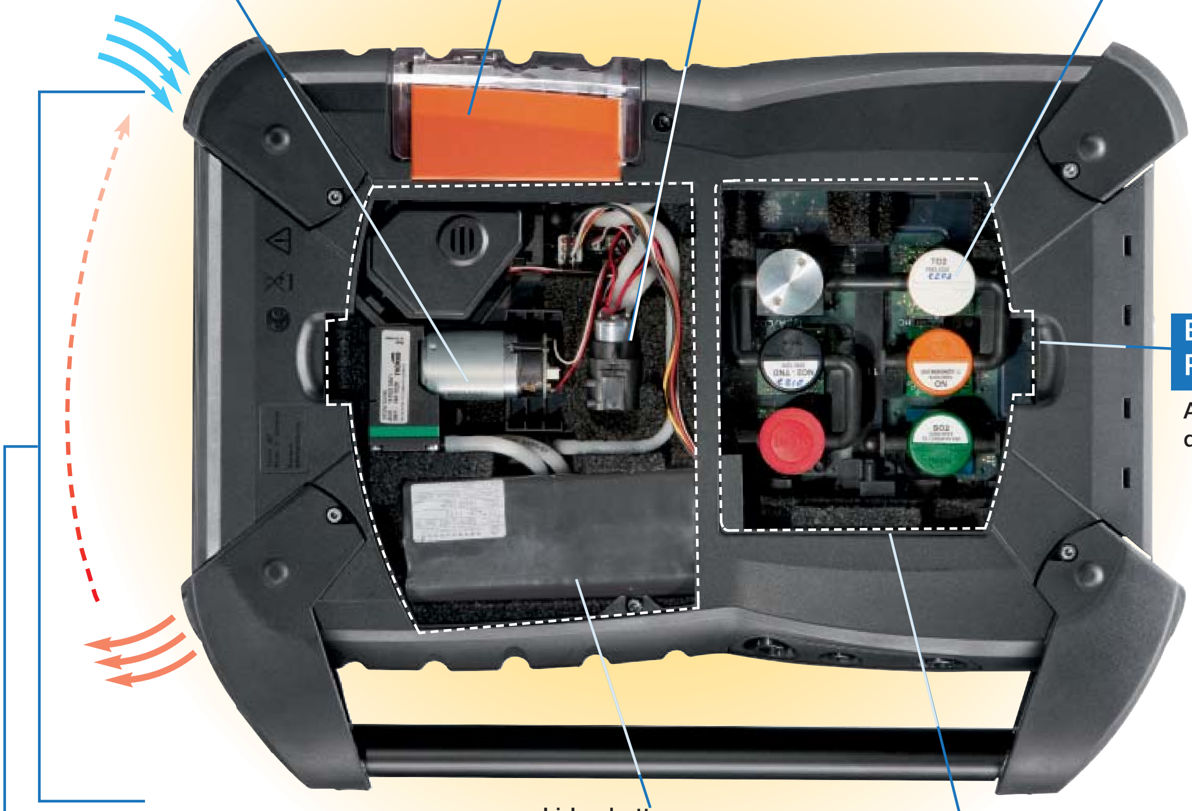
Fresh Air and Dilution Pump

Draws fresh air into purging sensors and to dilute high concentration gas samples.

Plug and Play Sensors

The digital platform provides easy swapping and sensor change-outs. Field replaceable in seconds and no calibration needed, the sensor electronics maintain the calibration and other critical information. Quick change interference filters assure the highest accuracy.

Condensate Trap



Enhanced Temperature Control

Easy-Access Panels

Allows for quick servicing.

Li-Ion battery

Cooling Loop

Enhances thermal control and analyzer efficiencies and is designed to isolate the electronics and sensors from harsh ambient conditions.

Separate Sensor Chamber

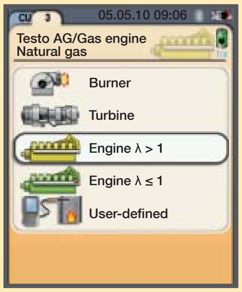
Ensures thermal stability and the highest accuracy. Minimizes temperature drift due to thermal changes.

Built for the Most Important Application – Yours...

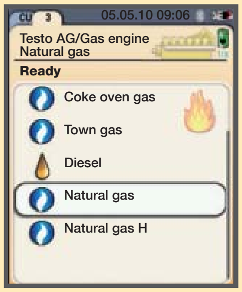
Knowing what you need, and what to expect, can challenge even the most experienced professional. But the **testo 350 removes much of the guess work with its intuitive application setup.**

To start testing, simply select the icon for your application and the analyzer will automatically set up the dilution system and the measurement parameters that you need. **The 350 makes testing easier in just four simple steps!**

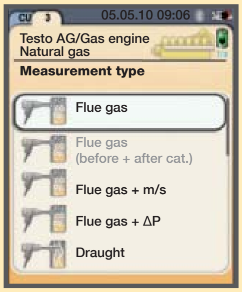
Four simple steps to testing...



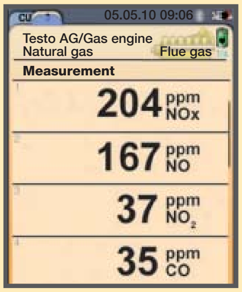
Select an Application



Select a Fuel



Select Test Type



204 ppm NOx
167 ppm NO
37 ppm NO_2
35 ppm CO

Start Measurement

Engine testing

Rich-burn engine exhaust, when uncontrolled, can have wide concentration ranges and both CO and NO_x can fluctuate significantly. **The on-board CO dilution system will automatically set-up for optimum testing, perfect for a rich burn engine.** Lean-burn engines have different exhaust characteristics, but NO_2 can make up a significant portion of the total NO_x measurement. **The 350 measures both NO and NO_2 for proper lean-burn engine set-up.**

Due to high concentration, replaceable interference filters keep the sensors stable and your readings accurate. High exhaust pressures and heavy particulate loading are easily controlled with the **special pressure relief valve (standard) on the engine probe configuration and the sintered filter for diesel testing.**

Boiler and burner tuning

Industrial boilers and burners have their own unique characteristics. When an unexpectedly high CO is detected, **the testo 350 will automatically adjust to the situation,** keeping the sensor protected at all times.

Don't worry about climbing and removing the probe from the stack, just hit the fresh air button. The measurements of O_2, CO, NO and SO_2, combined with automatic calculations (CO_2, efficiency, excess air), provide fast tuning solutions. The 350's **compact design is better for working on a platform or small space.** The automatic zero pressure measurement is **ideal to monitor flow or draft induction.** With a pitot tube you can quickly measure velocity and determine mass flow even during long term testing.

Emission and Combustion Testing... Made Easier

Industrial processes testing

Combustion analyses in industrial processes vary widely. O_2 and CO measurements are critical for proper combustion; NO_x or SO_2 measurements are important for today's pollution control devices. Sometimes extreme concentrations are also encountered and unexpected. The testo 350's dilution system provides the protection and accuracy to continue working.

High temperature sampling in kilns can be easily achieved with the wide array of probes and hose options for the testo 350.

For additional flexibility, a six channel analog output box can be looped in the system to provide a (user selected) 4-20 mA output.

Turbine testing

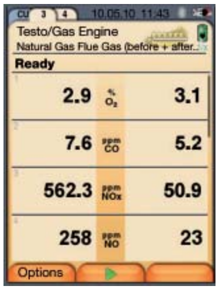
High horsepower and low emissions are typical of turbines and as a result, you need an analyzer that is **especially equipped to handle low thresholds and still deliver the highest accuracy.** When you need to make critical control or warranty decisions, the 0.1 ppm resolution will provide the highest accuracy. The low NO_x and low CO sensors are ideal for the accuracy today's turbines demand.

Multiport pre- and post-catalyst testing

Sometimes a single sample location is just not enough. Sometimes you need more information to give you better SCR performance, or even more data to help you design or troubleshoot a system. Whatever the requirement, **the unique multi-unit capability provides unlimited testing configurations.**

Select the "before and after CAT" test application to display simultaneous measurements from both locations. It makes it easy to see catalyst performance side-by-side in real time.

Connect multiple analyzer boxes (up to 16 total) through the testo BUS. The graphing display of real time NO_x or CO gives you information in real-time.



Testo/Gas Engine
Natural Gas Flue Gas (before + after...
Ready

2.9	% O_2	3.1
7.6	ppm CO	5.2
562.3	ppm NOx	50.9
258	ppm NO	23

With the testo 350, you have the ability to see pre- and post-test results simultaneously.

The testo 350: Performance Summary at a Glance

- Test up to six gases simultaneously, or swap sensors out for additional parameters: O_2, CO, CO_{low}, NO, NO_{low}, SO_2, H_2S, CO_2, CH (total hydrocarbons)
- Innovative dilution system for the widest testing ranges and greatest sensor protection: (CO to 400,000 ppm) (NO, NO_2, SO_2, H_2S to five times the sensor range)
- Advanced sample conditioning utilizes a thermoelectric chiller for moisture drop-out and a peristaltic hose pump for controlled water removal and EPA compliance
- Automatic flow-controlled pump with high strength sampling to over 50 feet away
- Proven sample gas path with Teflon® lined hoses
- Continuous temperature compensation for assured accuracy
- Flow rate and sensor temperature monitoring for US EPA CTM-030, -034 and ASTM D6522 requirements
- User defined programs with onboard memory to 250,000 values
- Integrated pressure measurement for draft, ΔP, velocity and mass emission
- Automatic testing programs
- Display refresh rate at one second intervals
- Real-time measurement averages can be shown on display
- Mass flow with pitot tube
- AC and rechargeable battery operation with optional DC connection operation
- Comprehensive calculations including O_2 corrections for NO_X, CO, and SO_2, mass measurement with pitot and stack dimension input
- User defined O_2 reference for EPA and state reporting

Better Diagnostics for Easier Testing

Onboard diagnostics keeps you testing

Press the “i” button for:

- Sensor status
- Battery life
- Pump hours and pump flow rate (liters/min)
- Error reports, and more

The analyzer will automatically alert you when servicing is needed and provides you up to the minute information about the “Health” of your analyzer and its components.

Box 3

In this measurement, very high CO concentrations can occur at short notice. In order to protect the sensors, and to achieve a longer sensor life, please plug the CO sensor into the dilution slot. The sensor may only be exchanged when the instrument is switched off!

Diagnostic function alerts you with text message on the display.

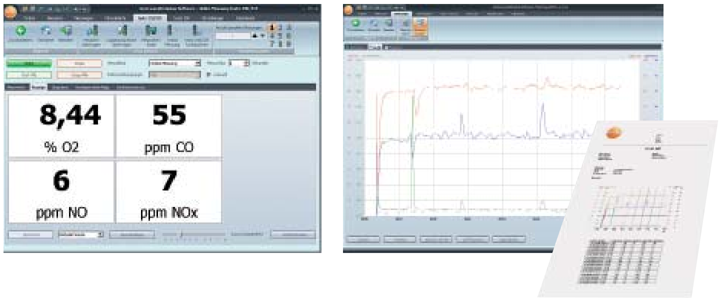
easyEmission Software

A powerful and efficient software tool

Have total control of the 350 with the easyEmission software package. This software provides extraordinary data management by giving you the power to import/export data in a variety of formats. easyEmission has the intuitive user interface of today's common Windows-based applications so you can easily prepare custom reports and documents for state, federal, and EPA requirements.

Some popular user-defined capabilities include:

- Real-time analyzer control with a PC, showing tabular, graphical and picture box results
- Complete sensor calibration
- Logging intervals 1/sec to 1/hr
- Custom formulas for specific report calculations
- Custom report generation
- Quick data transfer into Microsoft Excel and PDF file formats
- Extensive customer/location management functions
- Calculations of maximum, minimum, and average values



8,44	55
% O2	ppm CO
6	7
ppm NO	ppm NOx

Download our 30-day test version at www.testo350.com

Take your pick. Connecting to the testo 350 is easy as:

– – – Bluetooth (300 ft.)

IR Infrared (for printer)

— USB

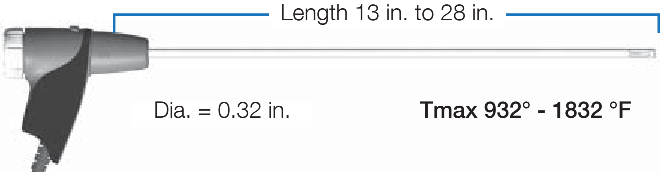
◯ Testo Databus

Sampling Probes for Every Application

The powerful pumps are uniquely engineered to combine both high velocity transport and minimal surface area contact to all but eliminate sample absorption. Our patented hoses offer high performance sampling at a fraction of the price. Hoses are available in 7 ft. lengths. Add 9 ft. extensions for additional length.

Standard gas sampling probe

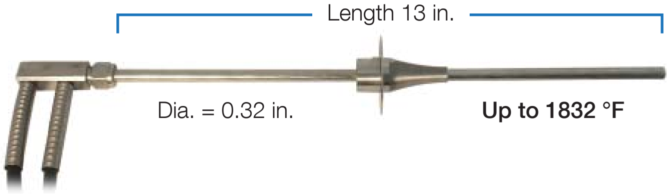
The standard stainless steel probes are available in 13 in. or 28 in. lengths and are equipped with integrated thermocouples.
Each can be upgraded with a sintered pre-filter for high particulate loading.



Probe shaft stainless steel Tmax 932° - 1832 °F
Hose length: Standard 7 ft.; Teflon lined
Nine foot hose extensions for lengths up to 50 ft.

Standard flue gas probes, available in two lengths, including probe stop, NiCr-Ni thermocouple, sintered filter options.

Engine probe



Probe shaft stainless steel, Tmax 1832 °F
Hose length: Standard 7 ft.; Teflon-lined
Nine foot hose extensions for lengths up to 50 feet
Thermocouple and sintered filter kits available

Industrial gas sampling probes

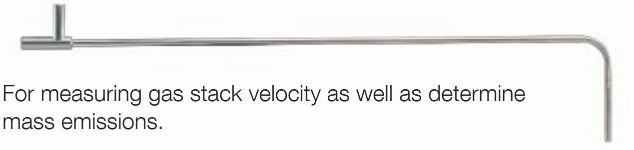
Testo is able to provide a sampling solution for your specific needs. Additional hoses and probes are available:

- For engine testing and high pressure applications
- For high particulate loading
- For compliance or cold weather sampling with heated lines

The industrial probe shafts come in lengths of 39 in. (one meter) long with rugged screw connections. Three probe shafts can be connected for a probe length of nearly 10 ft. The probe shafts are available in two materials - stainless steel for temperatures to 1112 °F or Inconel for temperatures to 2192 °F.

Ceramic pre-filters can be added for high particulate loading. The Al-oxide ceramic probe can withstand enormous thermal loads to 3272 °F.

Pitot tubes



For measuring gas stack velocity as well as determine mass emissions.

PART NUMBERS

testo 350 Control unit	Part no.
testo 350 control unit, displays measurement values and controls analyzer box, incl. rech. battery, measurement data store, USB interface and connection for Testo databus	0632 3511
testo 350 option for control unit testo 350	
Option Bluetooth® wireless transmission	
testo 350 accessories for control unit testo 350	
Power supply for testo 350 control unit, 230V / 8V / 1A	0554 1096

testo 350 analyzer box testo 350	Part no.
testo 350 analyzer box, equipped with O_2, incl. differential pressure sensor, temperature probe input Type K NiCr-Ni and Type S Pt10Rh-Pt, connection testo databus, rech. battery, integrated combustion air probe (NTC), trigger input, measurement data store, USB interface, updatable to max. 6 gas sensors selected from CO, CO_{low}, NO, NOlow, NO_2, SO_2, CO_2 NDIR, C_xH_Y, H_2S	0632 3510

OPTIONS

At least one additional sensor is needed for analyzer to operate. Up to 5 additional sensors can be installed.

- CO (H_2-compensated) sensor, 0 to 10000 ppm, resolution 1 ppm
- CO_{low} (H_2-compensated) sensor, 0 to 500 ppm, resolution 0.1 ppm
- NO sensor, 0 to 4000 ppm, resolution 1 ppm
- NO_{low} sensor, 0 to 300 ppm, resolution 0.1 ppm
- NO_2 sensor, 0 to 500 ppm, resolution 0.1 ppm
- SO_2 sensor, 0 to 5000 ppm, resolution 1 ppm
- CO_2 (NDIR) sensor, 0 to 50 Vol.%, resolution 0.01 Vol.%, infrared measurement principle, incl. absolute pressure measurement, condensate container filling level monitoring and CO_2 absorption filter with filler pack
- C_xH_y sensor, methane 100 to 40000 ppm, propane 100 to 21000 ppm, butane 100 to 18000 ppm, resolution 10 ppm.
- H_2S sensor, 0 to 300 ppm, resolution 0.1 ppm

More options:

- Bluetooth wireless transmission
- Peltier gas preparation incl. peristaltic pump for automatic condensate evacuation
- Fresh air valve for long-term measurement, incl. measuring range extension with dilution factor 5 for all sensors
- Measuring range extension for individual slot with the following selectable dilution factors: 0, 2, 5, 10, 20, 40
- DC voltage input 11V to 40V
- Special gas pump for long-term measurements with extended guarantee. For measurements >2 hours, the option Peltier gas preparation is additionally recommended.
- Automatic zeroing of pressure sensor for continuous flow velocity / differential pressure measurement
- Analog output box

ACCESSORIES

For testo 350 analyzer box and transport case	Part no.
Cable with battery terminals to connect to DC voltage input	0554 1337
Interchangeable filter NO sensor, blocks cross-gas SO_2	0554 4150
Transport case for analyzer probe and accessories, dimensions 22.5 x 18.5 x 8.5 in.	0516 3510
Carrying strap set for analyzer box	0554 0434
Spare dirt filter for analyzer box (20 per box)	0554 3381
Exhaust hose kit to remove gas from breathing space, length 16 ft.	0554 0451
Wall holder for analyzer, lockable	0554 0203
Current/voltage cable (0 to 1000 mV, 0 to 10 V, 0 to 20 mA)	0554 0007

PART NUMBERS

PC software and testo databus	Part no.
Software easyEmission, incl. USB connection cable instrument-PC.	0554 3334
Software easyEmission, incl. Testo databus controller with USB-connection cable instrument-PC, cable for Testo databus. For example, if several testo 350 emissions analyzer are connected to the Testo databus, they can be controlled via a PC (possible measurement interval in databus from 1 measurement per second)	0554 3336
Multiple software license easyEmission for emissions analyzer testo 350	0554 3337
6.5 ft. connection cable	0449 0075
16 ft. connection cable	0049 0076
65 ft. connection cable	0049 0077
Other cable lengths up to 3,000 ft. on request	

Printers and accessories	Part no.
Testo fast printer with wireless infrared interface, 1 roll of thermal paper and 4 batteries	0554 0549
Bluetooth printer kit with wireless Bluetooth interface, incl. 1 roll of thermal paper, rech. battery and power supply	0554 0553
Spare thermal paper for printer (6 rolls), 10 years legibility	0554 0568
Spare thermal paper for printer (6 rolls)	0554 0569
Other cable lengths up to 3,000 ft. on request	
Analog output box set, 6 channels, 4 to 20mA, to transfer values (i.e. analog recorder). Kit includes: analog output box, 6.5 ft. connection cable	0554 3149

Contact Testo for standard probes, engine probes, industrial probes, pitot tubes, and more.

TECHNICAL DATA

Measurement	Measurement range	Accuracy	Resolution	Reaction time	Reaction type
Temperature Type K (NiCr-Ni)	-200° to 1370 °C	±0.4 °C (-100° to 200 °C) ±1 °C (rest of range)	0.1 °C		
Temperature Type S (Pt10Rh-Pt)	0° to 1760 °C	±1 °C (0° to 1760 °C)	1 °C		
Efficiency	0 to 120 %		0.1 % (0 to +120%)		
Exhaust gas loss	0 to 99.9 %qA		0.1 % qA (-20 to +99.9 % qA)		
CO_2 calculation	0 to CO_2 max Vol.% CO_2	Calculated from O_2 ±0.2 Vol.%	0.01 Vol.% CO_2	40 s	t_{90}
Differential pressure 1	-16 to 16 "H_2O	±1.5% of m.v. -16 to -1 "H_2O ±1.5% of m.v. 1.2 to 16 "H_2O 0.1 "H_2O -1.20 to 1.20 "H_2O	0.004 "H_2O (-16 to 16 "H_2O)		
Differential pressure 2	-80 to 80 "H_2O	±1.5% of m.v. (-80 to 20 "H_2O) ±1.5% of m.v. (20 to 80 "H_2O) 0.2 "H_2O (-20 to +0 "H_2O)	0.004 "H_2O (-80 to 80 "H_2O)		
Flow velocity	0 to 131 ft./sec		0.1ft/sec to 131 ft./sec		
Absolute pressure (opt. if IR sensor equipped)	-240 to 461 "H_2O	± 4 "H_2O	0.4 "H_2O		
Flue gas dewpoint calculation	32° to 212 °F		0.18 °F (32° to 212 °F)		

TECHNICAL DATA

Analyzer Box testo 350

Measurement	Measurement range	Accuracy	Resolution	Reaction time	Reaction type
O_2	0 to 25 Vol.% O_2	±0.8% of fsv (0 to 25 Vol.% O_2)	0.01 Vol.% O_2 (0 to +25 Vol.% O_2)	20 s	t_{95}
CO (H_2 compensated)*	0 to 10000 ppm CO	±5 ppm CO (0 to 199 ppm CO) ±5% of mv (200 to 2000 ppm to 2000 ppm CO) ±10% of mv (2001 to 10000 ppm CO)	1 ppm CO (0 to 10000 ppm CO)	40 s	t_{90}
COlow (H_2 compensated)*	0 to 500 ppm CO	±2 ppm CO (0 to 39.9 ppm CO) ±5% of mv (40 to 500 ppm CO)	0.1 ppm CO (0 to 500 ppm CO)	40 s	t_{90}
NO	0 to 4000 ppm NO	±5 ppm NO (0 to 99 ppm NO) ±5% of mv (100 to 1999.9 ppm NO) ±10% of mv (2000 to 4000 ppm NO)	1 ppm NO (0 to 3000 ppm NO)	30 s	t_{90}
NOlow	0 to 300 ppm NO	±2 ppm NO (0 to 39.9 ppm NO) ±5% of mv (40 to 300 ppm NO)	0.1 ppm NO (0 to 300 ppm NO)	30 s	t_{90}
NO_2	0 to 500 ppm NO_2	±5 ppm NO_2 (0 to 99.9 ppm NO_2) ±5% of mv (100 to 500 ppm NO_2)	0.1 ppm NO_2 (0 to 500 ppm NO_2)	40 s	t_{90}
SO_2	0 to 5000 ppm SO_2	±5 ppm SO_2 (0 to 99 ppm SO_2) ±5% of mv (100 to 2000 ppm SO_2) ±10% of mv (2001 to 5000 ppm SO_2)	1 ppm SO_2 (0 to 5000 ppm SO_2)	30 s	t_{90}
CO_2 (IR)	0 to 50 Vol.% CO_2	±0.3 Vol. % CO_2 + 1% of mv (0 to 25 Vol.% CO_2) ±0.5 Vol. % CO_2 + 1.5% of mv (>25 to 50 Vol.% CO_2)	0.01 Vol.% CO_2 (0 to 25 Vol.% CO_2) 0.1 Vol.% CO_2 (>25 Vol.% CO_2)	10 s	t_{90}
H_2S	0 to 300 ppm H_2S	±2 ppm (0 to 39.9 ppm) ±5% of mv (40 to 300 ppm)	0.1 ppm (0 to 300 ppm)	35 s	t_{90}

* H_2 display only as an indicator **Accuracy can be increased with an on-site calibration. Contact Testo for details.

Technical data HC Sensor

Measurement	Measurement range[1]	Accuracy	Resolution	Min. O_2 requirement in flue gas	Response time t90	Response-factor [2]
Methane	100 to 40,000 ppm	< 400 ppm (100 to 4000 ppm) < 10 % of m.v. (> 4000 ppm)	10 ppm	2% + (2 x m.v. methane)	< 40 sec.	1
Propane	100 to 21,000 ppm	< 400 ppm (100 to 4000 ppm) < 10 % of m.v. (> 4000 ppm)	10 ppm	2% + (5 x m.v. propane)	< 40 sec.	1.5
Butane	100 to 18,000 ppm	< 400 ppm (100 to 4000 ppm) < 10 % of m.v. (> 4000 ppm)	10 ppm	2% + (6.5 x m.v. butane)	< 40 sec.	2

[1] Lower explosion limit must be adhered to.

[2] The HC sensor is adjusted to methane in the factory. It can be adjusted to another gas (propane or butane) by the user.

TECHNICAL DATA

Individual dilution with selectable dilution factor (x2, x5, x10, x20, x40)

Measurement	Measurement range	Accuracy	Resolution
CO (H_2 compensated)	dilution factor-dependent	±2 % of m.v. (additional error)	1 ppm
CO_{low} (H_2 compensated)	dilution factor-dependent	±2 % of m.v. (additional error)	0.1 ppm
NO	dilution factor-dependent	±2 % of m.v. (additional error)	0.1 ppm
NO_{low}	dilution factor-dependent	±2 % of m.v. (additional error)	0.1 ppm
SO_2	dilution factor-dependent	±2 % of m.v. (additional error)	1 ppm
HC-Pellistor	dilution factor-dependent	±2 % of m.v. (additional error)	10 ppm

Dilution of all sensors (Factor 5) Note: No O_2 reader is possible when activated.

Measurement	Measurement range	Accuracy	Resolution
CO (H_2 compensated)	2500 to 50000 ppm	±5 % of m.v. (additional error) Pressure range -40 to 0 "H_2O at probe tip	1 ppm
CO_{low} (H_2 compensated)	500 to 2500 ppm	±5 % of m.v. (additional error) Pressure range -40 to 0 "H_2O at probe tip	0.1 ppm
NO	1500 to 20000 ppm	±5 % of m.v. (additional error) Pressure range -40 to 0 "H_2O at probe tip	1 ppm
NO_{low}	300 to 1500 ppm	±5 % of m.v. (additional error) Pressure range -40 to 0 "H_2O at probe tip	0.1 ppm
SO_2	500 to 25000 ppm	±5 % of m.v. (additional error) Pressure range -40 to 0 "H_2O at probe tip	1 ppm
NO_2	500 to 2500 ppm	±5 % of m.v. (additional error) Pressure range -40 to 0 in "H_2O at probe tip	0.1 ppm
H_2S	200 to 1500 ppm	±5 % of m.v. (additional error) Pressure range -40 to 0 "H_2O at probe tip	0.1 ppm

Control Unit

Operating temperature	20° to 115 °F
Storage temperature	-4° to 122 °F
Battery type	Li-Ion
Battery life	5 hr. (without wireless connection)
Memory	2 MB (250,000 measurement values)
Weight	0.97 lbs.
Dimensions	10 x 4.5 x 2.3 in.
Warranty	2 years
Protection class	IP 40

TECHNICAL DATA

Other operational data

Dimensions	13 x 5 x 17.2 in.
Weight	10.58 lbs.
Storage temperature	-4° to 122 °F
Operating temperature	22° to 113 °F
Housing material	ABS
Memory	250,000 measurement values
Power supply	AC power supply 90V to 260V (47 to 65 Hz)
DC voltage supply	11V to 40V
Maximum dust load	20 g/m^3 dust in flue gas
Dewpoint calculation	32° to 212 °F
Maximum positive pressure flue gas	20 "H_2O
Maximum negative pressure	-120 "H_2O
Pump flow rate	1 l/min. with flow rate monitoring
Hose length	max 53 ft. (corresp. to 5 probe hose extensions)
Maximum humidity load	158°F at gas input of analyzer box (33.5 Vol.% H_2O)
Trigger input	Voltage 5 to 12 Volt (rising or falling flank) Impulse width > 1 sec Load: 5 V/max, 5 mA, 12 V/max. 40 mA
Protection class	IP40
Battery life	Maximum load approx. 2.5 hr. (Dependent upon analyzer configuration)

WARRANTY

Instrument*	2 years for instrument and probe (except for replaceable parts, i.e. gas sensors, battery...)
Gas sensors	$CO/NO/NO_2/SO_2/H_2S/C_XH_Y$: 1 year
O_2 sensor	1 ½ years
CO_2-IR sensor	2 years
Rechargeable battery	1 year

*Warranty applies for average sensor load.

Other combustion solutions from Testo

testo 310

Residential Combustion Analyzer

The fully featured testo 310 delivers more combustion parameters so you can get the job done right the first time - every time. Whether you need to perform basic combustion tuning, maintenance or safety checks, or install a new furnace or boiler the fully featured testo 310 delivers results. More features for more jobs with the ability to measure O_2, CO (with NOx filter standard), CO_2, draft, pressure, and more.

testo 320

Residential & Commercial
Combustion Analyzer

The bright, color graphic display is easy to see and understand with simple menu icons. The 320's rugged design and many innovative features assures a long lasting life. This comprehensive combustion analyzer can measure O_2, CO, CO_2, combustion calucations, draft, pressure, and the "flue gas matrix" offers optional software and more for more jobs.

testo 330-2G LL

Three-Gas Analyzer

The 330-2G LL measures O2, CO, optional NOx, tempeature, pressure, and other combustion parameters. Proper set up and maintenance are critical to safe and efficient equipment operation.

testo 330-1G LL

Three-Gas Analyzer

With a full color display, the 330-1G LL combustion analyzer allows the user to visualize the measurement data without watching numerical values.

testo 340

The Ultimate Tuner
Four-Gas Analyzer

The testo 340 is equipped with a standard O_2 sensor. Three additional gas sensors can be individually configured at any time so your analyzer is perfect for your job. Compact design, combined with reliable engineering, makes testo 340 the ideal analyzer for engine tuning, commissioning, service and maintenance.

Kalibrier-Protokoll

Certificate of conformity • Protocole d'étalonnage
Protocollo di collaudo • Informe de calibración

Gerät / Module type / Type de modèle / Modelo: **testo 350 M/XL · testo 454**

Serien-Nummer / Serial No. / No. de série / Número de serie: **01625751**

Schnittstellentest / Interface test / Test d'interface / Test interface:	ok
Druckertest / Printercheck / Test de l'imprimeur / Test de impresora:	ok
Segmenttest / Display test / Test d'affichage / Test del visualizador:	ok
Akkuladung / Recharching battery / Charge d'accus / Batería recargable:	ok
Stromaufnahme / Power supply / Alimentation / Alimentación:	ok

Sollwert **Reference** **Référence** **Referencia**	**Zulässige Toleranz** **Permissible tolerance** **Tolérance admise** **Tolerancia permitida**	**Istwert** **Actual Value** **Valeur réelle** **Valor medido**
Druck / pressure / Pression / Presión		
10.00 hPa	± 0.15 hPa	10.02 hPa
100.0 hPa	± 1.0 hPa	100.0 hPa

Meßwerte ohne Meßfühler / Measured values without probe /
Valeurs mesurées sans sonde de mesure / Valores medidos sin sonda de medición:

Typ K / Type K / Type K / Tipo K		
-100.0 °C	± 0.4 °C	-100.0 °C
0.0 °C	± 0.4 °C	-0.0 °C
200.0 °C	± 0.4 °C	200.0 °C
900.0 °C	± 1.0 °C	900.0 °C
NTC / NTC / CNT / NTC		
50.0 °C	± 0.2 °C	50.0 °C
Pt100 / Pt100 / Pt100 / Pt100		
80.0 °C	± 0.1 °C	80.1 °C
thermisch / hotwire / file chaude / hilo caliente		
10.00 m/s	± 0.04 m/s	10.00 m/s
Druck 100hPa / pressure 100hPa / Pression 100hPa / Presión 100hPa		
80.00 hPa	± 0.10 hPa	80.00 hPa
relative Luftfeuchte / relative humidity / humidité relative / humedad relativa		
12.0 %	± 1 Digit	12.0 %

Datum/Date/Date/Data/Fecha: 04.12.08 **Prüfer/Inspector/Vérificateur/Verificatore/Verificador: 609**

Kalibrier-Protokoll

Certificate of conformity • Protocole d'étalonnage
Protocollo di collaudo • Informe de calibración

Wir bestätigen, dass dieses Testo-Produkt unter Beachtung eines zertifizierten Quaitätssicherungssystems nach **DIN EN ISO 9001:2000** abgeglichen wurde.

Die dafür verwendeten Messeinrichtungen werden regelmäßig kalibriert und sind rückführbar auf die nationalen Normale der Physikalisch Technischen Bundesanstalt (PTB) Deutschlands oder auf andere nationale Normale. Wo keine nationalen Normale existieren, entspricht das Messverfahren den derzeit gültigen technischen Regeln und Normen.

Dieses Kalibrier-Protokoll belegt die Einhaltung der von uns zugesagten Toleranzen.

Sehr gerne informieren wir Sie über **Kalibrier-Zertifikate**, die die Toleranzen **des gesamten Messsystems** (Messgerät und Fühler) beinhalten.

Dieses Zertifikat benötigen Sie, wenn das Meßsystem in qualitäts-relevanten Prozessen innerhalb eines nach **DIN EN ISO 9001:2000** zertifiziertem Unternehmen eingesetzt wird.

Unsere Kalibrierlabors für Temperatur, Druck, Feuchte, Strömung und elektrische Messgrössen sind vom Deutschen Kalibrierdienst (DKD) akkreditierte Kalibrierlabors.

DKD-Kalibrierscheine werden für Messungen gefordert, bei denen die Genauigkeit eine entscheidende Rolle spielt.

We confirm that this Testo product was calibrated under the observation of a ***DIN EN ISO 9001:2000*** *certified quality assurance system.*

The measuring installations used for this calibration are calibrated regularly and can be traced back to the national standards of the German Federal Physical and Technical Institution (PTB), or to other national standards. Should no national standards exist, the measuring procedure corresponds with the currently valid technical regulations and standards.

This calibration protocol is proof of adherence to the tolerances as confirmed by us.

We would be delighted to inform you about ***certificates of conformities*** *which cover the tolerances for the* ***complete measuring system*** *(measuring instrument and probes).*

This certificate is required only if the measuring system is to be used in processes relevant to quality in a company certified to ***DIN EN ISO 9001:2000.***

Our calibration laboratories for temperature, pressure, humidity, velocity and electrical parameters are calibration laboratories accredited by the German Calibration Service (DKD).

DKD calibration certificates are required for measurements where accuracy plays a decisive role.

Nous confirmons par la présente que ce produit testo a été étalonné sous la surveillance d'un système d'assurance qualité selon la norme **DIN EN ISO 9001:2000**.

Les installations de mesure utilisées pour cet étalonnage sont étalonnées de facon régulière et s'appliquent aux normes nationales de l'Institut Fédéral de Techniques Physiques d'Allemagne (PTB) ou aux autres normes nationales. S'il n'existe aucune norme nationale, le processus de mesure est conforme aux règles et normes techniques actuellement valables.

Ce protocole d'étalonnage vous indique que cet appareil respecte bien les tolérances constructeurs annoncées dans nos documentations.

Un **certificat d'étalonnage** est nécessaire pour la vérification de la **chaîne complète** (appareils et sonde). N'hésitez pas à nous contacter pour de plus amples renseignements.

Ce certificat vous sera utile si vous vous trouvez être certifié ou en cours de certification **DIN EN ISO 9001:2000.**

Notre laboratoire d'étalonnage en température, pression, humidité, vitesse d'air et paramètres électriques a été accrédité par le DKD - équivalent BNM/COFRAC -, Bureau de Métrologie Allemand.

Les certificats d'étalonnage DKD/COFRAC sont indispensables lorsque les mesures effectuées doivent être précises.

Vi confermiamo che questo prodotto è stato collaudato seguendo il sistema di certificazione di qualità ***DIN EN ISO 9001:2000.***

Gli strumenti di misura elettronici utilizzati per la calibrazione sono a loro volta regolarmente verificati e possono essere ricondotti agli standard nazionali del PTB (Physikalisch Technische Bundesanstalt), l'istituto ufficiale tedesco per la determinazione degli standard tecnici.

Questo protocollo di collaudo documenta l'osservanza delle tolleranze da noi indicate.

Siamo a Vs. disposizione per fornire informazioni sui ***Certificati di Taratura*** *che comprendono le tolleranze del* ***sistema di misura completo*** *(strumento e sonda).*

Questo documento Vi sarà utile se già siete certificati o siete in corso di certificazione ***DIN EN ISO 9001:2000.***

I nostri laboratori di taratura per temperatura, pressione, umidità, velocità dell'aria e parametri elettrici sono stati accreditati dal PTB e sono in grado di rilasciare certificati ufficiali DKD indispensabili quando le misure effettuate devono essere precise o riferibili.

Queste regole, riconosciute in tutta Europa, sono equivalenti a quelle SIT italiane ed alle procedure tecniche standard utilizzate in tutto il mondo.

Confirmamos que este producto Testo se calibró de acuerdo con el sistema de garantía de calidad **DIN EN ISO 9001:2000**.

Las instalaciones de medición utilizadas para esta calibración se calibran con regularidad y pueden tracearse a los estándares nacionales del instituto Federal de Técnicas Físicas Alemán (PTB), o a otros estándares nacionales. Si no existe una norma nacional, el procedimiento de medición corresponde con las regulaciones técnicas y normas válidas en la actualidad.

Este informe de calibración es una prueba de las tolerancias que nosotros confirmamos.

Estaremos encantados en informales sobre **certificados de calibración** que cubran las tolerancias para el **sistema de medición completo** (instrumento de medición y sondas).

Nuestros laboratorios de calibración para temperatura, presión, humedad, velocidad y parámetros eléctricos son laboratorios de calibración acreditados por el Servicio de calibración alemán (DKD).

Los certificados de calibración DKD son necesarios para las mediciones donde la precisión sea muy importante.

Kalibrier-Protokoll

Certificate of conformity • Protocole d'étalonnage
Protocollo di collaudo • Informe de calibración

Gerät / Module type / Type de modèle / Prodotto / Modelo:	**t350 XL**
Serien-Nummer / Serial No. / No. de série / No. Serie strumento / n° de serie:	**1629483**

Temperaturmessung **Temperature measurement** **Mesure de température** **Misura della temperatura** **Medición de temperatura**	Sollwert Reference Référence Valore campione Referencia	Istwert Actual value Valeur effect. Valore misurato Valor medido	zulässige Abweichung Permissible deviation Différence admissible Scostamento ammesso Desviación permitida
Verbrennungslufttemp. / Ambient air temp. Température d'air de combustion Temperatura aria comburente Temperatura ambiente	100.0 °C	100.0 °C	+- 0.5 °C
Abgastemperatur / Flue gas temperature Température des fumées Temperatura fumi Temperatura gases	100.0 °C	100.0 °C	+- 0.5 °C
Zug-/Druckmessung **Draught/pressure measurement** **Mesure de tirage/de pression** **Misura della pressione/ tiraggio** **Medición de tiro/presión**	10.00 mbar	9.99 mbar	+- 0.12 mbar

Gasmeßwerte / Gas values / Valeurs de gaz mesurées / Parametri di misura dei gas / Gases patrón

Reg. Nr. Reg. No. Reg. No. Num.reg. n° certi	Gas Gas Gaz Gas Gas	Sollwert Reference Référence Valore campione Referencia	Istwert Actual value Valeur effective Valore misurato Valor medido	zulässige Abweichung Permissible deviation Différence admissible Scostamento ammesso Desviación permitida
0271C	O2	0.0 %	0.0 %	+- 0.2 %
D242484	O2	1.4 %	1.4 %	+- 0.2 %
3460A	O2	5.0 %	5.0 %	+- 0.2 %
0271C	CO	104 ppm	103 ppm	+- 10 ppm
3460A	CO	408 ppm	407 ppm	+- 20 ppm
D242484	CO	1008 ppm	1005 ppm	+- 50 ppm
0271C	NO	155 ppm	155 ppm	+- 8 ppm
775C	NO2	105.5 ppm	105.0 ppm	+- 5.5 ppm
1160B	CO2	17.00 %	16.96 %	+- 0.42 %
8778A	CO2	38.90 %	38.83 %	+- 0.78 %

Datum/Date/Date/Data/Fecha: 05.12.2008 **Prüfer/Inspector/Vérificateur/Verificatore/Verificador: 282**

Kalibrier-Protokoll

Certificate of conformity • Protocole d’étalonnage
Protocollo di collaudo • Informe de calibración

Wir bestätigen, dass dieses Testo-Produkt unter Beachtung eines zertifizierten Quaitätssicherungssystems nach **DIN EN ISO 9001:2000** abgeglichen wurde.

Die dafür verwendeten Messeinrichtungen werden regelmäßig kalibriert und sind rückführbar auf die nationalen Normale der Physikalisch Technischen Bundesanstalt (PTB) Deutschlands oder auf andere nationale Normale. Wo keine nationalen Normale existieren, entspricht das Messverfahren den derzeit gültigen technischen Regeln und Normen.

Dieses Kalibrier-Protokoll belegt die Einhaltung der von uns zugesagten Toleranzen.

Sehr gerne informieren wir Sie über **Kalibrier-Zertifikate**, die die Toleranzen **des gesamten Messsystems** (Messgerät und Fühler) beinhalten.

Dieses Zertifikat benötigen Sie, wenn das Meßsystem in qualitäts-relevanten Prozessen innerhalb eines nach **DIN EN ISO 9001:2000** zertifiziertem Unternehmen eingesetzt wird.

Unsere Kalibrierlabors für Temperatur, Druck, Feuchte, Strömung und elektrische Messgrössen sind vom Deutschen Kalibrierdienst (DKD) akkreditierte Kalibrierlabors.

DKD-Kalibrierscheine werden für Messungen gefordert, bei denen die Genauigkeit eine entscheidende Rolle spielt.

*We confirm that this Testo product was calibrated under the observation of a **DIN EN ISO 9001:2000** certified quality assurance system.*

The measuring installations used for this calibration are calibrated regularly and can be traced back to the national standards of the German Federal Physical and Technical Institution (PTB), or to other national standards. Should no national standards exist, the measuring procedure corresponds with the currently valid technical regulations and standards.

This calibration protocol is proof of adherence to the tolerances as confirmed by us.

*We would be delighted to inform you about **certificates of conformities** which cover the tolerances for the **complete measuring system** (measuring instrument and probes).*

*This certificate is required only if the measuring system is to be used in processes relevant to quality in a company certified to **DIN EN ISO 9001:2000**.*

Our calibration laboratories for temperature, pressure, humidity, velocity and electrical parameters are calibration laboratories accredited by the German Calibration Service (DKD).

DKD calibration certificates are required for measurements where accuracy plays a decisive role.

Nous confirmons par la présente que ce produit testo a été étalonné sous la surveillance d'un système d'assurance qualité selon la norme **DIN EN ISO 9001:2000**.

Les installations de mesure utilisées pour cet étalonnage sont étalonnées de facon régulière et s'appliquent aux normes nationales de l'Institut Fédéral de Techniques Physiques d'Allemagne (PTB) ou aux autres normes nationales. S'il n'existe aucune norme nationale, le processus de mesure est conforme aux règles et normes techniques actuellement valables.

Ce protocole d’étalonnage vous indique que cet appareil respecte bien les tolérances constructeurs annoncées dans nos documentations.

Un **certificat d’étalonnage** est nécessaire pour la vérification de la **chaîne complète** (appareils et sonde). N’hésitez pas à nous contacter pour de plus amples renseignements.

Ce certificat vous sera utile si vous vous trouvez être certifié ou en cours de certification **DIN EN ISO 9001:2000**.

Notre laboratoire d´étalonnage en température, pression, humidité, vitesse d´air et paramètres électriques a été accrédité par le DKD - équivalent BNM/COFRAC -, Bureau de Métrologie Allemand.

Les certificats d´étalonnage DKD/COFRAC sont indispensables lorsque les mesures effectuées doivent être précises.

*Vi confermiamo che questo prodotto è stato collaudato seguendo il sistema di certificazione di qualità **DIN EN ISO 9001:2000**.*

Gli strumenti di misura elettronici utilizzati per la calibrazione sono a loro volta regolarmente verificati e possono essere ricondotti agli standard nazionali del PTB (Physikalisch Technische Bundesanstalt), l´istituto ufficiale tedesco per la determinazione degli standard tecnici.

Questo protocollo di collaudo documenta l'osservanza delle tolleranze da noi indicate.

*Siamo a Vs. disposizione per fornire informazioni sui **Certificati di Taratura** che comprendono le tolleranze del **sistema di misura completo** (strumento e sonda).*

*Questo documento Vi sarà utile se già siete certificati o siete in corso di certificazione **DIN EN ISO 9001:2000**.*

I nostri laboratori di taratura per temperatura, pressione, umidità, velocità dell´aria e parametri elettrici sono stati accreditati dal PTB e sono in grado di rilasciare certificati ufficiali DKD indispensabili quando le misure effettuate devono essere precise o riferibili.

Queste regole, riconosciute in tutta Europa, sono equivalenti a quelle SIT italiane ed alle procedure tecniche standard utilizzate in tutto il mondo.

Confirmamos que este producto Testo se calibró de acuerdo con el sistema de garantía de calidad **DIN EN ISO 9001:2000**.

Las instalaciones de medición utilizadas para esta calibración se calibran con regularidad y pueden tracearse a los estándares nacionales del instituto Federal de Técnicas Físicas Alemán (PTB), o a otros estándares nacionales. Si no existe una norma nacional, el procedimiento de medición corresponde con las regulaciones técnicas y normas válidas en la actualidad.

Este informe de calibración es una prueba de las tolerancias que nosotros confirmamos.

Estaremos encantados en informales sobre **certificados de calibración** que cubran las tolerancias para el **sistema de medición completo** (instrumento de medición y sondas).

Nuestros laboratorios de calibración para temperatura, presión, humedad, velocidad y parámetros eléctricos son laboratorios de calibración acreditados por el Servicio de calibración alemán (DKD).

Los certificados de calibración DKD son necesarios para las mediciones donde la precisión sea muy importante.

Attachment 6

Flowmeter BROOKS GT-1350 Data Sheet

Data Sheet
DS-VA-1350E-eng
March, 2008

Sho-Rate™ "50" Model 1350E and Sho-Rate™ "150" Model 1355E

- Ten-to-one rangeability
- Heavy-wall, precision bore, borosilicate glass metering tubes
- A wide range of scales on the metering tube with contrasting background for easy readability
- Tubes sealed on compression gasket by threaded seal spindle
- Tubes removable without disconnecting instrument
- Integral float stops prevent loss of float during tube removal
- Interchangeable tubes and floats

DESCRIPTION

The Sho-Rate 1350 and 1355 Series of low flow indicators provides a cost-effective means of flow indication for both 5% (Model 1355) and 10% (Model 1350) accuracy requirements. Available options include the Standard or NRS™ integral needle control valves, as well as flow controllers on the inlet or outlet.

SPECIFICATIONS

Capacities

1350 Series: Refer to Tables 1 or 2, or 3 and 4
1355 Series: Refer to Tables 3 and 4, or 5

Accuracy

1350 Series Standard: Accuracy of ±10% of full scale from 100% to 10% of scale reading
1355 Series Standard: ±5% of full scale from 100% to 10% of scale reading

Repeatability

0.5% full scale

Rangeability

10 to 1

Pressure

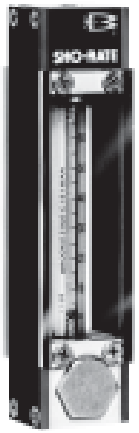
200 psig at temperatures up to 250°F

Pressure Drop

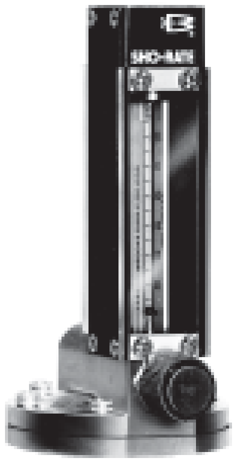
Inquire at factory

Flow Meter Assembly

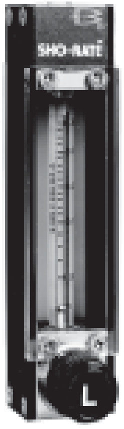
Pressure Equipment Directive (97/23/EC)
Note: Equipment falls under Sound Engineering Practice (SEP) according to the directive.



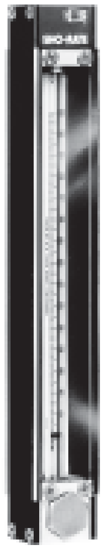
Model 1350E Sho-Rate "50" (No valve)



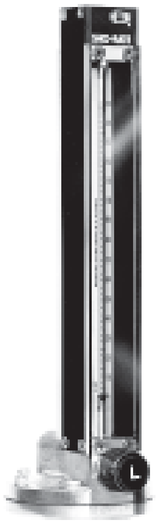
Model 1350E-8800 Sho-Rate "50" with optional integral flow controller



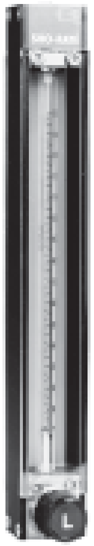
Model 1350E Sho-Rate "50" with optional needle valve



Model 1355E Sho-Rate "150" (No valve)



Model 1355E-8800 Sho-Rate "150" with optional integral flow controller



Model 1353E Sho-Rate "150" with optional needle valve

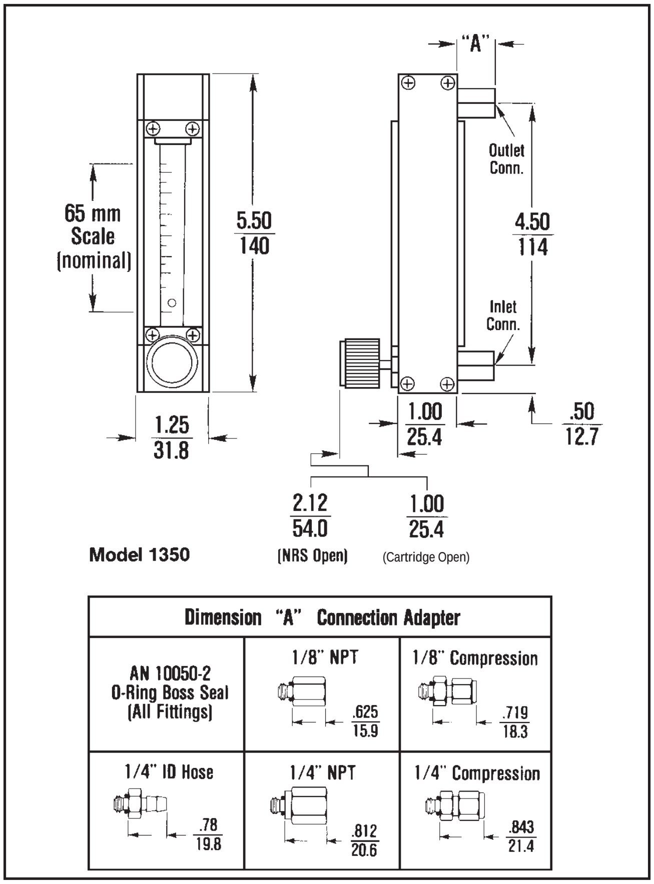


Figure 1 Dimensions - Sho-Rate 1350E

Scales
1350 Series:
Length: 65 mm, nominal
Graduations: Standard: 0-65mm, or 0-100 linear reference scale with air or water calibration table.

1355 Series:
Length: 150mm, nominal
Graduations: Standard: 0-150 mm, or 0-100 linear reference scale with air or water calibration table.
Optional: for either 65 mm or 150 mm direct reading scale, ceramic ink fused on glass tube or metal scale plate mounted beside tube
Type: Standard: Ceramic ink fused on meter tube with contrasting yellow background

Materials of Construction
Metering Tubes: Borosilicate glass

Floats: Glass, 316 stainless steel, sapphire, Carboloy®, tantalum

Structural Members:
End fittings: Chrome plated brass, black anodized aluminum, 316 stainless steel

Side Plates:
Standard: Black anodized aluminum
Optional: 316 stainless steel

Window: Clear polycarbonate; Back Window: Milk white polycarbonate

Float Stops:
Standard: Teflon®
Optional: 316 Stainless Steel

Tube Packing:
Standard: Buna-N (Brass and aluminum meters), Viton-A® fluoroelastomers (316 stainless steel meters)
Optional: Teflon, EPM (also known as EPR)

O-rings:
Standard: Buna-N (Brass and aluminum meters), Viton-A fluoroelastomers (316 stainless steel meters)
Optional: Teflon (not available with needle valves), EPM, Kalrez®

Connections
Standard: Horizontal female 1/8" NPT threaded adapters with locknuts for front of panel mounting

Dimensions
Refer to Figures 1, 2 and 4

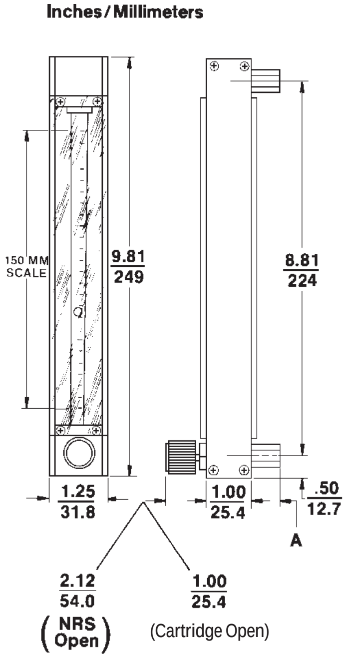
OPTIONAL EQUIPMENT
Standard integral flow control valve on inlet or outlet (See DS-VA-CART-eng).

NRS integral flow control valve on inlet or outlet (See DS-VA-8503-eng). These valves are particularly suitable for precise control requirements, and are recommended for flow rates below 500 sccm of Air (@STP) or 10 cc/min water.

Flush mounting bezels in aluminum

Threaded adapters and locknuts for front of panel mounting (standard with 1/8" NPT)
1/8" and 1/4" compression fittings
1/4" female NPT connections
1/4" ID serrated hose connections
Base plates, with or without level

ORDERING INFORMATION (Refer to Table 6)
1. Model
2. Size, connections, type
3. Quantity required
4. Fluid
5. Minimum, normal and maximum operating temperature



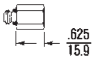
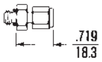
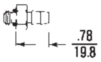
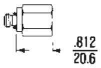
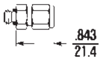
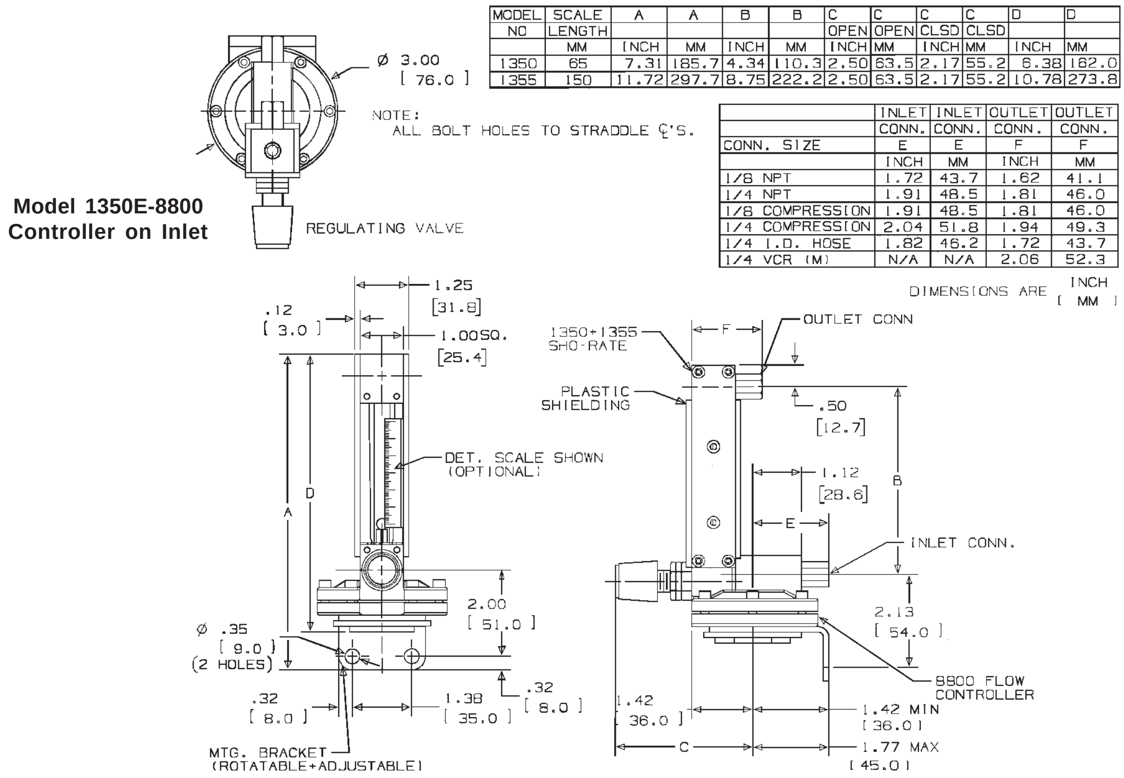
Dimension "A" Connection Adapter		
AN 10050-2 O-Ring Boss Seal (All Fittings)	1/8" NPT 	1/8" Compression 
1/4" ID Hose 	1/4" NPT 	1/4" Compression 

Figure 2 Dimensions - Sho-Rate 1355E

Model 1350E
Sho-Rate "50"
with optional needle valve and flush mounting bezel

Figure 3 Optional Equipment

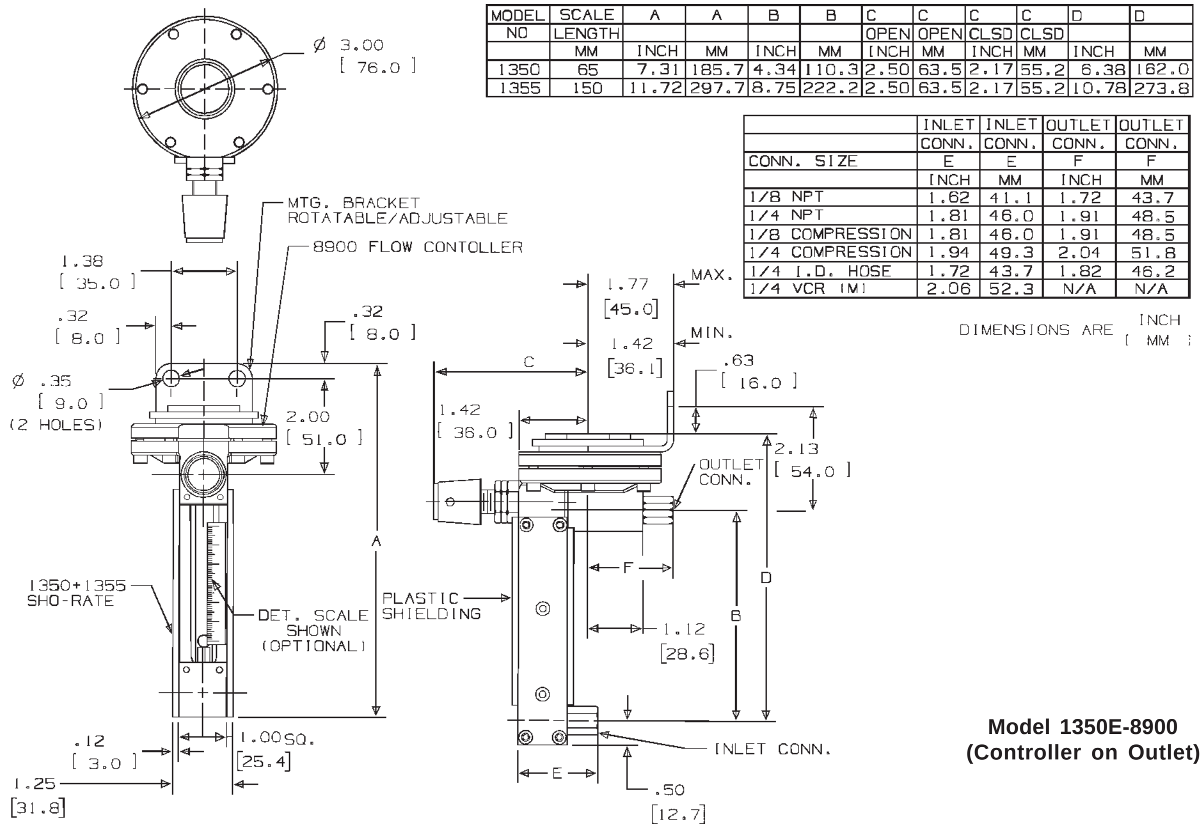
6. Minimum, normal and maximum operating pressure (inlet and outlet)
7. Minimum, normal and maximum flow rate
8. Materials of construction
   a. End fittings
   b. Side plates
   c. Bezel
   d. Elastomers
9. Fluid
10. Fluid specific gravity
11. Fluid viscosity
12. Unusual system conditions (For ranges and pressure drops other than those listed, consult factory).
13. Optional equipment
   a. Valve type and location
   b. Flow controller and type



Model 1350E-8800
Controller on Inlet

MODEL NO	SCALE LENGTH	A	A	B	B	C OPEN	C OPEN	C CLSD	C CLSD	D	D
	MM	INCH	MM	INCH	MM	INCH	MM	INCH	MM	INCH	MM
1350	65	7.31	185.7	4.34	110.3	2.50	63.5	2.17	55.2	6.38	162.0
1355	150	11.72	297.7	8.75	222.2	2.50	63.5	2.17	55.2	10.78	273.8

CONN. SIZE	INLET CONN. E	INLET CONN. E	OUTLET CONN. F	OUTLET CONN. F
	INCH	MM	INCH	MM
1/8 NPT	1.72	43.7	1.62	41.1
1/4 NPT	1.91	48.5	1.81	46.0
1/8 COMPRESSION	1.91	48.5	1.81	46.0
1/4 COMPRESSION	2.04	51.8	1.94	49.3
1/4 I.D. HOSE	1.82	46.2	1.72	43.7
1/4 VCR (M)	N/A	N/A	2.06	52.3



MODEL NO	SCALE LENGTH	A	A	B	B	C OPEN	C OPEN	C CLSD	C CLSD	D	D
	MM	INCH	MM	INCH	MM	INCH	MM	INCH	MM	INCH	MM
1350	65	7.31	185.7	4.34	110.3	2.50	63.5	2.17	55.2	6.38	162.0
1355	150	11.72	297.7	8.75	222.2	2.50	63.5	2.17	55.2	10.78	273.8

CONN. SIZE	INLET CONN. E	INLET CONN. E	OUTLET CONN. F	OUTLET CONN. F
	INCH	MM	INCH	MM
1/8 NPT	1.62	41.1	1.72	43.7
1/4 NPT	1.81	46.0	1.91	48.5
1/8 COMPRESSION	1.81	46.0	1.91	48.5
1/4 COMPRESSION	1.94	49.3	2.04	51.8
1/4 I.D. HOSE	1.72	43.7	1.82	46.2
1/4 VCR (M)	2.06	52.3	N/A	N/A

Model 1350E-8900
(Controller on Outlet)

Figure 4 Dimensions - Sho-Rate 1350E & 1355E with Integral Flow Controller

Table 1 Capacities for Sho-Rate Model 1350E Rib Guided Tubes, Spherical Floats

RIBBED TUBES, SPHERICAL FLOATS										
METER SIZE	TUBE NO.	FLOAT MATERIAL	MAXIMUM FLOW RATE							
			WATER				AIR*			
			GPH	CODE	LPH	CODE	SCFH	CODE	NLPH	CODE
2	R-2-65-A	GLASS	0.011	JB6	0.042	JB9	0.13	JB7	3.4	JB8
		SAPPHIRE	0.022	JC4	0.085	JC2	0.18	JC3	5.0	JC1
		STN. STL.	0.046	JC8	0.18	JC5	0.34	JC7	9.0	JC6
		CARBOLOY	0.10	JB4	0.38	JB5	0.65	JB2	17.0	JB3
		TANTALUM	0.11	JD2	0.42	JC9	0.70	JD1	19.0	JD3
	R-2-65-B	GLASS	0.013	KB8	0.048	KB2	0.15	KB7	4.0	KB9
		SAPPHIRE	0.026	KC1	0.10	KD3	0.22	KC2	5.5	KC3
		STN. STL.	0.06	KC5	0.22	KC6	0.42	KC7	11.0	KC8
		CARBOLOY	0.12	KB4	0.48	KB5	0.80	KB3	22.0	KB6
		TANTALUM	0.13	KD2	0.50	KD5	0.85	KD4	22.0	KD1
	R-2-65-C	GLASS	0.11	LB9	0.42	LB7	0.95	LB6	24.0	LB8
		SAPPHIRE	0.15	LC1	0.6	LC2	1.3	LC3	34.0	LC4
		STN. STL.	0.38	LC7	1.4	LC8	2.0	LC9	50.0	LC6
		CARBOLOY	0.65	LB3	2.4	LB2	3.0	LB4	80.0	LB5
		TANTALUM	0.65	LD1	2.6	LD2	3.2	LD3	85.0	LD4
	R-2-65-D	GLASS	0.65	MB9	2.4	MB7	3.8	MB8	100	MC1
		SAPPHIRE	0.95	MC2	3.6	MC3	5.0	MC4	130	MC5
		STN. STL.	1.60	MC7	6.0	MD1	7.5	MC6	200	MC8
		CARBOLOY	2.40	MB5	9.0	MB2	11.0	MB3	280	MB4
		TANTALUM	2.60	MD5	10.0	MD6	12.0	MD2	300	MD4
6	R-6-65-A	GLASS	2.40	NB8	8.5	NB7	13.0	NC1	340	NB9
		SAPPHIRE	3.40	NC4	13.0	NC3	17.0	NC6	460	NC5
		STN. STL.	5.50	ND1	20.0	ND3	26.0	NC9	650	ND2
		CARBOLOY	8.50	NB2	32.0	NB3	36.0	NB5	950	NB6
		TANTALUM	9.0	ND6	34.0	ND5	38.0	ND7	1000	ND4
	R-6-65-B	GLASS	8.0	PB9	30.0	PB8	44.0	PC1	1100	PB7
		SAPPHIRE	12.0	PC5	44.0	PC3	60.0	PC4	1500	PC2
		STN. STL.	19.0	PD1	70.0	PC9	85.0	PC8	2200	PC6
		CARBOLOY	28.0	PB3	100	PB2	130	PB6	3400	PB4
		TANTALUM	30.0	PD7	110	PD6	140	PD5	3600	PD4

*** FLOW RATES GIVEN ARE MAXIMUM VALUES. AIR FLOWS ARE AT 14.7 PSIA AND 70 DEGREES F.**

Table 2 Capacities for Sho-Rate Model 1350E Plain Tapered Tubes, Spherical Floats

PLAIN TAPER TUBES, SPHERICAL FLOATS							
TUBE AND FLOAT	SCFH AIR*	Press. Drop ** Inches W.C.	CODE	TUBE AND FLOAT	GPH WATER	Press. Drop ** Inches W.C.	CODE
1-65A GLASS	1.2	1.0	AB4	1-65C GLASS	0.14	1.8	AB5
2-65A GLASS	2.0	2.2	BA7	2-65C STN. STL.	0.5	4.0	DA5
2-65B STN. STL	5.0	10.8	CA4	2-65D STN. STL.	1.0	19.5	CA8
3-65A GLASS	6.0	12.4	EB4	3-65C GLASS	0.7	22.3	EB9
3-65B STN. STL	10	10.1	EB8	3-65D STN. STL	1.6	18.3	EC1
4-65A GLASS	12	10.4	FC3	4-65C GLASS	2.0	18.7	FD3
4-65B STN. STL	18	25	FC8	4-65D STN. STL	4.0	45	FD6
5-65A GLASS	45	60	GB6	5-65C GLASS	9.0	109	GC4
5-65B STN. STL	80	214	GC1	5-65D STN. STL	17	385	GC5
6-65A GLASS	55	73	HB8	6-65C GLASS	11	132	HC7
6-65B STN. STL	90	292	HC5	6-65D STN. STL	20	525	HD1
6-65E CARBOLOY	120	400	HD3	6-65F CARBOLOY	30	890	HD4

*** FLOW RATES ARE MAXIMUM VALUES. AIR FLOWS ARE AT 14.7 PSIA AND 70 DEGREES F**
**** PRESSURE DROPS ARE APPROXIMATE**

TRADEMARKS
Carboloy .... General Electric Co.
Kalrez .... DuPont Performance Elastomers
NRS .... Brooks Instrument, LLC
Sho-Rate .... Brooks Instrument, LLC
Teflon .... E.I. DuPont de Nemours & Co.
Viton-A .... DuPont Performance Elastomers

Models 1350E and 1355E

Table 3 Tube and Float Code, Detachable Scale Option, 1st Digit

CODE	MODEL 1350 TUBE	MODEL 1355 TUBE
A	1-65	R-2-15-A
B	2-65A	R-2-15-AA
C	2-65B & D	R-2-15-AAA
D	2-65C	R-2-15-B
E	3-65	R-2-15-C
F	4-65	R-2-15-D
G	5-65	R-6-15-A
H	6-65	R-6-15-B
J	R-2-65-A	
K	R-2-65-B	
L	R-2-65-C	
M	R-2-65-D	
N	R-6-65-A	
P	R-6-65-B	
Y	NO TUBE	NO TUBE

Table 4 Tube and Float Code, Detachable Scale Option, 2nd & 3rd Digits

METER ACCURACY	FLOAT MATERIAL	DETACHABLE SCALE INSCRIPTION				
		MM	0-100 LINEAR	SPECIAL SINGLE SCALE	SPECIAL DUAL SCALE	BLANK SCALE
STANDARD (1350-10%) (1355- 5%)	GLASS	1A	1N	2A	2N	3A
	STN. STL.	1B	1P	2B	2P	3B
	SAPPHIRE	1C	1Q	2C	2Q	3C
	CARBOLOY	1D	1R	2D	2R	3D
	TANTALUM	1E	1S	2E	2S	3E
	*ALUMINUM	1F	1T	2F	2T	3F
CALIBRATED (1350-5%) (1355-2%)	GLASS	1G	1U	2G	2U	
	STN. STL.	1H	1V	2H	2V	
	SAPPHIRE	1J	1W	2J	2W	
	CARBOLOY	1K	1X	2K	2X	
	TANTALUM	1L	1Y	2L	2Y	
	*ALUMINUM	1M	1Z	2M	2Z	
N/A	NONE	9A	9B			9C

*ALUMINUM SPOOL FLOAT FOR 15 CC/MIN AIR AVAILABLE ONLY WITH R-2-15-AAA

Table 5 Capacities for Sho-Rate Model 1355E Rib Guided Tubes, Spherical Floats

CAPACITIES (RIB GUIDE TUBES, SPHERICAL FLOATS) - FOR USE WITH 1355 SERIES ONLY							
			MAXIMUM FLOW RATE*		MODEL CODE - SCALE ON TUBE		
METER SIZE	TUBE NO.	FLOAT MATERIAL	WATER (CC/MIN.)	AIR	0-150 MM	10-100%	0-100 LINEAR
2	R-2-15-AAA	GLASS	0.524	47.1 SCC/M	CA6		CA1
		SAPPHIRE	1.02	73.3 SCC/M	CA8		CA3
		STN. STL.	2.42	140 SCC/M	CA7		CA2
		CARBOLOY	4.77	238 SCC/M	CA9		CA4
		TANTALUM	5.31	260 SCC/M	CB1		CA5
	R-2-15-AA	GLASS	0.964	83.8 SCC/M	BA6		BA1
		SAPPHIRE	1.86	128 SCC/M	BA8		BA3
		STN. STL.	4.34	245 SCC/M	BA7		BA2
		CARBOLOY	8.37	416 SCC/M	BA9		BA4
		TANTALUM	9.30	454 SCC/M	BB1		BA5
	R-2-15-D	GLASS	5.58	361 SCC/M	FA6		FA1
		SAPPHIRE	10.2	491 SCC/M	FA8		FA3
		STN. STL.	19.8	790 SCC/M	FA7		FA2
		CARBOLOY	31.9	1170 SCC/M	FA9		FA4
		TANTALUM	34.4	1250 SCC/M	FB1	LIQ. GAS	FA5
	R-2-15-A	GLASS	16.1	0.790 SLPM	AA6	AB7 AC3	AA1
		SAPPHIRE	25.2	1.04 SLPM	AA8	AB9 AC4	AA3
		STN. STL.	44.2	1.60 SLPM	AA7	AB8 AC6	AA2
		CARBOLOY	67.7	2.32 SLPM	AA9	AC1 AC5	AA4
		TANTALUM	72.5	2.46 SLPM	AB1	AC2 AC7	AA5
	R-2-15-B	GLASS	50.6	2.25 SLPM	DA6	DB2	DA1
		SAPPHIRE	76.2	2.92 SLPM	DA8	DB4	DA3
		STN. STL.	127	4.42 SLPM	DA7	DB3	DA2
		CARBOLOY	189	6.35 SLPM	DA9	DB5	DA4
		TANTALUM	202	6.74 SLPM	DB1	DB6	DA5
	R-2-15-C	GLASS	81.1	3.69 SLPM	EA6	EB2	EA1
		SAPPHIRE	123	4.81 SLPM	EA8	EB4	EA3
		STN. STL.	208	7.23 SLPM	EA7	EB3	EA2
		CARBOLOY	312	10.1 SLPM	EA9	EB5	EA4
		TANTALUM	333	10.6 SLPM	EB1	EB6	EA5
6	R-6-15-A	GLASS	191	8.26 SLPM	GA6	GB2	GA1
		SAPPHIRE	284	10.6 SLPM	GA8	GB4	GA3
		STN. STL.	468	15.7 SLPM	GA7	GB3	GA2
		CARBOLOY	690	22.0 SLPM	GA9	GB5	GA4
		TANTALUM	735	23.3 SLPM	GB1	GB6	GA5
	R-6-15-B	GLASS	548	22.6 SLPM	HA6	HB2	HA1
		SAPPHIRE	809	28.6 SLPM	HA8	HB4	HA3
		STN. STL.	1290	41.6 SLPM	HA7	HB3	HA2
		CARBOLOY	1850	58.1 SLPM	HA9	HB5	HA4
		TANTALUM	1960	61.4 SLPM	HB1	HB6	HA5

NOTE: ALL AIR FLOWS ARE AT 14.7 PSIA AND 70 DEGREES F.

* FLOW RATES SHOWN ARE MAXIMUM CAPACITIES. DIRECT READ SCALES MAY END AT SLIGHTLY DIFFERENT MAXIMUM FLOWS.

Table 6 Ordering Information and Model Code

PURGE FLOWMETER		**DESCRIPTION**	
1350E		65 MM TUBE, SIZES 1-6	
1355E		150 MM TUBE, SIZES 2-6	
		TUBE, SCALE AND FLOAT	
		MODEL 1350 OR 1355 DETACHABLE SCALE - SEE TABLES 3 & 4	
xxx	**Enter 3 Digit Model Code**	MODEL 1350 - SEE TABLE 1 OR 2	
		MODEL 1355 - SEE TABLE 5	
		TUBE PACKING	**O-RING MATERIAL (METER/VALVE ASSEMBLY)**
A		BUNA -N	BUNA-N (STD FOR ALUMINUM AND BRASS METERS)
B		VITON	BUNA-N
C		VITON	VITON (STD FOR STN. STL. METERS)
D		VITON	TEFLON (NO VALVE)
D		VITON	TEFLON 0-RINGS METER/KALREZ 0-RINGS VALVE
E		VITON	EPM
F		VITON	KALREZ (NO VALVE)
F		VITON	KALREZ (WITH VALVE)
G		TEFLON	BUNA-N
H		TEFLON	VITON
J		TEFLON	TEFLON (NO VALVE)
J		TEFLON	TEFLON 0-RINGS METER/KALREZ O-RINGS VALVE
K		TEFLON	EPM
L		TEFLON	KALREZ
L		TEFLON	KALREZ (WITH VALVE)
M		EPM	EPM
N		BUTYL	BUTYL
P		NO PACKING OR TUBE	BUNA-N
Q		NO PACKING OR TUBE	VITON
R		NO PACKING OR TUBE	TEFLON (NO VALVE)
R		NO PACKING OR TUBE	TEFLON O-RINGS METER/KALREZ O-RINGS VALVE
S		NO PACKING OR TUBE	EPM
T		NO PACKING OR TUBE	KALREZ
U		NO PACKING OR TUBE	BUTYL
		FITTING AND ADAPTER MATERIAL/PROCESS CONNECTION SIZE & TYPE	
A		BRASS/ 1/8" NPT	
D		BRASS/ THD 1/8" NPT WITH LOCKNUTS (STANDARD)	
G		BRASS/ 1/4" NPT (STD WITH FLOW CONT.)	
L		BRASS/ THD 1/4" NPT WITH LOCKNUTS	
P		BRASS/ 1/8" COMPRESSION	
S		BRASS/ THD 1/8" COMPRESSION WITH LOCKNUTS	
V		BRASS/ 1/4" COMPRESSION	
Y		BRASS/ THD 1/4" COMPRESSION WITH LOCKNUTS	
2		BRASS/ 1/4" I.D. HOSE	
5		BRASS/ NO ADAPTOR-INTEGRAL 5/16-24 THD	
E		ALUMINUM/ THD 1/8" NPT WITH LOCKNUTS (STANDARD)	
H		ALUMINUM/ 1/4" NPT (STD WITH FLOW CONT.)	
6		ALUMINUM/ NO ADAPTOR-INTEGRAL 5/16-24 THD	
C		316 STAINLESS STEEL/ 1/8" NPT	
F		316 STAINLESS STEEL/ THD 1/8" NPT WITH LOCKNUTS (STANDARD)	
J		316 STAINLESS STEEL/ 1/4" NPT (STD WITH FLOW CONT.)	
N		316 STAINLESS STEEL/ THD 1/4" NPT WITH LOCKNUTS	
R		316 STAINLESS STEEL/ 1/8" COMPRESSION	
U		316 STAINLESS STEEL/ THD 1/8 COMPRESSION WITH LOCKNUTS	
X		316 STAINLESS STEEL/ 1/4" COMPRESSION	
1		316 STAINLESS STEEL/ THD 1/4" COMPRESSION WITH LOCKNUTS	
4		316 STAINLESS STEEL/ 1/4" I.D. HOSE	
7		316 STAINLESS STEEL/ NO ADAPTOR-INTEGRAL 5/16-24 THD	
8		316 STAINLESS STEEL/ 1/4" VCR	
K		KYNAR 1/4" NPT (VALVE SHOULD BE 316 S.S. MATERIAL)	

Table 6 Ordering Information and Model Code Continued

	VALVE TYPE
A	VALVE PLUG
B	BRASS - LOW FLOW
C	BRASS - MEDIUM FLOW
D	BRASS - HIGH FLOW
E	316 STAINLESS STEEL - LOW FLOW
F	316 STAINLESS STEEL - MEDIUM FLOW
G	316 STAINLESS STEEL - HIGH FLOW
H	NRS-BRASS #1
J	NRS-BRASS #2
K	NRS-BRASS #3
L	NRS-BRASS #4
M	NRS-BRASS #5
N	NRS-BRASS #6
P	NRS - 316 STAINLESS STEEL #1
Q	NRS - 316 STAINLESS STEEL #2
R	NRS - 316 STAINLESS STEEL #3
S	NRS - 316 STAINLESS STEEL #4
T	NRS - 316 STAINLESS STEEL #5
U	NRS - 316 STAINLESS STEEL #6
V	TO INTEGRALLY MOUNTED FLOW CONTROLLER
W	STANDARD VALVE CAVITY - NO VALVE ASSEMBLY OR PLUG
X	NO VALVE CAVITY (MUST USE CODE 9 BELOW FOR VALVE CAVITY LOCATION)

	VALVE CAVITY LOCATION	CONNECTION ORIENTATION	
1	INLET	IN-BACK,	OUT-BACK (STANDARD)
2	INLET	IN-BACK,	OUT-FRONT
3	INLET	IN-FRONT,	OUT-BACK
4	INLET	IN-FRONT,	OUT-FRONT
5	OUTLET	IN-BACK,	OUT-BACK (STANDARD)
6	OUTLET	IN-BACK,	OUT-FRONT
7	OUTLET	IN-FRONT,	OUT-BACK
8	OUTLET	IN-FRONT,	OUT-FRONT
9	NONE (INLET SIDE) USE WITH CODE X ABOVE	IN-BACK,	OUT-BACK

	ACCESSORIES-1,2, OR 3 DIGIT FIELD
A	NONE
B	ALUMINUM FLUSH MOUNTING BEZEL
C	FLUSH PANEL MOUNTING FOR KYNAR METERS
E	TRIPOD BASE WITHOUT SPIRIT LEVEL
J	DEGREASE FOR OXYGEN SERVICE
L	STAINLESS STEEL SIDE PLATES
M	STAINLESS STEEL SPRING FLOAT STOPS
N	NIST CERTIFICATION INCLUDES CALIBRATION AND SCALE CHECK (10%, 1350; 5%, 135
Q	NO BROOKS IDENTIFICATION

Example: 1350EJB9 AAA1A

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407 West Vine Street
P.O. Box 903
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T (215) 362-3700
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Ordrebekreftelse Ordre 26476

Ordredato:	21.03.2016	Vår referanse:	Atle
Leveringsdato:	10.05.2016	Totalsum:	15 348,75
Deres referanse:	Harald Moen	Rekvisisjon:	NOA 3410
Lev.betingelser:	FCA Larvik	Lev.Måte:	Posten Bedriftspakke

Varenr	Varetekst	Antall	Pris	Sum
BRGT1350	**Brooks Sho-Rate VA Meter** Model:1355GAE3HBJG1AAA 0 N2 med 13% O2, 20°C,1 bara, 100-1000 nl/h	**1,00**	**4282,00**	**4282,00**
BRGT1350	**Brooks Sho-Rate VA Meter** Model:1350GAJ3HBJE1AAA 0 N2 med 3% NO, 20°C, 1 bara, 5.6-56 nl/h	**1,00**	**3869,00**	**3869,00**
BRGT1350	**Brooks Sho-Rate VA Meter** Model:1350GAJ3HGJE1AAA 0 N2 med 3% NH3, 20°C, 1 bara, 5.6-56 nl/h	**1,00**	**4128,00**	**4128,00**
Frakt	**Frakt, pakking og emballasje**	**1,00**		**0,00**

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Leveringsadresse:

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v/Harald Moen
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Ordrebekreftelse		**Ordre**	**26476**
Ordredato:	21.03.2016	Vår referanse:	Atle
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Varenr	**Varetekst**	**Antall**	**Pris**	**Sum**

Sum eks mva:	12 279,00
+ 25% m.v.a. av kr 12279	3 069,75
Totalsum:	**15 348,75**

Achilles JQS
Qualified

RENAS

Attachment 7

Thermometer Fluk 2176A Data Sheet

FLUKE®

Instruction Manual

Model

2166A

Multipoint
Digital Thermometer

P/N 445445

REV. 1 2/77

APRIL 1976

LIMITED WARRANTY

The JOHN FLUKE MFG. CO., INC., warrants each instrument it manufactures to be free from defects in material and workmanship under normal use and service for the period of one year from date of purchase. This warranty extends only to the original purchaser. This warranty shall not apply to fuses, disposable batteries (rechargeable type batteries are warranted for 90 days), or any product or parts which have been subject to misuse, neglect, accident or abnormal conditions of operations.

In the event of failure of a product covered by this warranty, John Fluke Mfg. Co., Inc., will repair and calibrate an instrument returned to an authorized Service Facility within one year of the original purchase; provided the warrantor's examination discloses to its satisfaction that the product was defective. The warrantor may, at its option, replace the product in lieu of repair. With regard to any instrument returned within one year of the original purchase, said repairs or replacement will be made without charge. If the fault has been caused by misuse, neglect, accident or abnormal conditions of operations, repairs will be billed at a nominal cost. In such case, an estimate will be submitted before work is started, if requested.

> ANY IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS SHALL BE LIMITED TO A PERIOD OF TWELVE MONTHS FROM THE DATE OF PURCHASE. THE FOREGOING WARRANTY IS IN LIEU OF ALL OTHER WARRANTIES, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO ANY IMPLIED WARRANTY OF MERCHANTABILITY, FITNESS OR ADEQUACY FOR ANY PARTICULAR PURPOSE OR USE. JOHN FLUKE MFG. CO., INC. SHALL NOT BE LIABLE FOR ANY SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES, WHETHER IN CONTRACT, TORT OR OTHERWISE.
>
> NOTE: Some states do not allow limitations on how long an implied warranty lasts, or the exclusion or limitation of incidental or consequential damages, so the above limitations or exclusion may not apply to you. This warranty gives you specific legal rights, and you may also have other rights which vary from state to state.

If any fault develops, the following steps should be taken:

1. Notify the John Fluke Mfg. Co., Inc. or nearest Service facility, giving full details of the difficulty, and include the Model number, type number, and serial number. On receipt of this information, service data or shipping instructions will be forwarded to you.
2. On receipt of the shipping instructions, forward the instrument, transportation prepaid. Repairs will be made at the Service Facility and the instrument returned, transportation prepaid.

SHIPPING TO MANUFACTURER FOR REPAIR OR ADJUSTMENT

All shipments of John Fluke Mfg. Co., Inc., instruments should be made via United Parcel Service or "Best Way*" prepaid. The instrument should be shipped in the original packing carton; or if it is not available, use any suitable container that is rigid and of adequate size. If a substitute container is used, the instrument should be wrapped in paper and surrounded with at least four inches of excelsior or similar shock-absorbing material.

CLAIM FOR DAMAGE IN SHIPMENT TO ORIGINAL PURCHASER

The instrument should be thoroughly inspected immediately upon original delivery to purchaser. All material in the container should be checked against the enclosed packing list. The manufacturer will not be responsible for shortages against the packing sheet unless notified immediately. If the instrument is damaged in any way, a claim should be filed with the carrier immediately. (To obtain a quotation to repair shipment damage, contact the nearest Fluke Technical Center.) Final claim and negotiations with the carrier must be completed by the customer.

The John Fluke Mfg. Co., Inc. will be happy to answer all application or use questions, which will enhance your use of this instrument. Please address your requests or correspondence to: JOHN FLUKE MFG. CO., INC., P.O. Box 43210, MOUNTLAKE TERRACE, WASHINGTON 98043, Atten: Sales Dept. For European Customers: FLUKE (Nederland) B.V., Zevenheuvelenweg 53, Tilburg, The Netherlands.

* For European customers, Air Freight prepaid.

John Fluke Mfg. Co., Inc. ● P.O. Box 43210 ● Mountlake Terrace, Washington 98043

Rev. 12/77

Change/Errata Information

Issue No: 2 4/78

This change/errata contains information necessary to ensure the accuracy of the following manual. Enter the corrections in the manual in the order given.

MANUAL

Title:	MODEL 2166A MULTIPOINT DIGITAL THERMOMETER
Print Date:	APRIL 1976
Rev and Date:	1 – 2/77

C/E PAGE EFFECTIVITY

Page No.	Print Date
1	4/78

CHANGE #1–11434

On page 5-6, add CR4 to reference designators CR6 thru CR15, and change total quantity from 10 to 11.

On page 5-7, change the stock number, supply code, and part numbers for Q27 and Q28 from:
272237, 07263, 2N4946
to:
477331, 04713, MPSU01A

On page 8-3, add diode CR4 between the +5 and +6.8V dc power supply outputs; cathode to +6.8V, anode to +5V.

CHANGE #2–11563
Rev H-1

On page 5-8, make the following changes:
Change the U1 entry from:
IC, dual opnl ampl; 404087; 49956; RC4739DP; 1; 1
To:
Op amp pcb assy; 488379; 89536; 488379

Add the following new entry (socket for U1):
XU1; Socket; IC, 14-pin DIP; 276527; 89536; 276527; 1; 1

Rev J

On page 5-8, change the entry for U1 from:
IC, dual opnl ampl; 404087; 49956; RC4739DP; 1; 1
To:
IC, dual opnl ampl, 8-pin DIP; 478032; 04713; MC4558NCPI; 1; 1

Section 1

Introduction & Specifications

1-1. INTRODUCTION

1-2. The Model 2166A Multipoint Digital Thermometer is a portable four-digit, manual-scan, thermocouple thermometer capable of measuring any 1 of 10 possible like-type thermocouple inputs and resolving 1°C or 1°F over a temperature range of −200 to +2328°C or −328 to +3999°F. It features switch selection of temperature (°C/°F) and thermocouple channel (1-10), a four digit LED display, reference junction compensation (to eliminate the need for an ice bath reference junction), the choice of any one of eight thermocouple types (J, K, T, E, R, S, B or C) as the input device, dual-slope measurement techniques, digital linearization of thermocouple inputs, and power inputs for both ac line and external 12V dc operation. Several options and accessories are also available for use with the 2166A.

1-3. Front panel switch controls include a push-button power switch (ON/OFF), a push-button temperature select switch (°C/°F), and a 10-position rotary switch for selecting the desired thermocouple. The rotary switch is labeled CHANNEL Select and the thermocouple inputs are identified as 1 through 10.

1-4. The front-panel display consists of five, seven-segment, high-intensity LED's, and features leading zero suppression. Four of the LED's are used to display numeric data, including a minus sign for negative temperature indications. The fifth LED displays the selected °C or °F scale character. An open-thermocouple detector causes the display to blink when an open circuit is sensed at any one of the selected thermocouple input terminals.

1-5. A plug-in module at the rear of the 2166A provides 10 pairs of screw-type input terminals for attaching individual thermocouples to the desired channels. These terminals are an integral part of an isothermal block and serve as the reference junction for the reference junction compensator. (The reference junction compensator provides the physical and electrical equivalent of, and eliminates the need for, an ice bath junction at 0°C or 32°F.)

NOTE

All thermocouples connected to the input terminals must be of the same type.

1-6. The actual measurement range of the 2166A is determined by the type of thermocouples being used as the input devices. Any one of eight thermocouple types can be used; J, K, T, E, R, S, B or C. To ensure the proper linearization of the selected thermocouple input, a corresponding linearization program must be selected on the interior of the unit. Selection is accomplished by installing a type select pcb which corresponds to the input thermocouple. A single type select pcb is supplied with the unit to match the thermo-

Table 1-1. 2166A ACCESSORIES

MODEL NO.	DESCRIPTION
C80	Carrying Case
C86	Carrying Case
P20J	J-Type Thermocouple Probe
P20K	K-Type Thermocouple Probe
P20T	T-Type Thermocouple Probe
M00-100-714	Front Panel Dust Cover
M00-200-611	Rack Mounting Kit, Offset
M00-200-612	Rack Mounting Kit, Center
M00-200-613	Rack Mounting Kit, Side-by-Side
2160A-7016	J-Type Select PCB
2160A-7017	K-Type Select PCB
2160A-7019	E-Type Select PCB
2160A-7018	T-Type Select PCB
2160A-7012	R-Type Select PCB
2160A-7013	S-Type Select PCB
2160A-7014	B-Type Select PCB
2160A-7015	C-Type Select PCB
2160A-7022	Interface Cable

couple specified at the time of purchase. The remaining pcb's are individually available as accessories and are described in Table 1-1.

1-7. Accessories and options available for use with the 2166A are listed and described in Tables 1-1 and 1-2, respectively. Both options are field installable. Either one, but not both, of the options can be installed in a unit. Detailed information concerning each option and accessory is given in Section 6 of this manual, Option and Accessory Information.

1-8. The 2166A is designed to operate from either ac line power or an external 12V dc source. A choice of any one of three line power configurations are available: 100V ac, 50 to 440 Hz; 115V ac, 50 to 440 Hz; and 230V ac, 50 to 440 Hz. Specify the required configuration at the time of purchase.

Table 1-2. 2166A OPTIONS

OPTION NUMBER	DESCRIPTION
–02	Digital Output Unit
–04	Analog Output Unit

1-9. SPECIFICATIONS

1-10. Specifications for the 2166A are given in Table 1-3.

Table 1-3. SPECIFICATIONS

ELECTRICAL

Compatible Thermocouple Types	Unit can be calibrated to operate with any one of the following thermocouple types: J, K, T, E, R, S, B or C
Measurement Method	Dual-slope integration over a 100 ms period
Zero Drift	None. Automatic zero correction
Reading Rate	2.5 readings per second
°C to °F Conversion	Switch selectable
Input Characteristics	
Input Connections	Screw terminals on isothermal connector
Input Circuit	Two-wire isolated per channel, 10-channel, switch selectable
Input Impedance	> 100 MΩ
Input Current	< 500 pA
Source Impedance	⩽ 5kΩ. 5kΩ causes <0.2°C (.36°F) error with k thermocouple
Overload	Display flashes when input voltage exceeds full-scale temperature range
Open Input	Display flashes to indicate open at input terminals
Maximum Input Voltage	130V dc or 130V ac (rms) between any pair of inputs
Maximum Input Voltage (without damage)	400V dc or ac peak continuously between inputs or between either input and ground
Maximum Common Mode Voltage (without damage)	400V dc or ac peak
Common Mode Rejection	⩾ 120 dB @ 50, 60, 400 Hz ±0.1% with 1kΩ source impedance unbalance
Normal Mode Rejection	⩾ 60 dB @ 50, 60, 400 Hz ±0.1%
Accuracy	See Table 1 for °C specifications and Table 2 for °F specifications
Response Time to Rated Accuracy	< 2.0 seconds
Linearization	Digital with eight selectable programs in LSI ROM
Linearization Programs	
J, K, T and E	32 straight line segments for positive inputs and 16 for negative inputs

Table 1-3. SPECIFICATIONS (Cont.)

Reference Junction Compensation

20 to 30°C (68 to 86°F)

J, K, T, E . . . . 0.025 degrees per degree

0 to 20°C, 30 to 50°C (32 to 68°F, 86 to 122°F)

J, K . . . . 0.032 degrees per degree

T, E . . . . 0.045 degrees per degree

Temperature Coefficient . . . . 0.005% of reading per °C

Internal Temperature Rise . . . . ≤ 8°C (14.4°F)

Table 1. ACCURACY SPECIFICATIONS °C

THERMOCOUPLE TYPE	TEMPERATURE RANGE °C	RESOLUTION AND REPEATABILITY (±C)	APPLICABLE TEMPERATURE RANGE °C	MAXIMUM ERROR INCLUDING NBS CONFORMITY (±°C)*				
				CALIBRATION ACCURACY	20 min. to 24 hrs. 23 to 27°C	90 Days 20 to 30°C	1 Year 15 to 35°C	NBS CONFORMITY (±°C)
J	−200 to 778	1	−200 to 0	1	1	1.5	1.5	.19
			0 to 778	1	1	1	1.5	.15
K	−200 to 1356	1	−200 to 0	1	1	1.5	2	.20
			0 to 1356	1	1	1.5	2	.18
T	−200 to 400	1	−200 to 0	1	1	1.5	2	.19
			0 to 400	1	1	1	1	.15
E	−200 to 1000	1	−200 to 0	1	1	1.5	2	.17
			0 to 1000	1	1	1	1.5	.18
R	0 to 1778	1	0 to 1778	1.5	1.5	2.5	3	.26
S	0 to 1778	1	0 to 1778	1.5	1.5	2	3	.22
B	533 to 1844	1	533 to 1844	1.5	1.5	2	2.5	.29
C	0 to 2328	1	0 to 2328	2	2	3	3	.36

* Includes reference junction and conformity errors. Excludes thermocouple errors.

Table 1-3. SPECIFICATIONS (Cont.)

Table 2 ACCURACY SPECIFICATIONS °F

THERMOCOUPLE TYPE	TEMPERATURE RANGE °F	RESOLUTION AND REPEATABILITY (±°F)	APPLICABLE TEMPERATURE RANGE °F	MAXIMUM ERROR INCLUDING NBS CONFORMITY (±°F)*				NBS CONFORMITY (±°F)
				CALIBRATION ACCURACY	20 min. to 24 hrs. 72 to 82°F	90 Days 68 to 86°F	1 Year 59 to 95°F	
J	–328 to 1432	1	–328 to 32 32 to 1432	1.5 1.5	2 1.5	2 1.5	3 2.5	0.27 0.2
K	–328 to 2472	1	–328 to 32 32 to 2472	2 1.5	2 1.5	2.5 2.5	3 3.5	0.28 0.26
T	–328 to 752	1	–328 to 32 32 to 752	2 1.5	2 1.5	2.5 1.5	3.5 2	0.3 0.2
E	–328 to 1832	1	–328 to 32 32 to 1832	2 1.5	2 1.5	2.5 2	3.5 3	0.25 0.25
R	32 to 3232	1	32 to 3232	2.5	2.5	4	5	0.4
S	32 to 3232	1	32 to 3232	2.5	2.5	4	5	0.33
B	1032 to 3352	1	1032 to 3352	2.5	2.5	4	4.5	0.45
C	32 to 3999	1	32 to 3999	3	3	5	5.5	0.58

*Includes reference junction and conformity errors. Excludes thermocouple errors.

GENERAL

Type of Display	LED, 0.56 in high.
Power Requirements	
Line Operation	115V ac ±10%, 50 to 440 Hz, 8W. 100V ac and 230V ac version are also available.
External DC Source	11 to 15V dc @ 400 mA
Size	2.52 in (H) x 8.55 in (W) x 9.9 in (D) (6.40 cm x 21,72 cm x 25,15 cm). See Figure 1-1.
Weight	3 lbs. 4 oz. (1.47 kg)

Table 1-3. SPECIFICATIONS, Cont.

ENVIRONMENTAL

Temperature	
Operating	0 to 50°C (32 to +122°F)
Storage	–40 to 75°C (–40 to 167°F)
Humidity	
0 to 50°C (32 to 122°F)	80% non-condensing
0 to 35°C (32 to 95°F)	90% non-condensing
Shock and Vibration	Meets requirements of MIL Standard 810

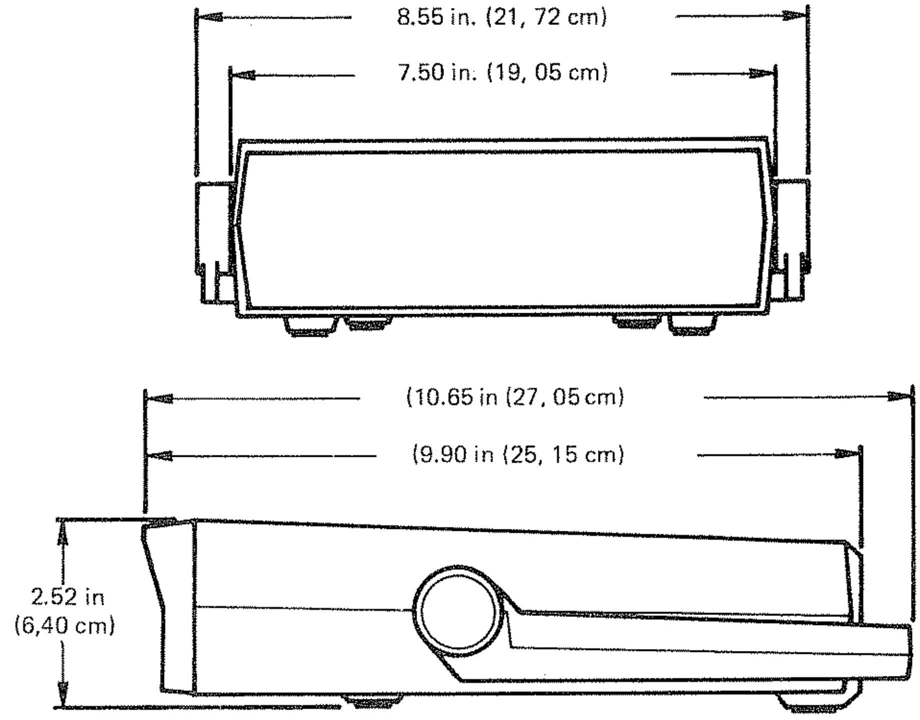
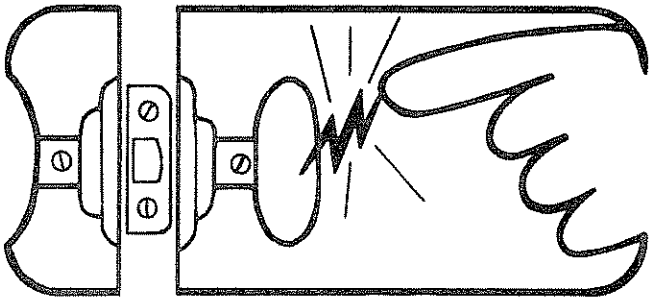


Figure 1-1. OUTLINE DRAWING

static awareness

A Message From

John Fluke Mfg. Co., Inc.

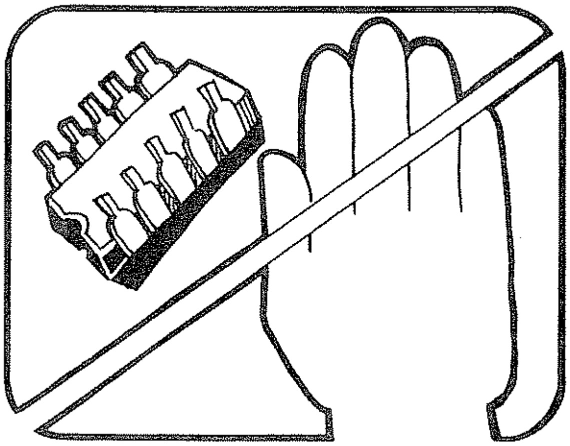


Some semiconductors and custom IC's can be damaged by electrostatic discharge during handling. This notice explains how you can minimize the chances of destroying such devices by:

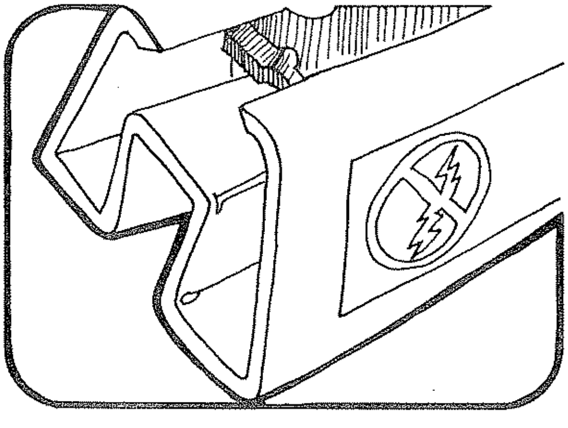
1. Knowing that there is a problem.
2. Learning the guidelines for handling them.
3. Using the procedures, and packaging and bench techniques that are recommended.

The Static Sensitive (S.S.) devices are identified in the Fluke technical manual parts list with the symbol "⊗".

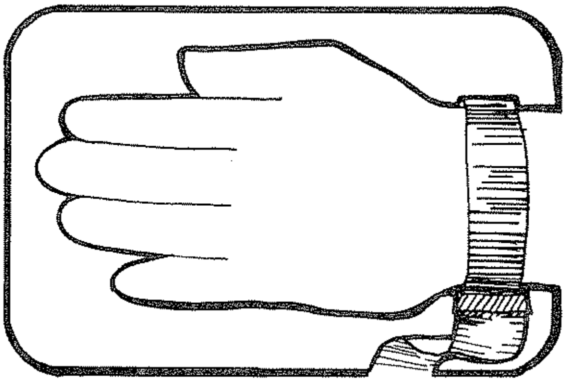
The following practices should be followed to minimize damage to S.S. devices.



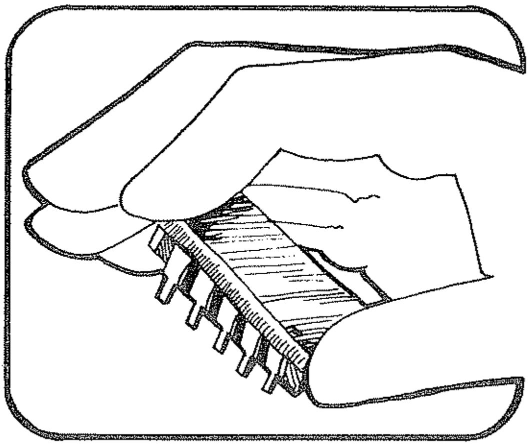
1. MINIMIZE HANDLING



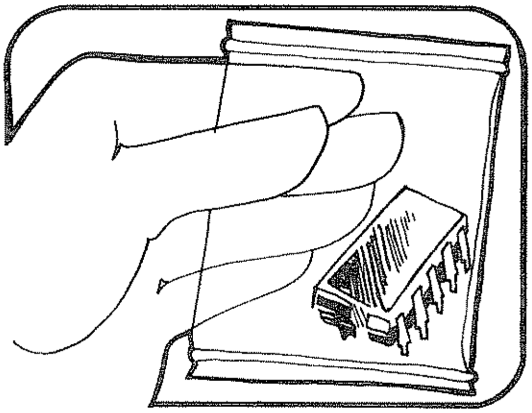
2. KEEP PARTS IN ORIGINAL CONTAINERS UNTIL READY FOR USE.



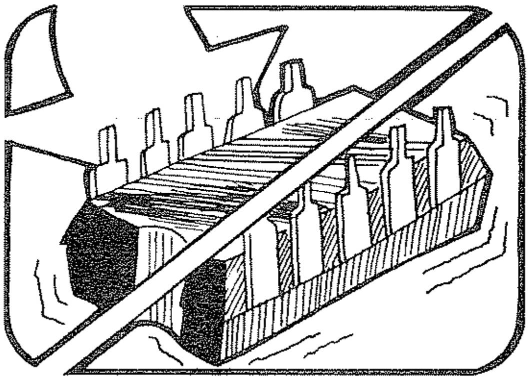
3. DISCHARGE PERSONAL STATIC BEFORE HANDLING DEVICES



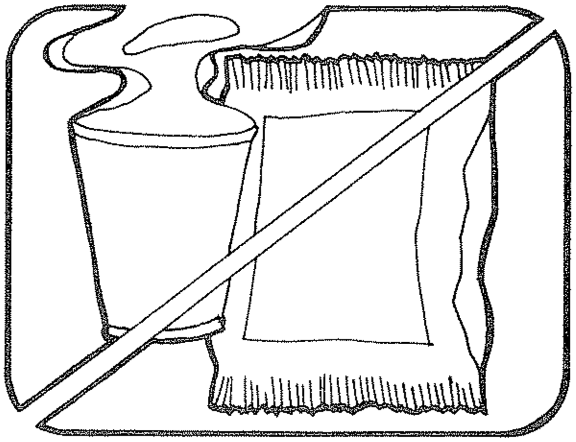
4. HANDLE S.S. DEVICES BY THE BODY



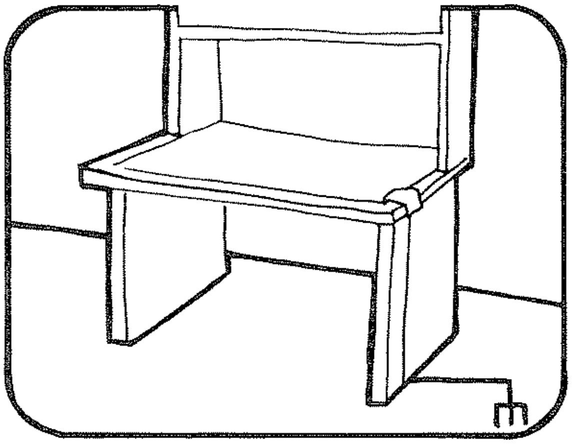
5. USE ANTI-STATIC CONTAINERS FOR HANDLING AND TRANSPORT



6. DO NOT SLIDE S.S. DEVICES OVER ANY SURFACE



7. AVOID PLASTIC, VINYL AND STYRAFOAM IN WORK AREA



8. HANDLE S.S. DEVICES ONLY AT A STATIC-FREE WORK STATION

9. ONLY ANTI-STATIC TYPE SOLDER-SUCKERS SHOULD BE USED.

10. ONLY GROUNDED TIP SOLDERING IRONS SHOULD BE USED.

Anti-static bags, for storing S.S. devices or pcbs with these devices on them, can be ordered from the John Fluke Mfg. Co., Inc.. See section 5 in any Fluke technical manual for ordering instructions. Use the following part numbers when ordering these special bags.

John Fluke Part No.	Bag Size
453522	6" x 8"
453530	8" x 12"
453548	16" x 24"
454025	12" x 15"

Section 2

Operating Instructions

WARNING!

Due to the possible presence of lethal voltages, the procedures in paragraphs 2-21 and 2-27 should be performed by qualified personnel only.

2-1. INTRODUCTION

2-2. This section of the manual contains information regarding installation and operation of the Model 2166A Multipoint Digital Thermometer. It is recommended that the contents of this section be read and understood before any attempt is made to operate the instrument. Should any difficulties arise during operation, please contact your nearest Fluke Technical Service Center, or the John Fluke Mfg. Co., Inc., P.O. Box 43210, Mountlake Terrace, WA 98043, Tel. (206) 774-2211. A list of Technical Service Centers is located in Section 7 of this manual.

2-3. SHIPPING INFORMATION

2-4. The 2166A is packaged and shipped in a foam-packed container. Upon receipt of the instrument, a thorough inspection should be made to reveal any possible shipping damage. Special instructions for inspection and claims are included in the shipping carton.

2-5. If reshipment of the instrument is necessary, the original container should be used. If the original container is not available, a new one can be obtained from the John Fluke Mfg. Co., Inc. Please reference the instrument model number when requesting a new shipping container.

2-6. INPUT POWER

2-7. The 2166A can be operated from either ac line power or an external 12V dc source. The unit is energized when either or both sources are connected to their proper input terminals, and the front-panel POWER switch is set to ON.

2-8. AC Line Voltage

2-9. The 2166A is factory wired to operate from one of three ac line voltages. These are: 100V ac, 50 to 440 Hz; 115V ac, 50 to 440 Hz; and 230V ac, 50 to 440 Hz. Before connecting the 2166A to the ac line, check to ensure that the instrument is wired to accommodate the local line voltage. A decal on the underside of the unit defines the particular line voltage required to operate the instrument.

2-10. The rear panel ac input connector is a three-prong, U-ground connector which permits the instrument to be connected, via the power cord, to the appropriate line voltage. The offset prong on this connector is connected to the 2166A power supply, and should be connected through the power cord to a high quality earth ground.

2-11. External 12V dc Source

2-12. The external 12V dc source connects to two screw terminals provided on the rear of the 2166A. The decal on the bottom of the unit defines their location and polarity. The external source should be capable of supplying at least 400 mA at 11V dc.

2-13. RACK INSTALLATION

2-14. The 2166A is designed for field and bench-top use or for installation in a standard 19-inch equipment rack using an accessory rack-mounting kit. Kits are available for left, right, center or side-by-side mounting of the 2166A. Information about the rack mounting accessories is given in Section 6 of this manual, Option and Accessory Information.

2-15. OPERATING FEATURES

2-16. The location of all 2166A controls, indicators and connectors are shown in Figure 2-1, and described in Table 2-1.

2-17. OPERATING NOTES

2-18. The following paragraphs describe various conditions which should be considered before operating the 2166A.

2-19. Option Information

2-20. Supplementary operating instructions are necessary when operating a 2166A which is equipped with one of the available options. Detailed information regarding the operation of each available option is given in Section 6 of this manual, Option and Accessory Information

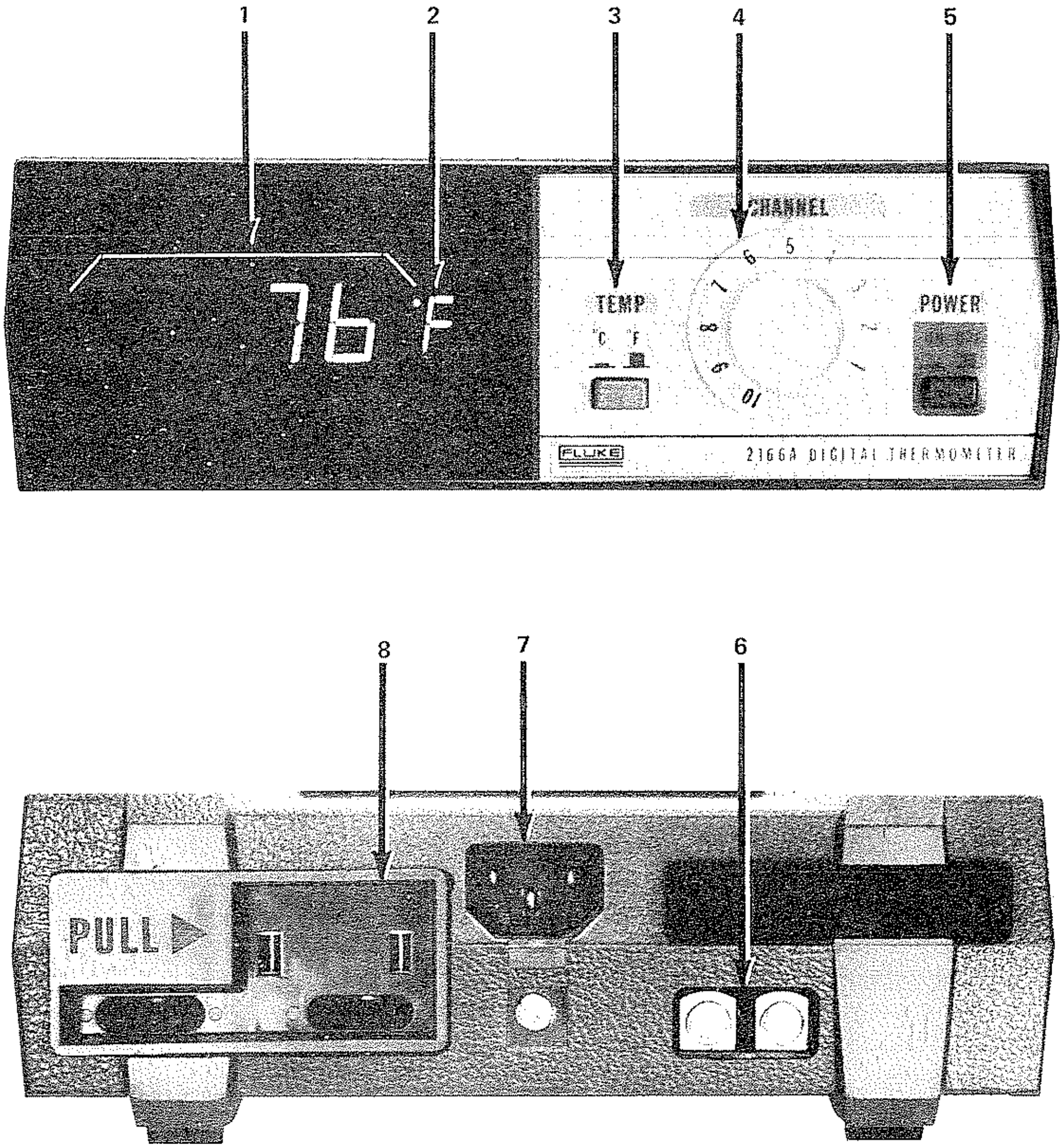


Figure 2-1. 2166A CONTROLS, INDICATORS AND CONNECTORS

Table 2-1. 2166A CONTROLS, INDICATORS AND CONNECTORS

REF. NO.	NAME	FUNCTION
1	Digital Display	Displays a four digit readout of the measured input temperature. Leading-zero suppression is also included. A minus sign is displayed for negative temperature measurements. The absence of a polarity sign indicates a positive temperature measurement.
2	Temperature Scale Indicator	Displays the temperature scale represented by the digital display data; °C or °F.
3	TEMP Scale Switch	Selects the temperature scale for the digital display. When the switch is depressed (IN), the °C scale is selected. The °F scale is selected when the switch is released (OUT).
4	CHANNEL SELECT Switch	Selects 1 of 10 possible thermocouple inputs to be used as the thermometer input. The temperature of the selected thermocouple is continuously read and displayed.
5	POWER Switch	Switches the 2166A on or off regardless of the input power source. The instrument is turned-on when the switch is depressed.
6	External 12V dc Input	Provides screw-type input terminals for connecting an external 12V dc power source. The 12V dc connections are not required when the unit is being operated from ac line power.
7	Input Power Connector	Provides the means of connecting the instrument through a power cord to ac line power. Line power is not required when the unit is being operated from an external 12V dc source.
8	Multipoint Input Module	Provides 10 pairs of screw-type input terminals for connecting up to 10 of the same type thermocouples. Slots are provided at the rear of the drawer for strain relief of the thermocouple bundles.

2-21. Fuse Replacement

2-22. The ac line-input section of the 2166A power supply is fuse protected. The fuse is located on the interior of the unit near the power transformer. To access the fuse, disconnect the unit from line power, remove the rear-panel retaining screw located beneath the ac line connector, and pull the case from the instrument. When replacement is necessary, use an MDL (Slo-blo) 1/8A fuse.

2-23. Overload and Open Thermocouple Indication

2-24. The front panel display, in addition to providing a measurement reading, is designed to serve as an overrange or open thermocouple indicator. When the measurement range of the input thermocouple is exceeded, or when the thermocouple inputs are open circuited, the display will blink. The blinking indication does not mean that the instrument is being exposed to a damaging input condition.

2-25. Thermocouple Connections

2-26. The 2166A is capable of monitoring the temperature of 1 of 10 thermocouple probes of the same type. The probes connect to the unit through a plug-in Multipoint Input Module as shown in Figure 2-2. Ten pairs of screw-type terminals are provided for completing the thermocouple input connections. Each set of terminals is identified by a channel number from 1 to 10 and the attached thermocouple probe assumes that channel number. A particular channel is selected and measured by setting the front panel CHANNEL Select switch to the corresponding channel number.

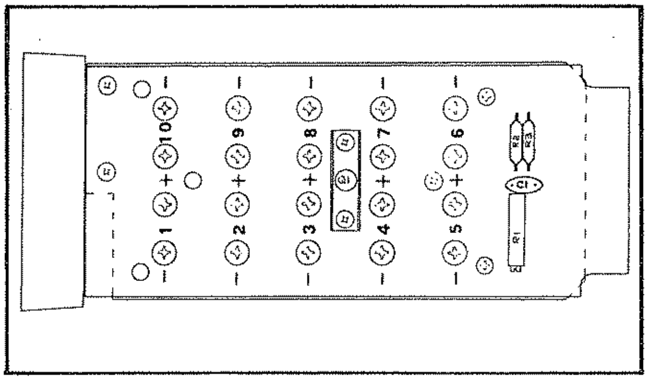


Figure 2-2. MULTIPOINT INPUT MODULE

2-27. Thermocouple Compatibility

2-28. The 2166A is designed to operate in conjunction with a selected type of thermocouple probe. A decal on the bottom of the unit identifies the compatible thermocouple type. When necessary, the 2166A can be modified in the field to accommodate any one of the following thermocouple types: J, K, T, E, R, S, B or C. Use the following procedure to change thermocouple types:

a. Refer to Table 1-1 in Section 1 of this manual and order the type select pcb which corresponds to the desired thermocouple type. These pcb's are low-cost items and can be purchased from any one of the John Fluke Technical Service Centers (See Section 7) or from the John Fluke Mfg. Co., Inc.

b. Disconnect the 2166A from line power.

c. Remove any ribbon-cable connectors that may be attached to the rear of the 2166A.

d. Disconnect the power cord from the rear of the unit.

e. Remove the rear-panel screw located just below the power input connector.

f. Pull the 2166A front panel and pcb assembly out the front of the plastic case.

g. Unplug and remove the currently installed type select pcb from the position shown in Figure 2-3, and install the new pcb in its place.

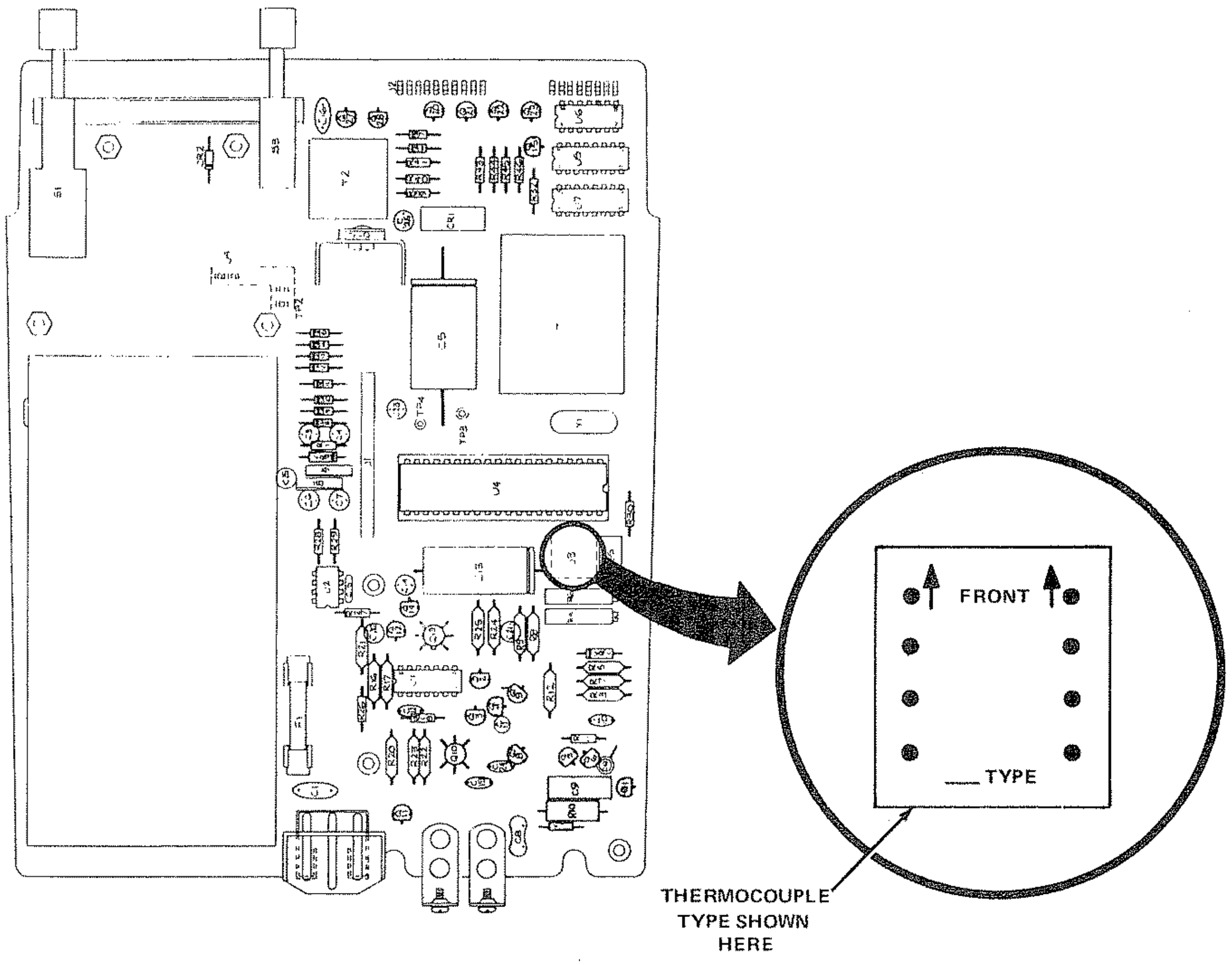


Figure 2-3. TYPE SELECT PCB, LOCATION AND INSTALLATION DETAILS

NOTE

The thermocouple type is etched on the type select pcb's. When properly installed the arrows on the pcb point toward the digital display.

h. Place a piece of tape over the thermocouple type indications on the bottom-side decal, and mark the new thermocouple type on it.

i. Connect the unit to line power, and complete the routine calibration procedure given in Section 4 (Maintenance) of this manual.

j. Install the unit in its case.

2-29. OPERATION

2-30. With reference to previous paragraphs in this section, use the following procedure to operate the 2166A:

a. Refer to the decal on the bottom of the unit and determine the compatible thermocouple type.

b. Locate the Multipoint Input Module on the rear of the unit.

c. Place your forefinger in the recess marked by the arrow and pull the drawer straight out the rear of the unit.

d. Guide the thermocouple probe connections through one of the module's rear panel openings and connect them to the desired thermocouple channel input terminals, 1 through 10. A total of 10 thermocouples (all the same type) can be simultaneously connected in this manner. Mark each probe so that it can be readily associated with its corresponding channel, 1-10.

e. Reposition the module in the 2166A and press it firmly into position.

f. Connect the unit to the appropriate line power, as defined on the bottom-decal, or to an external 12V dc source.

g. Energize the 2166A by depressing the POWER switch.

h. Determine the thermocouple probe to be monitored and set the CHANNEL Select switch to the corresponding channel.

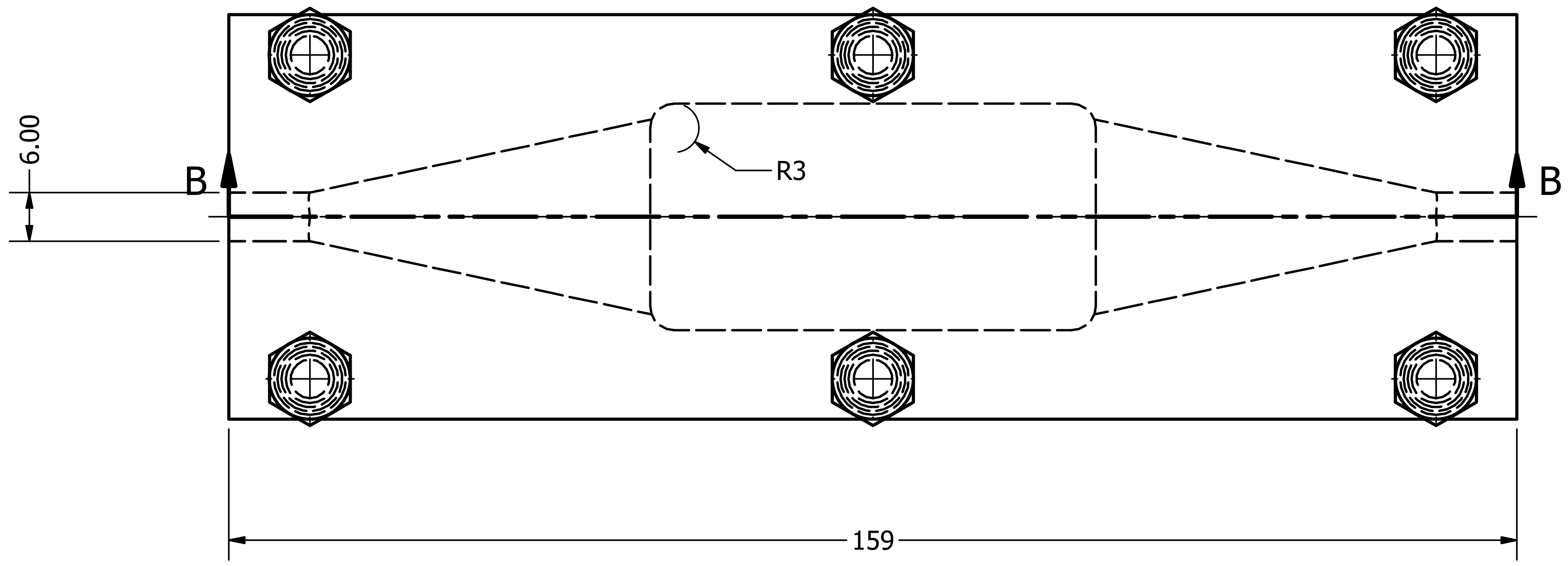
i. Set the TEMP switch to the desired temperature scale, °C or °F.

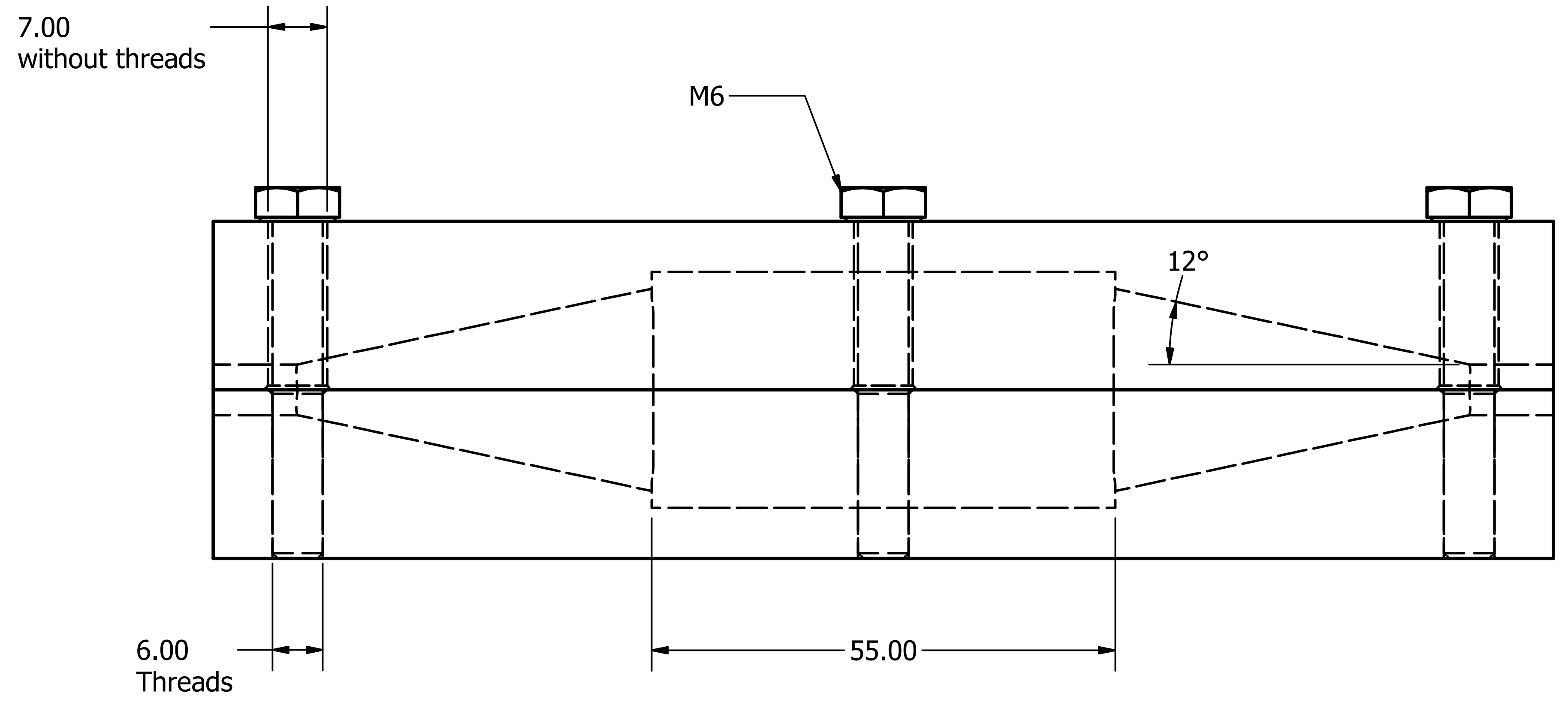
j. Refer to Section 6 of this manual for instructions concerning the operation of the –02 and –04 Options.

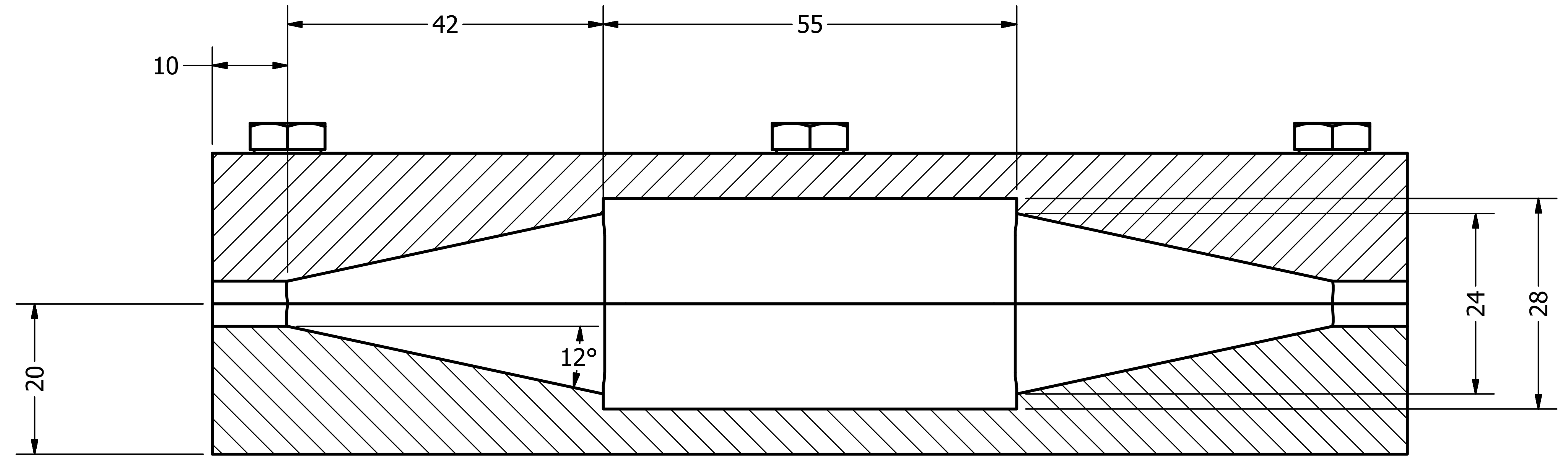
k. Expose the thermocouple assigned to the selected channel to a temperature within its specified range (See bottom decal). The probe temperature will be displayed on the front panel.

Attachment 8

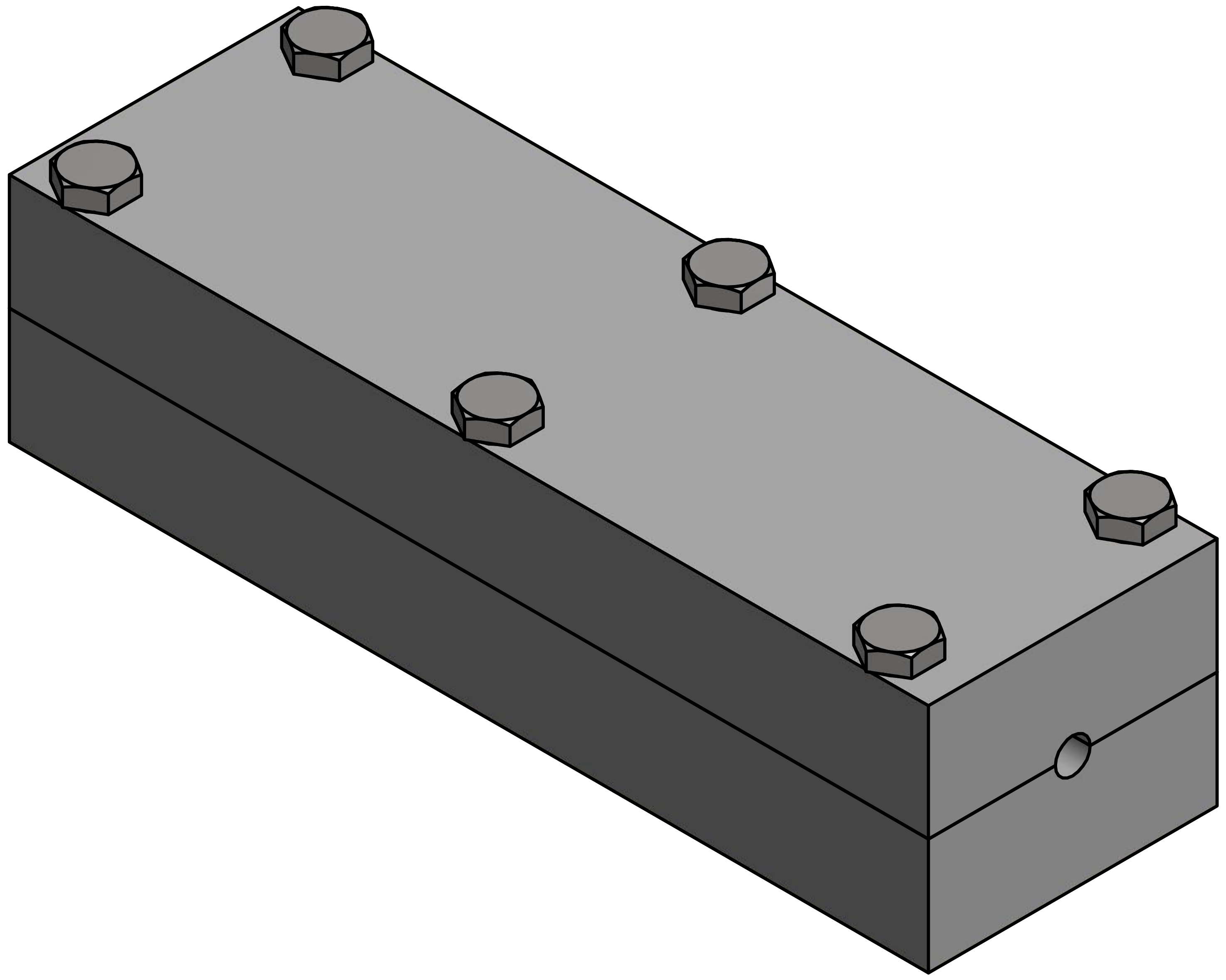
SCR-Reactor, 2D model and 3D model.



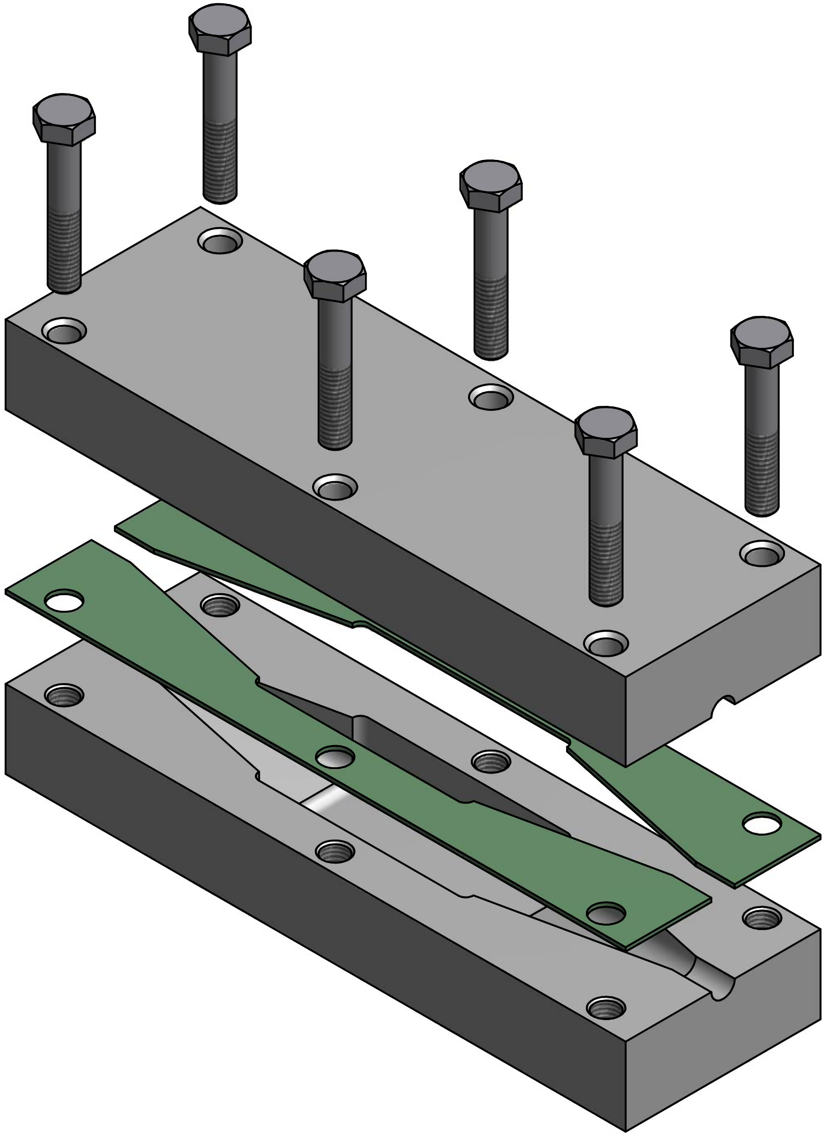




SECTION B-B
SCALE 1,3 : 1



DRAWN Vitaliya Makoveyenko	26.04.2016	
CHECKED		TITLE
QA		SCR - MicroReactor
MFG		
APPROVED		
		SIZE C · DWG NO Assembly Final 2D · REV
		SCALE 1,3:1 · SHEET 1 OF 1



DRAWN Vitaliya Makoveyenko	27.04.2016			
CHECKED		TITLE		
QA		SCR-MicroReactor		
MFG				
APPROVED				
		SIZE C	DWG NO	REV
		SCALE 1,5:1		SHEET 1 OF 1

Attachment 9 – System tests

System tests

As with any new system, functional tests are carried out for a number of reasons. The system has to be modified and optimized for its purpose, along with being safe to operate. The main goal is to determine if the system is capable of operating under similar conditions of that in a real marine SCR-process. As a result, a number of tests are carried out:

- Leakage test
- Heat test
- Pressure test

Attachment 7 A - Leakage test

The purpose of this test is to determine if the reactor is properly sealed. For this task 3 different thermal pastes are considered:

- Exhaust repair paste
- Thermal paste for ovens
- Thermal silicone

Thermal silicone is ruled out due to its temperature limitation of 350°C. The two first thermal pastes can withstand 600°C and 1500°C respectively. They are both potential candidates and are further tested for expansion. An expanding mass within a confined area could pose a risk to the brittle honeycomb structure, cracking it in a worst case scenario.

Both thermal pastes are applied to a piece of metal and inserted into the oven at increasing temperatures. Test results reveal that the “Thermal paste for ovens” has expanded and is therefore eliminated as a candidate for this project. The “Exhaust repair paste” retains its form throughout the test and proves to have the desired properties for this experiment.

The reactor is then bolted shut and sealed with thermal paste before put in the oven to harden. After the hardening process is complete and the reactor has cooled off, it is ready for the leakage test.

The reactor is connected to the system and sprayed with soap water on all surfaces. Air is run through the system at a pressure of 1 bar so that leaks can be spotted by bubbles forming at a potential leak-point. It is worth noting that this is an open system, meaning that even though air is run through at 1 bar, there is no way near 1 bar pressure inside the system. Under these condition the reactor holds tight.

The system is then plugged at the end so it holds a pressure of 1 bar, and bubbles are forming at the inlet of the reactor, Figure 1.

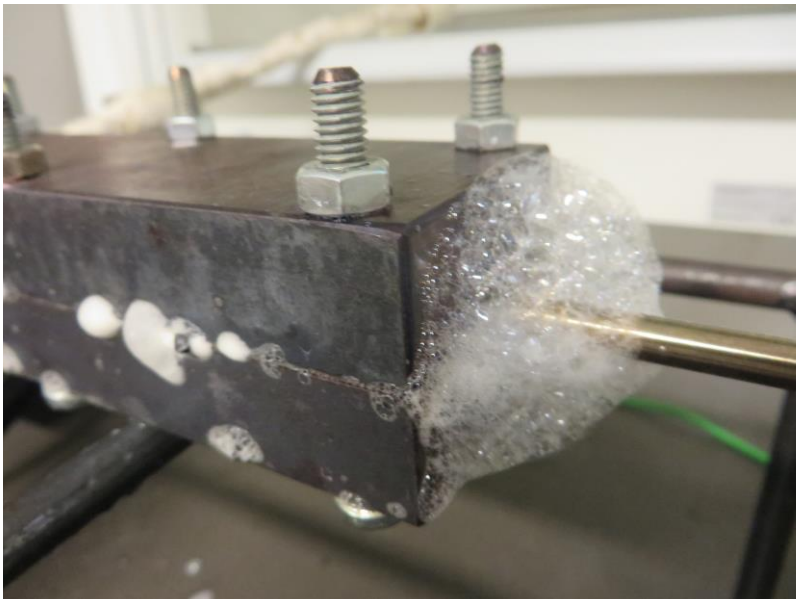


Figure 1 - SCR-reactor exposed for pressure of 2 bar

Even though our system will never actually experience a pressure of 1 bar under normal operating conditions, it is better to have a safety margin.

The reactor is re-opened, re-fitted with a fresh catalyst, then thoroughly sealed before being hardened again. Because the reactor in the first test, under normal operating conditions, would have been sufficiently sealed, it is assumed that after re-sealing the reactor more thoroughly a second time it should hold tight.

Attachment 7 B - Heat test

The purpose of the heat test is to adjust and optimize the system to operate under conditions as similar as possible to a real SCR-process, while at the same time being able to monitor what is going on inside the system. The test is divided into three parts. The first part will examine the systems thermal properties – the heating conditions within the finished system. The two next parts will cover how to improve the thermal capabilities of the system.

Heat test material list:

- Pressurized air as working fluid
- Flowmeter with a range of 0-1000 l/h
- 2x temperature sensors

Procedure:

To heat the system an airflow is directed through a spiralled tube inside the muffle oven before entering the system at high temperatures. The system is slowly heated as pressurized air at 1 bar runs through the system.

Heat test 1 Isolation: Single layer of fiberglass bandage.

Tid	0	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190
T_{in} [°C]	20,6	113,2	137,8	155,2	162	182,2	201,8	213,6	229,6	233,2	233,4	241	249,8	253,4	-	280,2	313,4	305,8
T_{out} [°C]	20,4	46,8	59,2	73,8	84,4	92,4	109,8	118,8	133,6	143,2	149,6	155,6	162	166,8	-	172,8	192,2	197,2
T_{oven} [°C]	0	343	391	400	400	400	443	450	450	450	450	491	500	500	-	592	600	600
Flow (l/h)	660	660	700	750	750	750	900	900	900	900	900	900	900	900	-	900	1000	900

‘

Heat test 2 Isolation: Double layer of fiberglass bandage.

Tid	0	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
T_{in} [°C]	21	56,8	115,6	173	225,4	257,8	275,6	281,2	283,4	284,6	285,4	285,8	286,2	286,4	286,4	-	285,6	286,8
T_{out} [°C]	21	29,2	48,4	74,8	105	132	155,2	173,4	186,4	195,4	202,2	207,2	210,6	213,2	217	-	217,8	218,8
T_{oven} [°C]	0	203	310	392	463	498	500	500	500	500	500	500	500	500	500	500	500	500
Flow (l/h)	900	880	890	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900

Heat test 3 Isolation: Double layer of fiberglass bandage with aluminium foil as an outer shell

Tid	0	20	30	40	50	60	70	80	90	100	110	120	130	140	150	180
T_{in} [°C]	21	102,4	164	216	-	279,4	298	-	304,6	307,6	308,6	309,2	308,6	308,2	309,8	310
T_{out} [°C]	21	43,8	70,2	99,4	-	154,6	179	-	205,4	216,4	224,4	230,6	234,2	237,4	241,2	246,6
T_{oven} [°C]	0	287	375	449	500	500	500	500	500	500	500	500	500	500	500	500
Flow (l/h)	900	860	900	900	900	820	900	900	900	900	900	900	900	900	900	900

Heat test 1

Conditions:

- System pressure 2 bar
- The system is isolated with 1 layer of fiberglass bandage.
- The test is conducted with varying flowrates between 660- 1000 l/h to get an indication how flowrate affects the heating process.
- Muffle oven temperature between 400- 600°C
- The test is conducted over a time period of 190 minutes.

Method:

- The first readings are registered at 343°C. During heating, the system temperatures are not what was first expected and the temperature is steadily increased over the timespan of the experiment to a maximum of 600°C to monitor how the system responds to the changes.

Results and Observations:

- A higher flowrate gives an overall higher system temperature.
- It is observed that T_{inlet} has a large temperature lead on T_{outlet} throughout the whole test. The gap is closing towards the end of the test when temperatures are stabilizing at the points. The difference is still significant.
- There is a large amount of heat lost on the section from the oven to the reactor, and especially from the reactor itself.
- It is observed that flowrate decreases with temperature. This is most likely caused by gas expanding as a result of the heating process, meaning less molecules can pass through a cross section of the pipe within a set time frame, thus lowering the flowrate.

Conclusion:

- Because the system temperature is directly affected by the flowrate, it should be kept above 900 l/h to keep system temperatures within marine SCR conditions. Max flowrate possible is 1000 l/h, though, from the calculations prior to this test, a flowrate of 760 l/h was estimated based on space velocity, catalyst size and reaction time. A flowrate of 900 l/h seems to be the absolute minimum for collecting reliable data, while still being closest to the theoretical calculations.
- For the same reason the oven must be set to a minimum of 500°C to keep system temperatures within marine SCR conditions.
- The flowrate must be frequently adjusted to compensate for gas expansion.

Heat test 2

Conditions:

- The system is isolated with a second layer of fiberglass bandage.
- A temperature of 500°C is maintained in the oven throughout the whole test. This temperature is chosen because the pipes inside the oven were glowing a bright red at the end of heat test 1, which is concerning in regard to HSE.
- A flowrate of 900 l/h is maintained throughout the whole test.
- The test is conducted over a time period of 180 minutes.

Results and Observations:

- T_{inlet} stagnates at 283,4°C after 90 minutes, and climbs by only 3,4°C the following 90 minutes.
- T_{outlet} stagnates at 217°C after 150 minutes, and climbs by only 1,8°C the following 30 minutes.
- After 3 hours of heating the temperatures are as follows:
  - T_{inlet} = 286,8 °C
  - T_{outlet} = 218,8 °C
  - ΔT =68 °C

Conclusion:

- The gap registered between T_{inlet} and T_{outlet} might be caused by pressure loss over the sensors, or pressure loss through the reactor because of the catalyst, or both. It is therefore necessary to examine the pressure conditions in the system in a test of its own.
- Because of the temperature difference between the two points, there is an uncertainty regarding the temperature in the centre of the reactor. To get a more accurate reading it is considered to place a temperature sensor inside the reactor to monitor the actual temperature of the reaction.
- The temperatures achieved after 3 hours of heating with the oven set to 500°C and a flowrate of 900 l/h, are still not high enough to simulate a marine SCR reaction. Ideally the temperature should be around 350°C, with the purpose of conducting tests within a range of 250- 350°C. With 350°C being the lowest temperature required for a successful marine SCR process using Urea as reduction medium.
- To improve the system, a number of measures are considered.
  - To improve isolation to reduce heat loss
  - To increase the temperature in the oven to 600 °C
  - To increase the flowrate to 1000 l/h.

Heat test 3

Conditions:

- The system is isolated with a layer of aluminium foil on top of the 2 layers of fiberglass bandage.
- Test parameters are the same as for test 2;
- A temperature of 500°C is maintained in the oven throughout the whole test.
- A flowrate of 900 l/h is maintained throughout the whole test.

Results and observations:

- T_{inlet} stagnates at 304.6°C after 90 minutes.
- T_{outlet} stagnates at 241°C after 150 minutes.
- After 3 hours of heating the temperatures are as follows:
    - $T_{inlet} = 310$ °C
    - $T_{outlet} = 246{,}6$ °C
    - $\Delta T = 63{,}4$ °C

Conclusion:

- The extra aluminium foil isolation resulted in a temperature increase of 23°C compared to previous tests.
- It is assumed that by adjusting the oven to 600°C the system temperature should increase even further.
- It is assumed that a higher flowrate will increase the system temperature even further.
- The temperature gap between T_{inlet} and T_{outlet} is still significant and approximately the same as in test 2.

Attachment 7 C - Pressure test

As established in heat test 2, the temperature difference between the inlet and the outlet of the reactor might be caused by either;

1. a pressure loss over the catalyst in the reactor.
2. temperature sensors inside the carrier pipe, disrupting the flowrate. The sensors in question are T_{inlet} and T_{outlet}.
3. Or a combination of the two.

To identify the cause, a pressure test is needed.

Conditions:

The system is configured for 1 bar to correspond with the measuring device which can only measure a max pressure of 1 bar. The working medium is pressurized air. The precision of the measuring device was tested in the following way:

- Air pressure is set to 1 bar.
- The system exits are plugged. If the system is sealed the (measuring device) will read 1 bar. If there is a leak the indicator will drop below 1 bar. The precision of the calibration might also be a factor affecting the outcome.
- 1 bar air pressure, 500 l/h flowrate, measures 0,97 bar on the (measuring device)
- 0,6 bar air pressure, 500 l/h flowrate, measures 0,613 bar on the (measuring device)

Based on these results the measuring device is adequately precise with an error margin of roughly 2-3%. Furthermore, the system proves air tight.

Procedure:

A total of 4 pressure tests are conducted:

- P1 and P2 are measured in the system before any changes are made to establish a baseline. P1 indicates the pressure after the reactor and P2 indicates the pressure in front of the reactor.
- P3 indicates the pressure in front of the reactor after rearranging T_{inlet} to no longer restrict the airflow.
- P4 indicates the pressure in front of the reactor after rearranging T_{outlet} to no longer restrict the airflow.

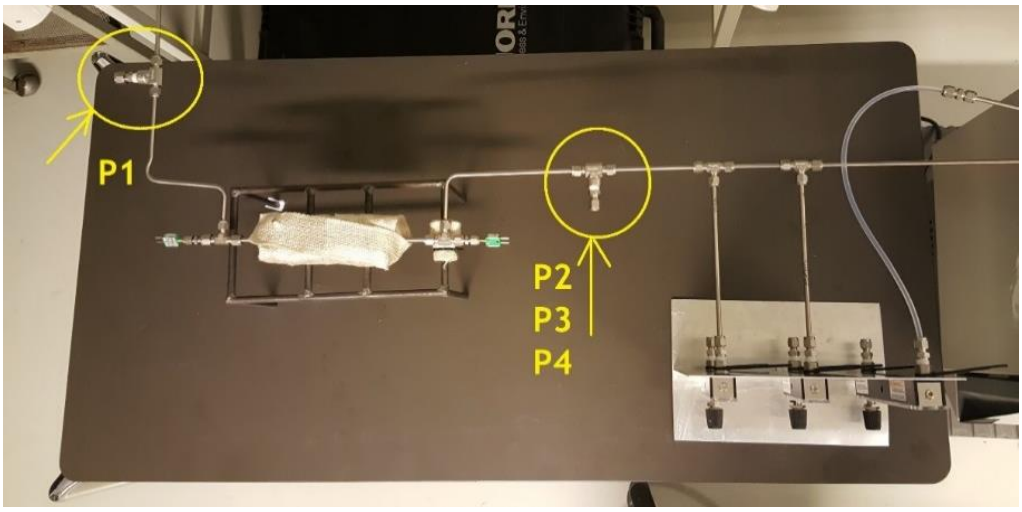


Figure 2 - Measuring points

Results and observations:

The results from the pressure testing is presented in Table 1. A flowrate of 0 l/h gives 0 bar pressure and is therefore not included in the table. Neither is 1000 l/h because a pressure of 1 bar does not allow such a flowrate.

Flowrate [l/h]	100	200	300	400	500	600	700	800	900
P1	0,001	0,002	0,003	0,006	0,011	0,017	0,025	0,032	0,038
P2	0,008	0,019	0,034	0,055	0,069	0,133	0,188	0,230	0,271
P3	0,005	0,013	0,024	0,041	0,07	0,096	0,137	0,169	0,196
P4	0,004	0,009	0,017	0,029	0,047	0,07	0,099	0,124	0,148

Table 1 - Results from the pressure test

The results are used to calculate the pressure drop on the distance between the two measuring points, T_{inlet} and T_{outlet}, outlined in yellow in Figure 2. The pressure drop is given the distinction Delta-P (ΔP), where:

- Δ(P2-P1) indicates the pressure drop in the original system design before any changes are made.
- Δ(P3-P1) indicates the pressure drop after rearranging T1 to no longer restrict the airflow.
- Δ(P4-P1) indicates the pressure drop after rearranging T2 to no longer restrict the airflow.

Flowrate [l/h]	100	200	300	400	500	600	700	800	900
Δ(P2-P1)	0,007	0,017	0,031	0,049	0,058	0,116	0,163	0,198	**0,233**
Δ(P3-P1)	0,004	0,011	0,021	0,035	0,059	0,079	0,112	0,137	**0,158**
Δ(P4-P1)	0,003	0,007	0,014	0,023	0,036	0,053	0,074	0,092	**0,11**

Table 2 - Preassure drop data

By rearranging both temperature sensors, the pressure drop is reduced by 52% (from 0,233 bar to 0,11 bar).

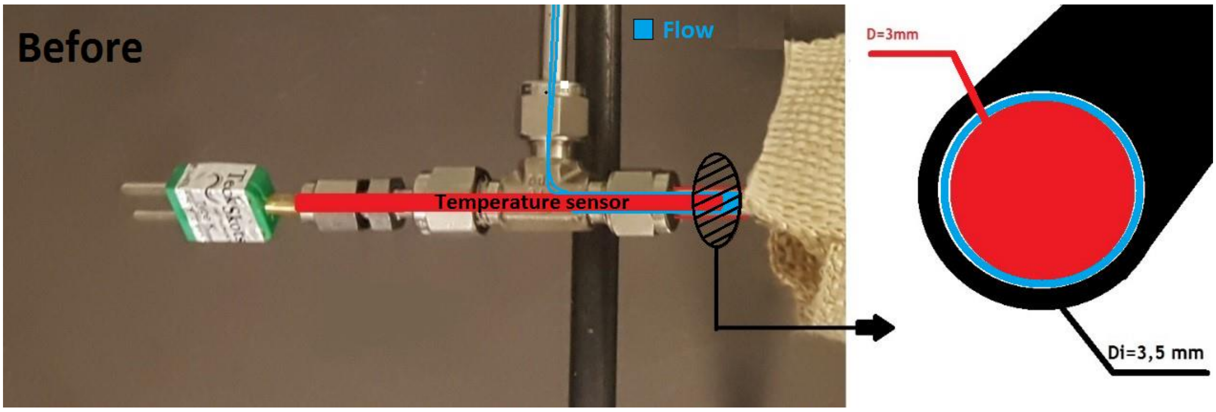


Figure 3 - Temperature sensor before rearranging

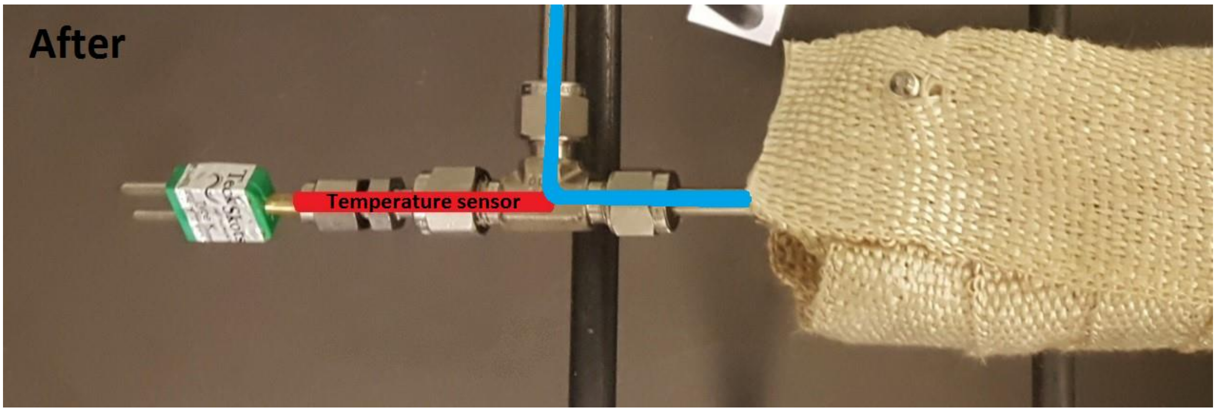


Figure 4 - Temperature sensor after rearranging

The remaining pressure drop in the system, 0,11 bar, might be due to the gas expansion followed by compression in the reactor in addition to the catalyst honeycomb restricting the flow. The pressure can also slightly drop in “elbows” and fittings along the section.

Even though pressure drop was minimized, the gap between T_{inlet} and T_{outlet} remains almost the same. It can be concluded that the gap between T_{inlet} and T_{outlet} is caused by heat loss through the wall of the system/reactor material.