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Development and Engine Testing of Coatings on Diesel Engine Components

January 1978—December 1978

February 1979

Prepared for
U.S. Department of Energy
Assistant Secretary for Energy Technology
Division of Fossil Fuel Utilization

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ABSTRACT

A series of coating has been tested in a laboratory combustion test rig in order to select coating for further testing on valves and pistons onboard ships. These coatings bonded well to the base material, but had different corrosion resistance. A nickel-chromium-aluminium-yttrium alloy proved to be the best alloy coatings as far as corrosion resistance is concerned. High proportion of oxide in a metal coating did increase the corrosion rate. Coatings of nickel-chromium-aluminium-yttrium alloy with an intermediate layer of chromium and a top coat of yttria stabilized zirconia show no sign of corrosion or cracks even after 120 hours testing in the combustion rig or after 6000 hours on a valve plate in a large bore diesel engine in service. A detailed microstructure analysis of the SI-thermalbarrier coating system used in full scale onboard a ship has to be postponed due to delay in getting the valves returned to Norway.

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1. INTRODUCTION

The use of cheaper, but potentially more corrosive fuels in combination with increased engine temperatures to achieve better efficiency, has required the exploration of new ways to control corrosion and damage due to thermal stresses. The use of coatings is one technically acceptable way of solving these problems.

Under normal operating conditions metals are thermodynamically unstable with respect to ambient combustion gases. In oxidizing atmospheres a number of metals form protective oxide films or scales, and these serve as diffusion barriers and slow down the rate of attack. The diffusion of the reacting atoms/ions must be as low as possible, and in addition the scale has to adhere well to the substrate in order to minimize material degradation.

The corrosive degradation of the materials in heat loaded parts in diesel engines is particularly due to such contaminants in the fuel oil and lubricating oil which result in fouling and formation of low melting salts, e.g. sodium sulfate (Na_2SO_4), vanadium pentoxide (V_2O_5) and sodium vanadates ($\text{Na}_2\text{O} \cdot 6\text{V}_2\text{O}_5$). The salts are aggressive in the liquid state only. This means that a reduction of the material temperature is a critical factor in increasing the life time of the components.

The aim of this investigation is to study corrosion and thermal shock resistant coatings and thermal barriers used on heat-loaded parts in diesel engines. This phase of the research period is concentrated on coatings on pistons and valves, particular thermal barriers.

The report will give a review of component damage mechanisms in diesel engine and criteria for selection of coatings, spraying procedures, a review of ship board tests conducted up to December 1978 is also given.

2. REACTIONS BETWEEN BASE ALLOY AND ENVIRONMENTS

Piston: The material in the pistons in large bore diesel engines is usually cast steel containing mainly $\sim 1\% \text{Cr} - 0.3-0.4\% \text{Mo} - 0.6-0.9\% \text{Mn}$. The corrosion/erosion of the piston heads during service makes it necessary to recondition the piston head after a total wear down of 25 mm. The degradation is due to a combined effect of high temperature and contaminants in the fuel, notably sulfur and sodium. Analyses have shown that Na_2SO_4 is a main part of the deposit on a piston top plane in addition to metal sulfides. The sulfides are created by incomplete combustion which gives local reducing atmosphere (1).

Tests carried out by Sarsten et al (2) show that the temperature just below the surface of the largebore piston head reaches 550°C and may even exceed this figure under abnormal conditions (Fig. 1a). The maximum stress in the surface under this running conditions was calculated to 344 MN/m^2 (assuming only elastic deformation), which is well above the yield point of the material at that temperature (Fig. 1b). The thermal and mechanical stresses will in addition be cyclic.

Further down on the piston where the temperature is below the dew point of the sulfurous gas, sulfuric acid is formed and the material is attacked (low temperature corrosion). In these regions abrasive wear caused by hard particles and residues of combustion products may occur.

Exhaust valves are exposed to the same corrosion hazards as the piston heads, but they normally have higher temperatures during service. The presence of vanadium-containing salts is probably the most important factor in causing corrosive degradation of the valves. The exhaust valves require coatings with high corrosion resistance.

Austenitic alloys of the type 20%Cr-9%Ni-2.5%W are mostly used today in larger engines. The temperature on the surface of the large bore valve in the seat-area has been estimated to 575 °C corresponding to a stress level of the order of 170 MN/m² as reported by Sarsten et al. (2) (Fig. 2a and 2b.). However, some of the results obtained at Central Institute for Industrial Research (SI) indicate that the temperature could be higher (3). The hottest area on the large bore valve plate was an area half-way between the outer edge and the centre and close to the valve seat. The valve seats are also exposed to tensile and compressive strain, which together with alternating temperatures (strain) and corrosion attack may lead to corrosion fatigue.

The temperature distribution in the exhaust valves of a medium speed diesel engine is usually as follows: The highest temperatures (up to 850 °C) are often found in the center of the valve plate and the area at the interface shaft/plate, while the temperatures on the valve seat are lower. This leads to tensile stress in the plate edge which in turn may lead to radial cracks, a well known problem on exhaust valves.

Corrosion and fouling on valves are complicated processes, and not fully understood. Fouling on the valves (around the valve seat) depends on composition of both the fuel oil, the cylinder oil and the alloy used in the valves (4). It is known that Na, V and S from the fuel oil form sodium vanadylvanadates, vanadium pentoxide and sodium sulfate during combustion. These compounds attack either the whole area or local spots at which grooves may be formed.

Hardfacing of the valve seat by welding, changes the structure of the alloy at the interface and contaminates the hardface by iron. The corrosion resistance and hardness of the hardface will thereby be reduced.

a)

b)

Fig. 1. Temperature a) and stress b) distribution in piston heads in service.

a)

THERMAL FIELD VALVE GV 850/1700
M/T "TANKER" TEST 3 (AUSTENTIC)
(SANDTORV & RASMUSSEN)

b)

STRESS FIELD OF COMBINED STRESSES.
STRESS FIELD IN MODIFIED GV VALVE.
STRESSES IN KP/CM² DUE TO COMBINED
GAS. PRESSURE AND THERMAL STRESSES.
MAX FIRING PRESSURE = 60KP/CM².
(SANDTORV & RASMUSSEN)

Fig. 2. Temperature a) and stress b) distribution in valves in service.

The thermal conductivity and expansion of a welded hardface is usually different from that of the valve alloy and creates thereby tensile stresses in the overlay. The fast cooling of the hardface material after the welding operation leads to strain large enough to create cracks.

Cracks in the valve seat material and hard deposits cause blowthrough of exhaust gas at closed valve (5). The same happens if the valves are not correctly installed. Blowthrough of exhaust gas leads to a strong, local increase of the temperature and stronger corrosion attack.

The main criteria for valve damages in diesel engines may be summarized as shown in Fig. 3. This agrees very well with the conclusion presented by a Japanese research group (6).

These may be divided into two groups: one due to the operational factors and the other to the design criteria. The various factors involved and how they are interacting are indicated in this flow scheme.

3. PROTECTION OF THE BASE ALLOY

3.1 Experiments

Plasma sprayed coatings of different nickel base alloys, oxides and alloy/oxide combinations on pistons and valves have been tested both in an accelerated corrosion test up to 900 °C and in diesel engines on board ships (Table I).

3.1.1 Plasma spraying. The structure and quality of coatings are usually dependent on several spraying parameters such as type of gas used, temperature, size and velocities of particles, particle size ratio, distance from nozzle to surface, etc.

Fig. 3. Criteria for damages of valves in diesel engines. The criteria are primarily based on results obtained by analysing damaged valves.

The following six points are carefully controlled in preparing the coating. These are:

1. Degreasing
2. Preheating
3. Sand blasting
4. Inspection
5. Spraying operation
6. Control of the coating

Comments. The surfaces which should be sprayed are chemically cleaned and preheated prior to sand blasting. All components are heated up to about 120 °C in order to remove moisture and oil. The steel sand used is G24 - G12 in half/half and the size of the nozzle is 1/4". The air is carefully checked for water and oil impurities. The blasting angle is about 75° to the surface.

All spraying is done manually with a Metco 3MB plasma gun. During the spraying operation the temperature of the samples is close to 150 °C. It is sprayed by rotation 30 m/min. The spraying distance is 5" for the bond coat (Ni-Cr-Al-Y), 5½" for the medium layer and 2½" for the top coat ($ZrO_2+Y_2O_3$). After the second top coat pass the spraying distance is increased approximately 1".

Optimum spraying procedures are developed both for argon/hydrogen and argon/nitrogen gas mixtures by microscopic examinations of test specimens. Slightly better results are obtained by using prepurified hydrogen/argon mixture, and Ar/H₂ is therefore used in spraying coating for trial tests.

The control of the coating is performed by means of a reference sample which is treated and sprayed simultaneously with the test components. This sample is examined metallographically in order to see if the microstructure is acceptable. If the microstructure corresponds to the specified structure, the components are shipped to the engine for test service.

3.1.2 Materials. Samples of cast steel (piston quality) 10 mm in diameter and 50 mm in length, were then sprayed after having been cleaned, preheated and blasted with steel sand.

All specimens were machined from a cast steel piston of ordinary quality. The piston and valves for the trial tests were all commercially made. Most of the valves were reconditioned by welding (13% chromiumsteel).

3.1.3 Corrosion test procedure. The laboratory corrosion tests were carried out in a combustion rig burning diesel fuel oils. Organic compounds of sulfur, sodium and vanadium were added in order to simulate heavy fuel oil quality. The oil was blended with 180 ppm vanadium, 60 ppm sodium and 2.5% sulfur in the present experiments. The amount of excess air during combustion was 80%. In order to accelerate the corrosion test, temperatures up to 900 °C were used. These temperatures are above the temperatures usually obtained in diesel engines. In two cases the temperature was cycled three times during a test period of 60 hours, while in two other cases the temperature was cycled 6 times during a test period of 120 hours. The cycling - a rapid heating to maximum temperature and a slow cooling to room temperature - was executed in order to check the thermal shock resistance of the coatings (Fig. 4). Sets of four coated samples were tested simultaneously in the exhaust channel next to the combustion chamber. After the corrosion tests the samples were examined by an optical microscope and an electron microprobe. Although the results from these experiments cannot be directly applied to conditions during normal operations, they give valuable data for further improvements of coatings for high temperature applications.

The trial tests were usually carried out onboard ships using the available bunker fuel oils. The tests are carried out on both large bore and medium speed diesel engines.

Fig. 4. Temperature cycles (heating and cooling rates) in the combustion test rig.

4. RESULTS

Corrosion/wear resistant:

The selection of the coating is mainly based on criteria given by the base alloy and the chemical and physical properties of the ambient combustion gases or condensates from the gas. This is summarized in Fig. 5.

Table I gives a list of the most promising tested coatings. These were well bonded to the base, but showed variable corrosion rates. A nickel-chromium-aluminum-yttrium alloy (No. 2S) proved to be the best alloy coating as far as corrosion resistance is concerned. The microstructure is shown in Fig. 6.

High proportions of oxide in the alloy/oxide combined coatings increased the corrosion rate. For some of these coatings internal oxidation and break-through was observed. A nickel-chromium-aluminum coating with a minor addition (< 5%) of oxides showed approximately the same corrosion rate as the alloy coating.

A coating with a nickel-chromium-aluminum bond coat and a zirconium-oxide-yttrium oxide top coat showed no signs of corrosion or defoliation after temperature cycling and total testing of 60 hours at 900 °C. The oxide top coat was, however, sensitive to impact (hammer test) and seemed to crack during cycling. Coatings of a similar type, nickel-chromium-aluminum-yttrium as bond coat, but with an intermediate layer of chromium and a thinner zirconium-oxide-yttrium-oxide coating, showed no signs of corrosion or cracks even after 120 hours of combustion rig testing. The improved properties of the latter sandwich coating, specifically the resistance to developing cracks in the oxide layer during temperature cycling, can be explained as follows: Chromium in the intermediate layer will oxidize when exposed to corrosive gases and the reaction products will fill the cracks

ENVIRONMENT/ APPLICATION

- Combustion gases
(flow rate, chemical composition)
- Temperature 20 -1100°C
and temperature cycling
- Geometry
- Erosion
- Abrasion

BASE ALLOY PROPERTIES

- Mechanical, physical,
chemical and thermal
properties
 - thermal expansion
 - chemical composition
 - thermal conductivity
- Microstructure etc.
- Surface finish

PROTECTION SYSTEM/COATING

◦ Mechanical, chemical,
physical and thermal
properties	- chemical composition
- high temperature
stability	- adherence
	- composite coating
	- thermal shock

Fig. 5. A sketch of the important properties involved in coating heat loaded parts in diesel engine. The properties of the base alloy, the coating system, and the environment have to be mutually adjusted to each other in order to obtain a practical useful system.

Table 1. Chemical composition of the tested coatings.

<u>Coating_No.</u>	<u>Composition</u>
1S	NiCrSiFe
2S	NiCrAl(Y)
3S	NiAl-NiAl+Al ₂ O ₃ +TiO ₂
4S	NiAl-NiCrAl+Y+Al ₂ O ₃ +TiO ₂
5S	NiCrSiBAL
6S	NiAl-NiAl+Al ₂ O ₃ +TiO ₂ -Al ₂ O ₃ -Al ₂ O ₃ +TiO ₂
7S	NiCrAl-NiCrAl+Al ₂ O ₃ +TiO ₂
8S	NiCrAl-NiCrAl+Al ₂ O ₃ +TiO ₂ -Al ₂ O ₃ +TiO ₂
9S	NiCrAlY-NiCr-ZrO ₂ +Y ₂ O ₃
10S	NiCrAl-ZrO ₂ +Y ₂ O ₃
11S	NiCrAlY-Cr-ZrO ₂ +Y ₂ O ₃

Fig. 6. Cross section of a NiCrAlY coated piston head after 7000 hrs service. The normal available bunker fuel oil (3000-4000 SRI) has been used. The typical structure of a plasma sprayed coating is not visible in this unetched sample.

and pores in the top coat. This will ensure a dense top coat firmly bonded to the lower high alloyed layer.

The microstructure of a trippel layer of coating exposed to combustion gases for 120 hrs at 900 °C is shown in Fig. 7.

Further investigations by means of the electron microprobe to check the bonding between coating and base showed that a diffusion had taken place during the test and that the bonding between coating and base was good. The diffusion zone was approximately 64 μm for sample No. 9 after 60 hours of testing and 84 μm after 120 hours of testing (Figs. 8 a-b). This gives an indication of the interdiffusion rate between coating and material.

The quality of a coating is strongly dependent on the surface condition of the base material. The work has shown that the quality of the reconditioned (welded) valve materials and pistons critically depends on the surface preparation.

4.1 Thermal isolation of heat-loaded parts

According to the Carnot principle the efficiency of heat engines increases with increasing temperature. During combustion in a diesel engine, parts like piston, valve, liner, cylinder cover etc. are strongly heated. The heat exchange occurs by convection, radiation from or by direct contact with the flame. The absorbed heat must be transported away in order to retain the mechanical, thermal and corrosive properties of the material. A great deal of the energy which is produced during the combustion process, is for that reason removed with cooling water/air. In order to save energy it is of advantage to protect the hot parts by a thermally insulating coating. This will reduce the heat transfer through the engine walls, and a greater part of the produced energy can be utilized, involving an increased output effect per unit of fuel. A reduction in the consumption of fuel is thus obtained if the engine can convert a larger part of the heat to mechanical work.

$\text{ZrO}_2 + \text{Y}_2\text{O}_3$
Cr
NiCrAlY

Fig. 7. Cross section of laboratory tested sample of coating No. 9S (SI-coating) (120 hrs at 900 °C). The sample is interference etched. (Further structures of laboratory samples are given in Thin Solid Films 53 (1978) 259-269).

Fig. 8. Element analysis in the diffusion zone between the coating and steel matrix in a sample kept at 900 °C in a) 60 hrs and b) 120 hrs respectively.

Heat isolating coatings. ZrO_2 has a relatively low thermal conductivity and a thermal expansion coefficient closer to metals than other oxides. A coating of ZrO_2 is therefore a candidate as an thermal insulator. ZrO_2 can be present in three modifications, with cubic (fluorite), tetragonal and monoclinic structures respectively, depending on temperature, composition and impurity concentration. The cubic fluorite structure can be stabilized by additions of di- and tri-valent metal oxides as CaO , MgO , Y_2O_3 , etc.

The work at SI has mainly been focused on ZrO_2 stabilized with 10-20 wt% Y_2O_3 . SI has developed a three layer coating, where Ni-Cr-Al-Y acts as a bond coat, the intermediate layer is Cr (or CrNi), and the top layer $\text{ZrO}_2+\text{Y}_2\text{O}_3$. A single Ni-Cr-Al-Y coating may also act as protection against corrosion. The three layer coating is for a long period used on test pistons and valves in regular service. Research is presently carried out to optimize the physical and structural properties of the coating.

Calculation of the possible benefit by using a thermal barrier in diesel engines. In a diesel engine, it is of advantage to use isolating coatings on valves, pistons, cylinder cover, etc. Generally, a surface coating of this kind reduces the heat transfer. An insulating layer on the hot metal side facing the combustion chamber involves an increased surface temperature towards the combustion gas, while the surface temperature of the piston is lowered. This principle is schematically illustrated in Fig. 9.

The heat transfer coefficient of the upper part of the piston crown depends strongly on its surface roughness. The spraying of an isolating coating on a smooth, metallic surface increases the roughness of the surface due to the powder and porosity of the coating. According to the literature, the heat

transfer coefficient for a plasma sprayed surface is a factor 1.3-1.9 higher than for a smooth, metallic surface. The reason for this is two-fold: first, the roughness of the coating increased the efficiency of the surface for heat absorption; secondly turbulations are formed in the gas layer adjacent the surface.

For a diesel engine it is difficult to estimate how surface depositions of combustion products (coke) and ingredients of the lubrication oil influence the heat transfer coefficient. If these deposits completely cover the surface, the heat transfer coefficient will be the same for a coated surface as for a metallic one.

The heat transfer depends on the emission (0-1) white-black and on the thermal diffusivity of the material.

$$\text{Thermal diffusivity} = \alpha = \frac{\lambda}{\zeta c}$$

λ - thermal conductivity

ζ - density

c - heat capacity

Calculations carried out by T. Hansen (7) have shown that a coating of thickness ~ 1.0 mm and $\lambda_{DS} = 2.0$ W/mK on the top surface of a piston crown reduces the metal surface temperature by 80-110 °C at running conditions corresponding to a heavy fuel oil service of 333 kp/cyl/415 r/min. The temperature field indicates that the piston crown is heat-loaded to the same level as for a diesel service of 300 kp/cyl/373 r/min. By a reduced heat flux to the piston, the energy loss to cooling water/air is reduced by approximately 20%, corresponding to a 2-3 g/Bhp.h reduction in fuel consumption.

Thermal stresses: A reduction of the temperature in the base material will also involve a reduction of the thermal stresses arising during service.

Calculations based on the figures in Fig. 9 give the following values of the heat fluxes with and without coating:

Without insulating coating : $q = 435 \text{ kW/m}^2$
 With " " : $q^* = 293 \text{ kW/m}^2$

Reduction in heat flux
 by using coating : $q_{\text{red.}} = 142 \text{ kW/m}^2$

The temperatures at both sides of the plate in Fig. 9 are reduced. (The plate has the same thickness as the material in the piston top surface.) The thermal stresses depend on the temperature difference across the plate thickness, and this difference can be estimated at:

Without insulating coating : $t_{ws} - t_{wi} = 87.5 \text{ }^\circ\text{C}$
 With " " : $t_{ws} - t_{wi} = 58.5 \text{ }^\circ\text{C}$

In other words, an insulating coating on the surface facing the combustion chamber involves a reduction in the temperature difference across the plate, and thus a reduction in thermal stresses.

Tests in services. All test results obtained up to December 1978 in service, are presented in Table II. The test ships are: "BERGE TASTA", "BERGE EDDA", "BERGE ADRIA", "SONG OF NORWAY", ("NORDIC PRINCE") and B/F "HERDLA". The tests are concentrated on pistons and valves. These are mostly prior to spraying re-conditioned by welding an upper layer consisting of 13% chromium steel.

The test, valves and pistons, were thoroughly checked for surface defects. Several pistons were rejected because of heavy slag inclusions, cracks and pores in the weld seam.

Table 2. Tests onboard ships in service.

Vessel and Engine type dimension cm	Piston or valve no	Coating no S	Service time, h	Burn down max mm/1000 h		Checked date	Remarks
				mm	mm		
M/S Marshall Clark 84 VT 2 BF	SB 617	1 (flame)	4,579	.0	.0	16.04.73	
	"	"	14,815	12.0	.8	17.10.74	
	"	"	20,352	17.5	.9	19.08.75	Cracked Ring grooves
	SB 618	2 (flame)	18,550	12.0	.6	22.08.75	
	"	"	26,156	20.0	.8	28.10.76	Spare onboard
	SB 619	2 (plasma)	6,593	.0	.0	09.09.73	Cracked ring grooves
M/T Bergeland (Hugo) 84 VT 2 BF	SB 117	3 (plasma)	8,191	16.0 18.5 17.0	2.3	03.04.75	Ship sold to foreign owners. Lay up since 1975. In service again 1978.
	SB 116	4 "	3,618	.0 1.0 .0	.3	"	
	SB 115	5 "	10,091	3.0 9.0 6.0	.9	"	
	SB 118	6 "	8,191	1.0 2.7 2.0	.3	"	
M/T Berge Edda K 98 FF	x) SB 1125(2)	7 (plasma)	3,600	.0	.0	24.11.76	Scav. port inspection: Remarkable good results compared to other cylinders.
	"	"	8,000	.0 3.0 .0	.4	05.08.77	Extremely high exhaust temperature in this cylinder last voyage. Upper part of piston red hot at full load.
			10,609	1.0 .0 1.0	.1	24.11.77	Installed again 28.2.1978.
M/T Berge Tasta K 98 FF	x) SB (1072(1)	8 (plasma)	10,242	2.6	.25	25.03.77	Still in Service
	x) SI 10.10.75 no 1 (valve)	7 "	4,780	A = .2 B = .5 C = 3.3 D = 1.8	.7		
	x) SI 10.10.75 no 2 (valve)	8 "	4,780	A = .0 B = .25 C = .15 D = .0	.05	05.09.76	Cannot be traced.
Vessel of Tor Dahl 10 04 VT 2 RF	x) 1	9 (plasma)		To be installed			

x) reconditioned by welding

Heavy fuel oil, viscosity 2000-3500 SR 1 at 38 °C

Speed for the 84 engine: 114 rev, min⁻¹

" " " 98 engine: 106 rev, min⁻¹

Table 2. Tests onboard ships in service (cont.).

Vessel and Engine type dimension cm	Piston or valve no	Coating no S	Service time, h	Burn down		Checked date	Remarks
				mm	max mm/1000 h		
M/T Berge Adria	SI 10.10.75 no 4 (valve)	8 (plasma)		.0	.0	Oct. 1976	Damaged in the sea- area. Returned to work shop.
	SI 1 (valve)	2 "					
	SI 2 "	10 "					
	x) 7-34 027-5 "	10 "					
	x) 7-34 027-1 "	2 "					
	7-34 032-1 "	9 "					Sprayed Feb. 1978 also in seat-area.
	8-34 044-10 "	9 "					February 1978.
	20.10.78						
	6-34 002-2 "	10 "					February 1978.
	7-34 015-4 "						
	5-34 081-5 "						
	6-34 079-4 "	10 "					February 1978.
	8-34 044-4 "						
	7-34 115-1 "	11 "					February 1978.
	7-34 027-23 "	10 "					Also on the seat-area
	9-34 044-1 "						February 1978.
	5-34 043-3 "	10 "					February 1978.
	7-34 115-5 "						
	7-34 027-24 "	11 "					Also on the seat-area.
	8-34 044-3 "						February 1978.

Also the reconditioned exhaust valves showed fine cracks and pores in the surface. These defects were ground off. In spite of the grinding one exhaust valve still showed a defect after being sprayed (SI, 10.10.1975 No 1). The defect was detected through discolouring of the coating due to moisture in the crack or pore underneath.

The piston marked SB 617 (flamesprayed in 1972) was taken out in 19.8.1975 because of cracks in the ring grooves. The maximum burn down was then .9 mm/1000 h. The other flamesprayed piston marked SB 618 has been in service for 26 000 hours and the maximum burn down was .8 mm/1000 h. This piston is now a spare part onboard the vessel. Piston SB 619 (plasmasprayed) showed cracked ring grooves after only 6590 hours in service.

The pistons in M/T "BERGELAND" (SB 115-118) have not been in service since 1975 when the vessel was sold to foreign owners and named "HUGO". The vessel was in service again in 1978, but no measurements have been reported so far.

The piston of M/T "BERGE EDDA" (SB 1125 N) was installed in May 1976. The last check was done in November 1977 after 10 000 hours in service. The piston crown had several cracks, approximately 5 mm in depth in the sprayed layer. Some coke was found on the upper part of the piston and on the inside. All rings were loose and in good condition. The maximum burn down was measured to .1 mm/1000 h. The piston was reinstalled in the end of February 1978.

The piston of M/T "BERGE TASTA" (SB 1072) has been in service for 10 000 hours with a maximum burn down of .25 mm/1000 h. This piston is still in service.

The valves named 1 and 2 of the same vessel were checked in September 1976 after approx. 4800 hours. The measurements of these valves showed a maximum burn down of .7 and .05 mm/1000 h respectively. After these measurements it has not been possible to trace the valves.

Only one of the early sprayed valves from M/T "BERGE ADRIA" has been inspected so far (SI, 10.10.1975 No 4). This valve has been taken out after an unknown service time. The valve showed two deep damages in the seat area (approx. 10 mm deep), but it was no burn down of the plasmacoating on the valve plate. Further tests onboard "BERGE ADRIA" (large bore engine) started 1978. Eight valves are sprayed on the plates, in addition some valves are also coated on the seat area. It is to note that the coating in the seat area is very thin. The coatings, which are on tests, are thermal barriers, coating No 10S, and 11S.

The test onboard "SONG OF NORWAY" and "NORDIC PRINCE" will start in April 1979. The engines are medium speed. The valves are prepared and coated with coating No 10S and 11S.

A piston sprayed with coating No 10S is presently on test in a ferry with a Wichman Engine (B/F "HERDLA"). The thermal shock on the piston is extremely high. Inspection after 500 hrs. could not observe any damages on the coating. The piston is shown in Fig. 10.

Fig. 10. Piston coated on the crown with the SI-coating system (No. 11S). The picture shows the piston after 500 hrs in service. The time in service is at present past 1000 hrs without failure.

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