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Author(s)	Department	Tel.	Signature
Ebert, Edgar	NGES3	96790	gez. Ebert
Wild, Werner	NGEM1	99302	gez. Wild

Project

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Summary*)

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1 Introduction

Metal surfaces in static or sliding contact under the tribological HTR conditions of dry helium up to 1000°C are subjected to excessive wear or diffusion welding (galling). The materials most frequently considered for HTR were the nickel base alloys INCONEL 617 and Hostalloy S and the austenitic material Incoloy 800. Other Materials considered are the Ni-base materials Nimonic 80A, Hastelloy X, INCONEL 625 or the austenite 1.4981. Coating of the surfaces of these materials is the method of choice in order to protect them against wear and corrosion damage in case of excessive specific surface pressures or sliding movements. The coatings have to meet requirements being, in principle, partly identical to those of FBR and LWR and partly being particular for the conditions of a HTR as follows:

- Physical characteristics:
  - melting point, sublimation point or dissociation temperature far above 1000°C
  - no internal or external diffusion of individual elements of the layer
  - phase-stability, high strength and hardness up to 1000°C
  - little or better no activation of individual elements of the coating
- Chemical characteristics:
  - Chemical compatibility between coating and substrate material
  - no tendency for alloy formation between alloy components
  - no reactions with the impurities in the HTR helium
- Technical characteristics:
  - good adherence of the coating layers to base material even after thermal shocks
  - Friction coefficient as low as possible even under large specific surface pressures
  - Low wear
- Manufacturing characteristics:
  - Coating of larger components with complicated shapes must be possible
  - Reproducability of process
  - low sensitivity to transport and assemblage
  - availability
  - low cost

2 Summary of Important Results

A comprehensive article about German work on coating performance requirements for components in high-temperature reactor applications. Kinds of coatings and methods of manufacturing these coatings has been published by Theymann et al in Ref. [1], from which later in this report parts are cited in shortened version.

In Table 1, a list of materials tested in special test facilities and in form of components in a component test loop is presented. The tests performed comprised friction tests, static welding tests, aging tests in dry HTR helium at temperatures up to 1000°C in order to provide their structural stability and thermal shock resistance. Ceramic materials apparently were the most promising candidates because of the compact structure of their crystal lattice resulting in a relatively low tendency for diffusion. The first long term results were obtained with sprayed-on LPPS coatings (Low Pressure Plasma Spraying), particularly the ZrO_2 (Y_2O_3) coating combined with the intermetallic phase NiCrAlY. It is assumed that the inert atmosphere conditions during the spraying process did not allow for a too high oxidation of the NiCrAlY-layer thus reducing the possibility of corrosion by diffusion of impurities from the helium along the ZrO_2 (Y_2O_3) protecting layer. The currently available spray chamber sizes are too small for coating larger components. therefor already at an early stage, tests were performed with specimens coated by the APS process (Air Plasma Spaying) where test durations of more than 30000 hours have been reached. The results from the experimental investigations permitted to recommend coating systems for applications in HTR classified by temperature range as follows:

- T up to 700°C $\Rightarrow$ Cr_3C_2/NiCr-Cermets
- T up to 850°C $\Rightarrow$ $Cr_{23}C_6$-$Cr_{23}C_6$/NiCr-Duplex
- T up to 950°C $\Rightarrow$ $ZrO_2(Y_2O_3)$-NiCrAlY

For more detailed information see Ref. [1], table 2. It was found out after tests with periods up to 37000 hors that the ceramic coating of type $ZrO_2(Y_2O_3)$-NiCrAlY containing at least 13 % Y_2O_3 is optimum for use in dry helium environment (mainly reducing conditions) up to 1000°C even under mechanical load, i. e. it offers the following important conditions, see Rev. [2]:

- favourable sliding characteristics
- low tendency of wear, i. e. no measurable wear up to 100 m sliding distance
- no diffusion welding (galling)

In another test, this special coating had been e. g. applied for the heat exchanger tubes (material: INCONEL 617) operated at temperatures of 950°C in order to prevent galling at the locations of the tube holding devices, see Ref. [3]. The $ZrO_2(Y_2O_3)$-layer was applied by air plasma-spray fusing (APS) and had a thickness of about 120 μm. This layer itself was protected by the NiCrAlY adhesion layer with a thickness of about 100 μm. The same layer system was applied on the inner surfaces of the holding devices so that during relative movements friction occured between ZrO_2 and ZrO_2. The tests described in Ref.[3] confirmed the excellent behaviour of the coating system.

Other coatings, however, of less complexity can be used for lower temperature levels as well. Further tests at room temperature with cycling loads up to 75000 with good results were performed at KFA Jülich, see Rev. [4], on a variety of materials pairs in order to examine the friction and wear behaviour under He [PNP-gas] and vacuum environments comprising pairings of Stellite 6, Stellite 20, Triballoy T 700 and Triballoy T 800, TiC, TiN, CrC as well as combinations of sliding lacquers, e. g. on MoS_2 base, with coatings of the types mentioned before. The base materials were steels like St37-2, X2 10Cr W12, X20 Cr13.

Table 1

Coatings as Wear Protection for Application in HTR Plants

Basic Criteria: Physical Properties Chemical Resistance	Experiments from Sheets for Coating Procedures or technical properties	Experimental Experience		
		Selection Phase	Verification Phase	Demonstration Phase
Ceramic Coatings –promising-	Oxides	Al_2O_3 CR_2O_3 ZrO_2 + mixed oxides $ZrO_2(Y_2O_3)$ $MgZrO_2$	$ZrO_2(Y_2O_3)$	$ZrO_2(Y_2O_3)$
	Carbides (preferred because of relatively simple manufacture)	Cr_3C_2 NbC TiC	NbC	
	Nitrides	TiN (also mixtures with others)		
	Borides (less frequently used	TiB_2		
Cermets (ceramic+metal) for T ≥ 700°C	Suitable Metals: W, Mo, Cr, Ni, Al, Ti			
Intermetallic phases: for special applications	Compounds: NiAl, NiCr, NiCrAlY	NiAl, NiCrAlY		NiCrAlY
Metal coatings: as intermediate layers	Ni_3Ti	Ni_3Ti		

3 Investigations at a Tribology Testing Machine at Interatom

3.1 Purpose of the Examination

Metal surfaces in sliding contact tend to undergo frictional wear and friction welding in the presence of the helium coolant in the main circuits of an HTR.

This is intolerable for components of which freedom of movement is essential to proper operation or which must be easy to dismantle. Furthermore, the integrity of items subject to high mechanical loadings may not be jeopardized by the effects of tribological degradation (e.g., abraded material, notch-like galling marks, high fatigue loading due to fretting).

Therefore:

- Material combinations have to be investigated with respect to their behaviour in friction and to establish limiting parameters in terms of temperature and contact pressure.

- Coatings must be developed and investigated which have a loading capacity greater than metallic material combinations and which reliably prevent wear and friction welding at maximum HTR service temperatures and contact pressures.

Zirconium oxide coating systems were selected in a screening procedure and were installed in the KVK test rig (Komponent-Versuchs-Kreislauf = component test rig) under PNP conditions (Projekt-Nukleare Prozeßwärme = nuclear process heat project). The results of first in-situ visual examinations of the coatings used were satisfactory.

Further examinations of the coatings used in the KVK test rig are intended to:

- demonstrate the reliability of extrapolations from laboratory (testing machine) to real conditions of service,

- confirm the serviceability of the coatings on full-scale components under realistic conditions,

- examine tribological variables (friction coefficient, abrasion as a function of service temperature.

The post-exposure examinations were performed by nondestructive and destructive methods. The main objective of the examination was to determine tribological characteristics as a function of the loading collectives of the component.

3.2 Experimental Setup

3.2.1 Layout of a Friction and Wear Testing Machine

3.2.1.1 Definition of Requirement Profile

The friction and wear performance of two or more materials in combination is a function of the loading collective and the structure of the tribological system itself. Interdependencies exist between all components and these are in turn affected by other variables in the loading collective (e.g., lubricant viscosity as a function of temperature). Friction coefficient and abrasion are therefore system properties and material properties.

On account of the complex interactions between the individual components of a tribological system, minor changes in individual system parameters can result in dramatic changes in overall system condition. This is typical of nonlinear systems. The consequence of this is that tribological extrapolations based on verisimilitude from a known system to a similar one are highly unreliable as such an approach implicitly assumes linear system behaviour. Therefore, in the simulation of tribological systems, the relevant state variables of the full-scale system must be understood as completely as possible as otherwise the extrapolation of the laboratory system will be inexact. In tribology the system is generally described by the loading collective and by variables which represent the system structure.

The variables which describe the system structure are as follows:

- System elements (base component, contacting component, intermediate medium, environmental fluid)
- Properties of system elements (mechanical, thermal and chemical properties)
- Interaction between system elements (intermediate medium affects wear mechanism).

All elements of the loading collective are significant in the simulation of a full-scale system.

Since the selection of system elements also dictates the properties thereof, the specimen geometry and the intermediate medium can be set as free parameters in the system structure. (Specimen geometry and the intermediate medium form that component of the interactive complex which can be externally manipulated.)
The following contrasts the real loading variables of the KVK test rig with the requirements placed on the loading collective for the simulation derived from them:

<u>1. Kind of motion</u>

- Reality:

  Predominantly alternating as a result of thermal expansion and other relative displacements in the full-scale system

- Test system:

  Alternating and continuous frictional displacements should be possible as general friction tests for determining abrasion characteristics, etc., are to be performed in addition to the simulation.

2. Rate of motion

- Reality:

  The time history of relative displacements of individual subassemblies and components is governed by a multitude of parameters and therefore cannot be predicted exactly. The maximum relative velocities are governed by the temperature change rates within the system in connection with the resulting thermal expansion of the components.

- Test system:

  The time history of the steady (rotational) and alternating frictional displacements must be freely selectable within the prevailing physical and technological limits.

  This requirement is met by generating a freely programmable path/time correlation in the controlling process computer which is applied in the form of a time-variable voltage to the drive. The movement dynamics are limited by the inertia of the actuated masses and the drive.

3. Normal force F_N

- Reality:

  The reactive forces due to component masses, constraints and thermal expansion are in part considerable. Time-variable forces resulting from thermal and/or fluid dynamic phenomena can only be quantified inexactly.

- Test system:

  The normal force should be variable over a wide range. Furthermore, it must be possible to apply steady superimposed vertical and horizontal force components to investigate cylindrical, conical and disk geometries.

  The forces which occur in reality exceed the possibilities of a universal testing system by far. However, since the tribologically relevant variable in this context is not so much the force as the contact pressure, this variable can be adjusted by adapting the contact surfaces to closely model real-life conditions.

4. Temperature

- Reality:

  The nominal maximum service temperature in the KVK test rig is 950°C.

- Test system:

  The effect of temperature on the response of tribological systems can only be modelled on laboratory scale if this important parameter is at least similar to the real-life situation.

  The test system should therefore be designed for test temperatures up to 1000°C.

5. Friction contact distance

- Reality:

  The exposure time of a component and the friction contact distance between two items in frictional contact is the independent variable from the tribiogical standpoint. This is because it is imposed from outside the system and the most important tribological variables (friction coefficient, abrasion) depend on it.

  The heat exchanger tubes of the various helium-to-helium heat exchanger designs are to be seen in this context. The relatively long heat exchanger tubes are exposed to very high temperatures. It is assumed that the frictional contact distances with the HX tube supports totalized over the component exposure time in the KVK are about 10 m.

- Test system:

  The frictional contact distance is obtained based on the total test duration and on the distance/time interval required for a complete predetermined cycle of movement (e.g., one revolution of a turntable or one reciprocating cycle of the actuator arm).

The requirements applied to the test system on the basis of the system structure simulation are as follows:

6. System elements

- Reality:

  The system structure consisting of base component, contacting component, intermediate medium and environmental fluid is determined by mechanical design details which have the purpose of allowing relative displacements between components to take place in as controlled a manner as possible (e.g., ceramic coating of HX tubing in support region) and by the environmental fluid helium with its impurities.

- Test system:

  Where full-scale parts from the KVK test rig are used for post-exposure examinations, only their size and the environmental fluid is relevant for design of the test system.
  The size of the test chamber should be suitable for the testing of portions of components and of geometries similar to real-life components.
  The defined use of gas as the environmental fluid demands vacuum-tight design of the test chamber as only thus is it possible to rule out significant adulterations due to changes in gas composition.

3.2.2 Testing Machine Design

To fulfil the requirements profile described above, a test system was developed with the following design data (Fig. 1 – 3):

Geometric data

Turntable diameter	[mm]	300
Test chamber diameter	[mm]	400
Text chamber height, max.	[mm]	250

Physical data

Test temperature range	[°C]	20 - 1000
Test pressure range	[mbar]	1000 - 10^{-3}
Environmental conditions		Vacuum, air, blanket gas

Friction in the presence of liquids possible.

Mechanical data

Modes of operation:

a) Continuous motion in friction — Turntable rotates, actuator arm fixed in central position

Range of turntable speed of rotation	[rpm]	0 – 14.5
Max. friction rate	[m/s]	0.3

b) Reciprocating motion in friction — Turntable at rest, actuator arm moves in accordance with predetermined time function (sinusoidal)

Travel range	[mm] 0 - ± 50
Max. actuator arm velocity	[m/s] 0.1
Normal force direction	Combinable in two planes
Max. normal force	[N] 1000

Specimen geometries

Large-area bodies in frictional contact (fastened to turntable)

Depending on mode of motion:

- Continuous friction: Rings, discs, cylinders, conical items (basically any rotationally symmetrical geometry)

- Reciprocating friction: Plates, bars, rods, bolts
  Small-area bodies in frictional contact (fastened to actuator arm)

Specimens with plane contact surfaces are mounted in a special universal-jointed fitting on the actuator arm which ensures that no skewing or tilting moments occur during testing.

Specimens with spherical (convex) contact surfaces are solidly mounted on the actuator arm head.

3.2.3 Test Evaluation, Documentation

The complete test is controlled and monitored by a process computer so that the reproducibility of the results is high.

3.2.3.1 Test Setup

In tribological tests a (small) contacting component is moved against a (large) base component with a defined normal force and at a defined sliding velocity. It is crucial to the test result that each contacting surface is subject to the same loading, i.e., the contacting component may not be skewed or exert a tilting moment on the base component. Since this condition is difficult to establish and maintain in the case of thin film coatings (running in not possible), it is common practice for the surface of the contacting component to be slightly spherically shaped (convex) and then coated.
This configuration rules out angular mismatch between contacting and base component; however, it has the major disadvantage that the contact surface is punctiform at first (Hertzian contact stress) with the result that inexactly defined contact stresses can occur with local overheating possible which in turn can decisively affect the tribological behavior of the items in friction. This approach seems totally unsuitable for obtaining reproducible measurements of reliable friction and wear

characteristics. Therefore, a specimen holder was developed in the course of this project for universal-jointed mounting of the contacting component. This special geometry of specimen mount and base component solved the problem of frictional movement direction of the tilting moments acting on the contacting component.

Using the universal-jointed specimen holder for the friction tests made it possible to test the components provided by the KVK for the performance of post-exposure testing without further preparation. It was necessary to extract the base and contacting component specimens from the respective materials by dry sawing and milling so as to rule out possible changes in the ceramic coatings which might affect their tribological behaviour.

A special specimen holder had to be developed and fabricated for the testing of the heat exchanger U-tubes and their supports. This mount was designed to permit as realistic a frictional contact between the coated tube and the tube support as possible (contact surface is also coated). On account of the cylindrical enclosure of the tube by the tube support, the items in frictional contact aligned themselves automatically parallel to the direction of movement without tilting moments. Alignment perpendicular to the direction of movement was performed by the freely rotating specimen case in the universal-jointed specimen holder.

During commissioning and trial operation of the testing machine numerous friction tests were performed to optimise the hardware and the software and to verify the test results. In this context problems were encountered regarding the comparability of the results with data given in the literature as the references used often did not define tribological system parameters in sufficient detail. Consequently the test results were initially verified by checking the force measurements in situ, i.e., the force signals transmitted to the computer had to be within the tolerance bands specified by the load cell manufacturer with allowance for the relative leverages (normal force measurement), proportionality factors and other parameters.

In connection with the travel-dependent correction of the measured friction forces the friction coefficient calculation was checked with the aid of a helical spring with a known force/travel correlation which applies a strictly location-dependent linear force function to the friction load cell (representing a friction contact). In the case of reciprocating motion, the location-dependent friction coefficient must ultimately be a straight line

$$F(x) = k \cdot x \qquad \mu(x) = \frac{F(x)}{F_N} = \frac{k \cdot x}{F_N}$$

with a gradient:

$$\frac{d\mu}{dx} = \frac{k}{F_N}$$

Where:
x = Instrument location
k = Spring constant
F_N = Normal force

The criterion was met within the allowable tolerance band.

The following coating parameters were measured prior to each friction test.

- Coat thickness

The coating thickness was measured by nondestructive means using a measuring system which can measure electrically conductive or non-conductive coatings on ferromagnetic substrates or non-conductive coatings on non-ferromagnetic electrically conductive substrates. The measurement methods are based on the change in electrical impedance of a coil (ferromagnetic substrates) and an eddy current measurement (non-ferromagnetic substrates).

Comparisons with coating thicknesses measured on microsections showed good agreement with measurements taken in this manner. The diameter of the measured area (minimum coated area) is approx. 7 mm.

- Surface Roughness

The surface roughness of the tested coatings was measured using a DIN standard profilometer made by Messrs Hommel. The plotter connected to the measuring instrument is capable of outputting a profile plot of the measured surface profile in hardcopy immediately on completion of the measurement so as to allow other information such as abrasion profiles from strip charts to be gained.

3.3 Test Performance

Trails were conducted on the testing machine by performing numerous preliminary tests on similar and identical coatings to those exposed in the KVK. The results of two preliminary tests are discussed in brief below.

- 1. Friction test with Al_2O_3 coatings (APS deposition process) at T = 600°C, coating thickness approx. 215 µm on austenitic substrate. Atmosphere: argon 1 bar, technically dry. Reciprocating frictional motion (sinusoidal) at 34.2 mm amplitude.

  The test is remarkable in that it covered three different material combinations in succession as a result of the severe abrasion which took place.

  After approx. 6 m frictional contact distance the Al_2O_3 coating of the contacting component was abraded away (over an area of approx. 1 cm²) so that the material combination was steel/Al_2O_3 up to approx. 35 m frictional contact distance. After 35 m frictional contact distance the coating on the base component was worn away and the material combination was steel on steel. The 'negative abrasion', i.e., the increase in specimen thickness, resulted from sporadic exchange of material between the two materials.

At the end of the test (frictional contact distance = 49.8 m) the surface profile and the directional friction coefficients took on bizarre forms.

- 2. Friction tests with ZrO_2 coatings (VPS deposition process), coating thickness approx. 150 µm, pressure: 3 N/mm²; otherwise identical parameters to test no. 1.

  Although neither of the two ZrO_2 coatings were penetrated during this test, the abrasion profile of the base component was also very uneven towards the end. Since the depression (in the plots of abrasion versus instrument location actual depressions appear as projections) formed with increasing friction coefficient and remained stationary, the cause of the pronounced depression after 52.9 m frictional contact distance seems to be a coating defect at this location.

3.4 Discussion of Results

The test system generated in the course of this project permits tribological examinations to be performed under conditions which closely resemble those of plant operation. This similarity relates to the most important variables in the loading collective – mode of motion, motion time history, contact pressure, temperature - and to representative elements of the system structure, i.e., contacting component, base component, intermediate medium, environmental fluid. The test system was dimensioned such that parts of full-scale components (e.g., lengths of HX tubing and their supports) and/or similar geometries can be tribologically tested under realistic conditions.

Furthermore the system permits tests to be conducted with almost any atmosphere or under vacuum at temperatures up to 1000°C and with normal forces up to 1000 N.

The process computer controlling the test system ensures high precision in test performance and therefore a very high reproducibility of the test results.

The universal-jointed high-temperature specimen holder developed for the test system was patented (patent no. GR89G67O6) and permits friction between plane surfaces without tilting moments or skewing.

The good experience made with this tribological test system demonstrates that the design and construction of the system are good. Consequently it can be used to perform qualified tests of tribological systems (high temperature). The applicability of the tribological simulations to real-life conditions can be termed very high.

The post-exposure examinations performed on ZrO_2 coatings related to the systems HX tubes and tube supports and to the 2^{nd} baffle plate (70°) of the U-tube heat exchanger from the KVK. The objective of the examination was to establish whether a dependence exists between the wear resistance of the coatings and their prior thermo-tribological conditioning based on the working hypothesis that temperature-dependent carbon depositions in the coatings – originating from impurities in the gas atmosphere - might also affect the abrasion resistance of the coatings.

This assumption appeared to be confirmed by the results of the tubing tests at first, but was called into question by EDS analyses of the carbon distribution versus coating depth.

REM examinations failed to provide significant information on the phenomenon under examination (elevated abrasion at low and high temperatures, very little abrasion at medium temperatures). The conclusion is therefore drawn that the causes are to be sought not in changes in the coating as a result of redistribution of individual elements but in tribologically induced changes in the coating morphology in near-surface regions. This assumption is backed up by the frequently made observation of a 'polishing effect' at temperatures above 300°C. In this process a shiny layer resembling a polish and having a high wear resistance develops in zones of intense frictional contact between the two items. At higher temperatures (above approx. 700°C) the positive effect of this layer is evidently offset by other phenomena which have a negative effect on abrasion resistance to such an extent that abrasion increases again. This is possibly due to the formation of microcracking networks resulting from differential thermal expansion of the coating and the substrate.

To date, it can only be said of the polish layer that it is only composed of coating constituents within the detection thresholds of REM examination.

No statements can yet be made on the morphology of the polished layer as the thickness is too small for diffractometric examination.

The results of friction tests on tribologically unexposed ZrO_2 coatings from the 2nd baffle plate are qualitatively identical although the boundary conditions of the tests on the tubes were inverted.

The following conclusions can therefore be drawn from the tube and baffle plate tests:

- Exposure of the coatings under scrutiny to temperatures of up to approx. 1000°C has no effect on the later tribological characteristics of the coating.
- Combination of the thermo-tribological loadings has an irreversible effect on the coatings in relation to the abrasion resistance of near-surface regions.
- This change in the coating condition caused by a particular thermo-tribological loading condition is evidently retained under smaller thermo-tribological loadings as well. However, a renewed change in coating characteristics occurs if the governing conditions are violated.

The observed peeling of coatings, especially in the medium service temperature range (approx. 400 to 600°C) is indicative of chemo-physical phenomena. Some studies suggest that the gaseous carbon compounds present in the KWK atmosphere give rise to catalytic carburization phenomena at the NiCrAlY bonding layer.

Thus it is assumed in Ref. [7] that in the medium temperature range CO and CO_2 diffusing into the ZrO_2/NiCrAlY coating system are converted into amorphous carbon by a catalytic reaction at the bonding layer. This hypothesis would provide a cogent explanation of spalling of the coating and of the dark layers of the substrate below.

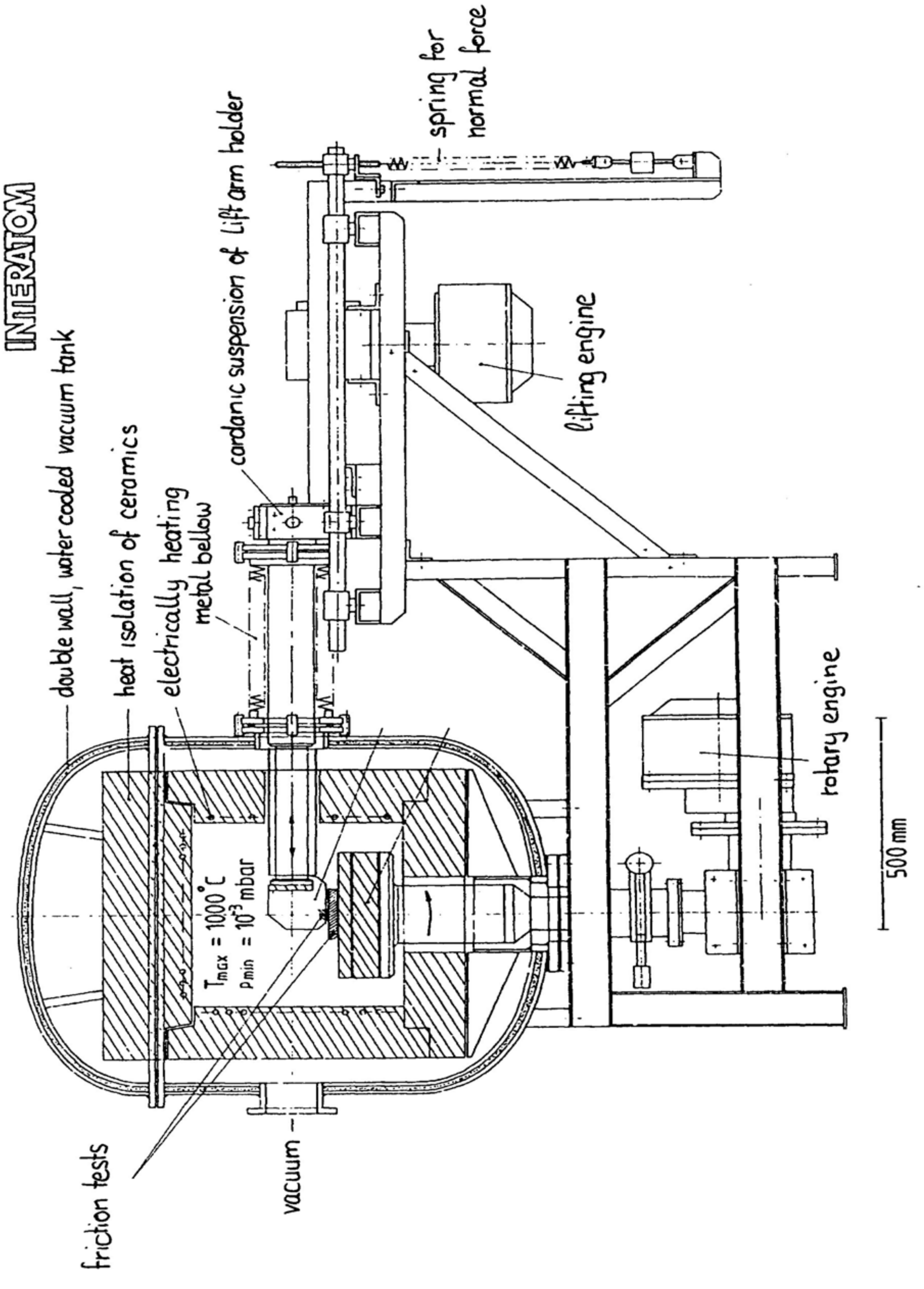

Figure 1: Testing machine for friction and wear
(Schematic principal of the test rig)

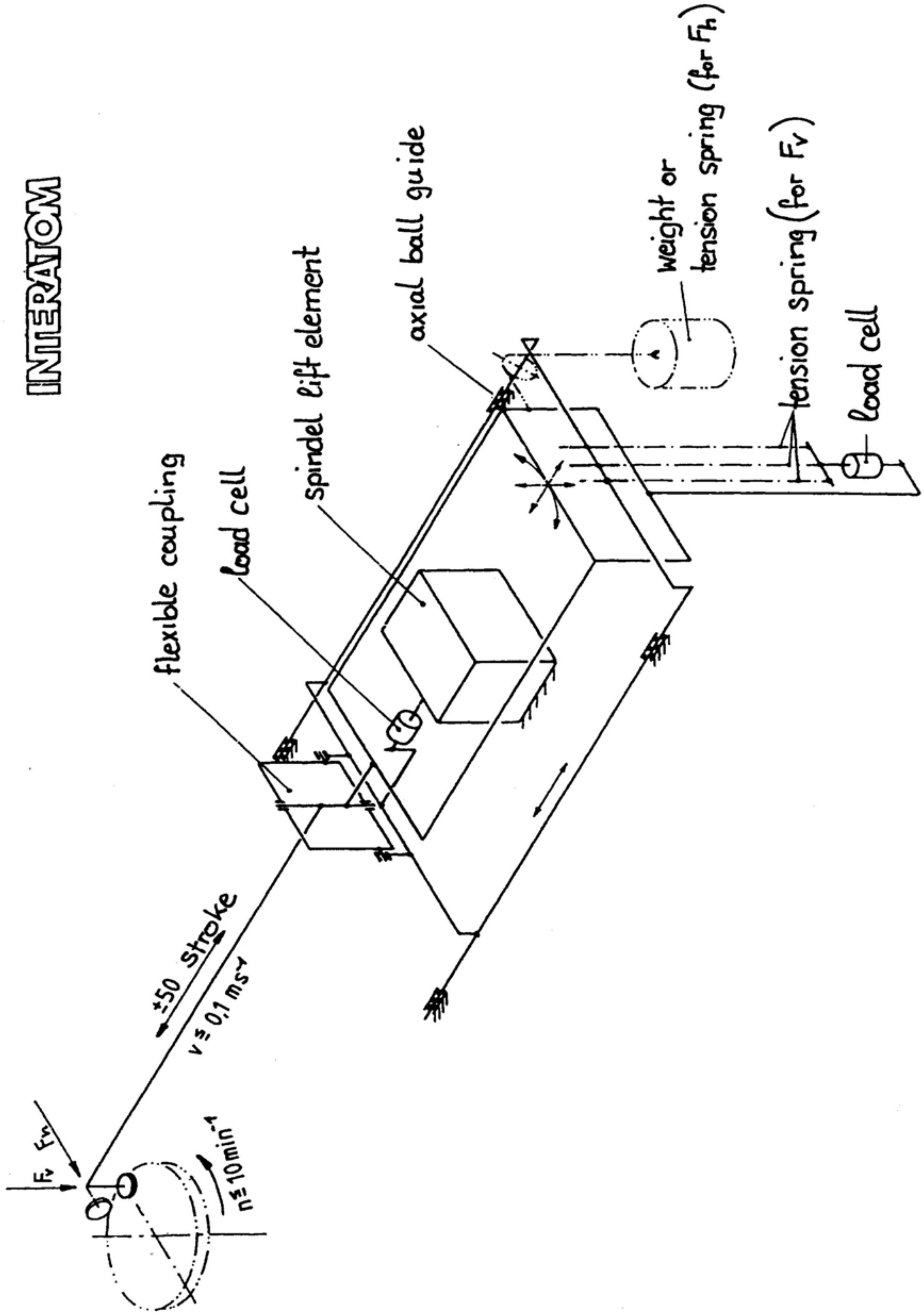

Figure 2: Testing machine for friction and wear
(functional diagram)

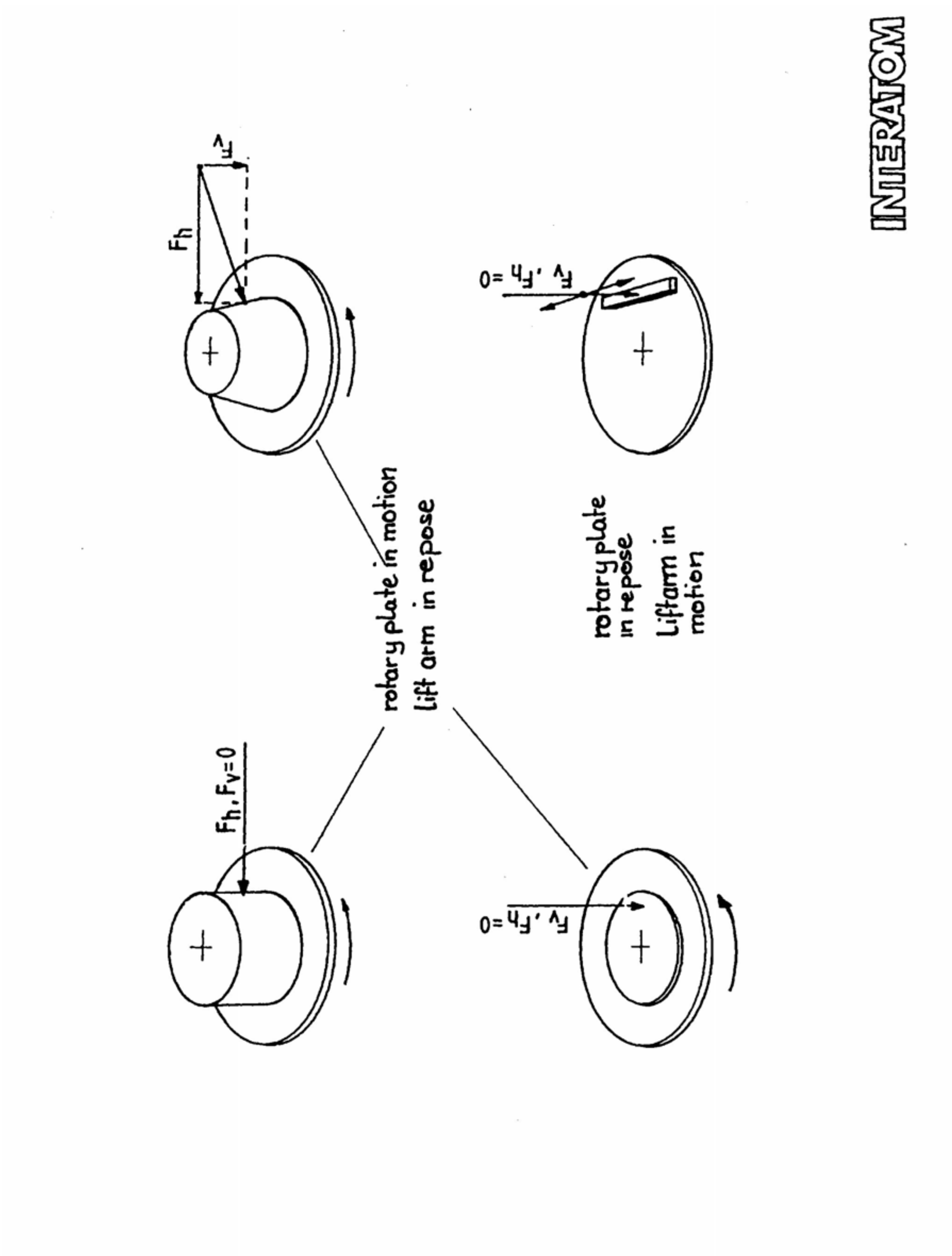

Figure 3: Testing machine for friction and wear
(Schematic representation of normal forces in dependent on the test geometry)

4 Investigations with a Helium Heat Exchanger Mock-up

The performance of coatings was also investigated in a heat exchanger mock-up built in a special helium test loop dedicated to tribologycal analyses, see Rev. [4].

A scheme of the helium test loop is presented in Figure 4.The loop consisted of 22 furnaces with metallic tubes (Inconell 600), four furnaces with ceramic tubes, three high cycle fatigue machines for investigations in helium and the heat exchanger mock-up. Inside this mock-up there were 18 tubes of Inconel 617 which were prepared with different layers of structures.

The tubes were heated up to 950°C and gas analyses were taken from the inlet and from the outlet of the tubes.

From the mechanical point of view there was the possibility to run a tube shift of 15 mm, i. e. ± 7.5 mm with a frequency of 18/h and a period of 200 s. This procedure was applied 2 hours per day. Additionally, there was the possibility of a vibrational excitation in the range of 2000 up to 3600 vibrations per minute. The tube shift should simulate the thermal expansion during heating up and cooling down the heat exchanger while the vibrational excitation should simulate the vibrations due to the fast coolant flow in the plant.

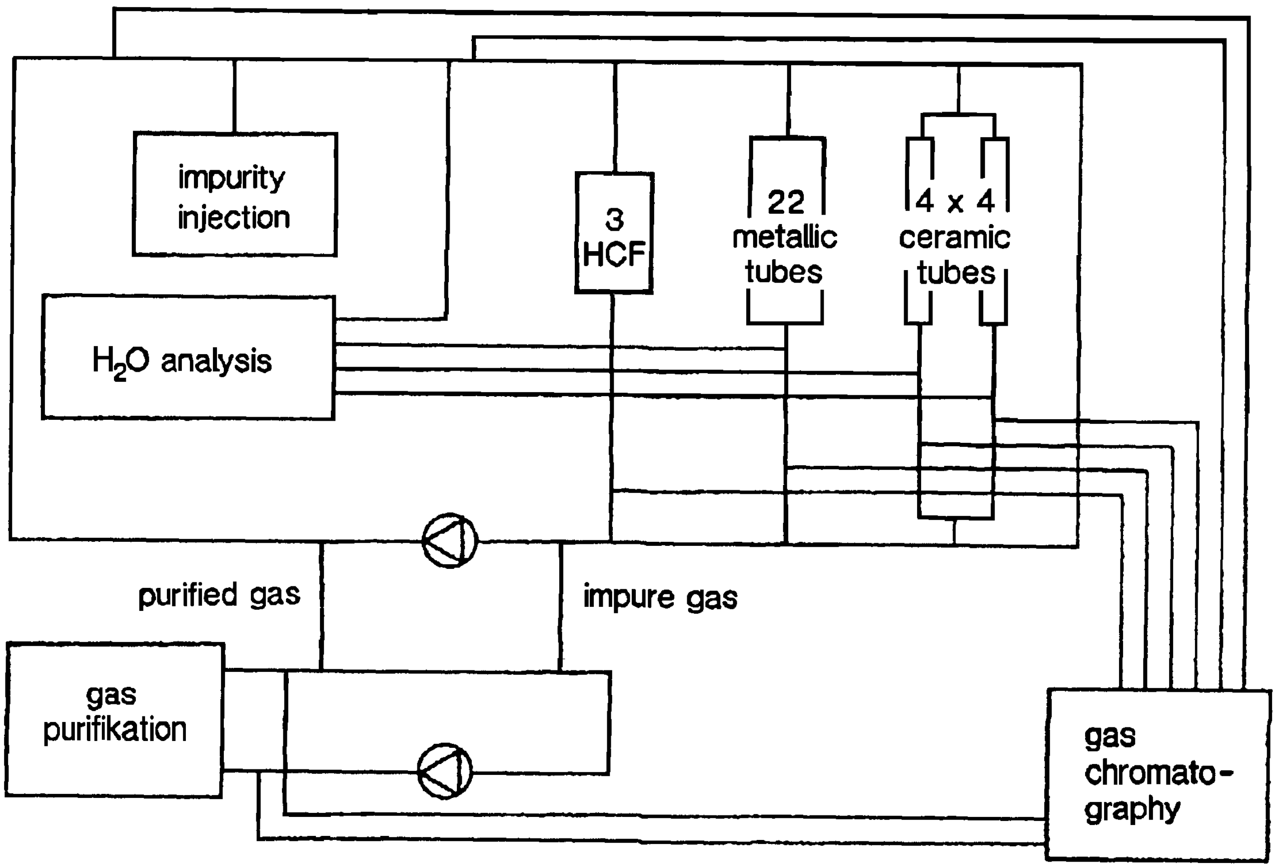

Figure 4: Scheme of the Helium Test Loop

The tube material under investigation was the nickel-base alloy Inconel 617, the tube diameter was 25 mm.

Parallel to the heat-exchanger mock-up coated specimens were investigated in two furnaces at 850°C and at 950°C in the same helium environment. The gas composition is given in table 2.

Table 2

Impurity Levels of the Helium [μbar]
System Pressure: 1.6 bar

H_2	H_2O	CO	CH_4	N_2
500	1.5	15	20	< 5

Results

The exposure of the coated specimens at 850°C at 5000h and at 950°C for 1050 h clearly revealed that from a great variety of layers (44 different layers) tested only the following layers were not damaged: CR_2C_3/NiCr, plasma sputtered in air and ZrO_2 + Y_3O_2 with a NiCrAlY intermediate layer, plasma sputtered in air.

All the other layers investigated in the furnaces exhibited more or less pronounced fissure ore peeling of. Especially, the layers which were plasma sputtering in vacuum were unexpectedly disappointing.

The friction tests with six different layers in the heat exchanger mock-up at 950°C for 7300 h confirmed this results. In principle the tendency could be observed that in spite of the additional friction and vibrational loading the results were better. Comparing these results with those found at the HRB/KFA Jülich there is an unexplainable discrepancy: D-gun sputtered $Cr_{23}C_6$/NiCr were excellent in the HRB/KFA-loop but not in the loop described here.

Still there is some uncertainty with respect to the long term behaviour of the layers. Small differences in the thickness of the layers, the sputtering parameters and other influences can obviously cause significant differences in the behaviour of the layers.

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