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Past experience from gas cooled reactor useful for VHTR

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RAPHAEL ***(ReActor for Process heat, Hydrogen And ELectricity generation)***

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Document title

Past experience from gas cooled reactor useful for VHTR

Abstract

This deliverable consists of 3 reports stemming from the 3 partners of this task: ANP-D, RTWH as sub-contractor of FZJ, and NNC. RWTH answered to the specification PVEI DC 05 0393 ESN “Technical specification related to the feedback from HTR (RWTH)”.

These reports provide the results of Germany and UK past experiences. The main results which can be extracted from those reports are as follows:
- Suitable materials for friction and wear use in VHTR atmosphere are:
  - Up to 350°C: MoS_2 solid lubricant
  - Up to 600°C: “standard” metal-based hard-facings as 75Ni-17Cr-3,1B-4,5Si-3,5Fe-1,0C and 50Ni-15Cr-32Mo3,0Si
  - 600 – 700°C: chromium carbides in a metal matrix (Cr_2C_3/NiCr)
  - Up to 850°C: chromium carbides as duplex layer ($Cr_{23}C_6$-$Cr_{23}C_6$/NiCr)
  - Up to 950°C: stabilized ZrO_2 on a NiCrAlY intermediate layer
- Parameters that influenced friction and wear behaviour:
  - Static adhesion when T>650°C for metal/metal
  - Adhesive transfer in metal/metal rubbing
  - No systematic effect of gas pressure
  - Influence of moisture level in gas
  - Wear rates increase with increasing helium purity
  - Ni-based alloys tended to perform better than austenitic SS in He
  - Graphite-graphite contacts wore little in He from 400 to 800°C. Wear increase with increasing gas purity
  - Influence of dwell at high temperature

Revisions

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Past Experience from gas cooled reactor useful for VHTR as part of HTR

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This report provides the results of Germany past experience with coatings inside test facilities and test components for the facilities ADI (HRB) and KVK (INTERATOM).This work represents AREVA NP GmbH contribution to RAPHAEL Deliverable D CT3.2.

Several parts of an HTR are subjected to relative motion under load and wear protecting materials are needed. Within the scope of investigation programs in Germany the available wear resistant materials and coatings were compiled and, after a selection phase, subjected to wear tests under different loads in artificial HTR-environment. Also aging tests were performed in order to gain information about the interaction of the partners in a temperature range where diffusion controlled processes will occur. Thermal cycling tests provided information about bonding strength and sensitivity to cracking and spalling.
The suitable material were classified into application temperature ranges where up to 600°C "standard" metal-based hard-facings as 75Ni-17Cr-3,1B-4,5Si-3,5Fe-1,0C and 50Ni-15Cr-32Mo-3,0Si could be applied, for 600 - 700°C chromium carbides in a metal matrix (Cr_2C_3/NiCr) are suitable, up to 850°C chromium carbides as duplex layer ($Cr_{23}C_6$ - $Cr_{23}C_6$ /NiCr) and up to 950°C stabilized ZrO_2 on a NiCrAlY intermediate layer is applicable.

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KEY WORDS

RAPHAEL ANTARRES PAST EXPERIENCE COATINGS

ABBREVIATIONS

ADI	High Temperature (up to 1000 °C) Test Facility for Insulation Systems of HRB
HTR	High Temperature Reactor
PNP	Prototype Nucelar Proces Heat
KVK	High Temperature (up to 1000 °C) Test Facility for Components of INTERATOM
SEM	Scanning Beam Electrone Microskope
RT	Room Temperature
URKO	U-tpye Intermediate Heat Exchanger

1 General Considerations on Friction, Wear and Tribological Systems

1.1 General

As a definition *friction* can be considered as the force resulting from the resistance of one body moving over another. *Wear* is a damage to one or both surfaces and *tribology* can be understood as "science and technology of interaction surfaces in relative motion". Wear mechanisms to be considered are *sliding, rolling, impact, fretting and relatives.* A more broad definition of *wear* includes mechanisms induced by interaction of a surface with also a liquid or gaseous environmental partner, e.g. *erosion, erosion corrosion, hydroabrasive erosion, cavitation, drop impact erosion and relatives.*

1.2 Tribological Systems

A *tribological system* (here an example for *sliding movement*) can be defined by all of the following parameters:

Partner #1 (material, incl. structure condition, surface roughness, surface treatment...)

Partner #2 (material, incl. structure condition, surface roughness, surface treatment...)

Design/dimensions of the mechanical system

Normal force

Sliding velocity

Sliding distance

Sliding frequency

Temperature (environmental temperature)

Environment (chemical composition, chemistry, physical state..)

In the discussion of wear related to sliding of solid partners the topography of the interacting surfaces is important. Even at a fine scale all solid surfaces are uneven, in the limit at a scale of individual atoms or molecules. Technical surfaces typically appear as "mountains and valleys" at a scale of about 10 to 50 μm (difference between the "deepest valley" and the "highest mountain").

Therefore, when two nominally plane and parallel surfaces are brought gently together, contact will initially occur at only a few points. When the normal load is increased, the surfaces move closer together and a larger number of the higher peaks (asperities) on the two surfaces come into contact.
For any study of friction or material's behaviour it is therefore of major importance to understand in which manner these asperities interact each other. Also one should bear in mind that a technical surface appears with a small zone of deformed metal resulting from the machining, an oxide-reaction layer and an adsorbed layer of environmental molecules (e.g. corrosion protecting Fe-Cr-Ni-oxide layer, adsorbed water film in steam conditions, water, lubricant).

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1.3 Friction Force

In an ideal sliding or rolling situation (e.g. two bodies loaded by a normal force F_N) a tangential force F_R is needed to move one body over the stationary counterpart. The ratio between this frictional force F_R and the normal load F_N is known as *coefficient of friction* ($\mu = F_R/F_N$ or $F_R = \mu \bullet F_N$). The coefficient of friction can vary from 0.001 in a lubricated lightly loaded roller bearing up to 10 and more for metals sliding against themselves ("self-mating couples") in vacuum.

The existing friction laws characterize that

- the friction force is proportional to the normal load
- the friction force is independent of the apparent contact area

This could generally be interpreted that the coefficient of friction μ is a constant term related to the material (mating).

1.4 Wear And Wear Mechanisms

The material loss can be divided into several mechanisms, where here only the mechanisms important in light of this report are mentioned.

The wear in a defined tribological system is also influenced by specific material properties as the solubility of mated materials, stacking fault energy, oxide layer formation, hard phases, difference in hardness and others.
The determination of the amount of wear acc. to e.g. Archads wear equation has therefore only a very limited applicability and other approaches have to be performed.

<u>Adhesive wear</u> could be defined as a close contact of asperities under high loads that leads to plastic deformation of the contact area and the combined partners tend to generate a bond between these areas by adhesion mechanism (or form fit). When parts are being moved, these "bridges" are sheared whereas the break is not necessarily in the former contact plane. Material is transferred to the other partner.

Remark:
Several publications provide different definitions for *adhesive wear* and also wording is different (e.g. *scuffing* in UK, *scoring* in US and *galling* for most severe surface damage).

<u>Abrasive wear</u> could be defined as close contact of asperities under high loads that leads to removal of material from the contact areas by scratching. The combined partners do not tend to generate a bond between the contact areas. When parts are being moved the roughness tips are sheared either by furrowing one partner or both surfaces. There is no bonding interaction between the partners.

<u>Fretting</u> is defined as oscillatory movement of small amplitude. When surfaces experience this type of motion there is tendency for fretting wear and if the surfaces are capable of reacting with the environment, also fretting corrosion will occur. The material loss is composed by the mechanisms of fatigue, sliding wear and corrosion. The primary mechanism is depending on the type of impact.

<u>Surface fatigue</u> takes place when the surface is subjected to repeated compressive stress. A common manifestation of this form of wear is in rolling element bearings.

2 Assessments and Investigations in the German R&D Programs Related to Wear Resistant Materials

2.1 Material Types

Generally hard-facing materials can be classified by their base material and the compound system. For the metallic systems base metals as Cobalt ("Stellites"), Nickel and Iron are available. The alloy systems (examples only) known for these are Co-Cr-W-C, Ni-Cr-C-B-Si and Fe-Cr-C where the hard phases are composed by e.g. carbides or/and borides and silicides.

Special different coating types are based on binary systems as Ti-N, Ti-C and Cr_x-C_y and oxide-based systems as Cr_2O_3, Al_2O_3 and ZrO_2.

Other systems are designed as compounds or cermets using a mixture of carbides or oxides in a metallic matrix.

A listing of all available technical systems is beyond the scope of this report and is reported in the referenced sources and the related common literature.

The cobalt base alloys were considered as not compatible for nuclear applications due to the fact that their debris due to wear can become activated and will then increase the dose rate of the plant. In a similar but different manner the Boron in some Nickel-base hard-facings could not be very suitable.
Then the number of remaining hard-facing alloys with good wear resistance behaviour reputation becomes sparse.

2.2 Corrosion Phenomenons and Thermal Interactions With Respect to HTR Operating Conditions

Within the German research and development program on friction and wear in HTRs the applications were classified into temperature ranges of below 700°C, 700°C to 850° and above 850°C.

Another classification characteristic is the thermal stability of the system itself, the interaction with the environment and the interaction with the partner in light of diffusion controlled processes.

As the application temperature in V/HTRs ranges from 250°C to 950°C, besides the interaction related to friction and wear also interactions related to high temperature have to be considered. As a rule, when a material is at temperatures above about $0{,}5T_m$ (where T_m is the material's melting point in absolute temperature) concentration differences of contacted materials can follow the equilibrium driving force.

So, inter-diffusion will take place. In case of base metals that are hard-faced with layers, several processes can happen:

- interaction between the mated surfaces (partner #1/partner #2)
- interaction of hard-facing and substrate metal
- interaction of buffer layer and substrate metal
- interaction of buffer layer and hard-facing material
- interaction of elements of the environment with all, the hard-facing, the buffer layer and the base metal

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Certainly it has to be respected that the materials themselves (hard-facing, buffer layer) show thermal stability at the design temperature or, the material degrading process is well known and acceptable, respectively.

Mechanisms to be considered here are

- thermal stability at operation temperature and element related partial pressure of the environment (e.g. oxides vs p_{O2}, carbides vs a_c, nitrides vs p_{N2}) considering Pourbaix-Ellingham diagrams
- selective oxidation
- carburization or de-carburization
- forming of layers different in concentration and composition due to inter-diffusion (e.g. forming of Al_2O_3 at a phase boundary of a MCrAlY buffer layer).

Therefore the qualification requirements for hard-facings suitable at high temperatures include the determination of the degradation/aging effects and the proof that the requested wear properties are still present at a sufficient level after a certain time of operation.

Beside the wear properties, bonding force to the base metal and resistance against thermal cycles will be influenced by long term aging processes and have to be considered.

Considering the aspects given above it becomes clear that the application of ceramic materials in the high-temperature-range may "release" other challenges because the base material would be a metallic Nickel-Base alloy (e.g. Alloy 617, Alloy X, Alloy 230, coefficient of thermal expansion (CTE) about 14E-6 m/(m*K)) or a metallic Iron-base alloy (e.g. Alloy 800 H, CTE about 18E-6 m/(m*K)).

Ceramic materials show CTE-values in the range of about 2,5 - 3,5 for Si_3N_4, about 6 - 8 for Al_2O_3 and about 9 - 13 for ZrO_2 (depending on stabilization ratio). Chromium-Carbides show up values in the range of 10.

This sometimes large misfit had to be considered in the technical design of the wear resistant materials. A solution of general kind is the application of a "compensation" layer on the metallic substrate material beneath the ceramic material. This buffer layer should show a CTE somewhere in between the metal's and the ceramic's CTE and should have properties that provide good bonding to both, the metal and the ceramic and shall have thermal and corrosion stability for the high temperature application in HTR environment.

2.3 Selection Phase - Verification Phase

From the selection phase is became clear that the application temperature of lubricants and "standard" metallic hard-facings would be limited due to diffusion controlled degradation of the material itself and/or increased interaction with the mating material.

Ceramic materials would then be the priority of choice due to their physical structure, their chemical bonding type, their diffusion characteristics and their thermal stability.

At very high temperatures also the corrosion interaction with the environment, in case of HTR especially the interaction based on the equilibrium of Carbon activity and Oxygen partial pressure is of major relevance [1, 2].

Investigations have been performed e.g. in the scope of the development of the German THTR (up to 750°C) and a research project related to nuclear process heat production (PNP). In the selection phase the candidate materials were exposed as couples to static loads (1 MPa - 20 MPa) at e.g. 950°C for 3000 hours and in one case for the chromium carbide at 1050°C for 100 hours [3]. The materials were evaluated by light optical-, electron optical, scanning microprobe and x-ray analysis with respect to their interaction behaviour by “welding”.

Additionally, thermal cycling has been performed where the specimens were heated to 950°C at a rate of 250°C/min and cooled at a rate of 150°C/min to 200°C [3, 4, 5]. Candidate material had to bear this procedure for 30, 100 and 300 cycles without defects. Temperature cycling effects are the determined metallographically.

In order to determine the thermochemical resistance also aging tests have been performed to prove the candidate materials’ structural stability and the secondary diffusion of important elements of the coating into the base metal. In the aging test facility the specimens were exposed load-free for a period of 30.000 hours in a gastight vessel. The gas was purified by passing it over heated graphite to gain helium with a low oxygen partial pressure.

Friction and wear tests were performed in equipments of special design [4, 6]. These test rigs operated up to 950°C in a HTR standard atmosphere environment where the contact area of the specimens was 400 mm^2 and surface pressures of up to 20 MPa were applied. The stroke of the relative specimen’s movement was 5 mm and at speeds of 1 to 2 mm/min a total wear distance of 5 m (selection phase) and 20 m (verification and demonstration phase) was achieved.

The evaluation included the determination of the coefficient of friction and the surface appearance was determined.

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2.4 Results

Considering ceramic materials as $Cr_{23}C_6$, Cr_2O_3, Al_2O_3, Mo_2C, $MgZrO_3$, ZrO_2 stabilized by CaO the results after the 1st selection phase were promising.

After further testing, especially after the isothermal exposure tests, materials could be classified:

- $Cr_{23}C_6$ on a buffer of $Cr_{23}C_6$ /NiCr-binder showed sufficient stability but somewhat spalling from the substrate. This was due to the synergism of phase instabilities and localized oxidation of the NiCr-matrix, since cracks at the top-coat subsurface-coat interface were associated with large elongated oxides.
- Cr_2O_3, Mo_2C and $MgZrO_3$ showed structural instabilities
- Al_2O_3 failed in thermal shock tests
- ZrO_2 stabilized by CaO showed total desintegration, CaO evaporated and zirconia powder left over
- Investigations on TiC, TiN and mixed TiC/TiN coatings deposed by CVD technique are reported

From these results it has been derived that modifications have to be performed.
The ZrO_2 ceramic was then (cubic) stabilized by Yttrium-oxide (Y_2O_3) at a level of about 13 vol.-% in order to prevent cracking by the volume shrinkage due to the phase transition of tetragonal phase to monoclinic phase.

Remark: ZrO_2 (monoclinic) $\underset{\xleftarrow[\Delta V\sim 3...9\%]{martensitic\sim 950°C}}{\xrightarrow{\sim 1170°C}}$ tetragonal $\xleftrightarrow{2370°C}$ cubic $\xleftrightarrow{2680°C}$ liquid

An interface layer is needed in order to “fit” the differences in thermal expansion between the ceramic surface layer and the Nickel-base substrate material. An alloy system based on NiCrAlY has been used as buffer layer.

This coating system was applied using air plasma spraying (APS) and low-pressure plasma spraying (LPPS) technique.

These systems have been tested and examined and were attributed to be a suitable anti wear system for operation temperatures above 850°C in HTR environment [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

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2.5 Summary of Tested and Applicable Coatings

The anti-friction and wear resistant coatings and coating systems found suitable for HTR application after all investigations could be summarized as

Operation Temperature	Coating/Coating System/Trade Name	Identification and Composition of Coatings Systems	Coating Procedure	Base Material Type
~ 600°C	Colmonoy 6	75Ni-17Cr-3,1B-4,5Si-3,5Fe-1,0C	Air Plasma Spraying (APS)	Nimonic 80 A
	Triballoy 700	50Ni-15Cr-32Mo-3,0Si	Detonation-Gun-Coating (D-Gun)	Hastelloy X
600 - 700°C	Chromium-Carbides in Metal Matrix	Cr_2C_3/NiCr	Detonation-Gun-Coating (D-Gun) UCAR/Praxair Types LC-1C, LC-1H	Inconel 625 and X 8 CrNi-MoNb 16 16 (Mat.-No. 1.4981)
up to 850°C	Chromium-Carbides in Metal Matrix- Duplex Coating	$Cr_{23}C_6$ - $Cr_{23}C_6$ /NiCr	Detonation-Gun-Coating (D-Gun) UCAR/Praxair Types LC-22, LC-24	Inconel 625
up to 950°C	Zirconium Oxide Coating on Bonding Layer	ZrO_2, stabilized by 13% Y_2O_3 - NiCrAlY Intermediate Layer	Low Pressure Plasma Spraying (LPPS) and Air Plasma Spraying (APS)	Inconel 625 Inconel 617 Incoloy 800

Table 1: Summary of Hard-facings Suitable for HTR Application

3 Long Term Behaviour of Zirconia Coatings With Respect to Degradation

Special investigations [15, 16] were performed assessing the bonding strength of the hard-facing and the buffer layer bonding with respect to long term effects.

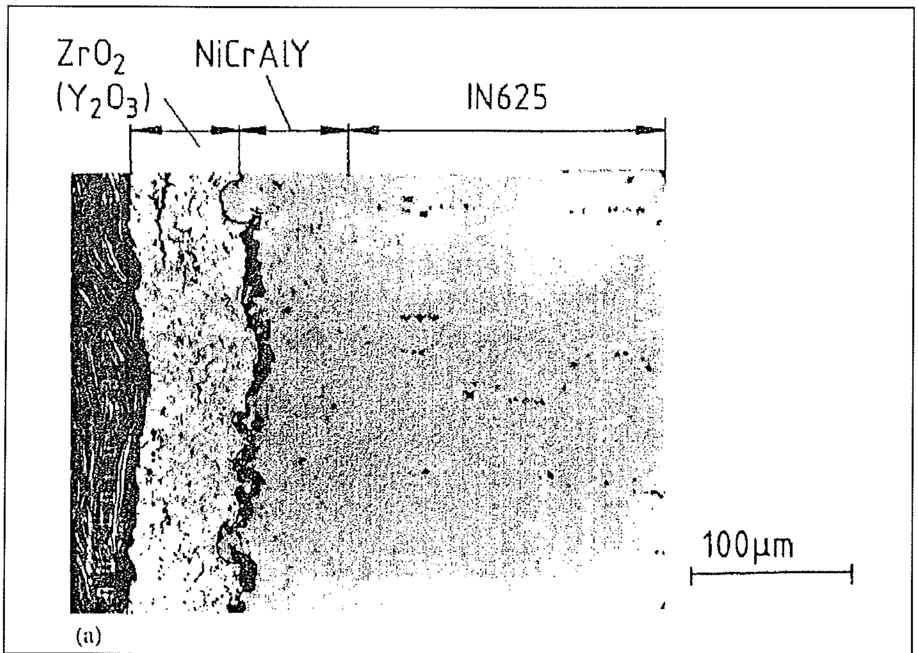
When the hard-faced material is exposed to elevated temperature, inter-diffusion between substrate (in case of this experiment Alloy 626) and the Ni-Cr-Al-Y intermediate layer takes place. Specimens were exposed to 950°C in HTR environment where some specimens have been exposed to load ("self welding test") and other were free of load.

From the base material Alloy 625 substantial amounts of Mo, Nb and Fe have entered the MCrAlY layer without the formation of a harmful phase.
After 3 different exposure times at 950°C the chemical composition in the cross sections has been determined.
The results are compiled in Table 2 and the chemical composition of the materials in the initial stage is given for comparison purposes.

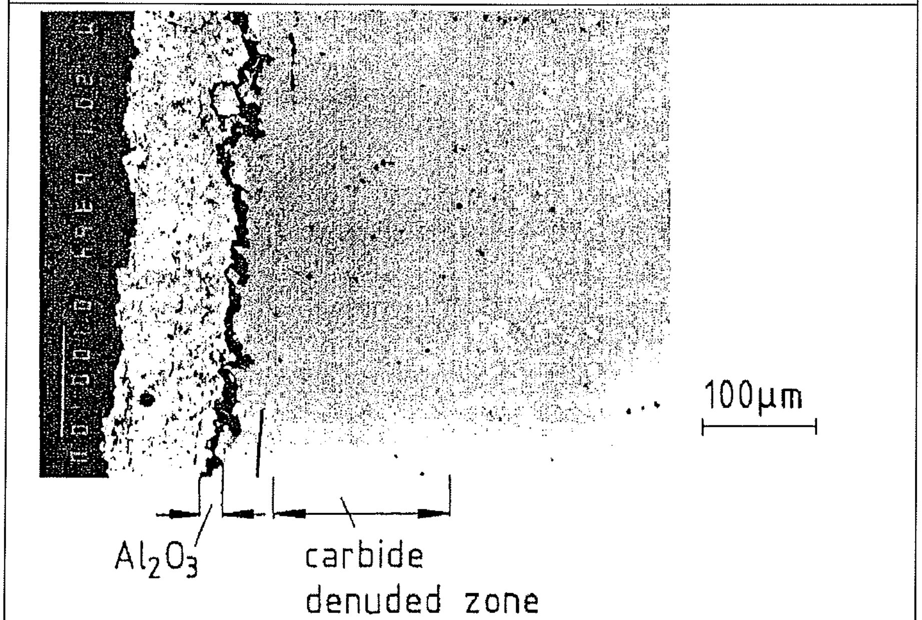
Material/ Condition	Composition in wt.-%								
	Ni	Cr	Al	Y	Mo	Nb	Fe	Ti	C
Ni-Cr-Al-Y (MAX)	bal.	16,5	5	0,3	-	-	-	-	-
Ni-Cr-Al-Y (MIN)	bal.	17,5	5,8	0,6	-	-	-	-	-
Inconel 625 (nominal)	bal.	22	0,2	-	9	4	3	0,2	0,05
Wear Specimen (about 330h/950°C)									
Ni-Cr-Al-Y Layer	bal.	19,98	2,44	*	1,92	1,47	1,17	-	*
Carbide Depleted Zone	bal.	20,26	1,49	*	4,41	1,67	1,61	-	*
Aged 950°C/3000 h - No Load	bal.	19,40	0,83	*	5,49	1,95	1,99	0,07	*
Aged 950°C/3000 h - 500 MPa Load	bal.	20,03	0,76	*	3,35	2,58	1,78	0,03	*
Aged 950°C/9000 h - No Load	bal.	20,51	0,01	*	6,8	2,14	2,49	-	*
Aged 950°C/9000 h - 500 MPa Load	bal.	21,18	0,43	*	4,59	0,99	2,00	0,05	*
- ... not present * ... not measured									

Table 2: Element Analysis of Composition

It shall be mentioned that there is a clear difference between the concentration of Mo, Nb and Fe when the specimens exposed under 500 MPa load are compared to the non loaded specimens. The mechanisms behind could not clearly be identified.
After 9000 h Aluminum has mostly disappeared in the intermediate layer and diffused to the substrate where beneath the formed Al_2O_3 precipitation zone, a carbide depleted zone in the substrate appears. The width of the carbide depleted zone is about 100 - 120 µm after 3000 hours at 950°C and approximately 175 µm after 9000 hours at 950°C (see Figure 1).



$ZrO_2(Y_2O_3)$//Ni-Cr-Al-Y, LPPS Coating
Exposed to HTR Helium for 3000 h at 950°C



$ZrO_2(Y_2O_3)$//Ni-Cr-Al-Y, LPPS Coating
Exposed to HTR Helium for 9000 h at 950°C

Figure 1: Formation and Altering of Bonding Line and Interface Layer

After 9000 hours exposition time the Aluminum-Oxides scale grows to a thickness of approximately 10 µm. From previous experience it is known that thick Aluminum-oxide layers are prone to spalling, which here could result in the loss of the wear protection layer.

Thermal shock experiments have been scheduled in on material exposed for long periods to obtain further data.
The depletion of the bonding layer in Aluminum has as consequence that no Al-oxide scale can be formed protecting for carburization.

As a third consequence the diffusion between the Ni-Cr-Al-Y layer and the base metal could lead to a loss of the load-bearing cross section due to altering of the material's e.g. creep properties by this change in chemical composition. This is valid only in case the thickness of the such modified zones (e.g. 200 µm) are comparable to the substrate thickness, e.g. for thin wall components.

For the determination of the properties after a certain exposure time wear tests and further characterization has been performed [10,12].

In the testing device developed by INTERATOM wear tests [12] on material (e.g. base metal + MCrAlY + ZrO_2) have been performed. After the "set-up phase" where specimens in the delivery condition were tested also specimens coming from the KVK-component test rig having an operation history were subjected to wear tests and further examinations.

The post-exposure examinations performed on ZrO_2 coatings were related to the heat exchanger tubes and the tube supports of the U-tube heat exchanger from the KVK and to the 2nd baffle plate, 70°.

The KVK specimens were altered in so far that they have been exposed for about 10.000 hours to operation temperature (7.000 h < 950°C and 3.000 h > 950°C) and to an interaction of the impurities in the HTR-Helium environment. Therefore both, change of properties due to inter-diffusion effects and based on the working hypothesis that temperature-dependent carbon depositions on/in the coatings may take place could be evaluated.

The wear test results of the operated tube/tube supports were generally comparable to the results gained by un-aged material, coefficient of friction was in the range of 0.8.

Further investigations showed some unexpected information of the surface, the appearance of a "polished" surface layer and the effect that the wear at low (RT) and high temperatures (950°C) is higher compared to the wear at intermediate temperatures (320°C - 650°C - 800°C).
Examination within the detection thresholds of SEM of this layer shows that it is composed by the coating constituents only. No further statements on it's morphology could be made due to very low thickness of this layer.

From the results the conclusion was drawn that a highly wear resistant layer is generated by "tribological reactions" at temperatures above 300°C. The reduced wear resistance at very high temperatures may be explained by the generation of microcracks at this temperature level that "overrules" the good wear behaviour of the polished layer.

Additionally, in the URKO rig spalling of the coating has been observed at locations where the operation temperature was below 650°C.
Investigations show that this effect was related to the high carbon activity of the test atmosphere in these areas that caused carburization reactions of individual components of the coating.

It shall be remarked here that large spalling of the upper layer did not impair the functional capability of the component.

Additional information about the thermal stability can be drawn also from the fact that this type of coating (base metal - MCrAlY - ZrO_2) is being used as standard system at gas turbine blades in order to reduce metal's temperature with good success.

4 Application of Detonation Gun Coatings

In the scope of the qualification of hard-facings useable for HTR several Detonation Gun Coatings have been investigated [14].

The detonation gun consists of a water cooled barrel about 1 m long with an inside diameter of about 25 mm and associated gas and powder metering equipment. In operation a mixture of oxygen and acetylene is fed into the barrel along with a charge of powder. The gas is detonated and the resultant hot gas accelerates the powder to about 840 m/s while heating it close to, or above, its melting point. Under detonation conditions a maximum temperature of 4200°C can be achieved. Per each pulse a circle of coating of approximately 25 mm in diameter and a few microns in thickness is deposed. Pulse frequency of 8 per second leads to quasi-continuous coating growth.

Depending on powder grade, the particle size of the powder is in the range of 5 µm to 60 µm. Particle size will have an effect on the coating properties where finer powders can result in denser coatings but with higher coating stress. The powder may be pre-alloyed or it may be a mechanical mixture of two or more components.

List of coating types of UCAR company (now PRAXAIR) and their general compositions [14]:

Coating Type UCAR Designation	Nominal Composition in wt.-% Coating	Nominal Composition in wt.-% Binder	Hardness VPN 300 HV0,3
LC-1B	65 Cr_3C_2 + 35 NiCr	80Ni-20Cr	700
LC-1C	80 Cr_3C_2 + 20 NiCr	80Ni-20Cr	800
LC-1H	65 Cr_3C_2 + 35 NiCr	80Ni-20Cr (fine particle powder)	800
LC-21	Cr_3C_2	-	950
LC-22	$Cr_{23}C_6$	-	800
LC-24	83 $Cr_{23}C_6$ + 17 NiCr	80Ni-20Cr (fine particle powder)	700
LW-5	25 WC + 5 Ni + mixed W-/Cr-carbides	-	1100
WT-1	83 WTiC + 17 Ni	no information available	1300
LDT-700	50 Ni 15 Cr 32 Mo 3 Si	no information available	800
LA-2	Al_2O_3	-	1100

Table 3: List of Detonation-Gun-Coatings, former UCAR company

Remark:
LC-21 has been used as top layer of duplex coatings with interlayer of LC-1H or LC-24, respectively.

The Chromium-Carbide - Nickel Chromium systems as LC-1B, LC-1C and LC-1H have been checked and qualified for application in light water reactors, sodium cooled reactors and in HTRs up to temperatures of approximately 600 - 750°C. These coatings are produced from mechanically mixed powders of Cr_3C_2 and metallic NiCr-binder.

For the application in HTRs the metallic matrix is the limiting factor at very high temperatures, e.g. at 950°C due to inter-diffusion reaction with the mated partner.

Therefore, duplex systems have been developed. The duplex coating consists of an inter-layer of ceramic phase in metallic binder in order to provide an interface for the mechanical properties, especially the coefficient of thermal expansion, between the Nickel-base alloy of the substrate material and the ceramic top layer.

For the duplex coating systems the coating grades LC-21, LC-23 and LC-24 were used.

Another reason to apply coating based on $Cr_{23}C_6$ carbides besides the Cr_3C_2 carbides is the (possibly) higher thermodynamic stability of the $Cr_{23}C_6$ carbide in HTR environments based on the relation of enthalpy of formation and carbon activity and should have a very long term microstructural phase stability due to the lower carbon content in the presence of chromium alloys.

As an example, the metallic base metal Alloy 625 (61Ni-22Cr-9Mo-5Fe) was coated with LC-24 (83 $Cr_{23}C_6$ + 17 NiCr) and LC-22 ($Cr_{23}C_6$) as cover layer.

For the check of suitability in HTR several materials and material combinations have been evaluated under static and dynamic conditions. Static "welding tests" were performed at loads of 100 N/cm^2 up to 2000 N/cm^2 and temperatures in the range of 950°C - 1050°C.

A short compilation of tests performed with some D-Gun coatings compared to other candidate coatings is given in Table 4. The applied travel speeds were in the range of 1 mm/min and 2 mm/min, loads in the range of 1 MPa to 10 MPa and total sliding distance per test up to 5,2 meters.

Material Mating	Test Temperature in °C	Coefficient of Friction	Comments	Notes
ZrO_2	950	0,7 - 0,9	No surface damages	-
Chromium-Carbide/NiCr-Binder LC-1H	950	71,5	NiCr binder of coating welded, surface damaged	a
Duplex $Cr_{23}C_6$ - $Cr_{23}C_6$+Binder LC-22 top LC-24 interface	1000	0,8 - 0,9	No surface damage	-
TiN	900	0,9 - 1,1	Deep wear marks	-
WC	600	0,5 - 0,7	No surface damage	-
Al_2O_3	850	0,6 - 0,7	Small grooves Little wear	-
NiAl	800	71,5	Coating destroyed	-

Table 4: Wear Properties of Detonation-Gun-Coatings Compared to other hard-facings

Note(s):
a...The D-Gun coating type LC-1H showed no surface damage at 700°C

From these investigations the suitability in HTR environment of coating type LC-1H in the temperature range of 600°C - 700°C due to reduced "self welding" is reported where the duplex layer type LC-22/LC-24 may be applied up to 850°C [6].

RAPHAEL CT3.2-Coatings.doc

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SP_ CT

Component Development

WP3 : Tribology

Slides presented by Pr. Kugeler

on September, 7th 2006 at Aachen.

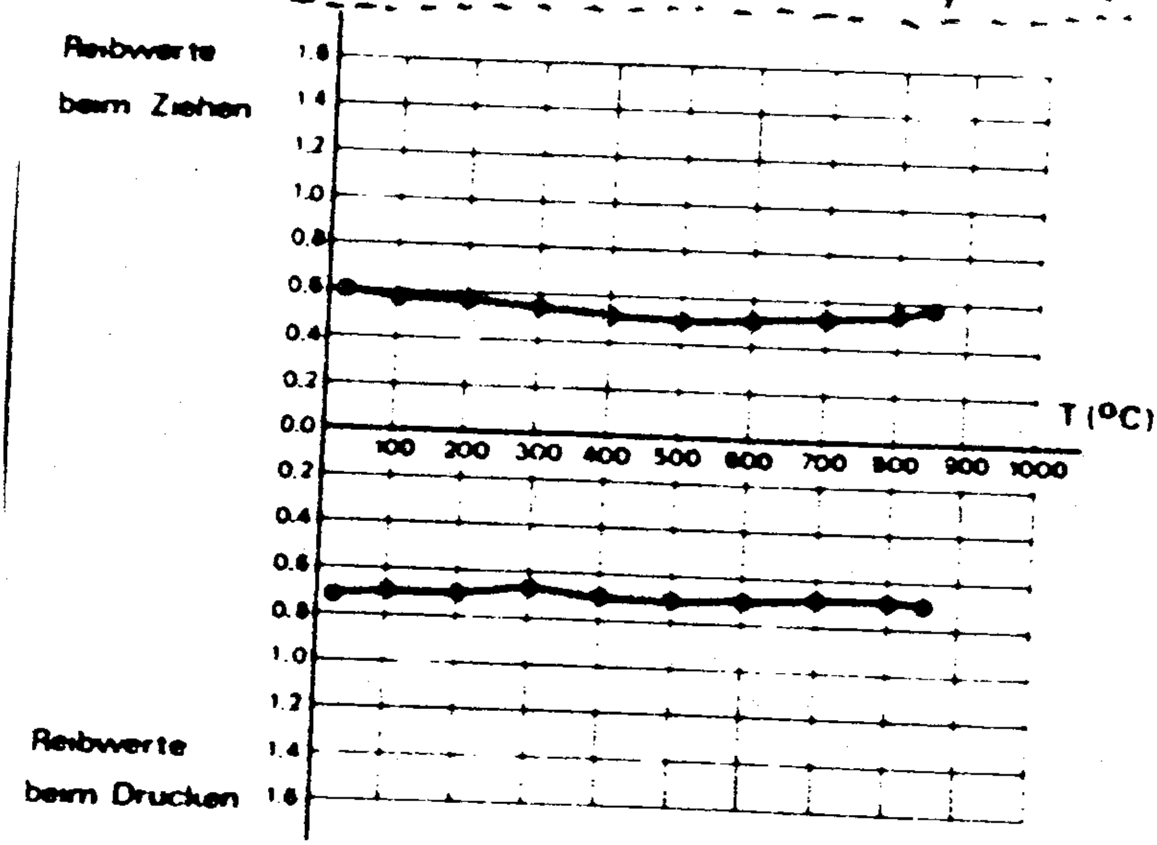
on Tribology - Friction

22 pages

1

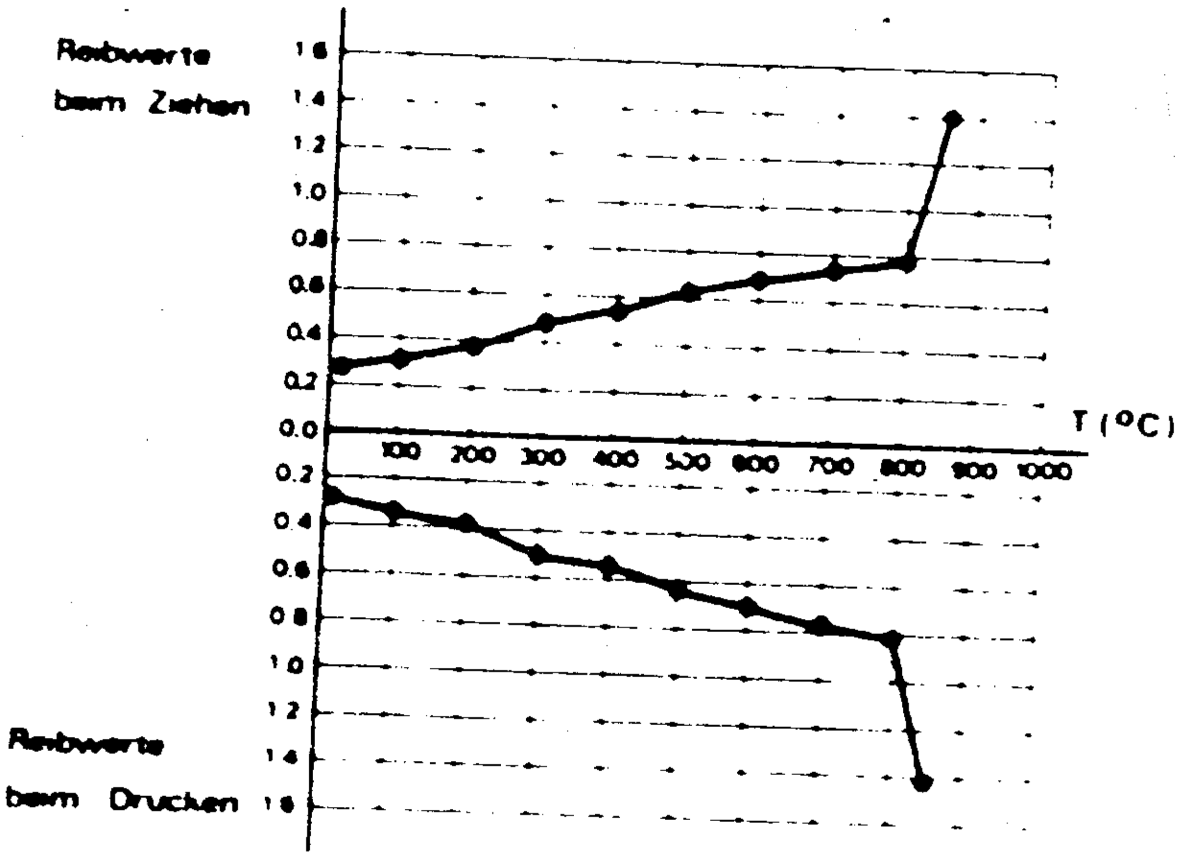
Friction

suitable and not suitable pairing



Materialpaarung: Inconel 625 auf Keramik (Al_2O_3)

Flächenpressung: 1000 N/cm²

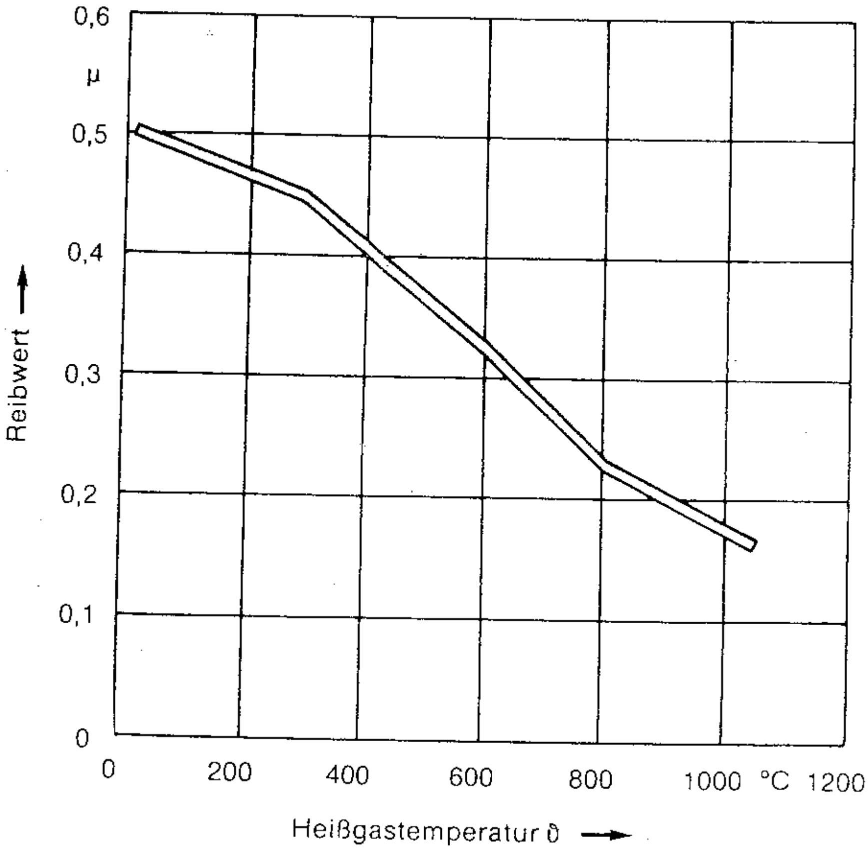


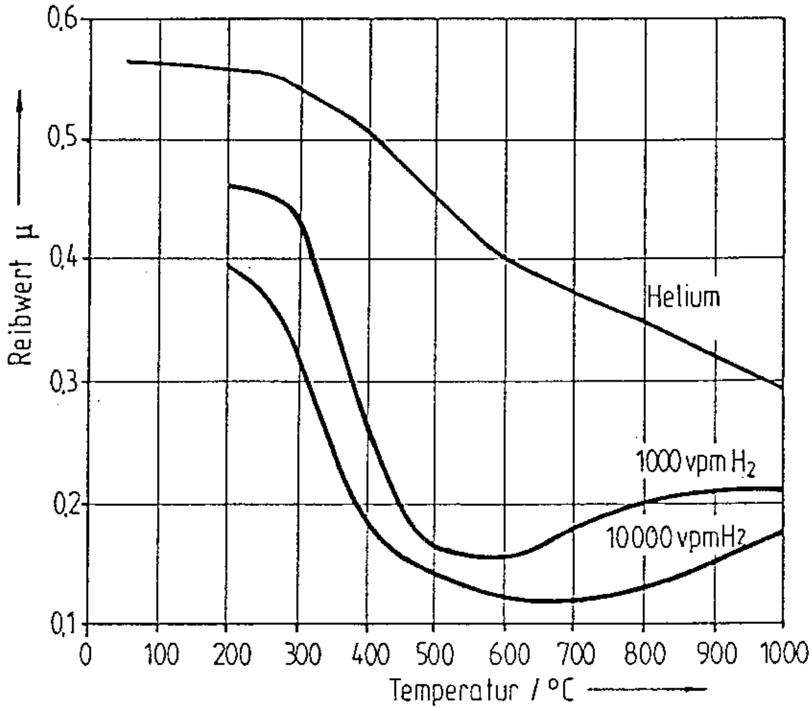
Materialpaarung Nimocast 713 LC auf Nimonic 75

Flächenpressung 1000 N/cm²

Friction

friction factors in the core





Friction

Impurities in helium circuits

	H_2O	CO_2	H_2	CO	CH_4	N_2	O_2
	cm^3/m^3						
EVO without degasification of sealing oil	< 0.1	20	2	2	< 0.5	240	20
EVO with degasification of sealing oil	15	1.4		5.5	< 0.5	8	< 0.1
EVO after a 2-week operation of the main circuit without He-purification operation	15	22.5		22	13	177	1
AVR Juelich *	0.1	0.5	30..50	125	0.4	20	
Dragon *	0.05	0.02	0.5	0.4	0.05	0.6	
Specified impurity limits of HHT *	5	1	50	50	5	5	0

* Radioactive impurities are not included

Friction

Metallic internals of THTR

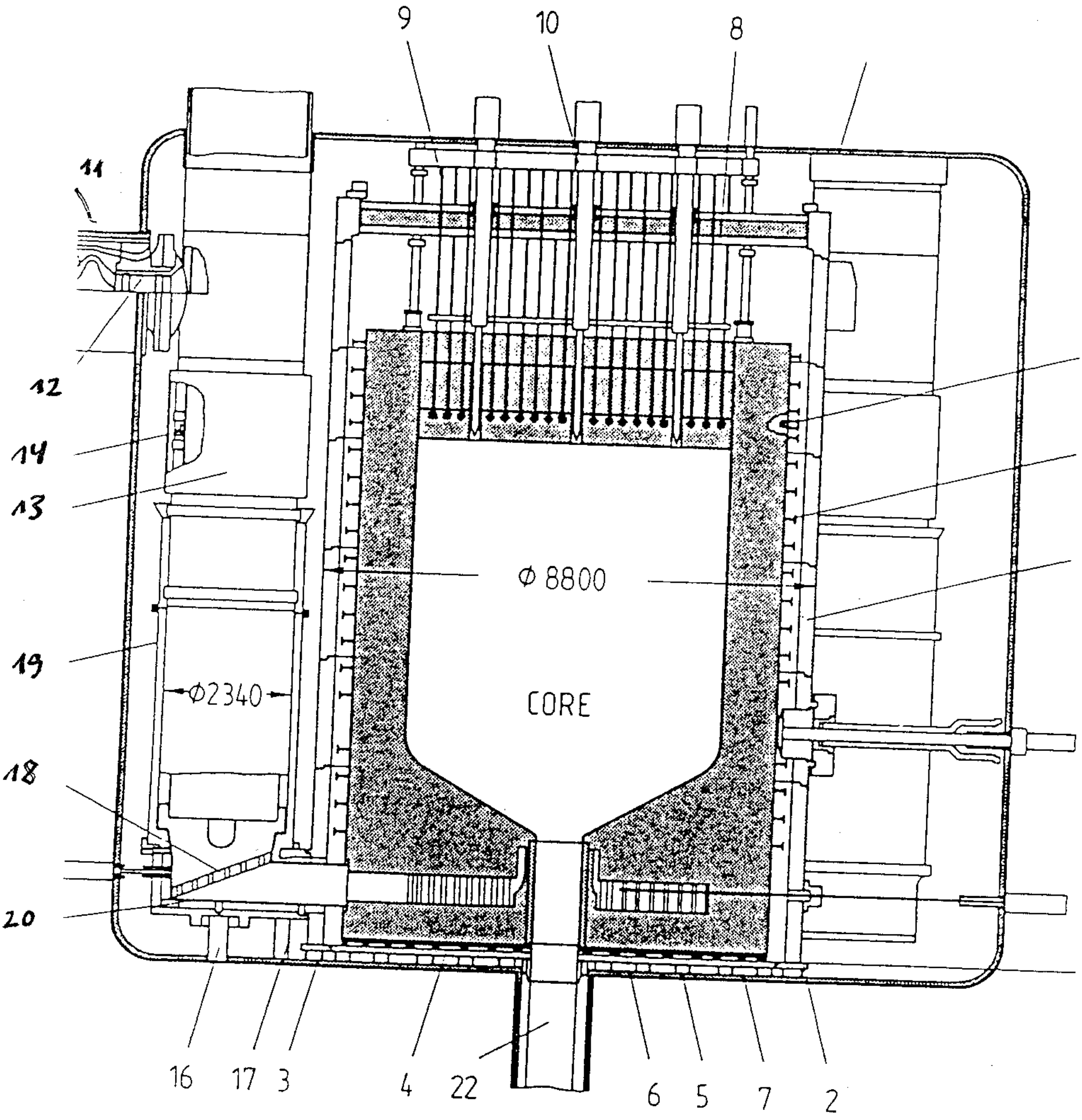
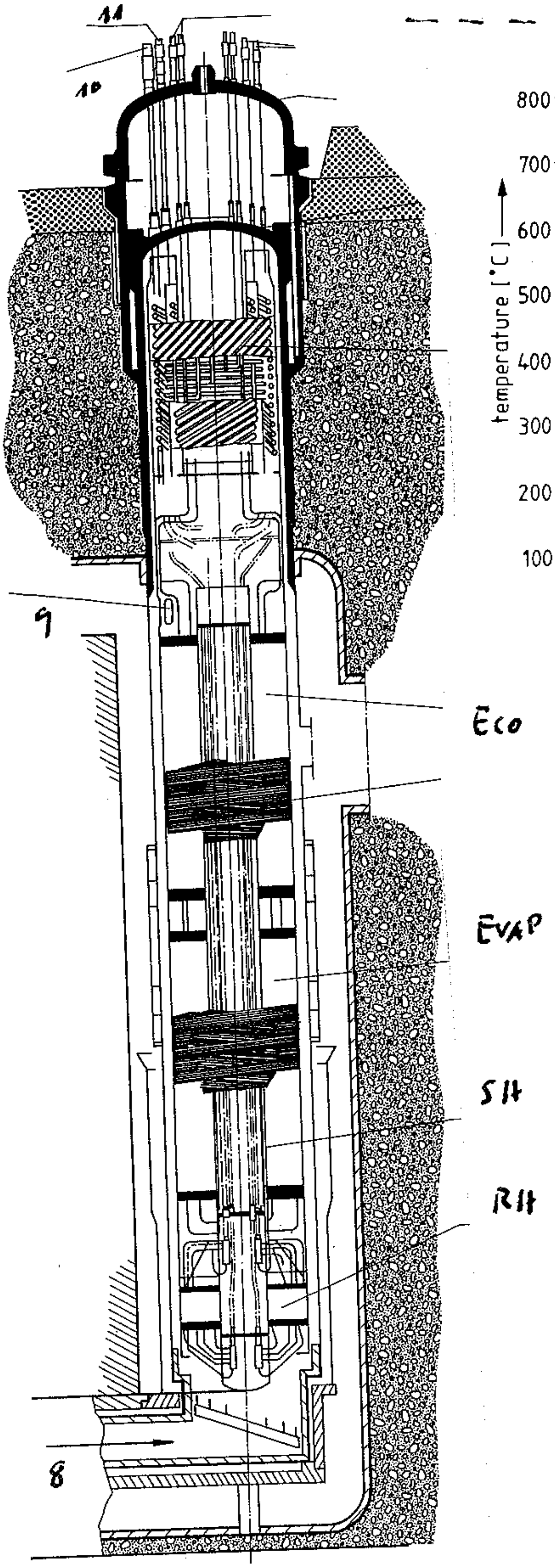
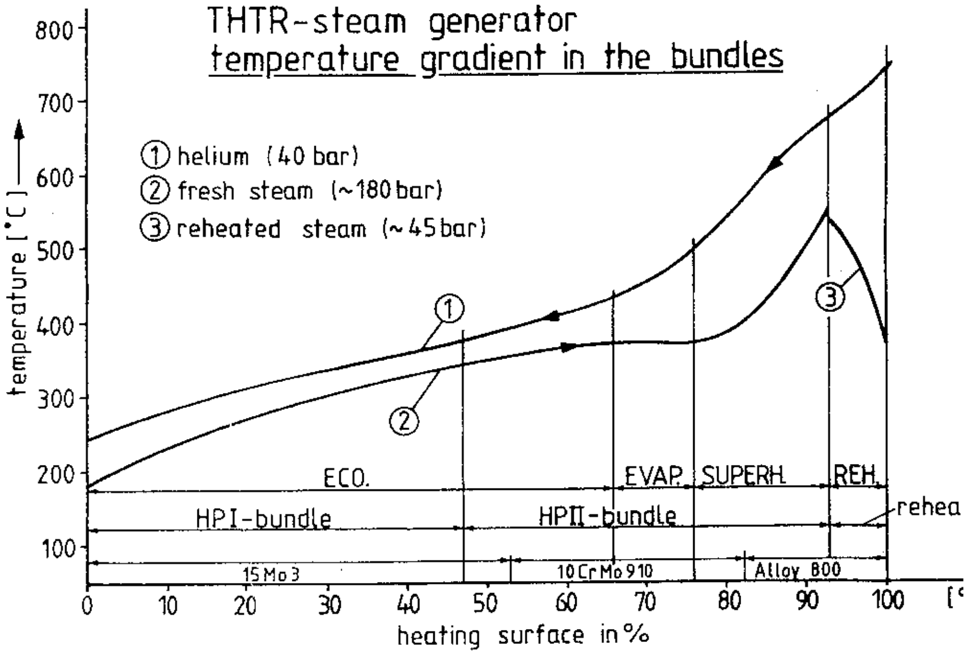


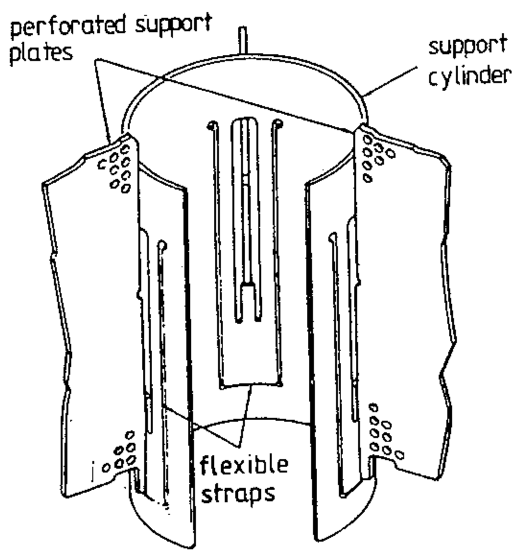
Abb. 4.27: Übersicht über die metallischen Coreeinbauten des THTR:
1. thermischer Schild, *2.* Bodenplatte, *3.* Doppelrollenlager, *4.* untere Bodenplatte, *5.* Rollenlager, *6.* Bodenplatten, *7.* Doppelrollenlager, *8.* thermischer Deckenschild, *9.* Zugstangen, *10.* Tragringe, *11.* Gebläseabschirmungen, *12.* Saugleitungen, *13.* Dampferzeugermäntel, *14.* Dichtelemente, *15.* Heißgaskanal, *16.* Fixpunkt, *17.* Doppelrollenlager, *18.* Lochplatte, *19.* Kaltgasführungsmäntel, *20.* Stützbolzen, *21.* Verdrehsicherung, *22.* Kugelabzugsrohr, *23.* Liner

Friction

THTR - steam generator



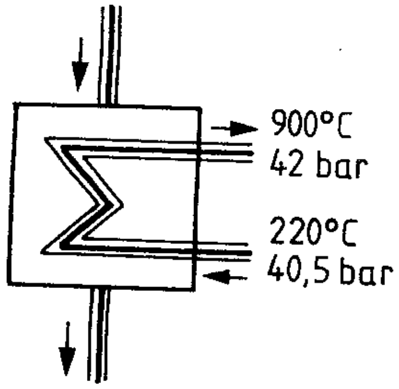


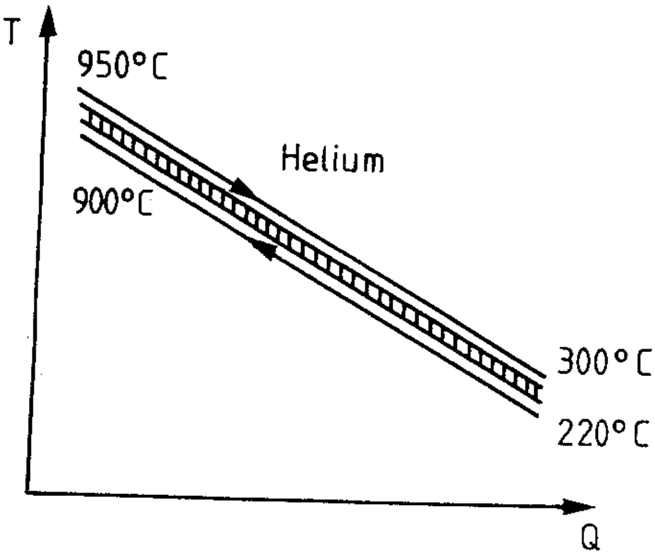


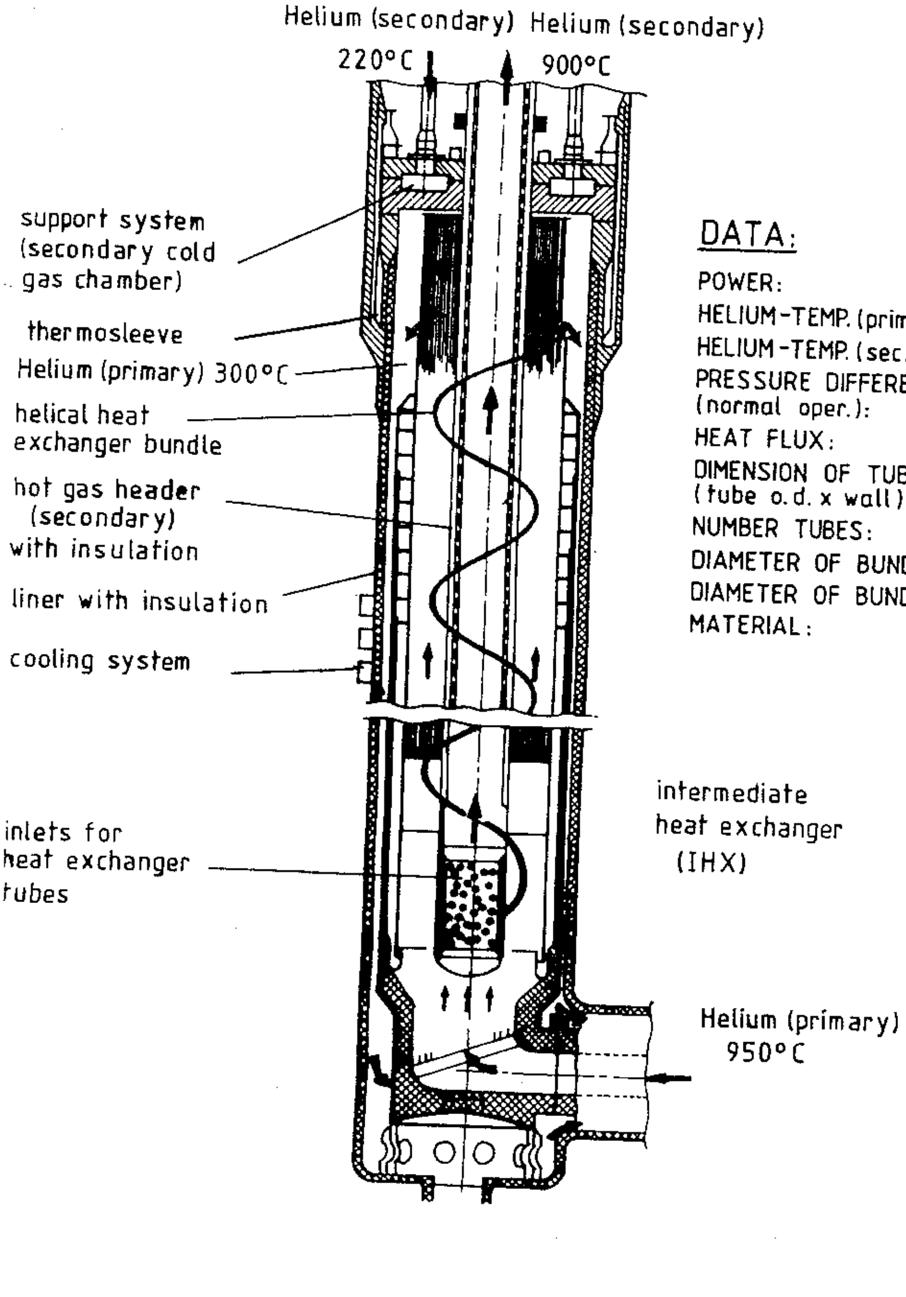
HELIUM FLOW RATE:	49,4 kg/s
HELIUM TEMP. INLET:	750°C
HELIUM TEMP. OUTLET:	250°C
HELIUM PRESSURE:	38,5 bar
PRESSURE DROP:	0,4 bar
FRESH-STEAM RATE:	155 t/h
FRESH-STEAM TEMP.:	530°C
FRESH-STEAM PRESSURE:	177,5 bar
REHEATER-STEAM TEMP.:	530°C
REHEATER-STEAM PRESSURE:	46,5 bar
FEEDWATER-TEMP.:	180°C
WEIGHT:	65 t
LENGTH:	19 m
DIAMETER:	2 m

Friction

Coatings for IHX-tubes





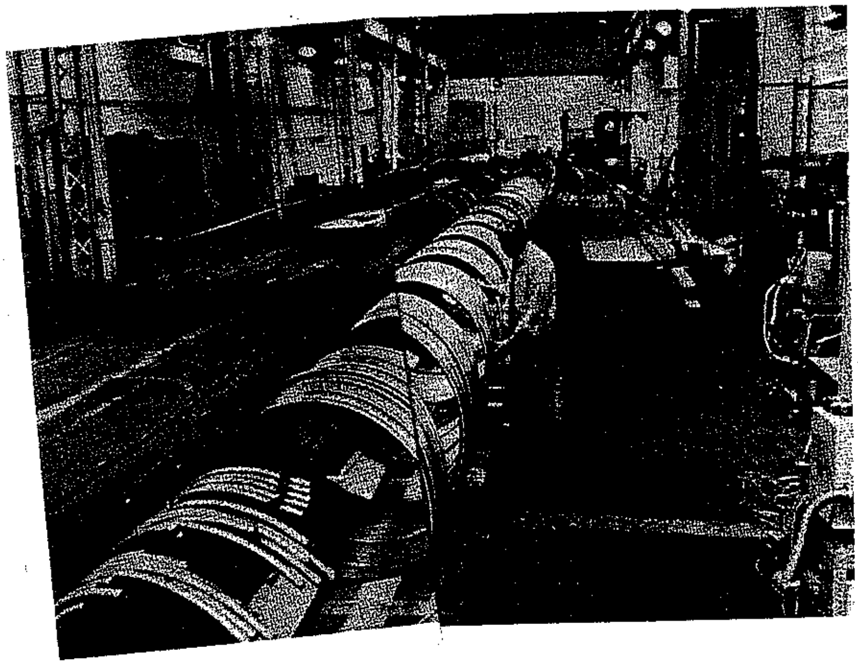


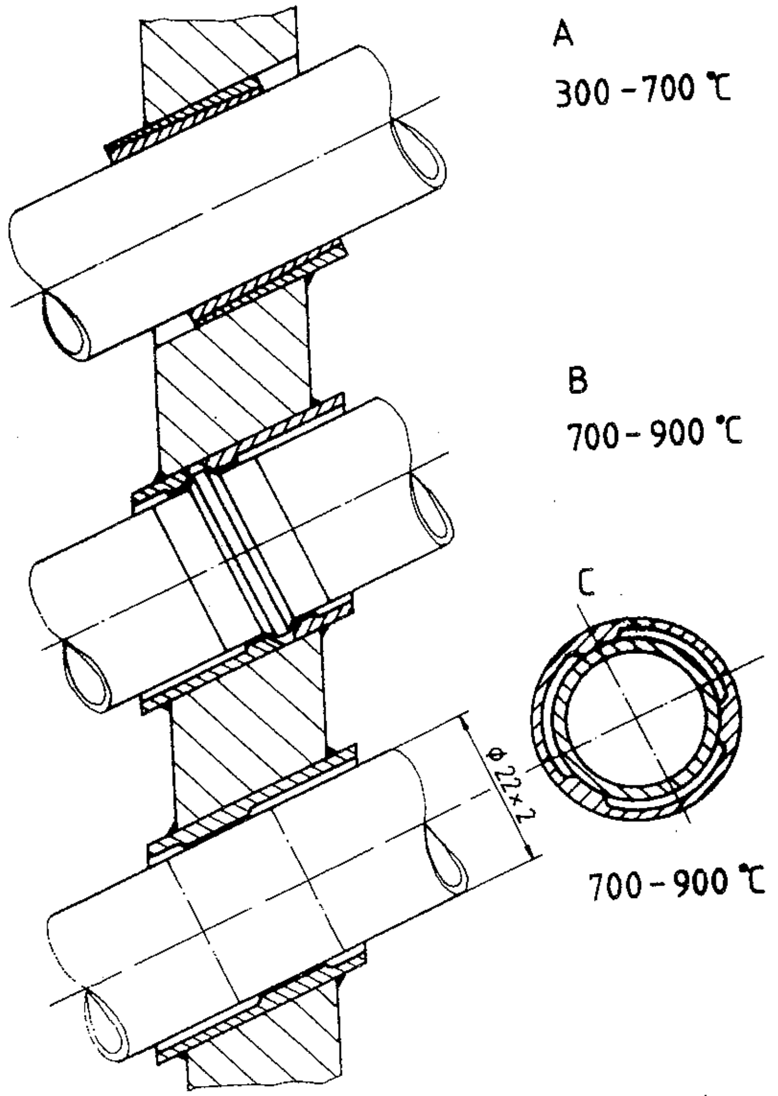
DATA:

POWER:	125 MW
HELIUM-TEMP. (prim.):	950 → 300°C
HELIUM-TEMP. (sec.):	220 → 900°C
PRESSURE DIFFERENCE ACROSS WALL (normal oper.):	~1 bar
HEAT FLUX:	29,4 kW/m²
DIMENSION OF TUBES (tube o.d. x wall):	22,4 × 2,25 mm
NUMBER TUBES:	1660
DIAMETER OF BUNDLE (outer):	2500 mm
DIAMETER OF BUNDLE (inner):	1080 mm
MATERIAL:	INCONEL 617

Friction

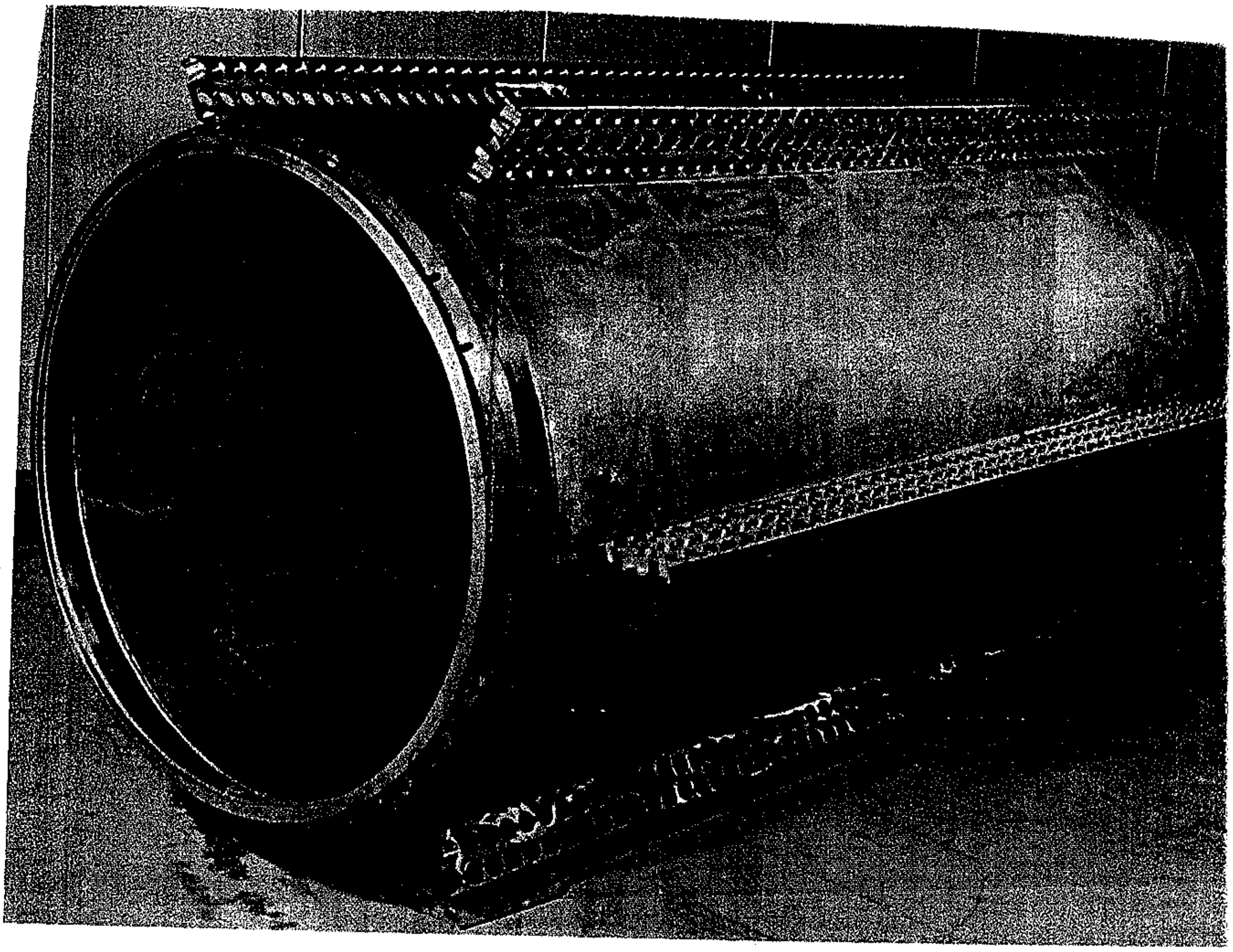
tube sheet assemblies

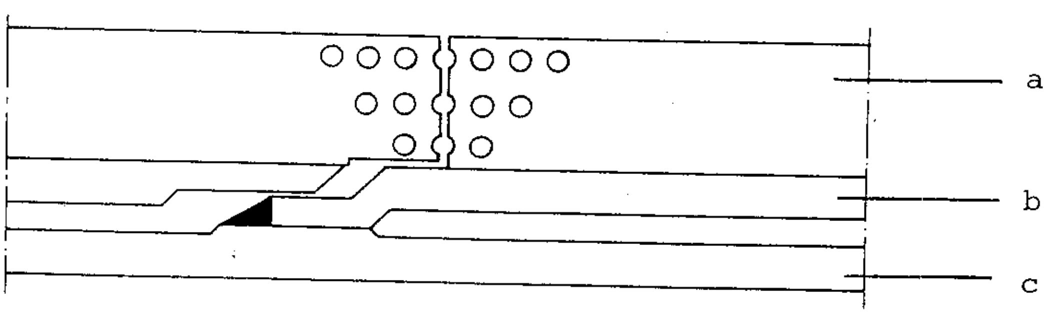




Friction

Supporting structure for IHX-tubes

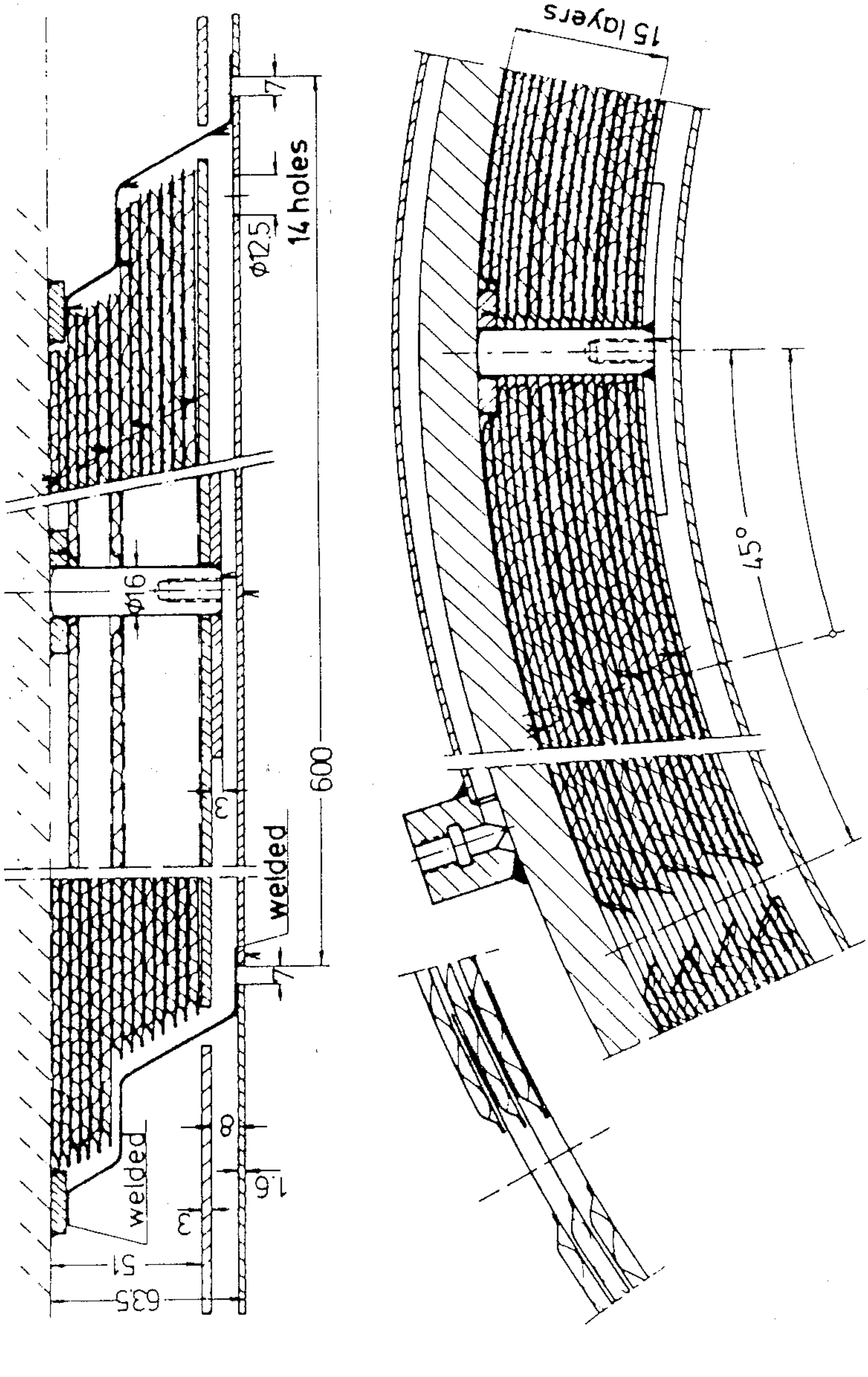




a) supporting plates with borings
b) Supporting cylinder
c) Hot gas return duct

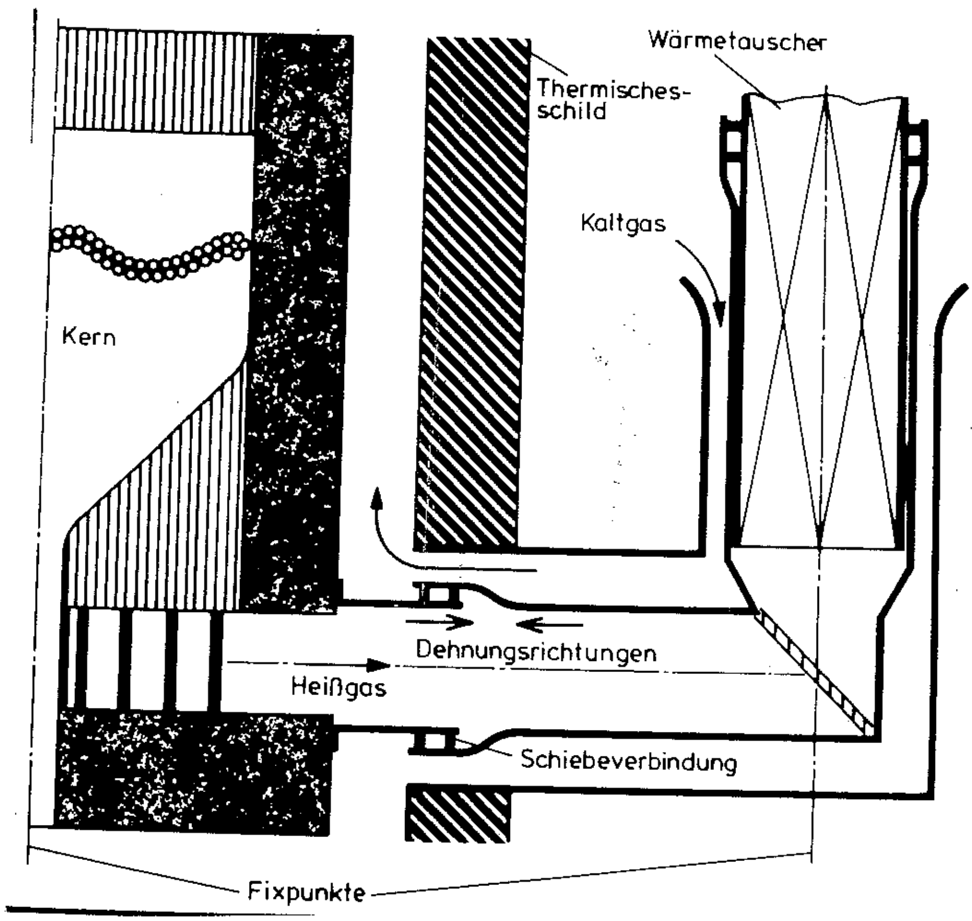
Friction

Metallic foil insulations

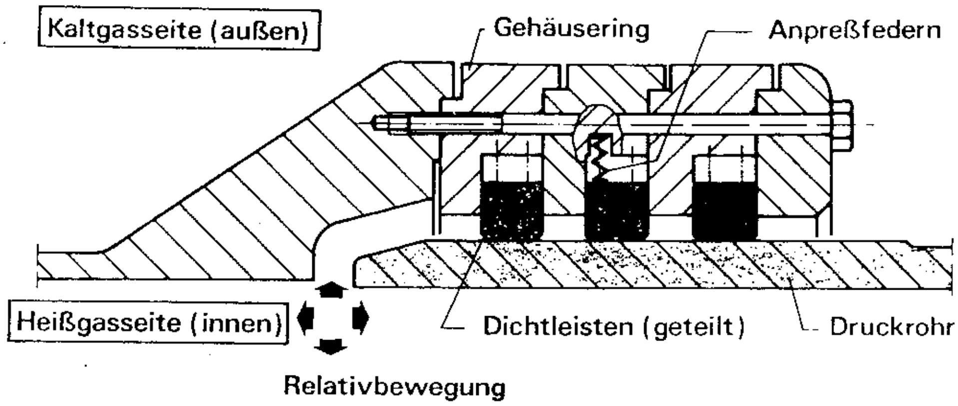


Friction

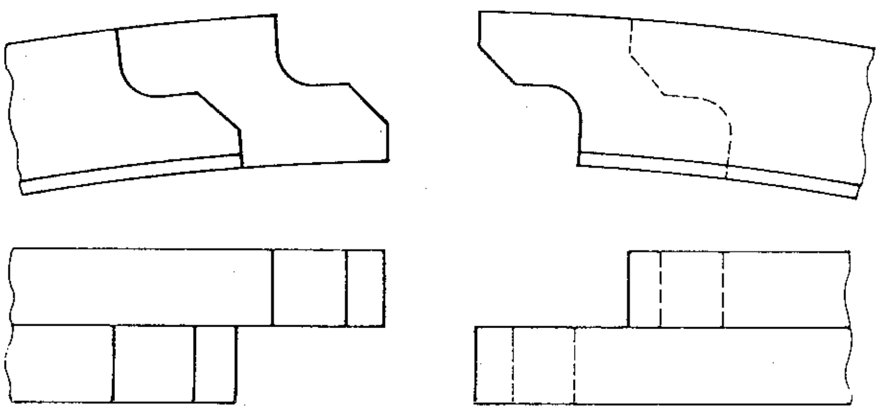
Hotgas connection



Principle of connection between Core and hotgas duct

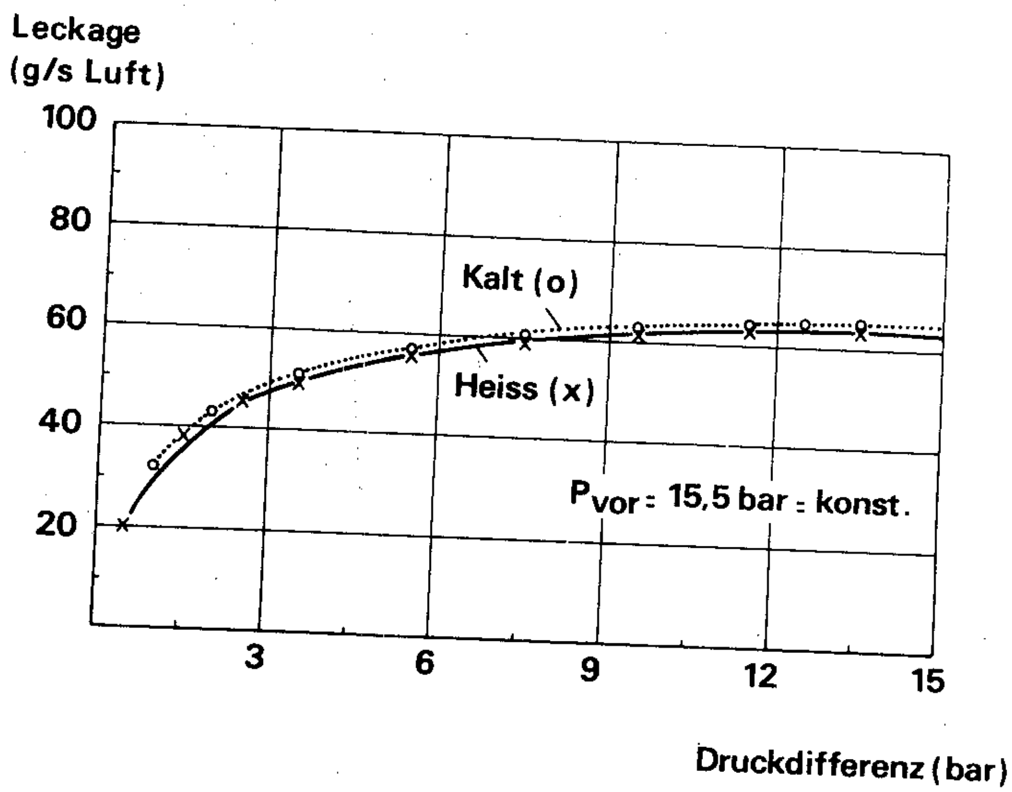


Detail of connection

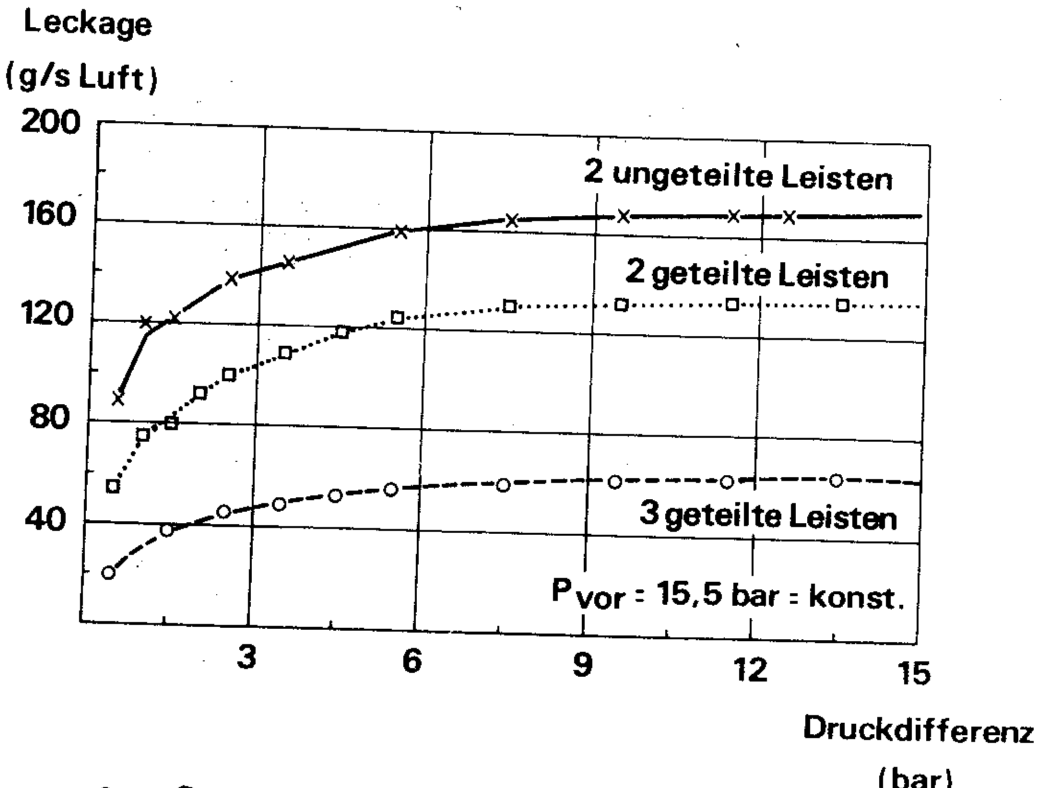


Friction

leckage at connections



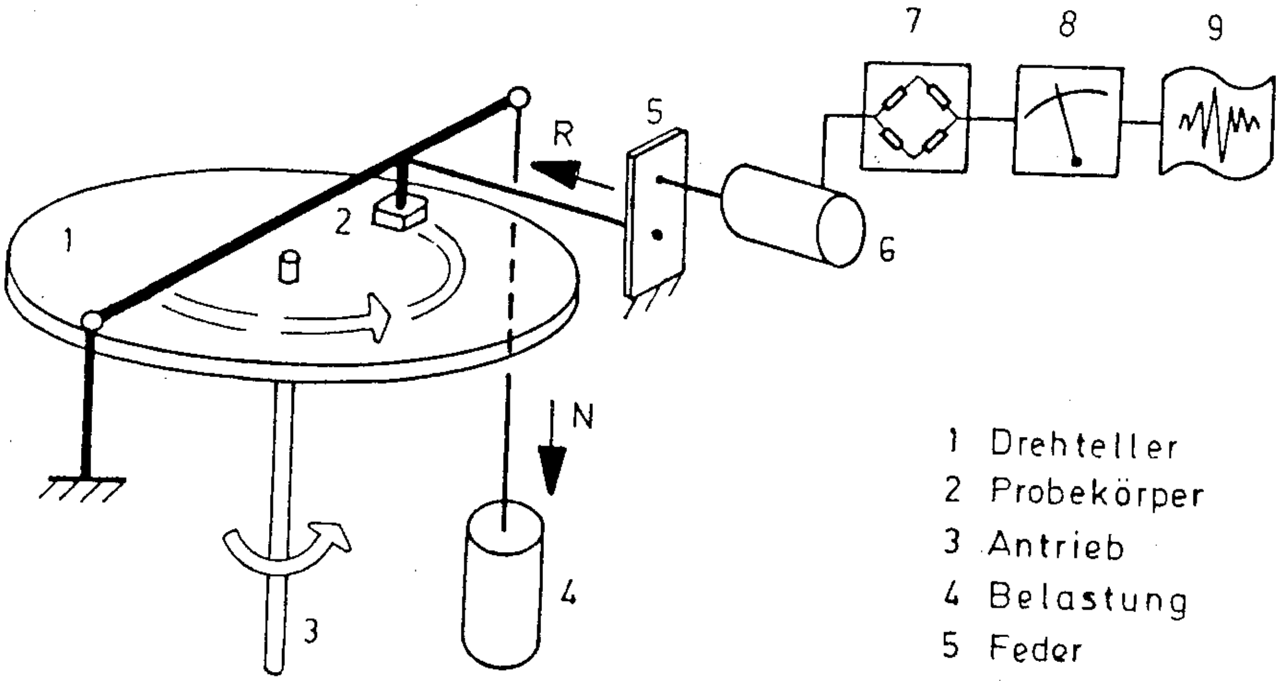
Influence of change „hot/cold" on leckage



Influence of number and geometry of elements on leckage

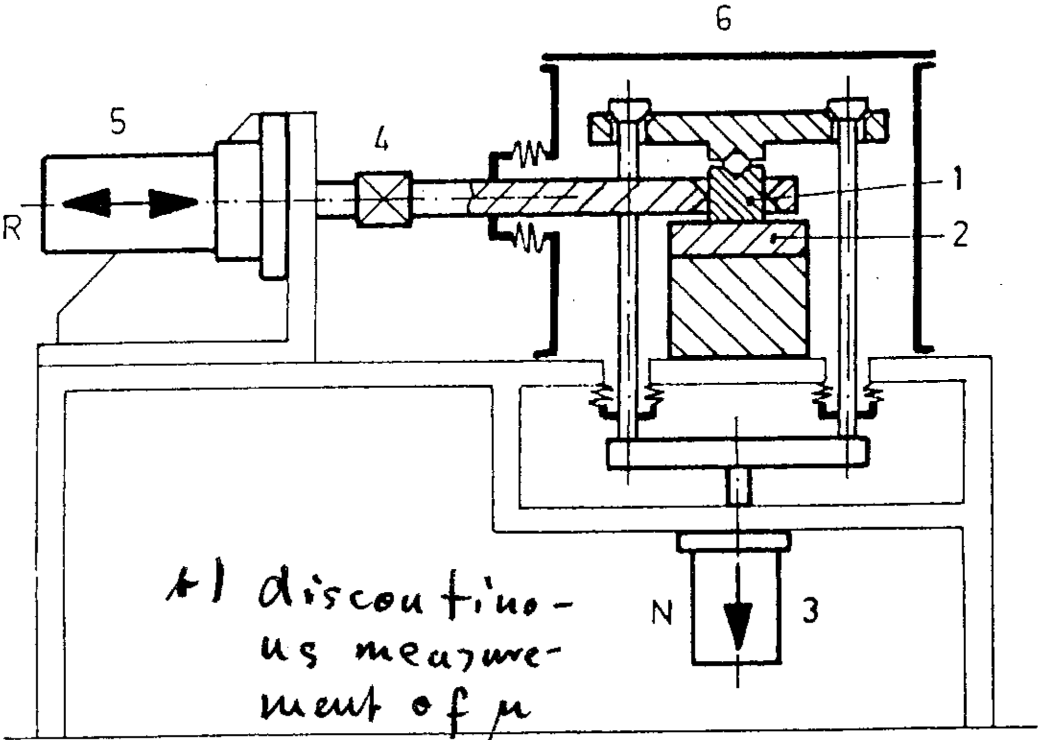
Friction

test facilities



1 Drehteller
2 Probekörper
3 Antrieb
4 Belastung
5 Feder
6 induktiver Wegaufnehmer
7 Meßbrücke
8 Anzeige
9 Schreiber

a) continous measurement of μ



1 Reibkörper
2 Auflage
3 Hydraulik f. Normalk
4 Kraftmeßdose mit Kompensationsschre
5 Hydraulik f. Reibkra
6 gasdichte Umhüllun

b) discontinous measurement of μ

Friction

results of measurement

Temp [°C]	Werkstoff - paarung	Reibkoeffizient μ (0,5 … 1,0)	Reibweg [m]	Flächenpressung [N/cm²]	Reibgeschw. [cm/min]
20	St 37,2 / St 37,2		4,2	1960	0,1
330	X 10 Cr Ni Ti 189 / X 10 Cr Ni Ti 189		300	50	1320
330	X 10 Cr Ni Ti 189 / (verchromt) X 10 Cr 13		300	50	1320
330	31 Cr Mo V9 (nitriert) / 31 Cr Mo V9		300	50	1320

Tab. 5.1 Reibwerte in Luft

He-Atmosphäre, Zus. A (O_2, H_2, H_2O < 2 Vpm)
B (CO=60, H_2=60, CO_2=6, CH_4=6, H_2O=6, N_2=5 Vpm)
C (CO, H_2, H_2O, N_2 < 20 Vpm)

*) kf = flächenzentriert
kr = raumzentriert

Temp. [°C]	Werkstoff - paarung	Reibkoeffizient μ (0,5 … 1,0 … 1,5)	Reibweg [m]	Flächen-pressung [N/cm 2]	Reibge-schw. [cm/min]	Kristall-struktur *)	Atmos-phäre
20	GG 22 / 31 Cr Mo V9		0,5	400÷800	1	kr	A
20	C 22 / C 22		62,2	11÷69	22,2	kr	C
200	Incoloy 800 / Incoloy 800		0,03	5000	0,2	kf	B
260	GG 22 / 31 Cr Mo V9		0,5	400÷800	1	kr	A
300	21 Cr Mo V511 / 21 Cr Mo V511		2	60	3,7	kr	A
330	X 10 Cr Ni Ti 189 / X 10 Cr Ni Ti 189		300	50	1320	kf	A
400	C 22 / C 22		62,2	11÷69	22,2	kr	C
400	10 Cr Mo 910 / X 105 Cr Mo 17		62,2	172,5	22,2	kf	C
500	GG 26 / 31 Cr Mo V9		150	13	42	kr	C
500	GG 26 / 15 Mo 3		150	13	42	kr	C
540	10 Cr Mo 910 / 10 Cr Ni Al Ti 3220		62,2	69	22,2	kf	C
600	GG 26 / 13 Cr Mo 44		50	15	2	kr	B
850	GG 26 / 13 Cr Mo 44		50	15	2	kr	B

Tab. 5.2 Reibwerte in He für verschiedene Gleitpaarungen

Werkstoffpaarung: Grund-werkstoff	Zwischen-schicht	Beschichtung	Reibkoeffizient μ bei Temp. 200°C	400°C	600°C	800°C	Reibweg [m]	Flächen-pressung [N/cm²]	Reibge-schw. [cm/min]	Atmos-phäre
Inconel 625	Ni 80% Cr 20% 30 μm dick	Cr_3C_2+10% NiCr / Cr_3C_2+10% NiCr (Plasmaverf.)	0,71	0,73	0,71		5	1000	0,1	B
Inconel 625	Ni 80% Cr 20% 30 μm dick	Al_2O_3 / Al_2O_3 (Plasmaverf.)	0,58	0,54	0,68	0,76	5	1000	0,1	B
Inconel 625	—	Al_2O_3+2% Cr_2O_3 / Al_2O_3+2% Cr_2O_3 (Plasmaverf.)	0,83	0,89	1,11	1,23	5	500	0,1	B
Inconel 625	—	TiC / TiC (CVP-Verf.)	0,29	0,30	0,53	0,75	5	500	0,1	B

Tab. 5.3 Reibwerte von keram. Beschichtungen in He in Abhängigkeit von der Temp.

Friction

results of measurements

Temp. [°C]	Werkstoffpaarung	Reibkoeffizient μ 0,5	Reibweg [m]	Flächenpressung [N/cm]	Reibgeschw. [cm/min]	Atmosphäre
200	31CrMoV9-nitriert / 31CrMoV9-nitriert		300	250	1320	A
220	H II / Incoloy 800 Cr_3C_2		100	200	0,5	B
260	GG 22 / X8CrNiMoNb 1616-Cr_3C_2		120	100	1320	B
260	GG 22 / X8CrNiMoNb 1616-WC		400	100	1320	B
260	GG 22 / X8 CrNiMoNb 1613 hart verchromt		400	100	1320	B
260	GG 22 / 31CrMoV9-nitriert		400	10	1320	B
300	21CrMoV511-pentr. / 21CrMoV511-pentr.		2	60	3,7	A
300	21CrMoV511-pentr+nitr. / 21CrMoV511-pentr+nitr.		2	60	3,7	A
330	X10CrNiTi 189-verchromt / X 10 Cr 13		300	50	1320	A
330	31CrMoV9-nitriert / 31CrMoV9-nitriert		300	50	1320	A
500	HII / Incoloy 800-Cr_3C_2		2	5000	0,2	B
700	Inconel 625-Cr_3C_2 / Inconel 625 Cr_3C_2		5	1000	0,1	B
750	Inconel 625 Al_2O_3 / Inconel 625 Al_2O_3		5	1000	0,1	B
825	Hartmetall P30-TiC / Hartmetall P30-TiC		60	9000	0,1	B
850	Hastelloy C-276-Ni Ag / Incoloy 800-Cr_3C_2		43	100	0,5	A
850	P30-Ti + A_2O_3 / Incoloy 800		10	1500	0,5	A
950	Inconel 625-TiC / Inconel 625-TiC		5	500	0,1	B

Tab. 5.4 Reibwerte in He für beschichtete Gleitpaarungen

R_t	Reibwert für Haftreibung: Luft 25°C	He (O_2, H_2, H_2O, <6 Vpm) 25°C	He (O_2, H_2, H_2O, <6 Vpm) 300°C
7	0,31	0,38	0,38
15	0,26	0,36	0,30
27	0,39	0,33	0,34

Tab. 5.5 Reibwert in Abhängigkeit von der Rauhtiefe für die Werkstoffpaarung GG 22 / 31 Cr Mo V9 nitriert

Friction

results of measurements

MoS_2-Gleitlack 321 R in Luft, 250°C
Reibgeschw. 1 mm/min Reibweg 0,25 m

Werkstoff	Rauhtiefe R_t /µm/	8			16			30		
	Belastung /N/	1470	1960	2450	1470	1960	2450	1470	1960	2450
St 37.2/ St 37.2	Reibwert µ (Mittelwert)	0,122	0,097	0,088	0,107	0,083	0,10	0,122	0,123	0,099
4541/ 4541		0,136	0,110	0,109	0,132	0,107	0,088	-	-	-

ab. 5.6 Reibwerte von MoS_2 beschichteten Werkstoffen bei verschiedener Belastung und Rauhtiefe

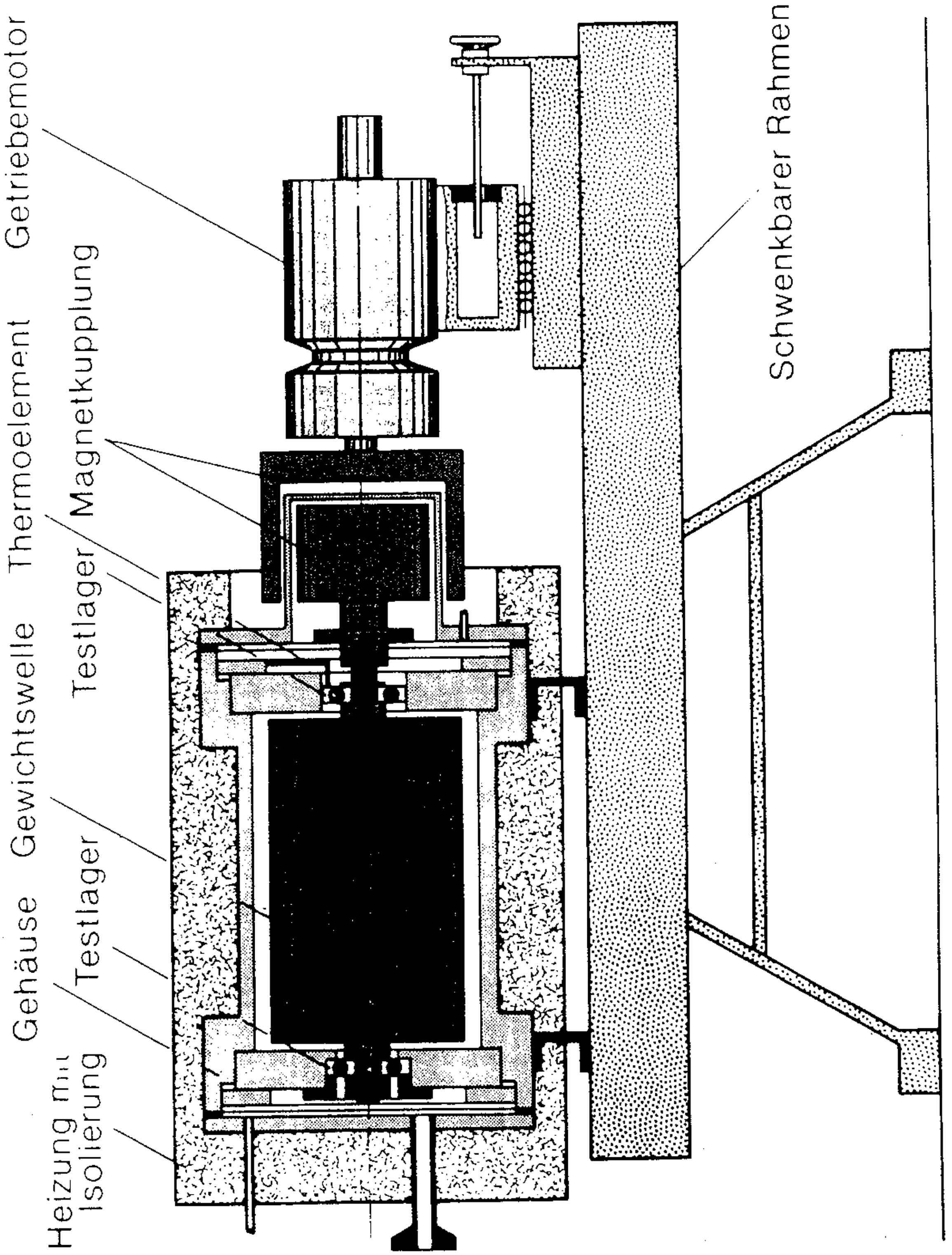
MoS_2-Gleitlack 321 R in Luft, 250°C
Reibgeschw. 1 mm/min Belastung 1960 N
Reibweg 0,25 m

Werkstoff	Rauhtiefe R_t /µm/	3	16			100
	mech. Bearbeitung	Schleifen	Hobeln =	Hobeln #	Sandstrahlen	Hobeln #
St 37.2/ St 37.2	Reibwert µ (Mittelwert)	0,112	0,144	0,134	0,083	0,102
4541/ 4541		0,104	0,109	0,152	0,075	0,120

ab. 5 7 Reibwerte von MoS_2 beschichteten Werkstoffen bei unterschiedlicher Rauhtiefe und verschiedener mechanischer Bearbeitungsverfahren

Friction

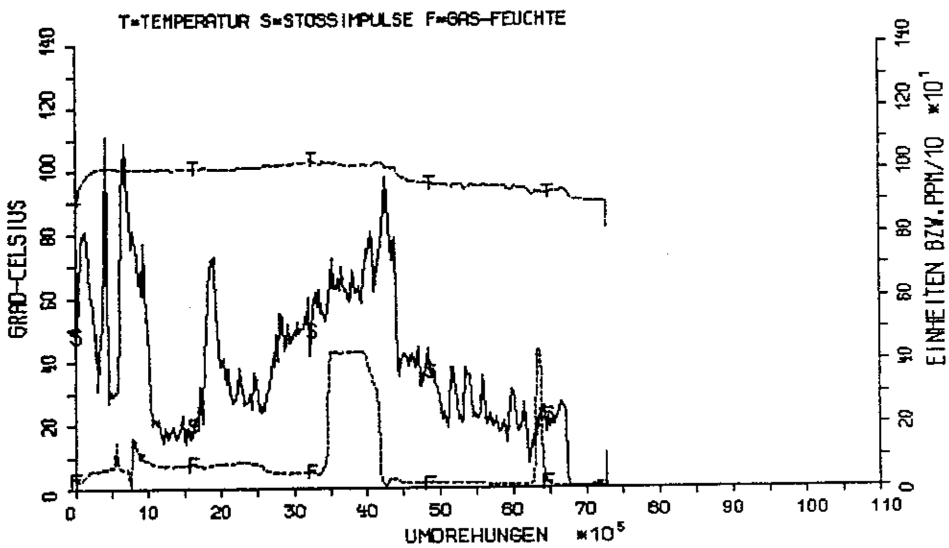
test facility for bearings



Friction

Test on bearings

Versuchsnummer 14, Lagernummer 5718



$=6{,}7.10^6$

$=1200$

n $=7{,}9923$

$=0{,}0012$

Rundheitsabweichungen:

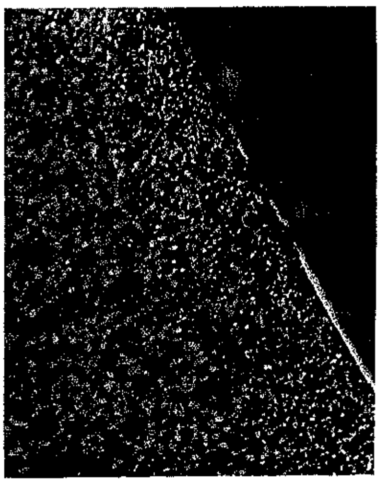
		gnA	gpA	RF	RA
	I	3	4	76	2
IR	II	4	4	76	1
	III	5	4	76	2,5
	I	16	20	–	–
AR	II	16	22	–	–
	III	17	30	–	–

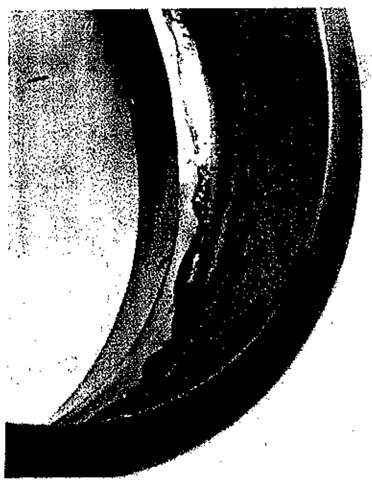
Härtewerte:

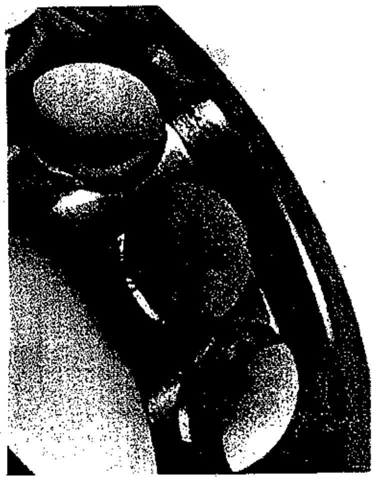
	Grund-material	Rand-zone
Kugel	1890 HV 0,2	1827 HV 0,2
Käfig	101 HV 0,05	154 HV 0,05
IR	912 HV 0,05	1011 HV 0,05
AR	981 HV 0,05	1031 HV 0,05

Grund für Versuchsende, Besonderheiten:

- Abbruch des Versuches wegen Klemmen am Lager 5719
- Duraloy - Schicht zerstört, Rattermarken auf dem Außenring

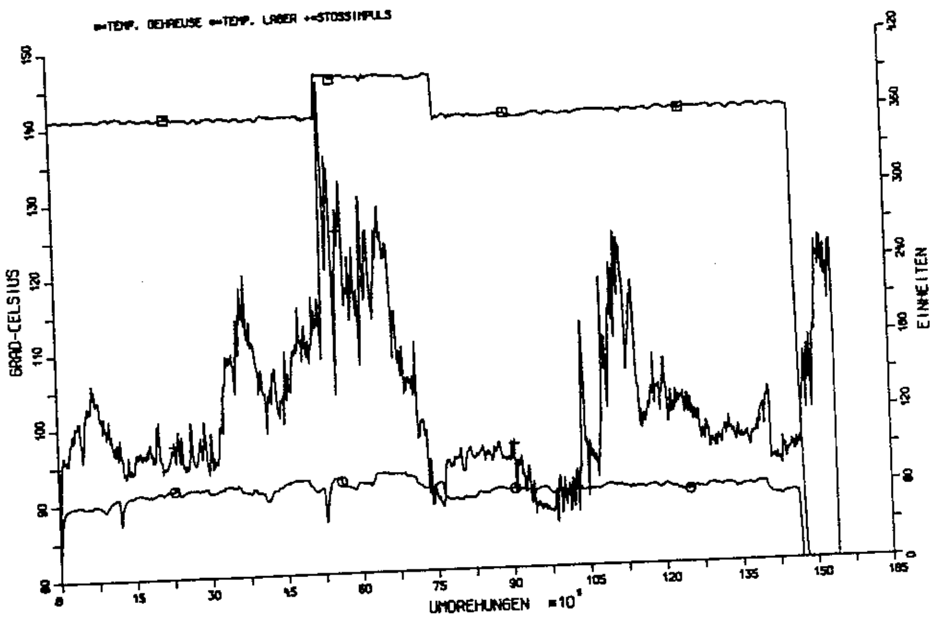






Friction test on bearings

Versuchsnummer 3, Lagernummer 5688



n = 1,5.10^7
i = 400
d_m = 7,9967
m = 0,0006

Rundheitsabweichungen:

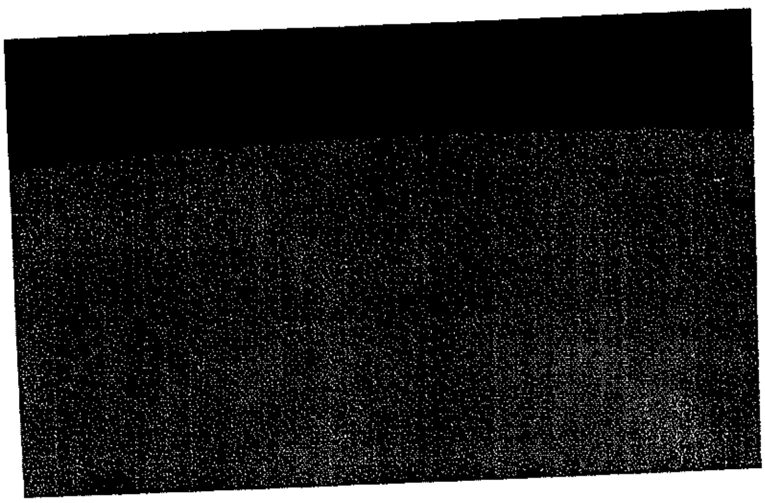
		gnA	gpA	RF	RA
	I	6	12	240	1,5
IR	II	5	6	unregelm.	
	III	2	4	"	
	I	10	9	-	-
AR	II	3	2	-	-
	III	2	2	-	-

Härtewerte:

	Grund-material	Rand-zone
Kugel	1063 HV 0,05	-
Käfig	-	-
IR	843 HV 0,05	-
AR	840 HV 0,05	-

Grund für Versuchsende, Besonderheiten:

- Geforderte Spielzahl erreicht
- keinerlei Veränderungen an den Kugeln



Friction test facility Hetrix I

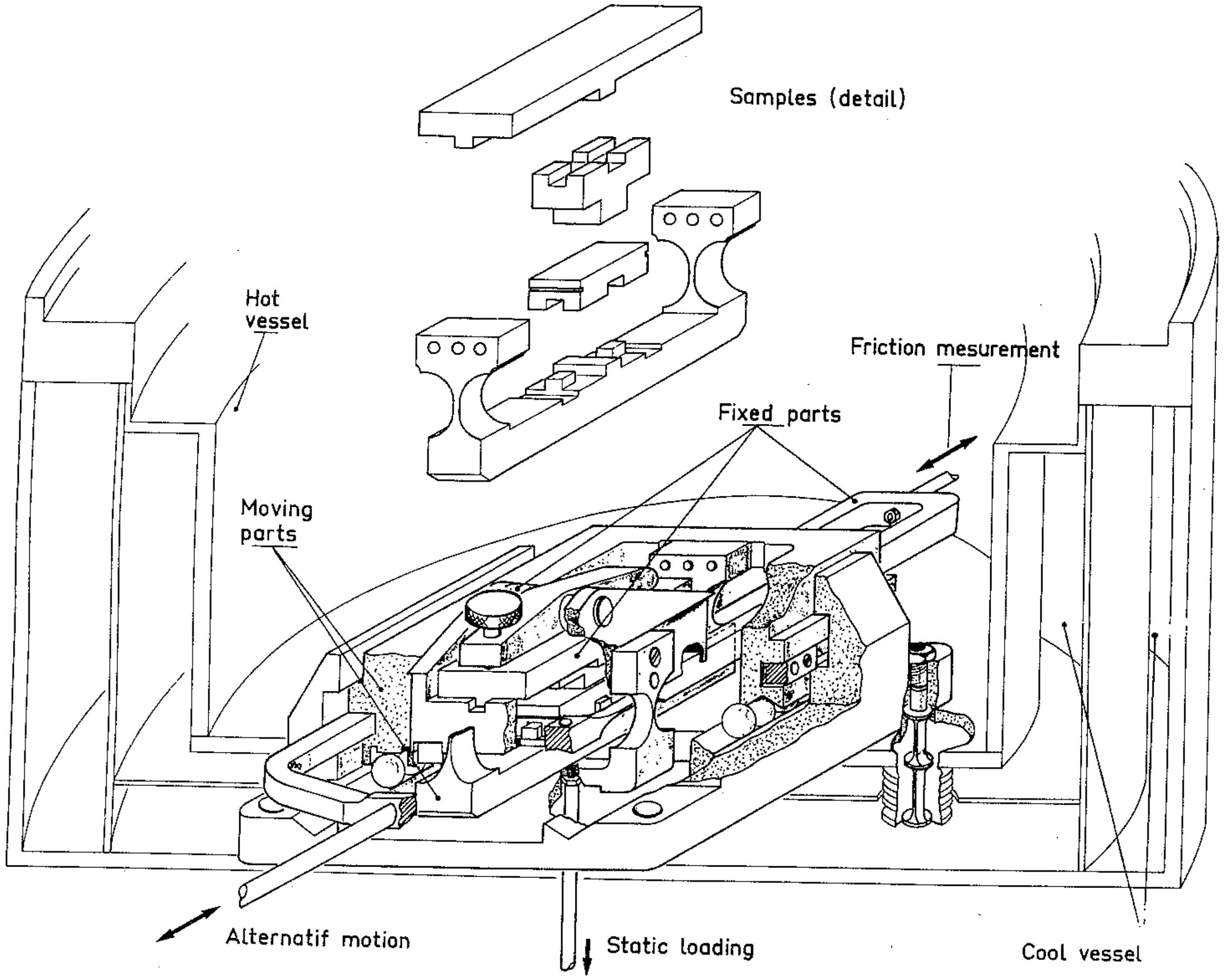


Fig. 5. Tribometer "HETRIX 1" sample holding unit

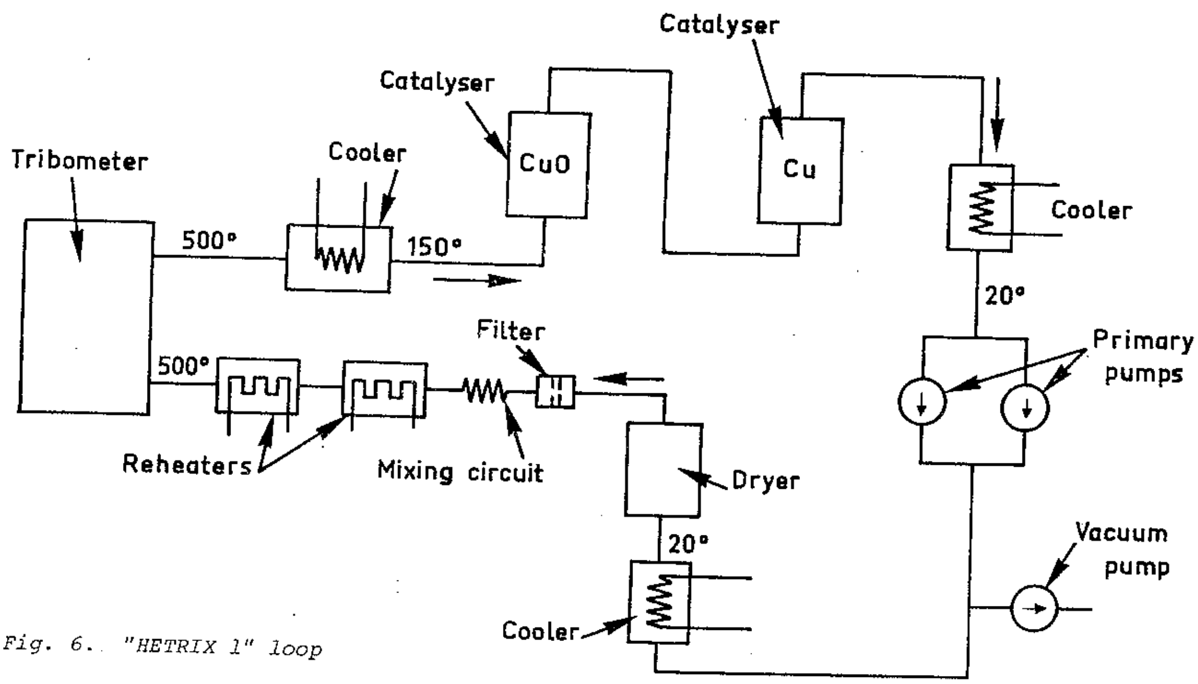


Fig. 6. "HETRIX 1" loop

Friction

HECO 1 - loop for gas conditioning

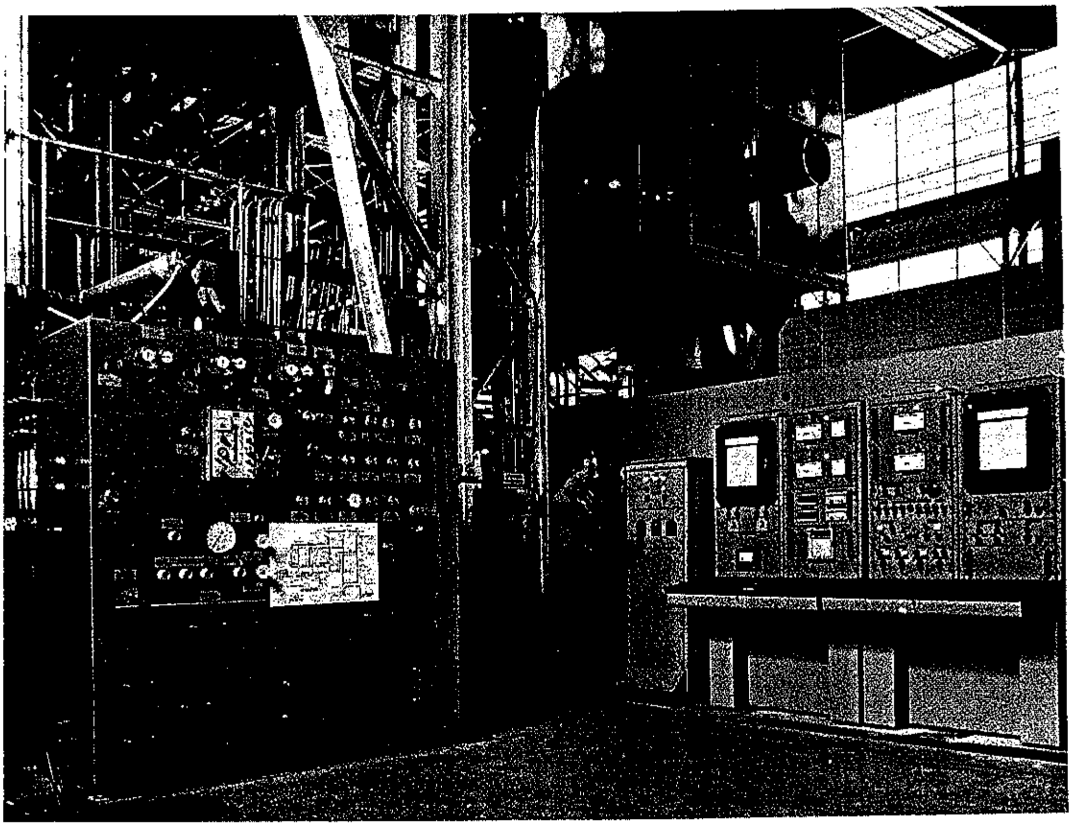
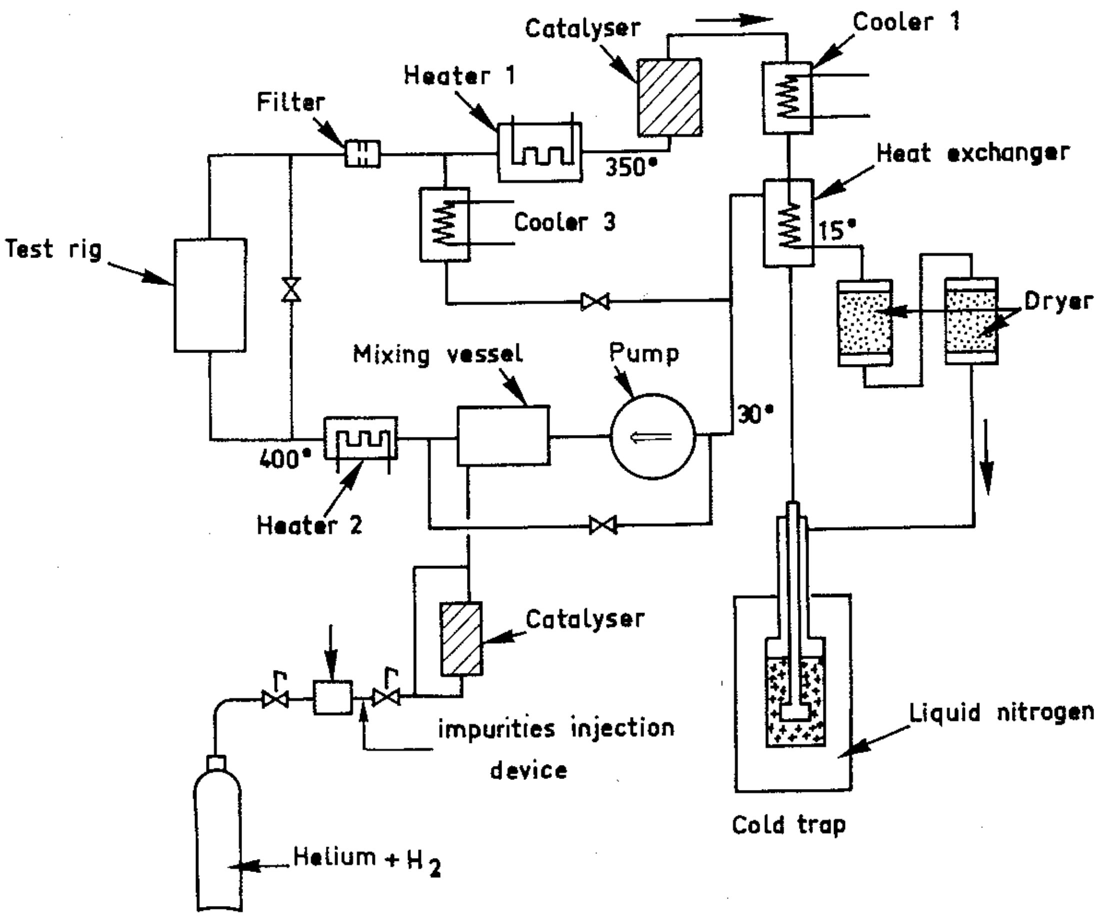
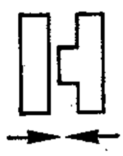


Fig. 7. "HECO 1" loop - general view



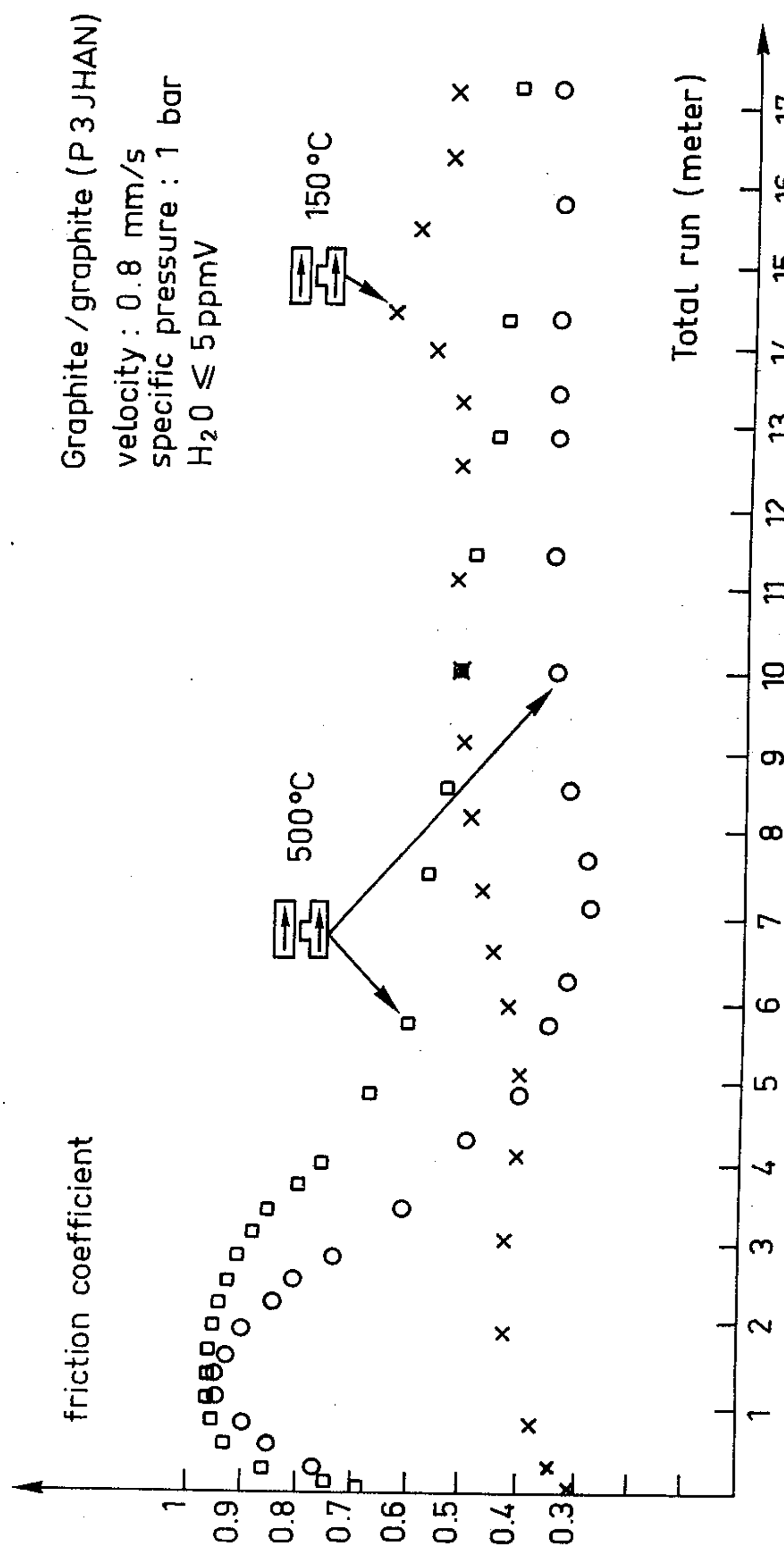
Friction

friction tests on grafit / grafit
(P3 ƎHAN)

Test condition	Friction coefficient								
	500°C			325°C			150°C		
	static	mini	max	static	mini	max	static	mini	max
	0.7	0.4	0.9	0.3	0.3	1	0.4	0.2	0.7
	0.7	0.7	1	0.3	0.3	1.2	0.3	0.3	0.3
Extruding direction	0.7	0.3	1	0.3	0.3	1.2	0.3	0.3	0.5
load : 1 bar	0.6	0.3	0.9				0.3	0.3	0.5
velocity : 0.8 mm/s							0.3	0.3	0.5
H_2O <10 ppmV									
Extruding direction	0.4	0.4	0.6	0.3	0.3	0.8	0.4	0.2	0.7
	0.3	0.3	0.6	0.3	0.3	0.8	0.3	0.3	0.8
	0.4	0.4	0.7	0.4	0.4	0.4			
Load : 8 bars				0.2	0.2	0.7			
velocity : 0.24 mm/s									
H_2O < 10 ppmV									

Friction

friction coefficient grafik / grafit



Past tribological experience from UK gas cooled reactors useful for VHTR

B F Riley

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1.0 SUMMARY

This report summarises experience gained in the UK during the test programmes for, and operation of, the Dragon and AGR reactor systems. It is the input to a technological review being carried out within SP CT Work package 3 of the RAPHAEL-IP. Tribological problems associated with both reactor systems are highlighted, and coatings solutions are presented. Coatings and coating performance have been reviewed. The tribology of graphite/graphite, graphite/metal and metal/metal surfaces has been addressed.

Static adhesion was not found to be a problem in helium at temperatures below 650°C. Above 650°C (like on like) tests showed varying levels of adhesion in metal/metal contacts, depending on the materials. For the tests reviewed there was no significant systematic effect of gas pressure on static adhesion, friction or wear. In general wear rates increase with increasing helium purity and for reactor helium, at 20 bar gas pressure, friction coefficients were highly dependent upon the moisture level in the gas. There was little wear in graphite to graphite contacts in helium at elevated temperatures. Surface treatments incorporating molybdenum disulphide found successful application on the Dragon Reactor and Detonation-Gun coating LC-1B has found widespread good operation in AGRs below 650°C, and where this was not feasible plasma sprayed LC-2 was employed.

2.0 INTRODUCTION

This report summarises experience gained in the UK during the test programmes for, and operation of, the Dragon and AGR reactor systems as input to a technological review being carried out within SP CT Work package 3 of the RAPHAEL-IP. Tribological problems associated with both reactor systems are highlighted, and coatings solutions are presented. Coatings and coating performance have been reviewed. The tribology of graphite/graphite, graphite/metal and metal/metal surfaces has also been addressed.

Some conclusions with relevance to VHTR and associated test work have been made.

This document contains the results of work at NNC on Deliverable D-CT 3.2 of the RAPHAEL Project.

3.0 REVIEW OF DRAGON AND HELIUM-COOLED HTR

3.1 Introduction

Frictional forces and wear (adhesive and fretting) in a helium-cooled reactor occur as a consequence of the insertion and withdrawal of reactor components and fuel, during the operation of mechanisms, as a result of rubbing caused by relative motion during temperature transients, and as a result of gas flow or noise-induced vibrations. The adhesion of stationary contacting surfaces can also give rise to problems, for example in bearings brought into operation after a period without use. Adhesive wear, fretting and adhesion were recognised as important concerns on the Dragon Project and each phenomenon was the subject of a test programme. Further testing was carried out in support of a planned commercial HTR, cooled by helium.

To a large extent, problems arising from tribological phenomena were designed out of the Dragon Reactor. Mechanisms were often located in cool regions or at the end of dead legs. Wherever possible, temperatures were kept low to reduce adhesion. Nevertheless, many potential HTR problems were identified during the Dragon Project.

3.2 Potential HTR problems highlighted by Dragon

At relatively low temperatures (≤350°C), static adhesion could give rise to problems in the purification plant, piston ring wear could occur in the compressors and peripheral seals could wear as a consequence of thermal movements. Other potential problem areas included the fretting of heat exchanger components, the adherence of insulation covers to underlying foils, the adjustment of circulator inlet guide vanes at gas inlet temperatures, and seizure and wear in valves operating in helium. Many of the problems identified were relevant to the relative movements of contacting surfaces in reactor systems in general. A list of potential HTR tribological problems is presented in Table 1. Some specific components are discussed below.

3.2.1 Fretting of heat exchanger components

Early in the operation of Dragon, waterside corrosion resulted in frequent tube failures in the primary heat exchangers. As a result of the failure investigation, some heat exchangers were redesigned using Incoloy 800 tubes, instead of the original mild steel tubes. Tests were carried out in helium at temperatures in the range 425 – 580°C on the fretting behaviour of the new tubes and En 16 clamps. Under conditions representative of the cooler section of the heat exchanger, the tubes and clamps wore at a similar rate, approximately equal to that of the materials in the original design. In tests representative of the hotter sections, (tube at 200 – 300°C, clamp at 600°C) material was removed from the clamp and deposited on the tube. A similar phenomenon had occurred with the original materials.

3.2.2 The performance of bearings and gears in helium

In Dragon, the bearings and gears of various mechanisms such as the fuel element charge-discharge machine and the control rod mechanism ran inside the pressure vessel. Some were exposed to high temperatures and to appreciable levels of radiation. Programmes of work were carried out to assess the performance of plain and ball bearings, gas bearings and gears under these conditions.

Plain and ball bearings

The majority of plain and ball bearings were operated under light load and at slow speed. Investigations were carried out into the use of ball bearings above the main shield plug, at temperatures of 50 – 100°C, and plain bearings at 350 – 500°C.

Metal, ceramic, plastic, carbon and graphite bearings were all tested Ref 1). The dryness of the helium was found to be critical in governing performance. When the water vapour concentration was greater than 100 vpm most materials ran together without seizure. Although coefficients of friction were in the range 0.5 – 1.0 and sometimes greater, the amount of wear was not excessive. When the water vapour concentration was reduced to below 20 vpm all the materials tested at 350°C either seized almost immediately (metals and ceramics) or wore excessively (carbons and graphite). The only way found to reduce the wear rate was to provide a coating of molybdenum disulphide. At lower temperatures, bearing materials which rely on PTFE for the lubricant were satisfactory. For very light duties, nitrided materials were acceptable. The only satisfactory plain bearing combination found for operation at elevated temperature in pure helium was molybdenum sulphide-treated carbon or graphite operating in conjunction with a fine finished hard material.

Tests on dry running ball bearings were carried out at 150°C. The following observations were made:

- En 31 (1% C, 1% Cr) bearings wore quickly but had little tendency to seize provided they had sufficient internal clearance.
- Martensitic stainless steel bearings wore more slowly but showed a tendency to transfer material between the rolling members. This led to early seizure.
- Tool steel bearings were found to be the best bearings for the application, with little tendency for pick-up.

- Dry lubricated (MoS_2) En 31 bearings were found to be a practical solution to the bearing problem, running with low friction and ery low wear.

Gas bearings

Gas bearing blowers were used to circulate the primary coolant on Dragon. A test programme was carried out to demonstrate that satisfactory running could be achieved and to discover whether jacking gas would be required to cater for the stop-start condition. A conventional gas bearing arrangement was found to be satisfactory for the 75 kW circulators. A 100 mm by 200 mm long bearing with an anti-whirl groove had sufficient load carrying capability and freedom from instability. Along with the use of DU (PTFE-bearing) materials for the bearing surfaces, a trouble-free circulator resulted, withstanding all running and stop-start conditions.

Gears

Suitable materials were sought to withstand the high contact pressures within the charge/discharge machine. Gears made from nitrided steel, vapour or sand-blasted, and coated with molybdenum disulphide, were found to perform very well, with extremely low frictional forces generated.

3.3 Static Adhesion

The static adhesion of candidate materials for a UK helium-cooled reactor system was investigated during the early 1970s (Ref 2). Tests were carried out on stacks of metallic and other specimens at temperatures in the range 400 – 800°C. Graphite, alumina and some coated alloys were included in the tests, as were Incoloy 800, Nimonic 75 and Nimonic 90. 'Pure' (< 2 μ-atmospheres water) and 'impure' (50 μ-atmospheres water) helium atmospheres were employed, at pressures of 1.24 bar and 42.4 bar. The interface pressure was 0.3 MPa.

At temperatures of 600°C and below, static adhesion was not a problem, with one exception: En 58J austenitic stainless steel, like-on-like. At temperatures of 650°C and above, adhesion was found between most of the metallic pairs, although most values were low. Only En 58J and the coating LC-1B (chromium carbide in a nickel-chromium matrix), both in a like-on-like configuration, gave high values of adhesion at these temperatures. The greatest degree of adhesion was found in the tests carried out in pure helium at 800°C. There was no effect of helium pressure in the tests.

Graphite (Gilsocarbon) reacted with, but did not adhere to, both En 58J and Nimonic 75 at temperatures of 650°C and above, in tests in impure gas at both gas pressures. Graphite-graphite couples did not adhere in any of the tests.

3.4 Friction and wear

3.4.1 Programme 1 – graphite/graphite and graphite/metal pairs

In the UK during the 1960s and 1970s, research was carried out into the friction and wear of pile grade and bearing graphites, in graphite-graphite and graphite-metal couples (Ref 3). The tribological properties of these materials in low pressure CO_2 and helium, each gas containing <10 vpm water vapour, were determined at temperatures between 20°C and 600°C. Specific wear rates and friction coefficients were determined in a crossed-cylinders configuration. Three bearing grades of graphite were rubbed against several alloys, including a nitrided steel (LK5) and an austenitic stainless steel (En 58B). A pile grade graphite was also tested, but in carbon dioxide only. The tests were performed in a crossed-cylinders configuration, under a load of 22 N.

In helium, the wear rate vs temperature graphs were similar for the three bearing graphites in tests against nitrided steel, as shown in Figure 1a. The specific wear rates of the graphites increased markedly above 400°C. The friction coefficients were low, at 0.1 – 0.4, and showed little systematic dependence on temperature. Graphite wore to a greater degree against austenitic stainless steel, as shown in Figure 1b. One grade of graphite (EY 105) wore severely. EY 105 was a nonmetallic-impregnated electro-graphite. A similar effect was seen for the same combination of materials in the carbon dioxide tests, but to a lesser degree. In general, friction and wear behaviour in helium was more diverse than in carbon dioxide. Pile grade graphite was subject to mild wear (~10^{-15} m^3/Nm) at all test temperatures in carbon dioxide, and gave rise to low values of μ (0.25 at 20°C, decreasing to 0.15 at 575°C).

3.4.2 Programme 2 – graphite/graphite and metal/metal pairs

Tests were carried out in 'pure' and reactor helium at temperatures from 20°C to 800°C (Ref 4). A large programme of work was carried out on five materials couples under specified conditions of contact pressure, gas pressure and temperature to determine

A. whether there is any significant difference between friction and wear performance in pure helium and in helium representative of gas composition in a reactor under water leakage conditions.

B. whether gas pressure affects friction and wear behaviour in pure helium.

The gases used were denoted 'pure' or 'reactor gas'. Tests in 'pure' gas were carried out at 1 bar and 50 bar. Reactor gas, at 20 bar, contained 25 vpm hydrogen, 25 vpm carbon monoxide, 2.5 vpm carbon dioxide and 2.5 vpm water.

Six materials were tested:

1. Type 316 stainless steel, roughness Ra = 0.6 – 1.0 µm

2. Graphite (Gilsocarbon), a fine grained isotropic material, Ra = 2 – 5 µm

3. LC-1B, plasma-sprayed onto Type 316 stainless steel, thickness approx. 125 µm, Ra = 0.3 – 0.7 µm

4. Nitrided En 40B steel, Ra = 0.20 – 0.25 µm

5. Nitrided En 41B steel, Ra = 0.20 – 0.22 µm

6. Alloy C weld deposit (Deloro Stellite Ltd), applied to Type 316 stainless steel, Ra = 0.15 – 0.35 µm

In each test, two pairs of discs, 12.7 mm and 25.4 mm in diameter, were mounted one above the other and rubbed simultaneously, the two specimens being subjected to equal contact pressures, usually 2.1 MPa or 6.5 MPa. Five materials combinations were chosen for the investigation of the effect of helium pressure and purity, and in some instances on the effect of moisture level, on friction and wear:

i. Type 316 stainless steel, like-on-like

ii. Graphite, like-on-like

iii. LC-1B, like-on-like

iv. Nitrided En 40B, like-on-like

v. Alloy C/Type 316 stainless steel

In the Type 316 stainless steel tests, the friction coefficient (µ) was of high value (µ > 1 in all tests) and wear performance was poor with extensive scoring. Pick-up occurred on the larger specimens, with welding in some cases. Tests at 6.5 MPa contact pressure were therefore not carried out. At 2.1 MPa contact pressure, there was no discernible trend in friction coefficient with temperature in the range 400 – 800°C, although the value was around twice that at 20°C (1.2).

Some moisture tests were carried out on the Type 316 specimens. At 20 bar gas pressure, µ was highly dependent on the moisture level. At 650°C, µ increased from 1.4 to 2.1 with a decrease in water content from 65 vpm to 2 vpm. The corresponding increase at 515°C was from 1.25 to 2. In reactor gas at 650°C, friction coefficients were generally lower (by approx. 20%) than in pure gas at 650°C, although the wear rates were similar.

Some results from the graphite tests are presented in Figures 2 to 4. In these tests, the friction coefficient seldom exceeded 0.4. Wear was low, and independent of temperature and contact pressure in the range 300 – 800°C. At 20°C, especially at high contact pressures, the wear rate was high. There was no significant effect of gas pressure on either friction or wear in the graphite tests at elevated temperatures.

The friction coefficient was mostly below 1.0 in tests on LC-1B. Wear performance was poor at 20°C but generally good at higher temperatures. μ tended to increase with increasing contact pressure but the wear rate tended to decrease (see Figure 5). There was a tendency for μ to increase with increasing gas pressure (see Figure 6). The effect of gas pressure on wear was not obvious.

No definite conclusions were drawn from the tests on nitrided En 40B. However, there were some indications (see Figure 7) that wear was less severe at high gas pressure.

In all tests, the performance of Alloy C vs Type 316 stainless steel was poor. In most tests μ exceeded 1 and wear was severe. Friction and wear tended to increase with increasing temperature.

The following conclusions were drawn from this test programme:

a. No significant or systematic difference was observed between wear behaviour in pure helium and in reactor gas.

b. In pure helium, no systematic effect of gas pressure was observed.

c. Friction and wear show some dependence on temperature, as described above.

d. There was no systematic effect of contact pressure on friction.

e. The water and oxygen content of the helium had considerable influence on the friction of steels.

f. Graphite (Gilsocarbon) gave good results in all tests at temperatures in the range 400°C to 800°C but wore rapidly at 20°C.

3.4.3 Programme 3 – metal/metal, graphite/metal and graphite/graphite pairs

A large number of materials couples with potential for use in a UK High Temperature Reactor were tested in a flat-on-cylinder arrangement in low pressure helium at 700°C (Ref 5). The level of water in the apparatus was < 2 vpm. The results are presented in Table 4.

In general, the tests confirmed the poor rubbing behaviour of structural alloys in helium at elevated temperature. In the main, nickel-based alloys behaved better than 316 or En 58B stainless steels. Incoloy 800, however, wore severely in like-on-like tests. Clearly, transfer effects are important in pure helium. Pick-up (adhesive transfer) from cylinder to pin was a feature of nearly all the tests and consequently it is difficult to define wear satisfactorily. The results for graphite (gilsocarbon), particularly in a like-on-like arrangement, were good. This combination was the subject of further tests at temperatures from 20°C to 800°C, before and after degassing the apparatus to reduce the impurity levels in the gas. The results are presented in Table 5. Degassing before test clearly had an effect on the tests at 20°C, the wear rate increasing with the purity of the gas. For the elevated temperature tests, the situation was less obvious.

3.4.4 Programme 4 - the effect of dwells on metal/metal and metal/graphite pairs

In a High Temperature Reactor, some surfaces will rub together during temperature cycles or when components are inserted or withdrawn from the reactor. In order to assess the effect of dwells between such operations, a series of plate-on-disc reciprocating motion tests was performed in low pressure (1.68 bar) helium at 450°C, 650°C and 750°C using several materials combinations (Ref 6). Not all combinations were tested at 450°C. The tests were performed in a controlled atmosphere containing 5 µ-atmospheres water. Here, the results of those tests with some relevance to VHTR will be discussed:

a. 316, like-on-like; 650°C and 750°C

b. Nimonic 90, like-on-like; 650°C and 750°C

c. Nimonic 90 vs 316; 650°C and 750°C

d. LC-1B, like-on-like; 650°C and 750°C

e. 316 vs graphite (EYC 9106); 450°C, 650°C and 750°C

The tests constituted either 100 continuous cycles, or 5 cycles per day for 20 days, under a contact pressure of 6.5 MPa. All tests were duplicated.

316 vs 316

The mean friction coefficients for this combination were between 0.8 and 1.2 for the continuous tests and between 0.8 and 1.4 for the dwell tests. The values of maximum dynamic friction were 1.1 – 2.1 for the continuous tests and 1.5 – 2.6 for the dwell tests. It was difficult to make a sensible comparison of wear rates in these tests because of material transfer. The greatest surface disruption was, however, found in the wear tracks of the discontinuous test specimens, particularly in the 650°C test specimens, indicating that static adhesion during the dwells had influenced the results.

Nimonic 90, like-on-like

The mean coefficients of friction were between 0.65 and 1.1 for tests with and without dwells. The greatest wear occurred during the dwell tests.

316 vs Nimonic 90

The results from this combination were strongly influenced by transfer from the 316 disc to the Nimonic 90 plate. The mean friction coefficients were between 0.8 and 1.3 and showed no significant variation due to the effects of either dwell or temperature. The effect of dwell was much more pronounced on the wear figures. At 650°C, material transfer was much greater for the dwell tests than for the continuous tests.

LC-1B, like-on-like

This material combination displayed very good friction and wear behaviour. Friction coefficients were low (0.3 – 0.5) and little wear resulted. There was no effect of dwell or temperature.

316 vs graphite

The friction coefficients in these tests were between 0.1 and 0.5. At 450°C, μ in the dwell tests was lower than in the continuous tests. This effect was not repeated at 650°C or 750°C. The wear profiles were smooth, the plate (316) not wearing significantly. The graphite wore much more, typically at a rate of 10^{-12} m^3/Nm.

Conclusions

LC-1B, like-on-like, and 316 vs graphite showed little or no effect of dwell on either friction or wear. For the other combinations, more severe wear occurred for the dwell tests than the continuous tests. Most of this wear took the form of material transfer from one specimen to the other, probably as a consequence of welding during dwell periods.

3.5 Fretting – metal/metal and graphite/graphite pairs

A programme of impact/slide fretting tests was carried out at a gas pressure of 1.2 – 1.4 bar and temperatures of 350°C and 750°C on several materials combinations (Ref 7), including

a. 316, like-on-like

b. Incoloy 800 vs 316

c. Graphite (Gilsocarbon), like-on-like

Tests were performed in 'pure' helium, containing < 1 vpm water, and a dosed helium, containing 50 vpm water. The tests were conducted at a frequency of 75 Hz, with a slip amplitude of 0.18 mm and a vibration amplitude of 0.254 mm. The test duration was variable, mostly up to 100 hours. The contact was flat-on-flat.

The test results are presented in Tables 6 – 11. At 750°C, the wear rates of metal-metal combinations fell within the range 10^{-14} – 10^{-13} m^3/Nm. The 750°C wear rates found in the graphite-graphite tests fell within the range 10^{-15} – 10^{-14} m^3/Nm. The following conclusions were drawn from the study:

Effect of gas purity

For metal-metal combinations in general, wear was more severe in pure rather than impure gas. For graphite combinations at high temperature, a change in gas purity has little effect.

Effect of temperature

For metal-metal combinations, on the basis of maximum peak-to-peak variation in wear profile, the fretting damage induced at 350°C was marginally worse than that at 750°C. In graphite the damage produced at 350°C was an order of magnitude worse than that produced at 750°C.

Effect of test duration

For 316 vs 316, there was a tendency for the most severe wear to occur early in the test, the effective wear rate falling with test duration. Apparently, after the early stages of the tests, the wear rate became constant. The same behaviour was found for the other metal-metal combinations, though to a lesser extent. The wear rate was constant with time in the graphite-graphite tests.

4.0 AGR TRIBOLOGICAL REVIEW

4.1 Introduction

Some of the tribological concerns on the AGR are shown in Table 12. The predominant concern was fretting, for example in the heat exchangers and circulators, but friction and wear in sliding contact was also a concern. Hard coatings have been widely used to overcome the tribological difficulties. This review concentrates on the characterisation of such coatings for application at temperatures up to 650°C.

4.2 Materials

A wide range of plain carbon, low alloy and austenitic stainless steels were employed in the AGR reactor. Austenitic stainless steels were specified almost exclusively for application at temperatures above 400°C although some nickel alloys were also used. A list of materials used in AGR, including the heat exchangers, for application at temperatures above 400°C is presented in Tables 13 – 18. The list is comprised mainly of austenitic alloys, which suffer fom poor tribological performance generally. A wider range of alloy types is employed for heat exchanger tubing, as shown in Table 19. Descriptions of the alloys used for high temperature application in AGR are supplied in Table 20.

4.3 Coatings

Four types of hard coating were applied to components to reduce friction, improve wear-resistance, prevent adhesion and to protect against corrosion. Detonation-Gun and Plasma Spray coatings were used widely in AGRs, and almost exclusively in the gas circuit. Spray-fused coatings and weld deposits were used mainly in ancillary plant, e.g. in valves. Chromised and other diffusion coatings are also employed in AGR reactors. The types of coating employed are described below. Coating compositions are given in Table 21.

4.3.1 Detonation-Gun coatings

Detonation-Gun (D-Gun) coatings were supplied by Union Carbide (now Praxair). These coatings are applied using a device similar to a rifle barrel, into which powdered coating material and an oxygen/acetylene gas mixture are introduced and then ignited by a spark discharge. The mixture detonates and the powder is propelled from the barrel at high velocity. The operating cycle is repeated many times to build up the coating.

Advantages of the technique are:

- High density deposits

- Good adhesion to the substrate
- Minimal surface preparation
- Low heat input to the substrate material.

Disadvantages are:

- Unsutable for some geometries, e.g. inside tubes
- One supplier

This technique was used to deposit LC-1B and LW-5 cermet coatings for use in AGR. Both coatings contain particles of great hardness bound together by a small amount of a softer, metallic phase. LC-1B consists of 65% (by weight) Cr_3C_2 in a Ni-Cr binder. LW-5 consists of 25% WC and 5% Ni together with mixed tungsten and chromium carbides.

4.3.2 Plasma Spray coatings

In this technique, powder is carried to the component surface in a high temperature stream of inert gas.

Advantages:

- A wide range of coating types may be applied
- Deposition on tube bores is standard

Disadvantages:

- Porosity greater and adhesion to substrate poorer than for D-Gun coatings

The only coating applied using this technique was LC-2 (from Union Carbide), which is similar in composition to LC-1B.

4.3.3 Spray-Fuse coatings

In this flame spraying technique, powder is deposited from an oxy-acetylene flame and further heating is supplied to fuse the deposit.

Advantages:

- Good adhesion to substrate
- Thick coatings (several mm) possible

- Good apparatus mobility

Disadvantages:

- High degree of substrate heating
- Post-deposition machining required
- Poor quality control

Coatings SF50 and SF60, from Deloro Stellite, were applied by the spray-fuse method. Both coatings are nickel-based and also contain chromium, iron, silicon, boron and carbon.

4.3.4 Weld deposits

The technique normally used was that of transferred arc inert gas (TIG) welding. The advantages and disadvantages of this technique are similar to those of spray-fused coatings. Nickel-based Alloy C, Alloy 50 and Alloy 60, from Deloro Stellite, were used in AGRs. Alloy C is of high chromium and molybdenum content, with some iron and tungsten. Alloy 50 and Alloy 60 are similar in composition to SF50 and SF60.

4.4 Coatings properties

4.4.1 Spalling

Spalling may result from a combination of factors, including internal stress resulting from the coating process, thermal stress due to temperature cycling and differential thermal expansion, oxidation, poor adhesion of the coating to the substrate and weakened adhesion as a result of coating/substrate interface corrosion. The nickel-based hard coatings were deemed to be better than the cermets with regard to these compatibility issues. Nevertheless, corrosion testing of LC-1B over many thousands of hours did not reveal a serious spalling problem.

4.4.2 Oxidation performance

LC-1B and LC-2

LC-1B and LC-2 coatings are of similar composition but LC-2 is applied by plasma spraying rather than by the D-Gun technique. LC-2 has a lower bond strength and greater porosity than LC-1B but its great advantage is that it can be applied to the bores of components, often an impossibility for D-Gun coatings. LC-1B and LC-2, in as-coated and as-ground conditions, were exposed under reactor conditions, at temperatures up to and beyond 700°C for tens of thousands of hours. All coatings performed satisfactorily at 600°C (Ref 8). At 700°C, as-coated LC-1B performed satisfactorily but both as-ground LC-1B and as-coated LC-2 showed detachment of small areas at corners after 10 kh exposure. Detachment resulted from additional stress where the coating was applied right up to the edges and corners. For the component under test, these were critical areas. In the absence of detachment, coating performance was excellent with the maximum oxide growth at 700°C of 3 µm well within design values (75 µm). Although the coatings were porous and internal oxidation of the coating occurred, there was no evidence of oxidation of the substrate. In other tests on LC-1B at 700°C, the coating showed no evidence of cracking or detachment from the substrate.

In conclusion, LC-1B and LC-2 coatings were deemed to be satisfactory for high temperature operation provided they have been correctly applied. Coating loss at edges may be expected but gross spalling does not occur. Test data for LC-1B are presented in Tables 22 – 24.

LW-5

Oxidation of the tungsten carbide constituent of LW-5 limits its use to temperatures below 400°C. LW-5 was tested on a mild steel substrate at 300°C and 400°C. At 300°C, the oxidation performance of the coating was excellent with a weight gain of only 0.1 mg cm^{-2} measured. At 400°C, gross oxidation of the substrate occurred though the coating remained intact. In practice, use of LW-5 on mild steel is limited to temperatures of less than or equal to 350°C. On austenitic stainless steels the coating may be used at temperatures up to 400°C. Test data for LW-5 are presented in Table 25.

SF50, SF60 and Alloy C

SF50 and SF60 were not used extensively in the gas circuit. Their use at high temperature in early designs of AGR was discontinued because of their poor oxidation performance. After long term exposure testing of Alloy C, this coating was also found to have limitations at high temperature. Though performing satisfactorily at 550°C, blistering gradually developed at 650°C. Test data for these coatings are presented in Table 26.

Chromised and chromaluminised coatings

In tests at 400°C, the oxidation performance of chromised mild steel was satisfactory at times up to 86 kh but blistering then occurred. Chromised and chromaluminised En 58B (18% Cr, 10% Ni) stainless steel was tested to 100 kh at 700°C and gave satisfactory oxidation performance though some spalling occurred.

4.4.3 Nuclear compatibility

The only element in any of the coatings which might cause a nuclear compatibility problem is boron. 20% of naturally occurring boron is in the form ^{10}B which has a high thermal neutron capture cross section. Boron is present in Alloys 50 and 60 at levels of 1.8% and 3.5%, respectively. These coatings have therefore not been used to any great extent in the gas circuit.

4.4.4 Tribology

Where coated components are in continuous or intermittent contact with other components and there is relative movement between the parts, seizure or malfunction will be governed by the value of friction coefficient. However, no single value of friction coefficient can be attributed to a materials pair for this parameter will change with temperature, loading, sliding speed, frequency of vibrational relative motion, etc. Also, two aspects must be considered: dynamic friction and static adhesion.

A great amount of friction testing, at various temperatures and gas pressures, and under different loadings, was carried out in support of the AGR programme (Ref 9). Mild and low carbon steels are susceptible to adhesion in carbon dioxide at temperatures of 300°C and above, while austenitic stainless steels will resist adhesion at temperatures up to approximately 550°C. Adhesion occurs largely as a result of the growing together of surface oxides but also by welding at metallic junctions. Hard coatings may be applied to overcome the risk of adhesion by protecting the underlying metal from oxidation. Adhesion trials were carried out in CO_2 at temperatures up to 650°C on a range of engineering materials and coatings.

The tribological performance of three coatings in particular: Detonation-Gun coatings LC-1B and LW-5, and spray fused SF60 compare favourably with most other engineering materials. They are not susceptible to adhesion in CO_2-based atmospheres and will protect mild steel and stainless steel against adhesion. Specific wear rates show variability and should not be regarded as absolute values. For design purposes a large safety factor should be used (Ref 10). The specific wear rates for LC-1B and LW-5 decrease with duration of rubbing provided the coating is not damaged. Wear rates for these coatings are highest at intermediate temperatures of between 200°C and 450°C and lowest at temperatures between 500°C and 600°C (see Figure 8). Wear rates in $C0_2$ are dependent on temperature, lower rates occurring in high pressure gas. The recommended design wear rates for various metal-metal contacts are presented in Figure 9.

4.5 Applications of coatings in-reactor

Considerations in the choice of coatings for AGR application are set out in Table 26. Whenever the design permitted, Detonation-Gun coatings were preferred for AGR application. LW-5 coatings were specified for temperatures below 300°C and LC-1B coatings for higher temperatures. For applications where Detonation-Gun coating was not feasible, plasma sprayed LC-2 was employed as an alternative to LC-1B. At the time of AGR construction, plasma spraying was generally accepted to result in an inferior coating to that deposited by Detonation-Gun. Components to which coatings were applied in three designs of AGR are described in Tables 28 - 30. A further list of coatings applied to AGR components is presented in Table 31.

5.0 CONCLUSIONS

Some conclusions with relevance to VHTR and associated testwork have been drawn from the work reported here:

- Static adhesion is not a problem in helium at temperatures of 600°C and below. Low values of adhesion usually resulted from tests on metal-metal contacts at temperatures of 650°C and above. Nickel-based alloys were included in the tests. LC-1B, in a like-on-like arrangement, gave rise to a high value of adhesion. No adhesion occurred in graphite-graphite contacts at temperatures up to 800°C. There was no effect of gas pressure on the static adhesion results.

- Adhesive transfer is a feature of metal-metal rubbing in helium.

- There was no systematic effect of gas pressure on friction and wear in pure helium.

- In reactor helium at 20 bar gas pressure, friction coefficients were highly dependent upon the moisture level in the gas.

- In general, wear rates increase with increasing helium purity.

- Nickel-based alloys tended to perform better than austenitic stainless steels in friction and wear tests in helium.

- Graphite-graphite contacts wore little in helium at temperatures in the range 400 – 800°C. The wear rates increased with increasing gas purity.

- Elevated temperature dwells usually resulted in more severe wear upon subsequent rubbing contact in helium. This was not true for LC-1B, like-on-like, and 316 vs graphite.

- Surface treatments incorporating molybdenum disulphide found successful application on Dragon.

- The chromium carbide/nickel-chromium Detonation-Gun coating LC-1B was the preferred choice of coating to combat wear in sliding and fretting situations in the AGR reactor system at temperatures up to 650°C. For applications where Detonation-Gun coating was not feasible, plasma sprayed LC-2 was employed as an alternative to LC-1B.

6.0 REFERENCES

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TABLES

Table 1 Potential HTR problems identified during the Dragon Project; Part 1

Component	Potential problem	Temperature range (°C)	Type of motion	Possible materials	Comments
Insulation foil	(a) Fretting due to noise (b) Movements on thermal cycling	350-800	(a) High frequency, low amplitude (b) Low frequency	18/8/1, 20/25/Nb	No problem found at Dragon
Boiler tubes	Fretting due to noise. Wear due to thermal movement.	350-800	High and low frequency. High and low amplitude.	Low temp: mild steel Medium temp: 2¼Cr/Mo, 9Cr High temp: 18/8/1, 20/25/Nb, Incoloy	Slight wear due to thermal movement found in Dragon primary heat exchanger
Channel gags	Wear of bearings at outlet temperature	600-850	Occasional sliding and/or rotation	Hard facing, graphite and MoS_2, cermets and ceramics	Need for gag adjustment depends on detailed design
Channel seals	Effects at high temperatures	400-850	Insertion and thermal movements	Graphite and MoS_2	Friction coefficient > 0.4 could give fault condition
Channel gag drives	Drying out of greases. High temp bearings	100-600	Sliding and/or rotation	Conventional materials + grease graphite + MoS_2 hard facings on lubricated metals. Dry lubricated metals.	Maximum temp/life of greases to be assessed.
Thermal expansion joints	Wear due to thermal movements	Ambient -800	Sliding intermittently	Mild steel - Nimonics	Iron piston rings on Nimonics used on Dragon
Articulated control rods	Wear and seizure	350-550	Rolling/sliding	18/8/1, Nimonics, 9Cr, Nitrided low alloy steel	No problem on Dragon.

Table 2 Potential HTR problems identified during the Dragon Project; Part 2

Component	Potential problem	Temperature range (°C)	Type of motion	Possible materials	Comments
Grapple, grabhead etc	Passes through high temp regions	350, 850	Sliding	Hard facing. Graphite + MoS_2 cermets. Unlubricated metal surfaces. Dry lubricated metal surfaces.	Operates in 350°C region after passing and operating through 850°C region.
Fuelling machine	Wear of rolling element bearings, gears, chains, sprockets and ball screws	150 (>150°C if charge chute is used)	Rotary and sliding	Conventional. As in CO_2.	Life of greases to be determined. Higher temperature bearings required if charge chute is used.
Control rod mechanisms	As for refuelling machines. Wear in chain links.	~600	-	Stainless steel	-
Fuel elements (graphite)	Wear due to insertion and withdrawal	850+	Sliding	Graphites	Dragon fuel elements not examined for wear but none was noticed. Gross wear might occur in dry conditions.
Fuel elements (other effects)	Static adhesion at support	350	Line contact	18/8/1	No adhesion recorded at Dragon. Type of contact dependent upon fuel element design.

Table 3 Potential HTR problems identified during the Dragon Project; Part 3

Component	Potential problem	Temperature range (°C)	Type of motion	Possible materials	Comments
Valves (reactor and purification plant)	Static adhesion, wear and leakage	<350	Sliding and line contact	Hard facings	Work up to 350°C was carried out on Dragon but operating experience limited >150°C
Blowers	High speed, long life. Oil deterioration.	150	Rotational movement. Journal and thrust bearings.	Nitrided steels. Graphite + MoS_2.	Peculiar to design. Oil problems generic. Gas bearings on Dragon.
Compressors (cleaning & recovery)	Piston rings in bores.	150	Reciprocating	Nitrided steels. S.G.irons	Diaphragm used on Dragon
Core	Brick restraints. Brick movements. Wear from control rods.	350-500	Thermal and sliding	Graphite on graphite; Graphite on steels.	Considerable wear could occur if movements were great enough.
Peripheral seals	Thermal movement of large components	350	Sliding	Mild steel	-

Table 4 Friction and wear results in pure helium at 700°C, flat-on-cylinder

Pin	Cylinder	μ_{max}	μ_{mean}	Wear rate, pin (m^3/Nm)	Wear rate, cylinder (m^3/Nm)
316	316	>2.0	>2.0	*	1.1E-11
		>2.0	>2.0	*	7.2E-12
		>2.0	1.0	*	5.2E-12
		>2.0	1.0	*	6.7E-12
		>2.0	1.2	*	1.5E-11
		>2.0	0.8	*	1.2E-11
		>2.0	0.7	*	8.4E-12
Esshete 1250	316	>2.0	>2.0	*	7.0E-12
		>2.0	>2.0	*	4.8E-12
En 58B	316	>2.0	1.0	*	7.2E-12
		>2.0	1.0	*	5.9E-12
316	Inconel 600	2.0	1.2	*	1.9E-12
		1.7	1.0	*	1.1E-12
316	Nimonic 90	1.5	0.7	*	5.1E-13
		1.5	0.8	*	8.7E-13
		1.7	1.2	*	5.4E-13
		2.0	1.0	*	9.0E-13
Inconel 600	316	<2.0	0.8	*	8.8E-12
		<2.0	1.0	*	1.2E-11
Nimonic 90	316	2.0	1.0	*	3.4E-12
		<2.0	1.0	*	3.2E-12
Incoloy 800	316	1.6	0.75	*	4.2E-12
		1.65	1.0	*	6.1E-12
Inconel 600	Inconel 600	1.5	0.8	*	7.2E-13
		1.6	0.9	*	4.8E-13
Nimonic 80	Inconel 625	1.7	0.5	*	1.1E-12
		1.5	0.6	*	1.0E-12
Nimonic 90	Inconel 625	1.7	0.65	*	1.1E-12
		1.6	0.5	*	1.2E-12
Incoloy 800	Hastelloy C	1.5	0.7	*	3.6E-13
		1.2	0.7	*	3.6E-13
Inconel 625	Hastelloy C	1.4	0.6	*	2.0E-12
		1.5	0.5	*	1.8E-12
Incoloy 800	Incoloy 800	<2.0	0.7	*	3.0E-11
		<2.0	0.9	*	5.2E-11
Hastelloy C	Incoloy 800	<2.0	0.9	*	2.9E-11
		<2.0	0.9	*	2.4E-11
LC-1B	LC-1B	1.3	0.8	*	8.2E-14
		1.2	0.7	1.0E-14	3.7E-14
LC-1B	316	2.0	1.1	*	3.9E-12
		2.0	1.1	*	4.1E-12
Gilsocarbon	Gilsocarbon	0.6	0.3	7.5E-14	-
		0.8	0.4	5.1E-14	-
Gilsocarbon	316	0.3	0.25	2.2E-13	-
		0.4	0.3	2.2E-13	-

* Pick-up (adhesive transfer)

Table 5 Friction and wear results from graphite (gilsocarbon), like-on-like, in pure helium

Temperature (°C)	Apparatus condition	μ_{max}	μ_{mean}	Pin wear rate (m^3/Nm)
20	Not degassed	0.4 0.4	0.4 0.35	1.6E-14 1.3E-14
20	2 days at 800°C	0.65 0.75	0.35 0.4	2.5E-13 2.7E-13
20	6 days at 800°C	0.65 0.7	0.3 0.35	4.3E-13 3.9E-13
400	Not degassed	0.3	0.3	2.1E-14
400	1.5 days at 800°C	1.2	0.55	3.5E-13
400	6 days at 800°C	0.85 0.7	0.4 0.35	6.0E-14 3.8E-14
700	Not degassed	1.0	0.55	8.7E-14
700	1.5 days at 800°C	0.9	0.55	4.4E-14
800	2 days at 800°C	0.5 0.55	0.3 0.3	5.0E-14 7.1E-14

Table 6 Fretting results from 316 austenitic stainless steel, like-on-like, impure gas

Temp. (°C)	Freq. (Hz)	Load (N)	Test time (h)	Wear rate ($x10^{-14}$ m^3/Nm)
750	75	25	5	2.8
			10	2.0
			15	3.4
			30	6.5
			80	1.4
750	150	25	5	7.1
			10	11
			15	14
			30	7.7
			80	6.5
750	150	50	30	1.1
750	75	50	5	16
			15	10
			30	8.1
			100	1.9
			602	1.7
750	75	50	30	1.6
750	75	50	30	7.3
750	75	50	30	3.3
350	75	50	30	7.2
			98	1.6
350	150	25	30	5.0

Table 7 Fretting results from 316 austenitic stainless steel, like-on-like, pure gas

Temp. (°C)	Freq. (Hz)	Load (N)	Test time (h)	Wear rate ($x10^{-14}$ m^3/Nm)
750	75	50	30	22
			49	13
750	75	50	30	1.4
750	75	50	30	2.1
750	75	50	30	5.6

Table 8 Fretting results from Incoloy 800 vs 316, impure gas

Temp. (°C)	Freq. (Hz)	Load (N)	Test time (h)	Wear rate ($x10^{-14}$ m^3/Nm)
750	75	50	5	5.1
750	150	25	50	1.2
750	75	50	30	0.5
750	75	50	30	1.7
350	75	50	50	8.8
			98	7.0
350	150	25	50	1.2

Table 9 Fretting results from Incoloy 800 vs 316, pure gas

Temp. (°C)	Freq. (Hz)	Load (N)	Test time (h)	Wear rate ($x10^{-14}$ m^3/Nm)
750	75	50	30	1.4
			48	11
750	75	50	30	7.2

Table 10 Fretting results from graphite (gilsocarbon), like-on-like, impure gas

Temp. (°C)	Freq. (Hz)	Load (N)	Test time (h)	Wear rate ($x10^{-14}$ m^3/Nm)
750	75	50	30	0.25
750	75	50	30	0.45
750	75	50	30	0.70
750	75	50	30	0.16
750	150	25	50	1.6
350	75	50	50	11
			100	12
350	150	25	50	4.2

Table 11 Fretting results from graphite (gilsocarbon), like-on-like, pure gas

Temp. (°C)	Freq. (Hz)	Load (N)	Test time (h)	Wear rate ($x10^{-14}$ m^3/Nm)
750	75	50	30	0.20
			50	0.25

Table 12 Tribological concerns in the AGR reactor

Plant area	Items	Materials	Comments and potential problems
Boilers	Tube straps; tube support locking feature	Tubes: mild steel; 9 Cr and 316. Strap: 310. Tube support: 316	Locking feature is subject to fretting and impact wear. A major test programme has suggested that lifetimes are greater than 30 years.
Boilers	Reheater	316 vs 316	Numerous potential sites for fretting wear. Adequate clearance required between tubes and associated steelwork.
Boilers	Reheater and superheater tails vs annulus gas baffle	316 vs chromised 316	Small effect of thermal and load cycling. No significant problem.
Boilers	Gas seal inner ring vs outer cylinder	LW5 vs LW5	A reactor trip combined with a valve failure could lead to interference and a build-up of stresses.
Gas circulators	Inner sealing rings/stop; dome/stop	LW5 vs LW5	Fretting could eventually remove the coating after 30 years but system would remain viable.
Gas circulators	Seals and bearings in general	-	Potential problems due to fretting will reduce efficiency of operation.
Insulation	-	310 and 321	No significant problems in AGR.
Labyrinth seal	Flange bolts/washer/ upper angle plate	Mild steel vs mild steel and 35 Cr 17 Mo	Galling will occur but effect taken up by Schnorr washer.
Labyrinth seal	Flange ring seal	Mild steel vs 321	Galling will occur but effect taken up by Schnorr washer.
Labyrinth seal	Thermocouples to thermocouple block etc	18/8 vs 18/8	Main problem is fretting. Few problems if properly restrained.
Guide tube	Interface with core	18/8/Ti vs graphite	Rough duplex oxide on the steel would give high wear rates. Vibration will also lead to high wear.
Core	All graphite/graphite interfaces	Graphite vs graphite	Fretting wear rate may be high. Low amplitude, high frequency test data required.
Reactor thermocouples	20/25 sheaths	20/25 vs various, including 302, 320, 321	Fretting between adjacent thermocouples, and between thermocouples and clips, leading to failure.
Neutron sources	Cup/cone joints	320 vs 320	Adhesion at higher temperatures in range 350°C to 460°C.
Superheater penetrations	-	Incoloy 800 vs Nimonic 80A	Contact due to misalignment could give rise to adhesion and wear.

Table 13 Materials used in the AGR reactor, T ³ 400°C, Part 1

Component	Part	Specification	Operating temp (°C)
Gag unit	Heat shield	BS 1631	650
	Universal joint ring	BS 1631	650
	Universal joint pin	En 58J	650
	Lower housing	BS 1631	
	Bellows	316	
	Gimbal joint ring	316	
	Gimbal joint pin	En 58J	
	Piston seal housing flange	BS 1631	
	Gimbal flange	321	
	Scatter plug flange	321	
	Tie rod spider	BS 1631	
	Coupling sleeve	347	
	Inner scatter plug	347	
	Scatter plug tube	321	
	Scatter plug sleeve	316	
	Centralising lug	BS 1631	
	Outer scatter plug	BS 1631	
	Scatter plug tube	321	
	Gag plug	316	
	Lower housing	BS 1631	
	Gag shaft guides	321	
	Guide retaining ring	316	650
	Lower housing	BS 1631	650
	Gag shaft	En 58B	650

Table 14 Materials used in the AGR reactor, T ^{3} 400°C, Part 2

Component	Part	Specification	Operating temp (°C)
Control rod joints	Mushroom pin	En 58	430
	Tube end	En 58	
Guide tubes	Gimbal cap	316	400
	Gimbal pin	En 58	
	Gimbal ring	BS 1631	
	Fuel guide tube	BS 1631	400-675
	Gimbal cap screws	WHB 24	400
	Tundish	BS 1631	675
Boiler unit casings	Channel	321	582
	Sideplate	321	589
	Angle	321	589
	Spacer	316	589
	Nuts & bolts	316	589
Super heater tailpipe tier	Tailpipe lug	316	589
	Tailpipe tie	321	
	Nuts & bolts	316	
	Packer	316	
	Washer	321	
Boiler thermocouple Trays (internal)	Tray	321	564
	Clamp	321	
	Tray support	321	
	Spacers	316	
	Nuts & bolts	316	

Table 15 Materials used in the AGR reactor, T ^{3} 400°C, Part 3

Component	Part	Specification	Operating temp (°C)
Boiler thermocouple Trays (external)	Tray	321	589
	Frame	321	
	Clamp	321	
	Spacer	316	
	Nuts & bolts	316	
	Taper washers	321	
Superheater bank ties	Ties	321	589
	Platen saucer	321	
	Tailpipe lug	321	
	Pipe strap	321	
	Connector plate	316	
	Nuts & bolts	316	
Acoustic baffle	Baffle	321	589
	Beam	321	589
	Spacer	316	589
	Nuts & bolts	316	589
	Access door	321	564
Baffle and casing flights	Flights	321	450 - 589
	Plate	321	
	Spacer	316	
	Nuts & bolts	316	
Element ladder ties	Tie plate	321	450 - 589
	Angle bracket	321	
	Packer	316	
	Nuts & bolts	316	

Table 16 Materials used in the AGR reactor, T ³ 400°C, Part 4

Component	Part	Specification	Operating temp (°C)
9 Cr platen/hanger	Links	316 and 321	564
	Stud	Nimonic 80A	
	Hanger bolts	316	
Superheater platen/hanger	Stud	316	589
	Nut	321	
	Beam flange	321	
	Hanger block	316	
	Washer	316	
Gas seal - reheater/main units	Seal strip	316	589
	Clamping strip	316	
	Spacer	316	
	Angle	321	
	Nuts & bolts	316	
Acoustic baffle seal	Baffle	321	589
	Cover plate	321	
	Washer	316	
	Spacer	316	
	Nuts & bolts	316	
Tailpipe cover plates	Baffle	321	589
	Cover plate	321	
	Spacer	316	
	Nuts & bolts	316	
Main beam cross tie bolts	Tie rod	321	564
	Block	321	
	Nuts	316	

Table 17 Materials used in the AGR reactor, T ³ 400°C, Part 5

Component	Part	Specification	Operating temp (°C)
Superheater penetrations	Seal plate	321	589
	Backplate	321	
	Clamp	321	
	Spacer	316	
	Penetrator	321	
	Casing frame	321	
	Casing side	321	
	Angle support	321	
	Seal ring	321	
	Nuts & bolts	316	
Superheater bank tie studs	Stud bolt	Nimonic 80A	589
	Nuts	SA 194 Gr 8T	
	Washer	321	
	Pipe spacer strap	316	
	Connector ploate	316	
	Lateral tie	321	
Reheater casing flights	Casing flight	321	610
	Casing plate	321	
	Spacer	316	
	Nuts & bolts	316	

Table 18 Materials used in the AGR reactor, T ³ 400°C, Part 6

Component	Part	Specification	Operating temp (°C)
Reheater platen/beam	Main beam	316	610
	Platen support block		
	Casing flange		
	Washer		
	Nuts & studs		
Reheater element/ladder ties	Plate	316	610
	Angle		
	Packer		
	Nuts & bolts		
Reheater tailpipe ties	Support tie	316	610
	Tailpipe lug		
	Packer		
	Nuts & bolts		

Table 19 AGR boiler tube materials

Component	Specification	Operating temp (°C)
Primary economiser	Mild steel 1 Cr	≤ 320 ≤ 345
Secondary economiser, evaporator, primary superheater	9 Cr	≤ 530
Secondary superheater, reheater	316	600

Table 20 Alloys used in AGR, T ^{3} 400°C

Specification	Alloy type
BS 1631	Austenitic Cr-Ni
En 58B	321
En 58J	316
316	Austenitic Cr-Ni
321	Austenitic Cr-Ni
347	Austenitic Cr-Ni
SA 194 Gr 8T	Austenitic Cr-Ni
Nimonic 80A	Ni-Cr
-	9 Cr

Table 21 Compositions of hard coatings used in UK AGRs

Coating	Manufacturer	Coating type	Deposition technique	Composition (%)
LC-1B	Union Carbide (now Praxair)	Cermet	D-Gun	80 vol Cr_2C_3, 20 vol NiCr
LC-2	Union Carbide (now Praxair)	Cermet	Plasma Gun	75 vol Cr_2C_3, 25 vol NiCr
LW-5	Union Carbide (now Praxair)	Cermet	D-Gun	25 WC, 70 mixed WC_3/Cr_2C_3, 5 Ni
Alloy C	Deloro Stellite	Metallic	TIG weld or cast	Ni base, 17 Cr, 17 Mo, 6 Fe, 5 W, 0.1 C
Alloy 50	Deloro Stellite	Metallic	TIG weld, cast or spray fused (SF50)	Ni base, 10 Cr, 4 Fe, 4 Si, 1.8 B, 0.5 Cu, 0.4 C
Alloy 60	Deloro Stellite	Metallic	TIG weld, cast or spray fused (SF60)	Ni base, 16 Cr, 4.5 Fe, 4.5 Si, 3.5 B, 0.5 C

Table 22 LC-1B vs LC-1B, friction and wear data at reactor gas pressure

Temp (°C)	Gas	Specific wear rate (10^{-9} mm^3 N^{-1} mm^{-1})		Friction coefficient		Comments
		A	B	Mean	Max	
200	AGR	2	2	0.3	0.35	Flat-on-flat, reciprocating sliding. A = plate, B = key. 12.7 mm stroke. Contact pressure 1.73 MPa.
550	AGR	0.5	0.2	0.2	0.25	
650	AGR	0.06	0.6	0.2	0.25	
650	AGR	10,700	2,500	0.35	0.7	Flat-on-flat, reciprocating sliding. A = plate, B = key. 12.7 mm stroke. Contact pressure 3.45 MPa.
40	Argon	-	250-380			Crossed-cylinders. No systematic effect of load.
40	CO_2	-	4-9			Crossed-cylinders. Greater wear at higher load.

Table 23 LC-1B vs LC-1B, fretting test data

Temp (°C)	Gas	Specific wear rate (10^{-9} mm^3 N^{-1} mm^{-1})		Comments
		A	B	
600	Air	0.2	0.2	Flat-on-flat, 40 Hz. Contact pressure 11 MPa.
230	CO_2	0.005-0.03	0.003-0.02	Flat-on-flat, 50 Hz. Contact pressure 3.9 MPa. Wear rate reducing with distance moved.
300	CO_2	0.06	0.05-0.15	
550	CO_2	0.002-0.004	0.002-0.007	
600	CO_2	0.004-0.006	0.002-0.005	
20	AGR	<7	<7	Flat-on-flat, 150 Hz. Contact pressure 1.1 MPa.
275	AGR	22	30	
650	AGR	<7	<7	
20	AGR	7-10	7-10	Flat-on-flat, 150 Hz. Contact pressure 1.1 MPa. Impact/slide mode.
275	AGR	100-400	100-220	
650	AGR	20-40	<7-15	

Table 24 LC-1B vs another: friction and wear data at reactor gas pressure

Materials		Temp (°C)	Gas	Specific wear rate (10^{-9} mm^3 N^{-1} mm^{-1})		Friction coefficient		Comments
A	B			A	B	Mean	Max	
LC-1B	316	550	AGR	-	-	1.4	2.3	Flat-on-flat, reciprocating sliding. A = plate, B = key. Stroke 12.7 mm. Contact pressure 3.45 MPa.
LC-1B	316	550	AGR	-	-	0.35	0.9	As above but contact pressure of 69 MPa.
LC-1B	316	650	AGR	2,400	14,900			Contact pressure 3.45 MPa.
LC-1B	316	650	AGR	Weight gain	4,000-10,000	0.75	0.8-0.9	Contact pressure 17 MPa.
LC-1B	Carr's 23S	20	CO_2	2	2	0.6	0.6	Sphere-on-flat
LC-1B	Carr's 23S	300	CO_2	Weight gain	1	0.25	0.6	
Carr's 23S	LC-1B	20	CO_2	4.2	7.4	0.8-0.9	0.9-1.0	Flat-on-flat. Contact pressure 17 MPa.
Carr's 23S	LC-1B	205	CO_2	3.7	57	0.8	1.1	
Carr's 23S	LC-1B	300	CO_2	6.6	81	0.8	1.0	

Note Carr's 23S is a high carbon, high chromium cold work tool steel

Table 25 LW-5 vs LW-5 and LW-5 vs another: friction and wear data at reactor gas pressure

Materials		Temp (°C)	Gas	Specific wear rate (10^{-9} mm^3 N^{-1} mm^{-1})		Friction coefficient		Comments
A	B			A	B	Mean	Max	
LW-5	LW-5	20	CO_2	3.5	4	0.65-0.85	0.9	Flat-on-flat, reciprocating sliding. Stroke 10 mm. Contact pressure 17 MPa.
LW-5	LW-5	200	CO_2	1.3	1	0.7	0.9	
LW-5	LW-5	300	CO_2	0.1	1.7	0.8	1.1	
LW-5	En 4 mild steel	20	CO_2	1.6	72	0.9	1.0	
LW-5	En 4 mild steel	205	CO_2	2.2	410	0.9	0.9	
LW-5	En 4 mild steel	300	CO_2	0	81	0.9	1.1	
LW-5	Carr's 23S	20	CO_2	0.25	3	0.7	0.85	
LW-5	Carr's 23S	205	CO_2	0.3	6	0.7	0.9	
LW-5	Carr's 23S	300	CO_2	0.8	6.5	1.1	1.4	
Carr's 23S	LW-5	20	CO_2	2.5	0.13	0.55	0.65	Contact pressure 136 MPa.
Carr's 23S	LW-5	205	CO_2	0.79	0.33	0.5	0.6	
Carr's 23S	LW-5	300	CO_2	0.31	0.17	0.4	0.5	

Table 26 Friction and wear data for Alloy C and SF60; tests at reactor gas pressure

Materials		Temp (°C)	Gas	Specific wear rate (10^{-9} mm^3 N^{-1} mm^{-1})		Friction coefficient		Comments
A	B			A	B	Mean	Max	
Alloy C	Alloy C	200	AGR	123	149	0.3	0.4	Flat-on-flat, reciprocating sliding. A = plate, B = key. Stroke 12.7 mm. Contact pressure 1.73 MPa.
Alloy C	Alloy C	550	AGR	242	417	0.3	0.4	
Alloy C	Alloy C	650	AGR	Pick-up	283	0.3	0.5	
Alloy C	Alloy C	550	AGR	-	-	0.6	1.3	Contact pressure 3.45 MPa.
Alloy C	Alloy C	650	AGR	-	-	0.4	0.5	
SF60	SF60	200	AGR	0.1	0.2	0.5	0.9	Flat-on-flat, reciprocating sliding. A = plate, B = key. Stroke 12.7 mm. Contact pressure 1.73 MPa.
SF60	SF60	450	AGR	1.7	2.2	0.9	1.05	
SF60	SF60	550	AGR	4.3	7.7	0.4	0.8	
En 58B	SF60	200	AGR	64	37	1.15	1.3	
En 58B	SF60	450	AGR	0.8	7	0.35	0.8	
En 58B	SF60	550	AGR	1.0	11	0.95	1.4	
En 58B	SF60	650	AGR	8.4	62	0.75	0.9	

Table 27 Considerations in choice of coating

Note: The magnitudes of friction coefficient and wear rate shown here are mean values for a range of conditions

Material pair	Friction coefficient	Design specific wear rate (m^2N^{-1})	Resistance to static adhesion	Oxidation resistance	Comments
LC-1B vs LC-1B LC-2 vs LC-2	0.24 ± 0.07	5×10^{-15}	Good	Good	Low substrate heating during deposition. Surface finishing usually not required.
LW-5 vs LW-5	0.75 ± 0.09	5×10^{-15}	-	-	Low substrate heating during deposition. Surface finishing usually not required. Not used above 300°C.
SF60 vs SF60	0.48 ± 0.24	2×10^{-15} – 2×10^{-14}	Poor	Poor	High substrate heating during deposition. Boron content (3.5%). Post-deposition finishing required.
Alloy C vs Alloy C	0.55	10-12	-	Fairly good	High substrate heating during deposition. Post-deposition finishing required. High wear rates and rough, galled surfaces.
SF60 vs En 58B (17/20 Cr, 7/10 Ni)	0.61 ± 0.25	5×10^{-12}	Poor	Poor	Best combination involving stainless steel.

Table 28 Coatings used in the UK AGR reactor – System A

Component	Coating	Coating thickness (µm)	Counterface	Action	Temp (°C)
Control rod joint	LC-1B	50 min	LC-1B	Rocking	560
Interstitial guide tube	LW-5	50 min	BS 3100 347C17 (18/21 Cr, 9/12 Ni) casting	Sliding	400
Gag orifice	LC-1B	50 min	LC-1B	Sliding/fretting	650
Gag plug fins	LC-1B	50 min	LC-1B	Sliding/fretting	650
Gag shaft vibration snubber and rubbing button	Alloy C	50-100	Mild steel	Sliding/fretting	300
Gag drive shaft-Hooke joint-pin	Alloy C	50-100	Alloy C	Sliding	650
Gag drive shaft guide bearing	LC-1B	50 min	En 58B (17/20 Cr, 7/10 Ni)	Sliding/fretting	650
Fuel assembly-sealed gimbal joint-pivot pins	Alloy C	150 min	BS 3100 347C17 (18/21 Cr, 9/12 Ni) casting	Sliding	650
Fuel assembly - gag coupling universal joint	LC-1B	75-100	BS 3100 347C17 (18/21 Cr, 9/12 Ni) casting	Sliding/fretting	650
Motor piston ring - gas circulator	LW-5	50-75	LW-5	Sliding	280
Inner seal ring-circulator dome transfer ring	LW-5	50-75	Mild steel	Sliding	280
Transfer ring bore-circulator dome	LW-5	75-100	LW-5	Sliding	280
Dome operating rods - gas circulator	LW-5	175-225	Nitrided En 40B (3 Cr-Mo)	Sliding	280

Table 29 Coatings used in the UK AGR reactor – System B

Component	Coating	Counterface	Temp (°C)
Top bush retaining ring – gas circulator	LW-5		280
Dome guide – gas circulator (or stop ring)	LW-5		280
Isolating dome - gas circulator	LW-5		280
Seal ring (piston ring) – gas circulator	LW-5		280
Inner sealing ring – gas circulator	LW-5		280
Bottom bush – gas circulator	LW-5		280
Dome operating rods – gas circulator	LW-5		280
Fuelling guide tube top bearing (hub and housing)	LC-2	LC-2	650
Control rod guide tube top bearing (hub and housing)	LC-2	LC-2	
Dome thermocouple penetration – thermal baffle:segmented ring	LC-1B	En 58B (17/20 Cr, 7/10 Ni)	300-400
Control rod joints	LC-1B	LC-1B	600 max
Flux scan penetration – gas sample pipe bearing seal	LW-5	En 58B (17/20 Cr, 7/10 Ni)	300
Core restraint	Stellite Alloy 50		350
Hot box labyrinth seal	LW-5		280

Table 30 Coatings used in the UK AGR reactor – System C

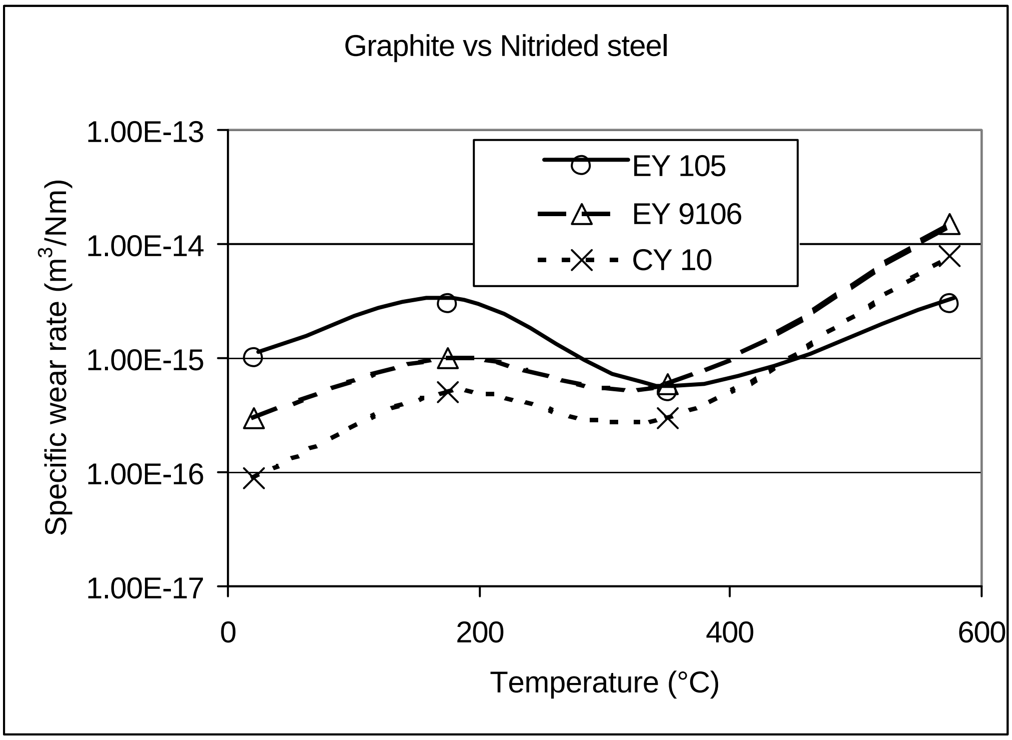
Component	Coating	Counterface	Action	Temp (°C)
Control rod shock absorber – piston in swage tube	Alloy C		Rubbing	350-750
Boiler hangers – anchors and guides	Alloy C		Rubbing/adhesion	280-650
Boiler interbank seals	Alloy C welded	Alloy C cast	Sliding	500 & 600
Boiler thermocouple duct liners	‘High Cr’ Alloy C welded	‘High Cr’ Alloy C cast	Adhesion	290-640
Boiler spectacle plates on upper tail pipes	Alloy C cast		Bearing location	640
Control plug unit – brake friction pad	LW-5		Rubbing	75
Fuel stringer – IC tube insert	Stellite SF-60		Rubbing	725

Table 31 AGR coatings operating at temperatures above 300°C

Coating	Base material	Max temp (°C)	Component
LC-1B	En 58E or F	560	Control rod joint
	BS 1631B	650	Gag orifice, guide bearing, universal joint
	316	650	Gag plug fins
	-	400	Thermal baffle
	-	600	Control rod joints
	BS 1631B	650	Gag orifice
	321	650	Gag drive shaft
	316	650	Fuel assembly
	304	650	Plug unit assembly, gimbal pin and bush
LW-5	BS 1631B	400	I/S guide tube
	321	300	Seal in flux scan penetration
	Mild steel, 316	300	Gag and circulator items, gas bypass bellows
	321	320	SSD tail pipe
	304	400	I/S guide tube adaptor sleeve
LC-2	-	650	Fuelling and controlling rod guide tube
SF50	-	650	Gag drive shaft
Alloy 50	-	370	Core restraint
SF60	18/8	725	Fuel stringer – I.C. tube insert
	304	300	SSD
Alloy C	Mild steel	300	Gag shaft
	316	650	Gimbal joint
	321	750	Control rod
	-	650	Boiler hangers
	-	600	Boiler seals
	-	640	Upper tail pipes
PW-60	304	350	SSD pipework support
Chromised	Mild steel	438	
	316	630	S/H tail tube grid support

FIGURES

Figure 1: **Wear rates of bearing graphites in 'dry' helium**



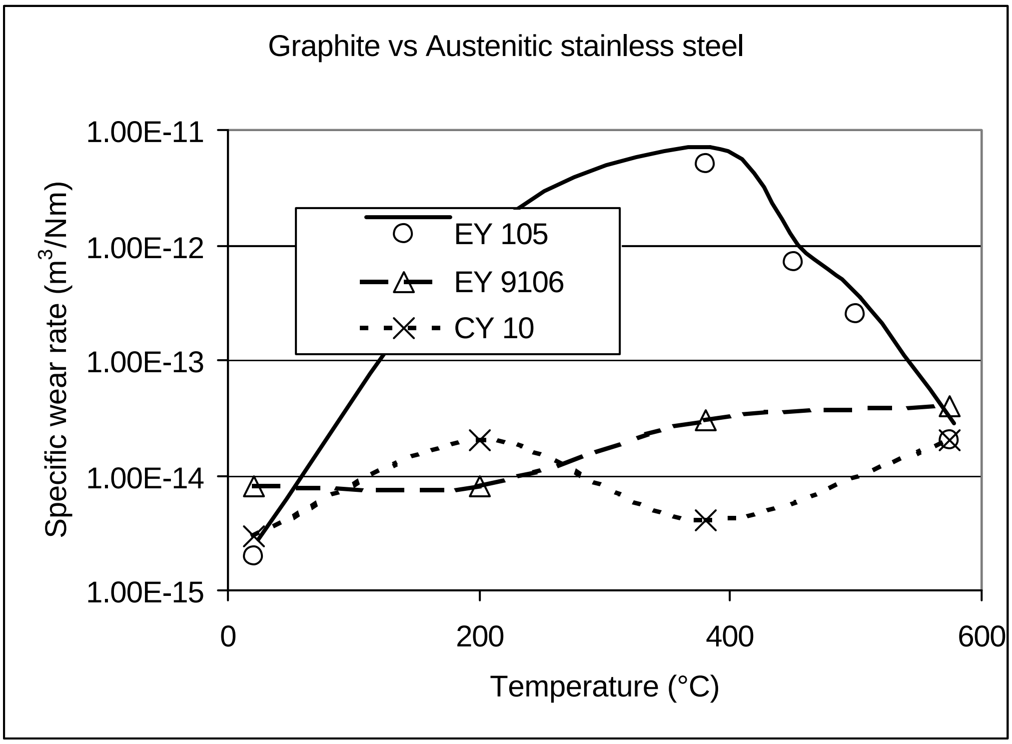
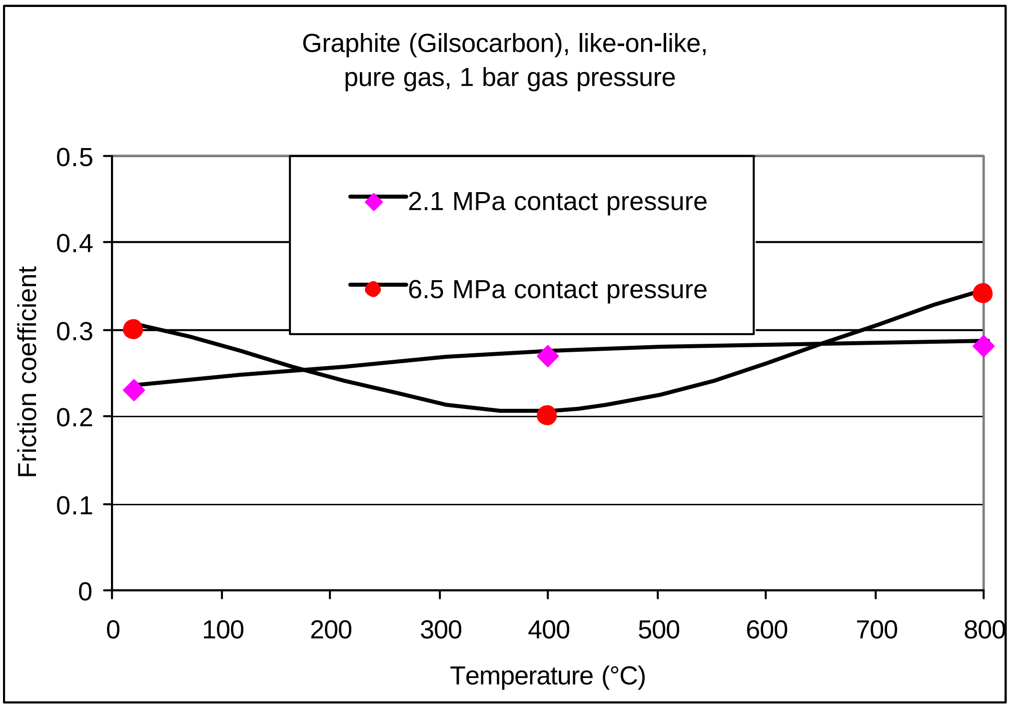


Figure 2: Effect of contact pressure on friction and wear of graphite in helium, 25.4 mm specimen



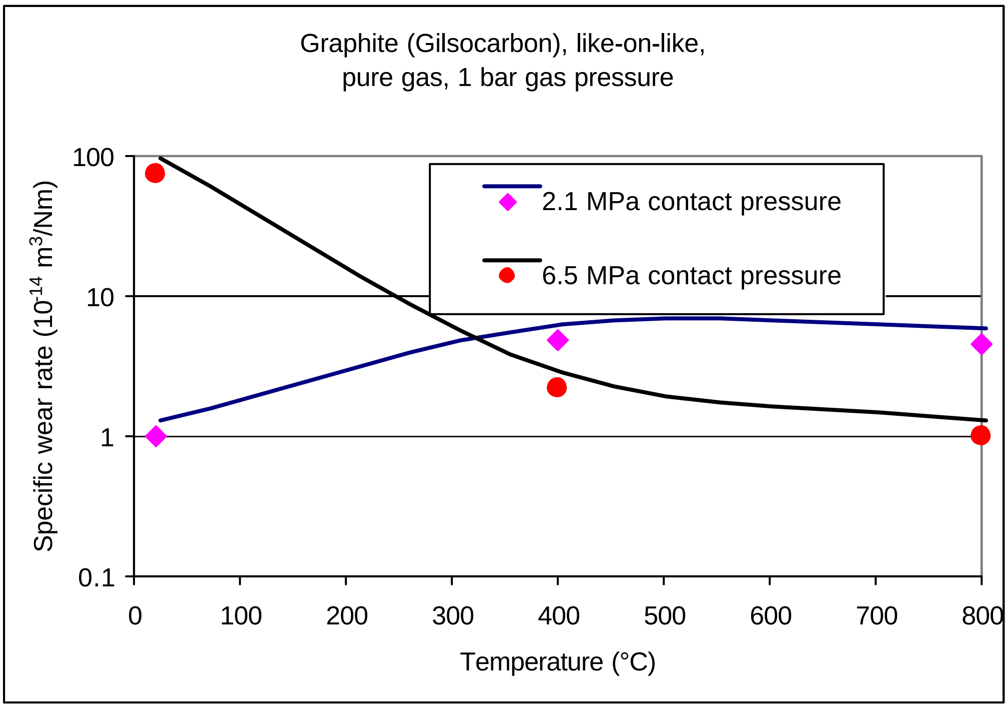
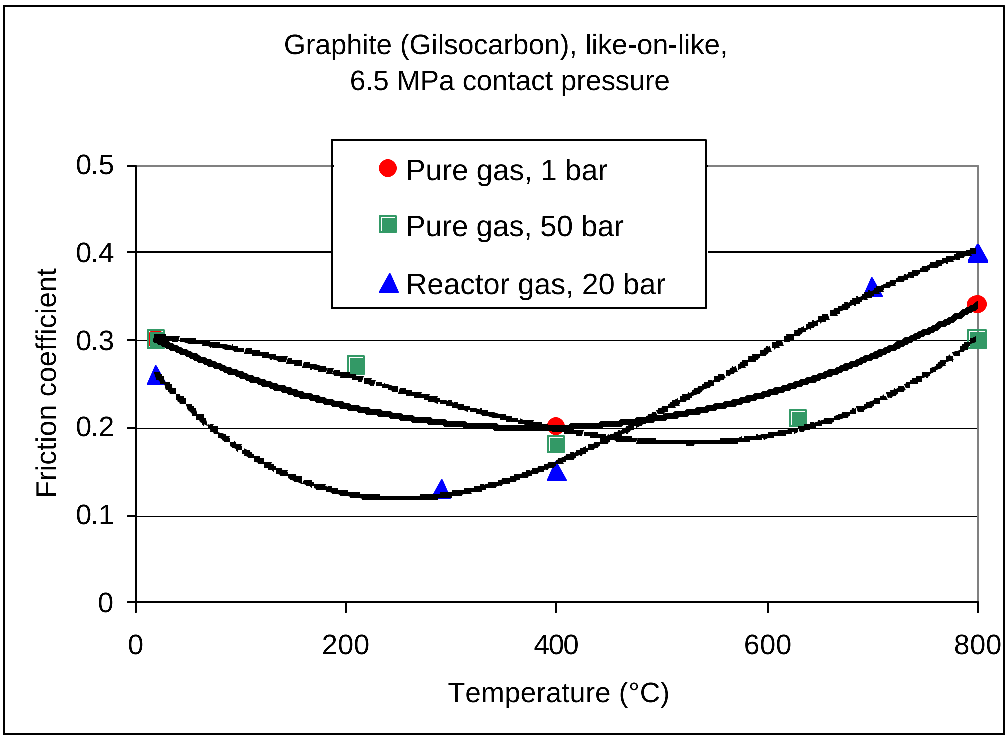


Figure 3: **Effect of gas pressure on friction and wear of graphite in helium, 25.4 mm specimen**



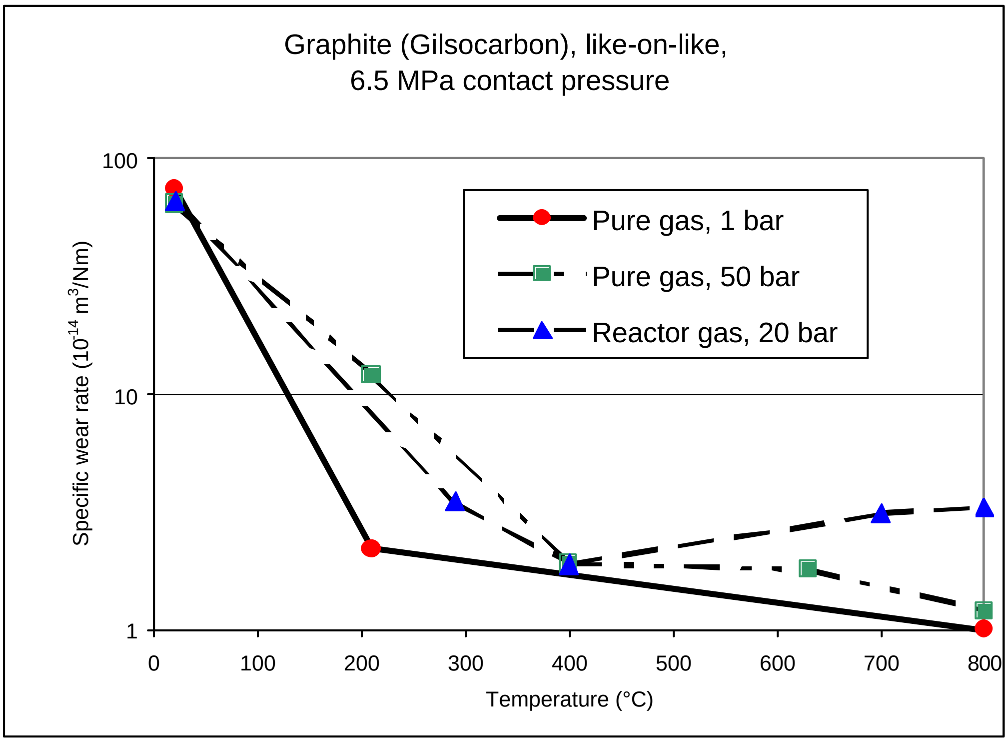


Figure 4: Effect of gas pressure on friction and wear of graphite in helium, 12.7 mm specimen

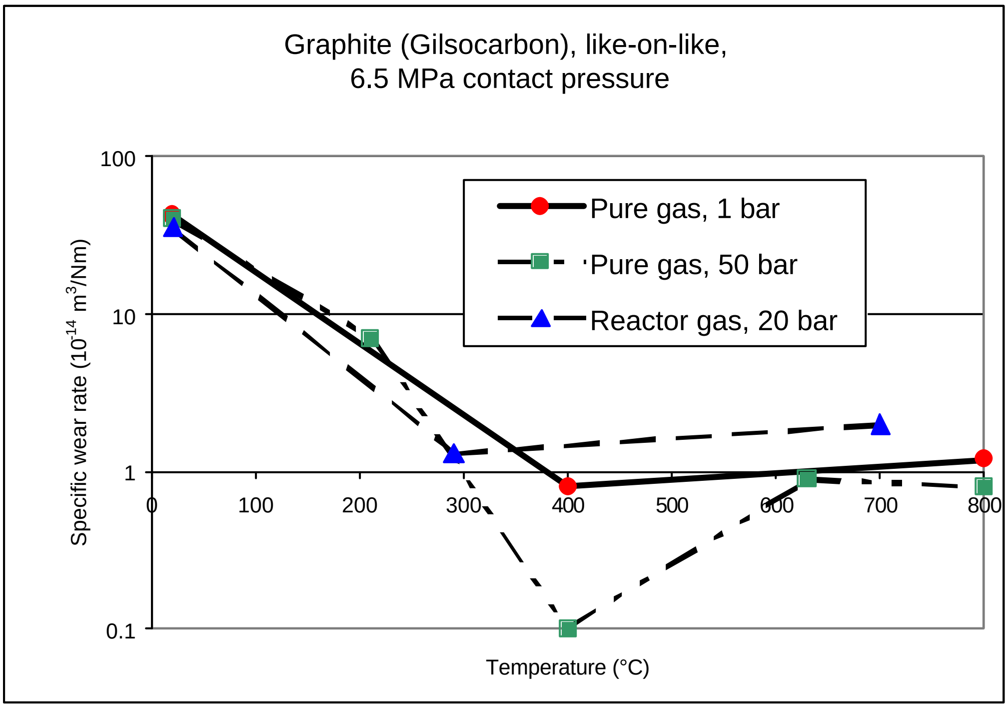
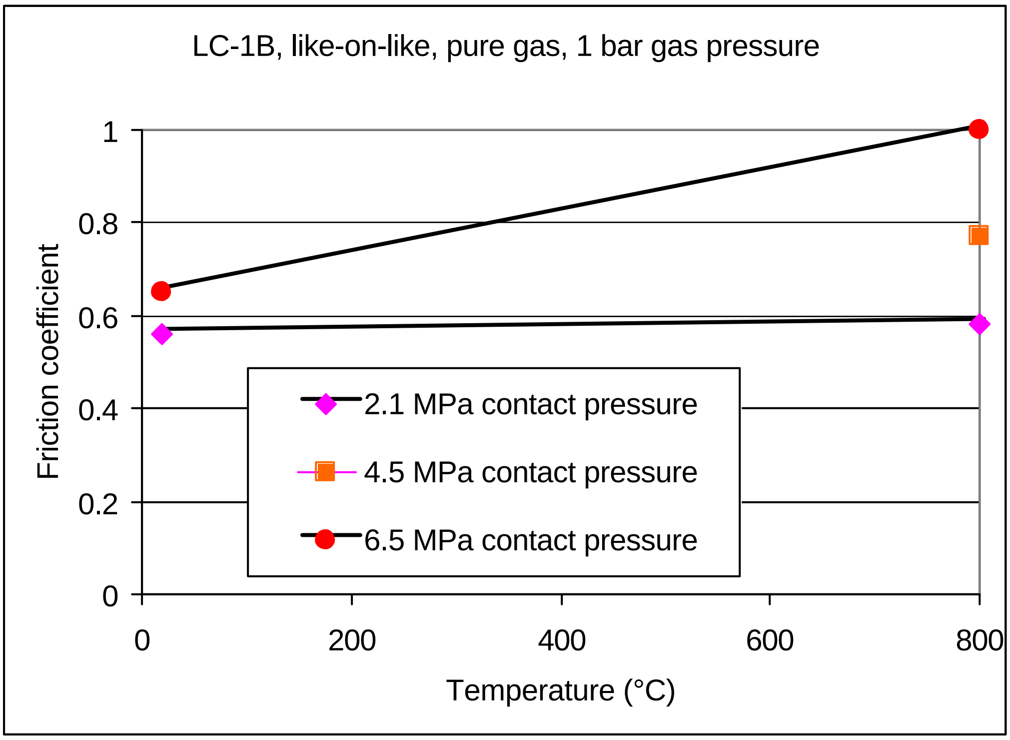


Figure 5: Effect of contact pressure on friction and wear of LC-1B in helium



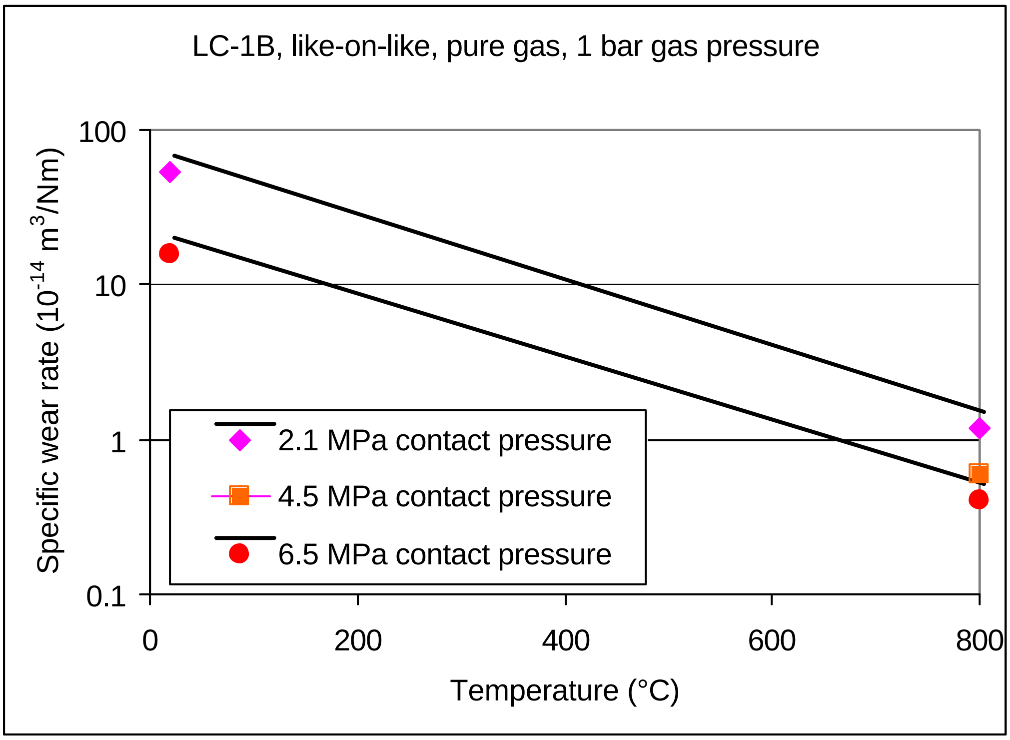
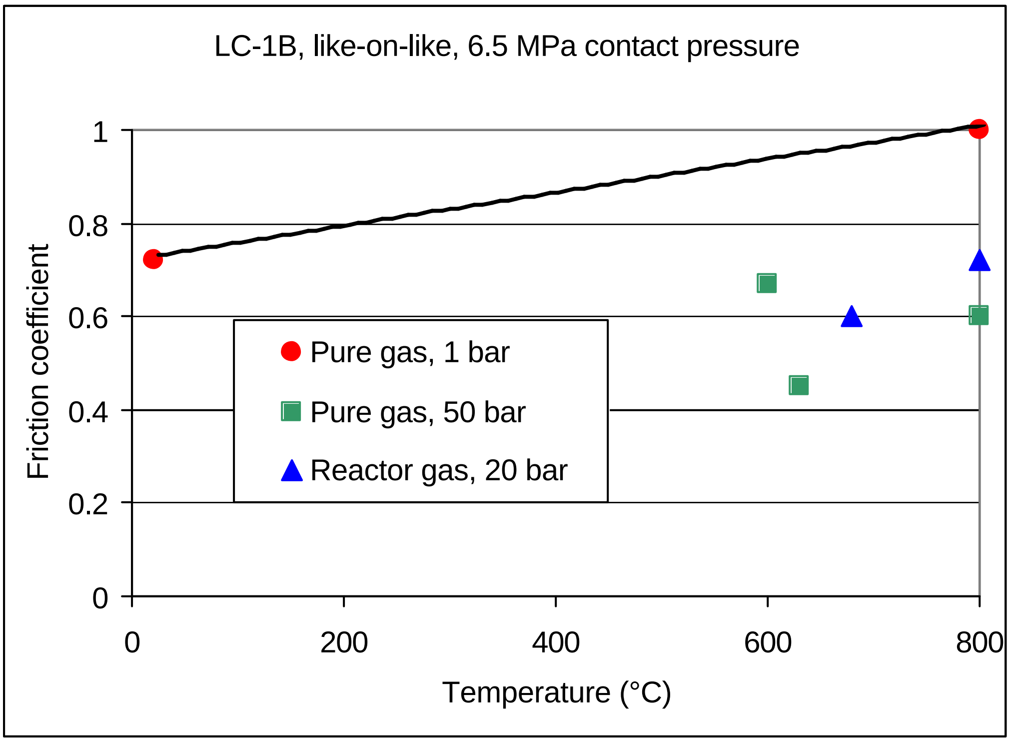


Figure 6: Effect of gas pressure on friction and wear of LC-1B in helium



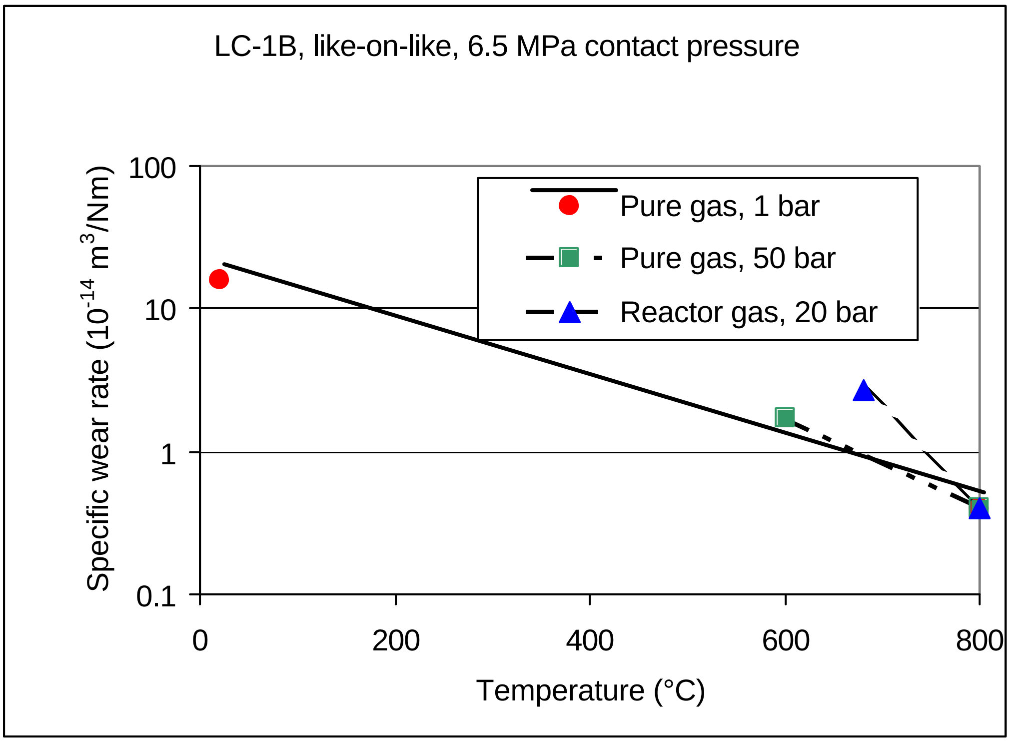
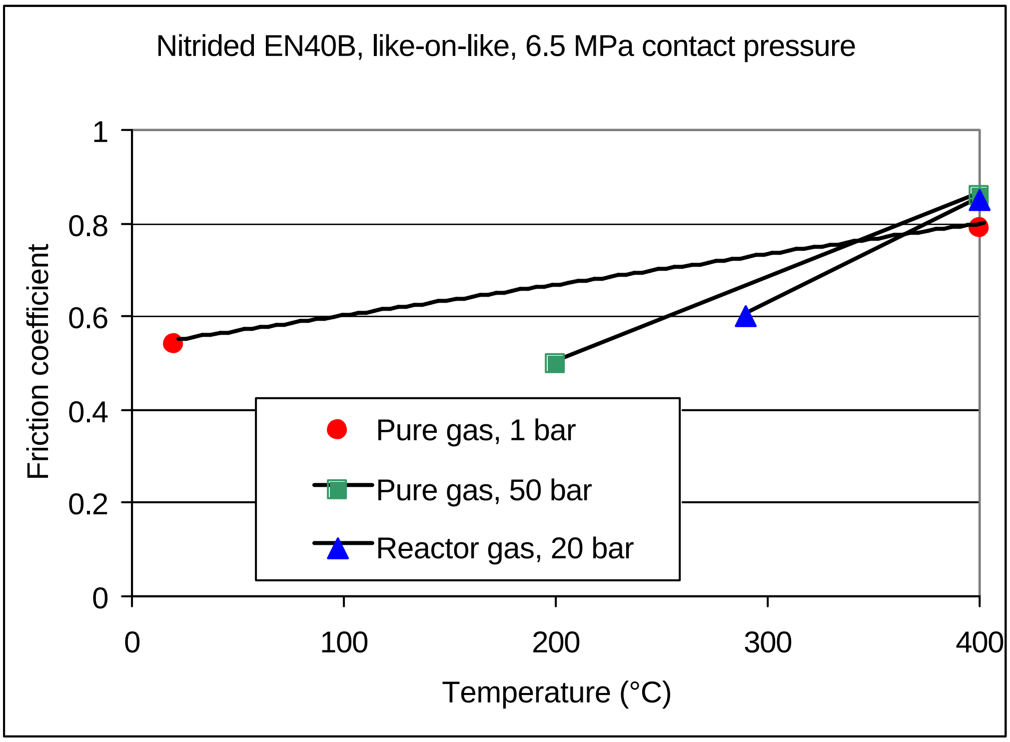


Figure 7: Effect of gas pressure on friction and wear of nitrided En 40B in helium



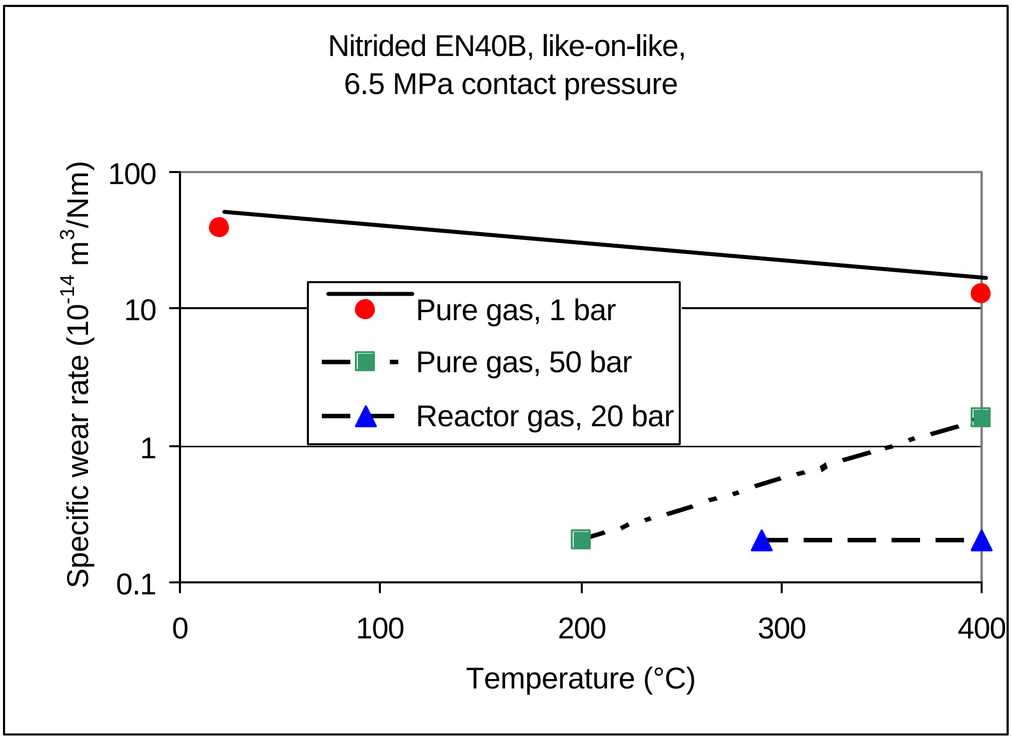


Figure 8 Fretting test data from materials in like-on-like configuration. Tests in air at low pressure.

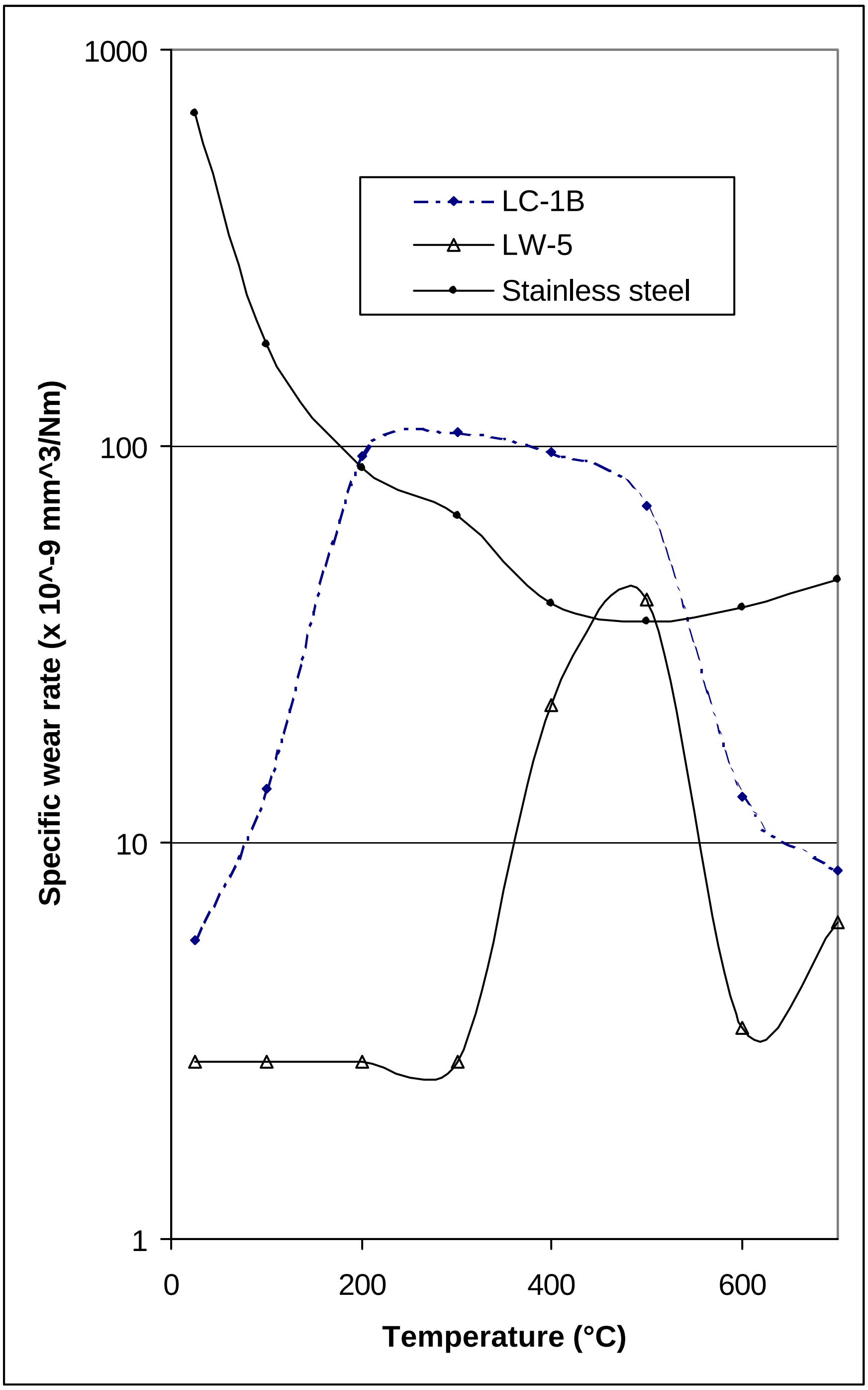


Figure 9 Recommended Design Wear Rates for AGR

Note: A safety factor is incorporated into these values