Materials and Coatings used in the UK AGR and Dragon reactors

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C6940/TR/0004
Issue 01
May 2003

DOCUMENT ISSUE RECORD
(engineering documents)

Adding value through knowledge

Document Title :	Materials and Coatings used in the UK AGR and Dragon reactors
Project Reference:	69401

Purpose of Issue : Interim Draft

Security Class : Commercial-in-Confidence

Issue	Description of Amendment	Originator/ Author	Checker	Approver	Date
		B. Riley	D. Buckthorpe	T. Lennox	

Total number of pages:	Intro:	(i)-(v)	Text	1-9	Tables	T1-T20	Figures	F1-F2	Appendices	

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Distribution: I. Bobin (Framatome), D. Buckthorpe, T. Lennox, B. Riley, File

3050aOct99 Controlling procedure - QP11, QP40 DSC Ref

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Summary

This report covers a review and identification of materials used in the UK Advanced Gas – Cooled Reactor (AGR) and the Dragon. The report contributes to deliverable D39 of the HTR-E Project. The results from this work will assist in establishing a first classification of materials and coatings before further tests are undertaken.

1 Introduction

This report covers a review and identification of materials used in the UK Advanced Gas – Cooled Reactor (AGR) and the Dragon. The report contributes to deliverable D39 of the HTR-E Project.

Coatings have been employed in the Dragon and AGR reactors to confer suitable tribological properties to, principally, austenitic stainless steel and mild steel. Many coatings were incorporated at the design stage and others were introduced to overcome specific problems.

The purpose of this document is to provide where possible available information on the materials and coatings used and the different environmental and tribological conditions (type of contact, contact conditions, loading conditions) experienced. The results from this work will assist in establishing a first classification of materials and coatings before further tests are undertaken.

This document contains the results of work at NNC on Deliverable D38 of the HTR-E Project.

2 Materials and coatings employed in the AGR

2.1 Introduction

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.

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.

2.2 Materials

A list of materials used in AGR, including the heat exchangers, for application at temperatures above 400°C is presented in Table 1 a-f. The list is comprised mainly of austenitic alloys, which suffer from poor tribological performance generally. A wider range of alloy types is employed for heat exchanger tubing, as shown in Table 2. Descriptions of the alloys used for high temperature application in AGR are supplied in Table 3.

2.3 Coatings

2.3.1 Introduction

Hard coatings were used to moderate friction levels and reduce wear in rubbing contact at a range of frequencies. The types of coating employed are described below. Coating compositions are given in Table 4.

2.3.2 Detonation-Gun coatings

Detonation-Gun, or 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.

2.3.3 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.

2.3.4 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.

2.3.5 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.

2.4 Coatings properties (Ref. 6.1- 6.3)

2.4.1 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.

2.4.2 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. 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 Table 5-7.

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 8.

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 9.

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.

2.4.3 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.

2.4.4 Friction, static adhesion and wear

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.

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. 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. Wear rates in $C0_2$ are dependent on temperature, lower rates occurring in high pressure gas.

2.5 Applications of coatings in-reactor

Considerations in the choice of coatings for AGR application are set out in Table 10.

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 11-13. A further list of coatings applied to AGR components is presented in Table 14.

2.6 AGR heat exchangers and circulators

Sliding and, in particular, fretting wear was a widespread problem in the heat exchangers and circulators of early designs of AGR. Design changes and coatings were employed to overcome the problems. The coatings used in three designs of AGR were included in Tables 11-13.

3 Materials and Coatings employed in Dragon

3.1 Dragon heat exchanger materials (Ref 6.4)

Water side corrosion resulted in frequent tube failures in Dragon primary heat exchangers early in its operation. A programme of redesign and manufacture of replacement heat exchangers was carried out. As a result of the failure investigation some heat exchangers were redesigned using Incoloy 800 tubes. The tube bundles in Dragon were clamped to a supporting structure to minimise vibration. In the original heat exchangers with mild steel tubes the clamps were made from stainless steel and the satisfactory performance of this materials combination was confirmed by examination following their removal from the reactor. The change to Incoloy 800 tube material and changes to the bundle geometry necessitated a new clamp design. The material selected was En 16 (manganese-molybdenum steel).

Tests were carried out on the fretting behaviour of heat exchanger tubes and tube clamps at temperatures in the range 425-580°C (Ref 1). The original and replacement materials combinations were tested. Under conditions representative of the cooler section of the heat exchanger both combinations wore similarly, tubes and clamps wearing by similar amounts. In tests more representative of hotter sections (clamp at 600°C, tube at 200-300°C) material was removed from the clamp and deposited on the tube. Both combinations wore similarly.

3.2 Coatings (Ref 6.5-6.12)

During the Dragon Project, friction and wear tests were performed on a range of materials and coatings, under various conditions, to ascertain the effects of helium purity and pressure.

3.3 Friction and wear

A programme of reciprocating sliding tests was conducted. The tests were carried out in pure helium at 0.1 MPa or 5 MPa pressure, or impure (reactor) helium at 2 MPa, at temperatures from 20°C to 800°C. Contact pressures of 2.1 MPa and 6.5 MPa were employed. The partial pressures of the impurities in the reactor helium were as follows. H_2O: 5 Pa, H_2: 50 Pa and CO: 50 Pa.

Materials couples that were tested included the following:

- Chromium carbide (LC-1B), like-on-like

This couple wore severely at 20°C in both atmospheres. With increasing temperature the wear rate fell; at the higher temperatures it was very low. Friction coefficients were moderate, in the range 0.5 - 1.0.

- Deloro Alloy C v Type 316 stainless steel

The performance in all tests was poor. The lowest friction coefficient observed was 1.0. In most tests there was severe galling.

- Tungsten carbide (LW-5), like-on-like; Chromium carbide (LC-2), like-on-like

These combinations were tested in pure helium only, at 0.1 MPa gas pressure and 6.5 MPa contact pressure. Results from the two couples were broadly similar, with friction coefficients around 0.5 at 20°C and 800°C, and with severe wear at the lower temperature but very low wear at 800°C. Following the tests at 800°C, the LC-2 specimens adhered.

- Stellite 6, like-on-like

This couple galled in pure helium at high temperature.

- Nitrided En40B v Type 316 stainless steel

- Chromium carbide (LC-1B) v Type 316 stainless steel

This combination was entirely unsatisfactory at all temperatures in pure helium, galling badly.

Several important conclusions were drawn from the reciprocating sliding tests:

i. No significant or systematic difference was observed between wear behaviour in pure helium and in reactor gas.
ii. In pure helium, no systematic effect of gas pressure was observed.
iii. Of the parameters varied during the tests, temperature had by far the greatest effect, though this was not necessarily the same on both coefficient of friction and wear for the different material combinations.
iv. There was no systematic effect of contact pressure on friction but when wear was high a significant increase with contact pressure was apparent.
v. No materials combination behaved well under all test conditions.
vi. No combination behaved entirely satisfactorily at 20°C.

Results from a further programme of work on alloy couples endorsed the above conclusions. They also showed that the concentration of water, and more significantly, oxygen in the helium had a considerable influence on the coefficient of friction. This was attributed to the formation of lubricating oxide films.

In a HTR, some rubbing interfaces associated with reactor components and structures will move only during temperature cycles or when components are inserted or withdrawn from the reactor. To assess the effect of a dwell, a series of tests were performed in reactor-composition helium at temperatures between 450°C and 750°C on seven materials combinations. Each combination was tested in low speed reciprocating relative motion for 100 cycles and the results were compared with those from tests comprising 5 cycles each day for 20 days. Tests were performed on the following combinations:

i. Deloro Alloy C v AISI 316
ii. AISI 316 v AISI 316; 650°C and 750°C
iii. Nimonic 90 v AISI 316; 650°C and 750°C
iv. Nimonic 90, like-on-like; 650°C and 750°C
v. Chromium carbide LC-1B, like-on-like; 650°C and 750°C
vi. AISI 316 v EYC9106 Graphite; 450-750°C
vii. En40B, like-on-like; 450°C

No materials combination showed an unambiguous difference in friction coefficient between the dwell tests and the continuous tests. Chromium carbide LC-1B, like-on-like, and AISI 316 v EYC9106 also showed no effect of dwell on load. The remainder of the materials pairs, though, showed more severe wear in the dwell tests than in the continuous tests. Most of the wear took the form of transfer of material from one specimen to the other and was attributed to welding during the dwell periods. In rubbing applications where there are small clearances, transferred material could give rise to interference forces between the contacting surfaces and consequently an increase in frictional forces.

3.4 Fretting

Experimental work was carried out to assess the wear damage produced by impact sliding fretting of several combinations of materials. The tests were done at 350°C and 750°C, at frequencies of 75 Hz and 150 Hz in dry, pure helium (<0.1 Pa H_2O) and in reference wet gas (5 Pa H_2O.

The impact fretting behaviour of metal-metal combinations with respect to gas purity and temperature were similar in that the effective specific wear rates were within the range 10^{-13} - 10^{-12} $m^3kg^{-1}m^{-1}$. At 750°C, the wear rates in 'pure' gas were marginally greater than in 'impure' gas. In 'impure' gas, wear rates at 350°C were marginally greater than at 750°C. Long duration (100 h) tests resulted in localised welding between components.

3.5 Static adhesion

The static adhesion of various potential HTR materials was assessed at temperatures in the range 400-800°C in the 'pure' and 'impure' helium atmospheres used for the fretting tests. Materials included stainless steels, mild and low alloy steels, Nimonic alloys, Incoloy 800, hard facing alloys and graphites, alumina and flame sprayed alloys. Dead weight loading was applied to produce an interfacial pressure of 0.3 MPa. Specimen pairs were parted in tension after cooling to ambient temperature in helium.

The results indicated little or no adhesion of materials at 400°C in either of the two atmospheres but between 650°C and 800°C all metallic pairs examined showed adhesion with the exception of Nimonic 90 v En 58J stainless steel. At 650°C adhesion was comparable with that found in carbon dioxide. With increasing temperature, a much higher degree of adhesion was found. The most powerful static adhesion was found in self couples of En 58J stainless steel. After 1000 h exposure at 800°C a parting pressure of 7 MPa was required.

4 Coatings applied to gas turbine components (Ref. 6.13)

Hard coatings, mostly applied by Detonation-Gun and plasma spraying, are used on hundreds of parts in production aircraft gas turbines. Praxair is a leading company in the supply of coating services to the aerospace industry. They supply a comprehensive range of coating types for different temperature applications. An indication of the different types of coating which have been applied within various parts of the gas turbine is given in Tables 15 and 16.

5 Coatings recommended for HTR

Results from AGR and Dragon verify the recommendation of D37 for the use of Cr_3C_2/Ni-Cr cermets at temperatures of 600-700°C. UK experience has shown that this type of coating also finds effective utilisation at temperatures down to 350°C, below which WC/Co cermets are favoured.

6 References

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Table 1a Materials used in the AGR reactor, $T \geq 400$°C

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 1b Materials used in the AGR reactor, T ³ 400°C

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 1c Materials used in the AGR reactor, T ³ 400°C

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 1d Materials used in the AGR reactor, T ≥ 400°C

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 1e Materials used in the AGR reactor, T ^{3} 400°C

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 1f Materials used in the AGR reactor, T ³ 400°C

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 2 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 3 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 4 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 5 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 6 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 7 LC-1B vs another: friction and wear data at reactor gas pressure

Materials A	Materials B	Temp (°C)	Gas	Specific wear rate (10^{-9} mm^3 N^{-1} mm^{-1}) A	Specific wear rate B	Friction coefficient Mean	Friction coefficient Max	Comments
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 8 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	EN4 mild steel	20	CO_2	1.6	72	0.9	1.0	
LW-5	EN4 mild steel	205	CO_2	2.2	410	0.9	0.9	
LW-5	EN4 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 9 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	
EN58B	SF60	200	AGR	64	37	1.15	1.3	
EN58B	SF60	450	AGR	0.8	7	0.35	0.8	
EN58B	SF60	550	AGR	1.0	11	0.95	1.4	
EN58B	SF60	650	AGR	8.4	62	0.75	0.9	

Table 10 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 $x10^{-15}$	Good	Good	Low substrate heating during deposition. Surface finishing usually not required.
LW-5 vs LW-5	0.75 ± 0.09	5 $x10^{-15}$	-	-	Low substrate heating during deposition. Surface finishing usually not required. Not used above 300°C.
SF60 vs SF60	0.48 ± 0.24	2 $x10^{-15}$ – 2 $x10^{-14}$	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 EN58B (17/20 Cr, 7/10 Ni)	0.61 ± 0.25	5 $x10^{-12}$	Poor	Poor	Best combination involving stainless steel.

Table 11 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 EN40B (3 Cr-Mo)	Sliding	280

Table 12 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	EN58B (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	EN58B (17/20 Cr, 7/10 Ni)	300
Core restraint	Stellite Alloy 50		350
Hot box labyrinth seal	LW-5		280

Table 13 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 14 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

Table 15 Coatings applied to gas turbine components in the compressor section, T < 1000°F (538°C)

Components	Coated area	Tribological problem	Coating type
Fan and compressor blades	Shroud pads	Fretting	Tungsten carbide/cobalt
Fan and compressor blades	Root section pressure faces	Galling	Copper-nickel-indium
Variable vane trunions, drive arms, bearings, etc	Bearing surfaces	Fretting	Tungsten carbide/cobalt
Compressor hubs	Bearing journal diameters	Fretting	Tungsten carbide/cobalt
Compressor blades	Airfoils	Particle erosion	Tungsten-titanium carbide/nickel, tungsten carbide/cobalt, titanium nitride
Compressor hubs and discs	Snap diameters	Fretting	Tungsten carbide/cobalt
Expansion joints	Sealing surfaces	Sliding and fretting	Tungsten carbide/cobalt
Diffusers and impellors	Vane surfaces	Particle erosion	Tungsten-titanium carbide/nickel, tungsten carbide/cobalt, titanium nitride
Bearings	Sealing surfaces	Sliding	Chromium carbide/nickel-chromium, tungsten carbide/cobalt,
Bearings	Sealing surfaces	Fretting	Tungsten carbide/cobalt
Gears	Bearing surfaces and journals	Fretting	Tungsten carbide/cobalt
Labyrinth seal fins	Knife edge tips and face	Rubbing	Tungsten carbide/cobalt, chromium carbide/nickel-chromium, aluminium oxide

Table 16 Coatings applied to gas turbine components in the combustion and turbine sections, T > 1000°F (538°C)

Components	Coated area	Tribological problem	Coating type
Combustion chamber positioning pins and bushes	Bearing surfaces	Fretting	Tungsten carbide/cobalt, chromium carbide/nickel-chromium
Fuel nozzle and swirler	Bearing surfaces	Fretting	Chromium carbide/nickel-chromium
Fuel nozzle and swirler	Threads	Loosening	Copper-nickel-indium
Combustion chamber	Interior surfaces	Thermal barrier required	Duplex McrAlY/partially stabilised zirconia
Turbine blades	Unshrouded tip	Rubbing	Cobalt alloy cermet (with alumina dispersion)
Outer airseals	Sealing surfaces	Rubbing	Cobalt alloy
Outer airseals	Sealing surfaces	Thermal barrier required with erosion resistance	Duplex McrAlY/partially stabilised zirconia
Turbine stator shrouds	Shroud flanges	Fretting	Chromium carbide/nickel-chromium, cobalt alloy cermet (with alumina dispersion)
Turbine vanes	Inner-foot pads	Fretting	Chromium carbide/nickel-chromium, cobalt alloy cermet (with alumina dispersion)
Exhaust fairing pins and bushes	Bearing surfaces	Fretting	Tungsten carbide/cobalt

Figure 1 Fretting test data from materials in like-on-like configuration. Tests in air at low pressure.

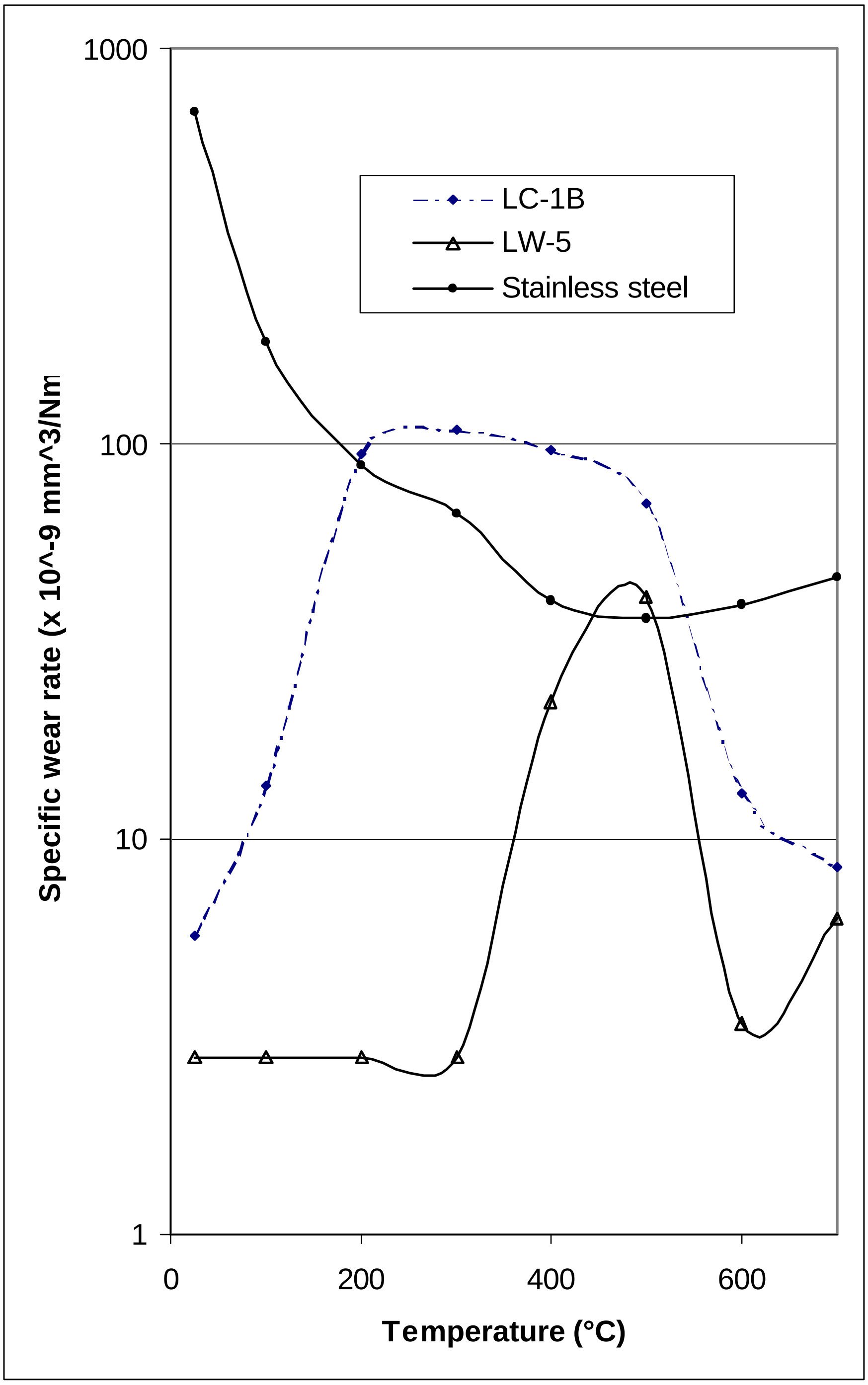

Figure 2 Recommended Design Wear Rates

Note: A safety factor is incorporated into these values