# Performance of NOREM™ Hardfacing Alloys

**TR-112993**

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# REPORT SUMMARY


The iron-base hardfacing NOREM™ alloys provide outstanding resistance to galling (adhesive) wear and cavitation erosion wear. This report summarizes key results from the many evaluations of NOREM alloys and provides information about current applications in nuclear, hydroelectric, and fossil generating plants. It also identifies possible limits on NOREM use in critical nuclear plant valves.

## Background

EPRI developed the iron-base NOREM hardfacing alloys to serve as a generic substitute for the cobalt-base Stellite™ alloys in nuclear valve applications. When used in place of Stellite, NOREM alloys reduce a source of cobalt that contributes to nuclear plant personnel exposure to ionizing radiation. Wide-ranging industry evaluations have revealed other potential applications of NOREM alloys, and a number of utilities have implemented demonstrations that take advantage of other alloy attributes.

## Objectives

- To compile in a single document key attributes of the NOREM hardfacing alloys obtained from laboratory evaluations, tests of valves with NOREM hardfacing in loop facilities designed to simulate reactor operating conditions, and plant applications.
- To identify the use of NOREM alloys in operating power plants and any limitations, especially in critical nuclear valve applications.

## Approach

The author reviewed reports describing the performance of the NOREM and Stellite hardfacing alloys and summarized and compiled key results. Information reviewed included diverse laboratory evaluations of wear and corrosion resistance, friction coefficient measurements, and weldability evaluations. The author also summarized information about valve and NOREM performance, deduced from valve testing in loop facilities operating under simulated commercial reactor conditions. Finally, the author compiled information about NOREM field performance, including the following areas: 1) valves with NOREM hardfacing that were placed in service in commercial nuclear reactors, 2) hydroelectric repair applications, and 3) other plant applications.

## Results

NOREM is "welder friendly," with various product forms (powder, rod, and wire) easily deposited on carbon and stainless steel substrates using conventional welding practices. Welding is the application method of choice for nuclear plant applications. Other applications of hardfacing alloys make use of non-fusion processes, such as thermal spray technology, to effect

mechanical bonding between the hardfacing and the substrate. A laser, rather than a conventional welding torch, can also be used as a heat source to deposit hardfacing alloys.

The response of NOREM was equal to or better than that of the long-established Stellite hardfacing alloys in a wide range of laboratory evaluations. These results were confirmed by tests of valves subjected to extensive stroke cycling in loop facilities simulating commercial nuclear reactor conditions. The results of all evaluations are consistent, with two exceptions. First, NOREM tested against itself was inferior to Stellite 6 in friction coefficient and galling susceptibility measurements, performed by Battelle Columbus Laboratories, using specimens characterized by large contact areas and long stroke lengths (EPRI report TR-109655). Second, leak rates were higher than a standard specified by Electricité de France (EdF) in a 6-in gate test, conducted under simulated PWR operating conditions (TR-109345).

Plausible explanations exist for the response of NOREM in these two tests, but the results suggest caution is appropriate when specifying NOREM for use in large gate valve applications in nuclear power plants. NOREM is suitable as a substitute for cobalt-base hardfacing alloys in all nuclear plant stop and swing check, globe, and butterfly valves. NOREM is also acceptable for use in repairing gate valve discs, provided Stellite is used for the valve seat. Valves with NOREM trim have performed satisfactorily when placed in service in any nuclear plant, and the alloy was used successfully to perform an in situ repair of a large 24-in feedwater check valve at Grand Gulf BWR.

In hydroelectric applications, NOREM performed well in field repair of hydroturbine runners. It also exhibited lower wear than duplex stainless steel in tests at BC Hydro’s Gordon Shrum Station, though the optimum deposit chemistry was not used. While NOREM has seen limited service in fossil plant valves, no evaluations are yet available.

## EPRI Perspective

This report will help make utility personnel aware of possible uses of NOREM hardfacing alloy for replacement and repair applications in nuclear, fossil, and hydroelectric plants. Detailed discussions of the range of applications for nuclear plant valves are provided in EPRI’s *Compilation and Evaluation of NOREM Test Results: Implications for Valve Applications* (TR-109343). NOREM is the leading candidate for replacing cobalt-base hardfacing alloys in the U.S. naval nuclear program. In addition, Taiwan Power is using NOREM in a significant number of valves to be installed in two new BWRs. EdF plans additional tests of valves with NOREM hardfacing in its loop facilities.


## TR-112993

## Keywords

Wear-resistant materials
Radiation buildup
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# ACKNOWLEDGEMENTS

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# 1 INTRODUCTION

Limiting the exposure of plant maintenance personnel to ionizing radiation is a long-standing goal of the nuclear industry. Measurements of deposited activity on component surfaces in contact with the primary coolant show the largest contributor to personnel exposure is the gamma-emitting isotope, Co-60. One major source of the Co-59 isotope that is the sole precursor of Co-60 is wear and corrosion of the cobalt-base alloys sold under the Stellite™ name. These alloys have long been used in nuclear plants as a hardfacing on valves and other components that are subjected to demanding wear conditions. The selection of cobalt-base hardfacing alloys for use in the earliest nuclear plants was based on observations that these alloys performed well in similar applications in other industries, but evidence that released cobalt played such a major role in contributing to worker exposure came later.

Budinski [1] notes that parts wear by various mechanisms, but before one can identify a potential solution it is first necessary to pinpoint the type of wear causing the problem. While hundreds of terms are used to describe various wear effects, it is possible to reduce wear processes into four main categories:

- Adhesive wear is loss of material or transfer of material from solid surfaces in relative motion. When surfaces are in intimate contact at high stresses a severe form of adhesive wear, designated galling, can occur. Oscillatory movement of small amplitude between two solid surfaces can cause fretting wear, a type of adhesive wear.
- Erosive wear is loss of material from a solid surface due to the mechanical interaction between that surface and a fluid or impinging fluid stream.
- Abrasive wear is produce by hard particles or protuberances that are forced against and move along a solid surface, the abrasive agent being harder than the surface being damaged.
- Surface fatigue, which results in fracture of material from a solid surface, is caused by cyclic stress produced by repeated rolling or sliding on a surface.

One advantage of this classification scheme is that relatively simple laboratory tests can be used to evaluate and compare the ability of new and established materials to resist various types of wear damage.

Laboratory measurements of sliding (adhesive) wear resistance showed that the commercially available nickel-base alloys on the market in the early 1980's were indeed inferior to the cobalt-base ones [2]. This led EPRI to sponsor a program to develop a hardfacing alloy with attributes that would match those of the long-established cobalt-base alloys. The initial focus was on developing an alloy resistant to adhesive wear that would serve as a generic substitute for the Stellites in nuclear plant valves.

This report summarizes the key evaluations that have been performed on the NOREM hardfacing alloys, the range of valve designs that have currently been purchased and installed by nuclear utilities, and possible concerns about the use of NOREM in nuclear plant valves. Other laboratory evaluations have shown NOREM is resistant to wear damage caused by other mechanisms. This report summarizes the encouraging results from these other types of wear tests and also the nature and the field applications that put these attributes to use. Penetrating the hardfacing market demands that suitable techniques for depositing hardfacing alloys in the shop and in the field be developed, and the successes in developing welding and thermal spray techniques for the NOREM alloys will first be presented.

# 2
# NOREM ALLOY DEVELOPMENT

EPRI's program to develop an alloy that would provide an alternative to the cobalt-base Stellites started in 1984 and evaluated a number of iron-base alloys in an extensive series of laboratory experiments. The primary focus was on identifying alloys that would be resistant to adhesive (galling) wear under high-applied stresses. This is the type of wear encountered when valve components, such as discs and seats, make contact. It is the outstanding ability of the cobalt-base alloys to resist this type of wear damage that makes them the standard for use in valves subject to demanding operating conditions, and it is resistance to adhesive wear that has proven most difficult to obtain in alloys that do not contain cobalt.

Building on some promising developments described by Schumacher [3], EPRI's program identified iron-base alloys with galling wear resistance matching that of the Stellites [4]. These alloys were subsequently trademarked under the name NOREM. Most of these early evaluations were performed on castings, but the encouraging results led to the development of techniques for depositing the better-performing compositions by plasma transferred arc welding (PTAW). The early NOREM specimens produced by PTAW were found to be more galling resistant than castings of similar composition.

In addition to extensive laboratory evaluations, the NOREM alloys have been evaluated by depositing them on valves that were tested in loop facilities where they were subjected to operating conditions designed to simulate those found in commercial nuclear power plants. Three-inch gate valves were tested by Atomic Energy of Canada, Ltd., and a six-inch gate valve was tested by Electricité de France. The main goal in these tests was to obtain information about the ability of the valves to maintain their sealing capabilities after many opening and closing cycles, but other valuable information was obtained in these tests.

# 3
# APPLYING THE NOREM ALLOYS

Hardfacing alloys are deposited by any number of welding processes, because welding is a fusion process that leads to a sound metallurgical bond between the hardfacing and the substrate. Welding is the application method of choice for nuclear plant applications. Other applications of hardfacing alloys make use of non-fusion processes, such as thermal spray technology, to effect mechanical bonding between the hardfacing and the substrate. This section will briefly summarize results from the extensive welding evaluations using conventional welding processes, laser deposition and thermal spray deposition.

## Plasma Arc Welding

NOREM welding products and procedures were developed for gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), shielded metal arc welding (SMAW), and submerged arc welding (SAW). The GMAW process is desirable because of its ability to be automated and for its high deposition rates. The SMAW process is of particular interest because of its inherent flexibility and simple equipment requirements. The submerged arc welding (SAW) process is desirable for single layer manufacturing applications with high production rates. The goal was to deposit multi-layer defect free overlays on carbon and stainless steel substrates with no loss in the attributes achieved with powder deposited by plasma transferred arc welding (PTAW).

Many NOREM variants were evaluated to meet the two demanding challenges of performing such repairs without the need for preheating the substrate and being able to deposit at least two sound, defect-free layers. These goals were met with NOREM variants with lower levels of silicon, manganese, and nitrogen than was present in earlier versions. However, adhesive (galling) wear tests confirmed that these chemistry changes had little effect on this attribute. Compositions that were easy to weld but which did not show good performance in galling wear tests were deemed unacceptable. These new versions show resistance to galling wear exceeding that of Stellite 21, the cobalt-base version typically used in nuclear plants to perform valve repairs. These compositions show resistance to galling wear comparable to that of Stellite 6. NOREM chemistry specifications for various welding processes are given in Table 3-1. The compositions of the best-performing of two earlier NOREM variants (01 and 04) that were used to hardface valves that were tested in a loop facility operated by Atomic Energy of Canada, Ltd., are given in Table 3-2, together with other compositions that were investigated to improve the alloy's weldability.

**Table 3-1**
**Current NOREM Product Chemistry Purchase Specifications**

| Alloy Designation | Process | C | Si | Cr | Mn | Ni | Mo | N | P | S | B | O | Application |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 02 | PTAW | 1.1-1.35 | 3.1-3.5 | 23-26 | 4.0-5.0 | 3.7-5.0 | 1.8-2.2 | <0.18 | <.020 | <.010 | <.002 | <200 ppm | Galling |
| 02A | GTAW | 1.1-1.35 | 3.1-3.5 | 23-26 | 4.0-5.0 | 3.7-5.0 | 1.8-2.2 | <0.06 | <.020 | <.010 | <.002 | <200 ppm | Galling |
| 03A | GMAW | 0.9-1.2 | 2.4-3.2 | 20-23.5 | 3.5-4.5 | 4.0-5.0 | 1.7-2.2 | <0.1 | <.02 | <.01 | <.006 | <200 ppm | Galling |
| 03B | GMAW | 0.7-1.1 | 2.2-3.0 | 20-24 | 3.0-4.0 | 4.0-5.5 | 1.7-2.2 | <0.1 | <.02 | <.01 | <.006 | <200 ppm | Cavitation/Erosion |
| 04A | SMAW | 0.9-1.2 | 2.4-3.2 | 20-24 | 4.0-5.0 | 3.7-5.0 | 1.7-2.2 | <0.1 | <.02 | <.01 | <.006 | <200 ppm | Galling |
| 04B | SMAW | 0.7-1.1 | 2.2-3.0 | 20-24 | 3.0-4.5 | 3.5-5.5 | 1.7-2.2 | <0.1 | <.02 | <.01 | <.006 | <200 ppm | Cavitation/Erosion |
| 05A | SAW | 1.0-1.3 | 2.4-3.2 | 20-23.5 | 4.0-5.0 | 3.5-5.0 | 1.7-2.2 | <0.1 | <.02 | <.01 | <.006 | <200 ppm | Galling |
| 05B | SAW | 0.8-1.2 | 2.2-3.0 | 20-24 | 3.5-4.5 | 3.2-5.5 | 1.7-2.2 | <0.1 | <.02 | <.01 | <.006 | <200 ppm | Cavitation/Erosion |

Notes:

1 Undiluted weld metal chemistry on CS with 100% argon gas shielding.
2 Undiluted weld metal chemistry on CS with 75/25 Ar/CO2 gas shielding.
3 Undiluted weld metal chemistry on CS substrate.
4 Undiluted weld metal chemistry on CS substrate.

These welding studies also demonstrated that NOREM can be used to repair defects in Stellite 6 weld overlays. This information is summarized in Welding Procedure Guidelines for NOREM that provide the guidance necessary to qualify welding procedures to the requirements established in the ASME Boiler and Pressure Vessel Code, Section IX. Such guidelines have been developed for a number of manual and machine welding processes for deposition on carbon and stainless steel substrates. These guidelines also include information to insure that users can order high-quality welding consumables from the organizations licensed to produce NOREM products. These evaluations demonstrated the importance of keeping the content of residual impurities at levels as low as practical and ensuring there are no contaminants on the surface of the welding consumables [5].

A number of valve manufacturers, valve service organizations, and nuclear utilities also have qualified welding procedures for these new NOREM variations. Typically, three or more layers have been successfully deposited on carbon and stainless steel without using preheating or butter layers. However, when depositing NOREM in-situ on all cast or wrought substrates other than stainless steel, a butter layer should be used. Preheating should be used at the discretion of the utility and vendor.

**Table 3-2**
**Earlier NOREM Alloy Compositions**

| Alloy Designation | Process | C | Si | Cr | Mn | Ni | Mo | N |
|---|---|---|---|---|---|---|---|---|
| 01 | PTAW | 1.00 | 3.30 | 25.00 | 9.30 | 4.02 | 2.0 | 0.10 |
| 04 | PTAW | 1.05 | 5.17 | 24.81 | 12.0 | 8.05 | 1.96 | 0.23 |
| M2 | laser | 1.2 | 3.0 | 25.1 | 3.2 | 7.9 | 1.8 | NA |

Note: Powder analysis from the mill certificate

## Laser Deposition

A laser, rather than a conventional welding torch, can be used as a heat source to deposit hardfacing alloys. One potential advantage of laser welding is that it lowers weld-induced residual stresses, thereby lowering the propensity for cracking. A second advantage is that a laser lowers dilution (intermixing) of the hardfacing and the substrate, which could reduce the number of deposited layers that would be required to achieve the desired wear resistance. A Nd:YAG laser system was used to evaluate the potential for depositing NOREM M2 and Stellite 21 weld wire. The feasibility of using this approach was demonstrated [6]. Sound deposits were obtained, and the galling wear resistance of laser-deposited overlays was similar to those obtained using conventional welding techniques.

## Thermal Spray Deposition

Praxair Surface Technologies deposited NOREM using thermal spray technology. Powder was manufactured by vacuum induction melting and argon gas atomization. The Super D-Gun™ coating technology was used to deposit the powder. The coating, which met the NOREM chemistry specification, exhibits a lamellar structure, typical of all thermal spray coatings. The apparent porosity of the coating based on metallographic evaluations is less than 0.5%. These examinations showed slight oxidation occurred during the coating operation, indicated by dark lamellar inclusions in the deposit. The bond strength was >10,00 psi, which was measured by using ASTM procedure C-633.

# 4
# ALLOY STRUCTURE

NOREM is an iron-base alloy. X-ray diffraction data and metallographic examinations show a solid-solution strengthened austenitic matrix with a continuous network of eutectic $M_7C_3$ and non-eutectic ($M_6C$ and $M_3C$) carbides at the grain boundaries. Representative microstructures of weld overlays obtained using the current alloy formulations (Table 3-1) and standard welding practice are shown in Figures 4-1and 4-2.

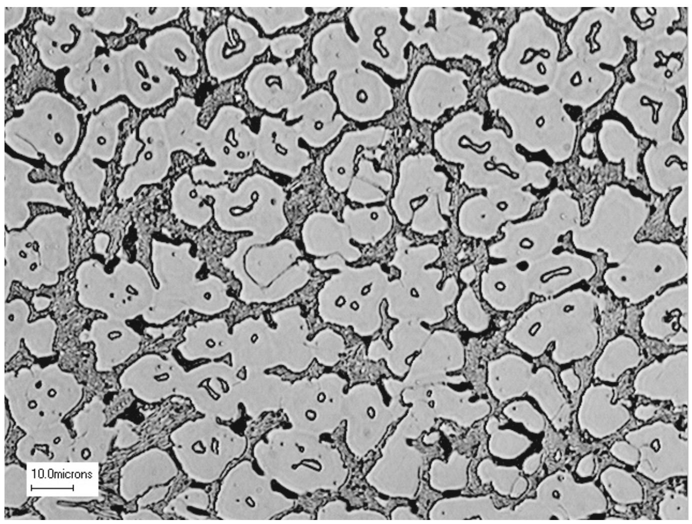


**Figure 4-1**
**Microstructure of NOREM 02 Deposited by Plasma Transferred Arc Welding (third layer of deposit ~500x)**

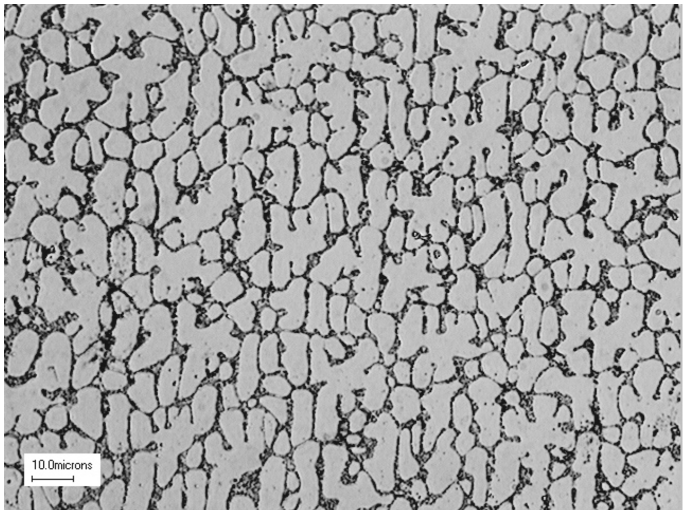


**Figure 4-2**
**Microstructure of NOREM 02A Deposited by Gas Tungsten Arc Welding (third layer of deposit ~500x)**

# 5
# WEAR MEASUREMENTS—LABORATORY EVALUATIONS

## Galling (Adhesive) Wear Measurements

Resistance to adhesive (galling) wear is an important attribute if valves subjected to high load are to perform effectively. This is the type of wear encountered when valve components, such as discs and seats, make contact. Excessive wear and galling of valve sliding surfaces, especially seats and disks, can lead to unacceptable increases in leakage or to valve malfunction. It is the outstanding ability of cobalt-base alloys to resist this type of wear damage that makes them the standard for use in valves subject to demanding operating conditions, and it is resistance to adhesive wear that has proven most difficult to obtain in alloys that do not contain cobalt.

Galling wear tests were performed at the AMAX Research Center (where the NOREM alloys were developed) and later at EPRI's Repair and Replacement Applications Center (RRAC) using a procedure based on ASTM standard G 98-91. Tests were performed in air and deionized water on cast specimens and weld overlays where both the pin and the plate were overlaid with the same alloy. The diameter of the pin used in the tests at these two laboratories was 0.375″. The wear test surfaces were ground and machined to a surface finish of $R_a$<0.4 µm arithmetic average measured normal to the grinding direction. The test procedure consisted of loading the surface of the pin specimen against the plate specimen using a modified bearing press. Such pin-on-plate tests are a common method for demonstrating the relative galling resistance of hardfacing alloys. The imposed stresses were 20, 40 and 60 ksi (140, 275 and 415 MPa). The pin specimen was rotated manually around its vertical axis through 120 degrees, ten times in alternate directions. After completing the test, the degree of damage was determined from surface profilometry using average peak-to-valley surface roughness measurements. The surface profile was obtained from each circular wear scar on the test plate in directions both perpendicular to the original grinding marks and then averaged. Tests were performed in deionized water typically at ambient temperature. Some pin on plate galling wear tests were later performed at RRAC at a temperature of 200 F in deionized water.

Table 5-1 shows that the galling wear resistance of the various NOREM compositions tested closely approximates or exceeds that of the cobalt-base Stellite 6 and 21 alloys [7]. The galling wear resistance of laser-deposited weld overlays is similar to that of overlays deposited by using conventional welding processes. The data in Table 5-1 also show that the galling resistance of both alloys is also significantly higher than of the most common nickel-base hardfacing alloys that have been used in nuclear plant valves.

**Table 5-1**
**Pin-on-Plate Galling Wear Tests**

| | Surface Damage (µm) at Indicated Stress (ksi) | | | | | |
|---|---|---|---|---|---|---|
| | **air** | **air** | **air** | **water** | **water** | **water** |
| | **20** | **40** | **60** | **20** | **40** | **60** |
| *Cobalt-base alloys* | | | | | | |
| Stellite 6/PTAW | 1.9 | 2.1 | 2.0 | NA | NA | NA |
| Stellite 6/PTAW | 2.2 | 2.6 | 2.8 | 1.1 | 1.7 | 1.6 |
| Stellite 6/GTAW | 0.6 | 1.2 | 1.8 | 0.4 | 0.6 | 0.9 |
| Stellite 21/GTAW | 0.9 | 1.7 | 1.2 | 0.4 | 0.9 | 1.2 |
| Stellite 21/GTAW | 1.3 | 1.9 | 2.4 | 0.5 | 1.0 | 1.5 |
| Stellite 21/laser | 0.7 | 0.9 | 1.0 | NA | NA | NA |
| | **20** | **40** | **60** | **20** | **40** | **60** |
| *Iron-base alloys* | | | | | | |
| NOREM 01/PTAW | 1.1 | 1.7 | 4.1 | 0.5 | 0.7 | 1.5 |
| NOREM 04/PTAW | 2.3 | 2.3 | 3.1 | 1.0 | 0.9 | 1.1 |
| NOREM 02/GTAW | 0.5 | 1.4 | 2.0 | 0.3 | 1.0 | 1.3 |
| NOREM 02/SMAW | 0.12 | 1.6 | 1.8 | 0.16 | 1.4 | 1.8 |
| NOREM 02/GMAW | 0.4 | 0.7 | 1.5 | 0.4 | 0.4 | 1.3 |
| NOREM 02A/GTAW | 0.2 | 0.7 | 1.1 | 0.2 | 0.6 | 1.1 |
| NOREM 02A/GTAW (185 F)* | | | | 0.53 | NA | NA |
| NOREM M2/laser | 2.1 | 2.2 | 3.1 | NA | NA | NA |
| | **20** | **40** | **60** | **20** | **40** | **60** |
| *Nickel-base alloys* | | | | | | |
| Deloro 40/GTAW | 37.1 | 41.3 | 50 | 16.9 | 15.9 | 17.9 |
| Deloro 50/GTAW | 38.6 | NA | 76.0 | 17.5 | NA | 27.1 |
| Tribaloy T700/PTAW | 23 | 39.0 | 27.0 | 12.8 | 11.8 | 11.7 |

Note: A test at 10 ksi in 185°F water yielded a surface damage value of 0.40 µm

Bechtel Bettis Atomic Power Laboratory evaluated the galling wear of the various hardfacing alloys using a procedure also based on the ASTM standard G 98-91 [8]. The button (pin) specimen was rotated in a 120-degree arc 10 times within 30 to 90 seconds across a block at a given applied stress. The diameter of the pin used in these tests was 0.500″. After rotation, the specimens were examined both visually and with a 10X eyepiece for signs of adhesive damage and galling. If no galling was observed, the procedure was repeated on a new set of specimens at a higher load. Testing was continued until galling damage was observed. The threshold galling stress (TGS) was then taken as the average stress between the highest non-galled stress and the lowest galled stress. Tests were performed in deionized water at ambient temperature.

Surface damage values measured by AMAX and RRAC with a profilometer as described above were < 2µm for both NOREM and the cobalt-base alloys at stresses applied up to 60 ksi. The TGS as measured by Bettis was 93.5 ksi for NOREM; the TGS for Stellite exceeds 170 ksi. Surface damage was measured by RRAC with a profilometer on the two Bettis specimens that served to establish the TGS as 93.5 ksi. The surface damage value was 1.8 µm on the non-galled specimen tested at 88.9 ksi and 3.6 µm on the galled specimen tested at 98.1 ksi. The galling resistance of the nickel-base Deloro alloys at ambient temperatures is much lower than that of NOREM or Stellite based on pin-on-plate tests performed in all three laboratories.

## Cavitation-Erosion Wear Measurements

Cavitation-erosion is caused by vapor bubbles in a fluid collapsing on metal surfaces due to reductions in dynamic pressures. The collapse of vapor bubbles produces very high-localized pressures, which damage adjacent metals through erosion. It also occurs in fluid valves subject to large differential pressures, such as globe valves. Hardfacing materials were weld deposited on SA516 Grade 70 plate. Specimens measuring 1.5-inches x 1.5-inches x 1-inch thick were machined to a finished hardfacing thickness of 0.125 inch. Measurements were performed using the cavitation jet apparatus at TVA’s Engineering Laboratory in Norris, Tennessee. This method uses a submerged cavitating jet to erode the specimen located directly in front of the jet’s path. A pressure of 6000 psi was initially selected. During all tests, a consistent spacing of 0.875 was maintained between the nozzle and the specimen. The samples were then weighed to determine material loss, and the results were averaged to determine an erosion rate [9]. Cavitation-erosion data are shown in Table 5-2. Later measurements supported by the U. S. Army Corps of Engineers were performed at the same facility at an imposed pressure of 4,000 psi; NOREM provided the best resistance to cavitation-erosion damage [10].

An alternative approach to measuring cavitation erosion rates is specified in the ASTM G-32 standard. This test consists of periodically measuring the weight loss of a specimen fixed to the end of a vibrating horn. Rao [11] has reported the results of such measurements. Weld overlay samples were vibrated at 20 kHz at a peak-to-peak vibration amplitude of 50 microns. All tests were conducted in distilled water maintained at room temperature. A cavitation rate was calculated by interrupting the test and weighing the specimens at selected intervals. The steady-state cavitation erosion rates found in these tests were 14.9, 2.2, and 1.3 for 316 stainless steel, NOREM, and Stellite 21, respectively.

**Table 5-2**
**Cavitation-Erosion Wear Tests (TVA Cavitating Jet Apparatus)**

| | | Cavitation Erosion Rate | |
|---|---|---|---|
| **Alloy** | **Welding Procedure** | **(mg/hr)** | **Relative to 308 stainless steel standard** |
| NOREM 02 | GMAW | 3.0 | 0.09 |
| NOREM 04 | GTAW | 4.4 | 0.14 |
| NOREM 01 | GTAW | 5.9 | 0.19 |
| HQ 913 | GTAW | 6.1 | 0.19 |
| Stellite 21 | GTAW | 7.3 | 0.23 |

Note: Test pressure 6000 psi

The cavitation-erosion wear resistance of the thermal spray NOREM coating prepared by Praxair was evaluated using a procedure similar to that described in the ASTM G 32-85 standard. The equipment generates ultrasonic vibrations, which strike a coated rectangular specimen. The amount of damage is determined by measuring the weight change of the specimen at thirty-minute intervals. Similar measurements were made on a sample coated with a Ti-6Al-4V alloy, one of the most cavitation-erosion resistant alloys. After testing for 90 minutes, the cumulative weight loss of the two alloys was nearly identical, but after 150 minutes the cumulative weight loss of the NOREM coating was ~75% higher than that of the Ti-base alloy, a result which was deemed to show the high potential of NOREM.

## Abrasive Wear Measurements

Abrasive wear resistance was measured using the procedure defined by the ASTM G-65 standard. This procedure, described as the dry sand on rubber wheel abrasion test, consists of dragging loose silica sand by means of a rotating rubber wheel under a known force over the surface of a test specimen. This is considered to be a low-stress test because the sand is not crushed as it passes over the test surface. The ASTM procedure specifies parameters such as the type of rubber wheel, its rotational velocity, sand flow rate, test duration, etc. Abrasive wear is measured as the wear volume after a given number of rotations of the rubber wheel. Abrasive wear data of two NOREM variants are shown in Table 5-3.

**Table 5-3**
**Abrasive Wear of NOREM (ASTM G65-80 Test Procedure)**

| Alloy | Weld Procedure | Weight Loss (gm) |
|---|---|---|
| NOREM 02 | GTAW | 2.262 |
| NOREM 02 | GTAW | 2.274 |
| NOREM 02 | GMAW | 2.276 |
| NOREM 02 | GMAW | 2.397 |
| NOREM NT-1 | GMAW | 2.149 |
| NOREM NT-1 | GMAW | 2.163 |

Note: Stellite 6 values range between 0.8-1.3 gm

## Sliding Wear Tests: Measurements of Friction Coefficients and Wear

A wear-related parameter of concern in selecting a hardfacing alloy for use in gate valves is the coefficient of friction between the disk and the seat and the disk and body guide materials. The friction coefficient affects the thrust required to open or close a gate valve under flow and differential pressure conditions. The use of replacement hardfacing alloys on either the disk/body seats or one or both of the guide surfaces may result in increased thrust requirements that may exceed the output capability of the motor, air, or hydraulic actuator. Accordingly, friction coefficients of prospective new hardfacing alloys must be evaluated.

Measurements of coefficients of friction for NOREM and a cobalt-base Stellite 6 standard were performed initially at Rensselaer Polytechnic Institute (RPI). In the tests, an MT-1 oscillating slider test apparatus was used to move a pin back and forth against an alloy plate at an applied stress of 15 ksi. This is a typical apparatus to measure coefficients of friction. The diameter of the pin used in this test was 0.25″. The pin was held at one end in a housing mounted to an arm. The arm was pivoted at one end and driven at the other by means of a pneumatic drive reciprocating motor. The stroke length was 1 inch and the velocity was 1 inch/s. The plate on which the pin end was loaded was held in a stainless steel cup that also held the desired lubricant. For the room temperature (70°F) tests, the lubricant was tap water. Heaters were placed in the upper and lower specimen holder for elevated temperature tests. Steam introduced into the upper heater block was superheated and the dry steam impinged directly in front of the pin sliding on the plate. The load was applied through the yoke arrangement directly above the test specimen by means of a pneumatic load cylinder. The friction force was monitored on the driven end of the arm. Measurements could be constantly monitored with the use of the strain gage conditioning instrument and an oscillograph. Spot checks were run on a daily basis by applying a known force to the strain gauge and recording the output. Wear also was evaluated in these tests by measuring the pre- and post-test weights of the specimens.

Table 5-4 presents coefficients of friction calculated from the RPI tests. In tap water at 70°F, the NOREM coefficient of friction is virtually identical to that of Stellite 6. In the dry steam tests conducted at 600°F, the NOREM coefficient of friction tended to be slightly higher, but was still comparable to that of Stellite 6. These tests demonstrated that under self-mated conditions, the coefficients of friction of high-cobalt alloys tend to be somewhat lower than for low-cobalt alloys. Wear rates in these tests were deduced from weight change measurements; the values calculated for NOREM and Stellite 6 were virtually identical.

**Table 5-4**
**Friction Coefficient Measurements (RPI)**

| Alloy | Temp (F) | Environment | μ 1 Cycle | μ 100 Cycles | μ 1000 Cycles |
|---|---|---|---|---|---|
| NOREM 01 | 72 | tap water | .15 | .32 | .33 |
| NOREM 04 | 72 | tap water | .14 | .27 | .27 |
| NOREM 02 | 72 | tap water | .17 | .25 | .28 |
| Stellite 6 | 72 | tap water | .18 | .26 | .26 |
| NOREM 01 | 600 | dry steam | .29 | .34 | .38 |
| NOREM 04 | 600 | dry steam | .26 | .33 | .35 |
| NOREM 02 | 600 | dry steam | .32 | .34 | .36 |
| Stellite 6 | 600 | dry steam | .22 | .32 | .36 |

Each entry is the average of three tests at the indicated condition.
All tests were performed at an applied stress of 15 ksi.

Friction coefficients of NOREM 02 were measured by GEC Alsthom Velan on specimens that were prepared by plasma transferred arc welding. Tests were performed at an applied stress of 14.5 ksi. The test procedures used are sketchy. A friction coefficient of 0.51 was reported for measurements performed at ambient temperature (20°C) after 500 cycles. In tests performed at 280°C, a friction coefficient of 0.45 was reported after 1000 cycles. The friction coefficient reported for Stellite 6 tested under these conditions was 0.40 [12].

Tests later were conducted at Battelle Columbus Laboratories (BCL) [13] with the objective of defining the galling thresholds and friction coefficients of self-mated NOREM 02 and 02A in deionized water under a wide range of contact stresses, temperature and loaded relative sliding distances. These tests were designed to provide friction coefficients and galling thresholds data for the EPRI Motor-Operated Valve Performance Prediction Program Gate Valve Methodology. This methodology predicts the thrust required to open or close a gate valve under design basis flow and differential pressure conditions. Currently, the methodology is limited to analyzing the performance of gate valves using Stellite 6 as the hardfacing material. The aim was to develop data to expand the applicability of the methodology to gate valves with NOREM 02 trim.

Two rigs, an ambient pressure and an autoclave rig, were used by BCL to conduct friction and galling threshold testing. Tests were conducted in the ambient pressure rig in deionized water at temperatures up to 200°F. One specimen is translated relative to the other in a linear unidirectional or reciprocating motion with stroke lengths up to 3 inches. The smaller of the two rectangular test specimens are larger ( 0.2 x 1.0 inch) than those used in the ASTM Standard G 98-91 test and *move* in a linear (rather than circular) stroke. Axial force is applied to the lower test specimen by a hydraulic cylinder and normal force is applied to the upper specimen using a pneumatic bladder. Both axial and normal forces are measured using in-line load cells allowing the evaluation of friction coefficients. The surface condition of the test specimens is monitored visually during testing to determine whether adhesive wear (galling) occurs at which time the test is terminated.

Tests were conducted in an autoclave rig in deionized water at temperatures up to 550°F and pressures up to 1050 psi with a unidirectional linear motion with stroke lengths up to 1.6 inches. The autoclave applies an axial force using a hydraulic cylinder to pull two inner specimens from between two stationary outer specimens. The normal force is applied by hydraulic pressure expanding an internal bellows assembly. The smaller (outer) specimens measure approximately 0.2 x 1.0 inches. An in-line load cell measures axial force while normal force is determined by correlating bellows pressure to normal force. The surfaces of the test specimens are examined after each test series to assess surface damage.

The BCL test is the first in which the galling susceptibility of NOREM 02 and Stellite 6 were evaluated for loaded stroke lengths greater than 0.5 inches. The loaded stroke lengths were less than 0.5 inches in the RRAC galling wear tests and in the valve tests performed in loop facilities that are discussed later.

Table 5-5 shows the BCL test results. NOREM 02 did not exhibit adhesive wear (galling) at nominal contact stresses up to 15 ksi, and loaded stroke lengths up to 0.5 inches in water at temperatures up to and including 550°F. The BCL tests indicated that NOREM 02 does not gall at 10 ksi and stroke lengths up to and including 3 inches in room temperature water.

**Table 5-5**
**Friction Coefficient Measurements (BCL Results)**

| Test Number | Stationary Specimen Material | Moving Specimen Material | Fluid Temperature (F) | Contact Stress (ksi) | Dwell Time (sec) | Stroke Length (in) | Total Strokes | Peak Friction Coefficient | Galled? | Strokes Before Galling | Post Test Surface Condition |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| 1 | NOREM02A | NOREM02A | 70 | 2 | 1 | 3 | 150 | 0.46 | No | | Light Scoring |
| 2 | NOREM02A | NOREM02A | 70 | 10 | 1 | 3 | 201 | 0.5 | No | | Light Scoring |
| 3 | NOREM02A | NOREM02A | 70 | 10 | 1 | 3 | 150 | 0.47 | No | | Light Scoring |
| 4 | NOREM02A | NOREM02A | 200 | 10 | 1 | 3 | 3 | 0.94 | Yes | 3 | Significant Material Disruption |
| 5 | NOREM02A | NOREM02A | 70 | 10 | 1 | 3 | 150 | 0.49 | No | | Light Scoring |
| 6 | NOREM02A | NOREM02A | 70-140 | 10 | 1 | 3 | 138 | 0.95 | Yes | 138 | Significant Material Disruption |
| 7 | Stellite 6 | Stellite 6 | 70 | 10 | 1 | 3 | 279 | 0.6 | No | | Light Scoring |
| 8 | Stellite 6 | Stellite 6 | 200 | 10 | 1 | 2.5 | 3 | NM | No | | Light Scoring |
| 9 | Stellite 6 | Stellite 6 | 200 | 10 | 1 | 2.5 | 150 | 0.46 | No | | Light Scoring |
| 10 | NOREM02A | NOREM02A | 200 | 10 | 30 | 0.5 | 250 | 0.69 | No | | Scoring |
| 13 | NOREM02A | NOREM02A | 200 | 10 | 30 | 3 | 47 | 0.8 | Yes | 47 | Significant Material Disruption |
| 20 | NOREM02 | NOREM02 | 70 | 10 | 60 | 3 | 158 | 0.57 | No | | Light Scoring |
| 21 | NOREM02A | NOREM02A | 120 | 10 | 60 | 3 (1.5) | 1 | 0.72 | Yes | 1 | Significant Material Disruption |
| 22 | NOREM02 | NOREM02 | 200 | 10 | 60 | 3 (2.1) | 4 | 1.1 | Yes | 2.7 | Significant Material Disruption |
| 23 | NOREM02 | NOREM02 | 200 | 10 | 1 | 3 (0.9) | 1 | 0.76 | Yes | 1 | Significant Material Disruption |
| 24 | NOREM02 | NOREM02 | 200 | 10 | 60 | 3 (1.7) | 1 | 0.66 | Yes | 1 | Significant Material Disruption |
| | | | | | | | | | | | |
| AC4 | NOREM02 | NOREM02 | 550 | 15.6 | >60 | 0.435 | 50 | 0.82 | No | | Scoring |
| AC5 | NOREM02 | NOREM02 | 550 | 15 | >60 | 1.6 | 1 | 0.8 | No | | N/A |
| AC6 | NOREM02 | NOREM02 | 550 | 15 | >60 | 1.6 | 21 | 0.87 | No | | Scoring/Light pull outs |
| AC7 | NOREM02 | NOREM02 | 200 | 1.5 | >60 | 1.6 | 1 | 0.71 | No | | N/A |
| AC8 | NOREM02 | NOREM02 | 200 | 10 | >60 | 1.6 | 25 | 0.64 | No | | Scoring/Light Pull outs |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 25 | NOREM02 | NOREM02 | 200 | 1.5 | >60 | 1.6 | 1 | 0.38 | No | | N/A |
| 26 | NOREM02 | NOREM02 | 200 | 10 | >60 | 1.6 | 25 | 0.51 | No | | Scoring/Light Pull outs |
| 27 | NOREM02 | NOREM02 | 200 | 1.5 | >60 | 1.6 | 1 | 0.4 | No | | N/A |
| 28 | NOREM02 | NOREM02 | 200 | 15 | >60 | 1.6 | 25 | 0.61 | No | | Scoring/Light Pull outs |
| 29 | NOREM02 | NOREM02 | 200 | 1.5 | >60 | 3 | 1 | 0.21 | No | | N/A |
| 30 | NOREM02 | NOREM02 | 200 | 15 | >60 | 3 | 25 | 0.64 | Yes | | Significant Material Disruption |
| 31 | NOREM02 | NOREM02 | 200 | 15 | >60 | 3 | 25 | 0.66 | Yes | | Significant Material Disruption |
| 32 | NOREM02 | NOREM02 | 200 | 1.5 | >60 | 1.6 | 1 | 0.24 | No | | N/A |
| 33 | NOREM02 | NOREM02 | 200 | 15 | >60 | 1.6 | 120 | 0.67 | Yes | 110 | Significant Material Disruption |
| 34 | NOREM02 | NOREM02 | 200 | 1.5 | >60 | 3 | 25 | 0.5 | No | | Very Light Scoring |
| | | | | | | | | | | | |
| AC9 | NOREM02 | NOREM02 | 199 | 1.4 | >60 | 1.6 | 1 | 0.53 | No | No | N/A |
| AC10 | NOREM02 | NOREM02 | 199 | 10 | >60 | 1.6 | 25 | 0.61 | No | No | Scoring/Light Pull outs |
| AC11 | NOREM02 | NOREM02 | 205 | 3 | >60 | 1.6 | 1 | 0.54 | No | No | N/A |
| AC12 | NOREM02 | NOREM02 | 205 | 10 | >60 | 1.6 | 25 | 0.65 | No | No | Scoring/Light Pull outs |
| AC13 | NOREM02 | NOREM02 | 200 | 1.5 | >60 | 1.6 | 1 | 0.67 | No | No | N/A |
| AC14 | NOREM02 | NOREM02 | 200 | 15 | >60 | 1.6 | 25 | 0.74 | No | No | Scoring/Light Pull outs |
| AC15 | NOREM02 | NOREM02 | 550 | 1.5 | >60 | 1.6 | 1 | 0.88 | No | No | N/A |
| AC16 | NOREM02 | NOREM02 | 550 | 15 | >60 | 1.6 | 25 | 0.85 | No | No | Heavy Scoring/Pull outs/ 1 Plow |
| AC17 | NOREM02 | NOREM02 | 550 | 15 | >60 | 1.6 | 25 | 0.84 | No | No | Heavy Scoring/Pull outs/ 1 Plow |
| | | | | | | | | | | | |
| 15 | Stellite 6 | NOREM02A | 200 | 10 | 30 | 3 | 150 | 0.5 | No | | Scoring |
| 16 | Stellite 6 | NOREM02A | 200 | 10 | 1 | 3 | 150 | 0.52 | No | | Scoring |
| 17 | Stellite 6 | NOREM02A | 70 | 10 | 1 | 3 | 200 | 0.57 | No | | Light Scoring |
| 18 | Stellite 6 | NOREM02A | 200 | 40 | 60 | 3 | 1 | 0.57 | Yes | 1 | Significant Material Disruption |

However, with a loaded stroke length of 1.6 inches, galling was observed for nominal contact stresses of 10 and 15 ksi in 200°F water. Galling was not observed in tests of NOREM 02 at 550°F with a loaded stroke length of 1.6 inches. Tests were performed with NOREM 02A mated with Stellite 6 at 200°F and subject to a stroke length of 3 inches. There was no evidence of galling at an applied stress of 10 ksi, but galling occurred at 40 ksi.

Electricité de France also calculated NOREM friction coefficients from tests of a 6″gate valve that will be discussed later. Friction coefficients were calculated from the measured forces required to open and close the valve in both the cold water and elevated temperature water parts of the test. The coefficient of friction (μ) in cold water was nearly identical during both opening and closing of the valve: it started at ~0.5, increased to a maximum value of 0.62 at stroke ~80, and then decreased to ~0.4 at stroke 860. There were larger variations in the coefficient of friction between opening and closing at elevated temperatures. During valve opening, μ was nearly constant over the entire test. It started at ~0.4, increased to ~0.48, and then decreased to ~0.44 after 1500 cycles. During valve closing, μ started at 0.33, increased to 0.47 after ~200 cycles, decreased to ~0.25 after 1000 cycles and then increased to ~0.33 after 1500 cycles. EdF considered the friction characteristics of NOREM 02 to be somewhat higher but acceptable and comparable to the values obtained with Stellite in similar valve tests. The measured coefficient of friction for NOREM decreased by approximately 33% during the cycling tests, and EdF noted the “mirror-like” finish of the NOREM seating surfaces at the end of the test.

# 6
# CORROSION MEASUREMENTS

The hardfaced valve components (discs) in the AECL loop tests were examined for evidence of corrosion damage at the end of the test. The oxides that built up over the course of the exposure on the NOREM discs were uniform in thickness and there was no indication of localized corrosion attack. Other coupons exposed in the loop were evaluated for corrosion, as were coupons that were exposed in an autoclave where the environment simulated CANDU chemistry conditions. The results of these evaluations are shown in Tables 6-1 and 6-2, which report average values obtained from three coupons.

Corrosion coupons also were prepared at AECL by cutting pieces from welding procedure qualification rings provided by the valve supplier. After surface grinding and cleaning, the coupons were secured to stainless steel fixtures that were inserted into the outlet bore of two of the valves.

**Table 6-1**
**NOREM Corrosion Under Simulated PWR and CANDU Conditions**

| Chemistry | Exposure Time (days) | Weight Change ($mg/dm^2$) | |
|---|---|---|---|
| | | NOREM 01 | NOREM 04 |
| PWR (loop) | 89 | 15.6 | 10.6 |
| | 172 | 36.7 | 50.0 |
| | 229 | 69.2 | 93.4 |
| | 320 | 178.9 | 204.4 |
| CANDU (autoclave) | 129 | -8.4 | -6.6 |
| | 156 | -14.5 | -10.2 |
| | 209 | -8.0 | -6.9 |
| | 367 | -11.6 | -10.6 |

**Table 6-2**
**NOREM Corrosion Under Simulated BWR and CANDU Conditions**

| Chemistry | Exposure Time (days) | Weight Change ($mg/dm^2$) | |
|---|---|---|---|
| | | NOREM 01 | NOREM 04 |
| BWR (loop) | 192 | -29.6 | -29.8 |
| CANDU (autoclave) | 180 | -6.3 | -3.5 |

AECL also evaluated the corrosion resistance of NOREM under conditions designed to simulate crevice corrosion environments that may occur under various CANDU shutdown conditions (Table 6-3). In some tests at room temperature, the pH reached values as low as 3.0. There was no evidence of corrosion-induced damage after exposure times of ~ 30 days.

**Table 6-3**
**Corrosion Tests of NOREM Under CANDU Shutdown Chemistry Conditions**

| Condition | Heat Transfer System (HTS) | Main Moderator (normal operation) | Main Moderator (Over-poisoned guaranteed shutdown [OPGSS]) | Main Moderator (drained guaranteed shutdown state) [DGSS] | Liquid Zone Control [LZG] |
|---|---|---|---|---|---|
| T (ºC) | 300 | 65 | 25 | 25 | 66 |
| P (psig) | 1450 | atm | atm | atm | atm |
| pH | 10.0-10.5 | 4.5-6.5<br>(5.0 actual) | 4-5 | 2-3 | 6.5 |
| oxygen | <10 ppb | sat | sat | sat | sat |
| chemical addition | LiOH | B as B2O3<br>(0.5 mg/kg H2O) | Gd nitrate | HNO3* | none |

*This condition arises because it is not possible to completely drain systems of HNO3.

Only limited evaluations of the corrosion resistance of NOREM following exposure to chemical decontamination solvents have been performed. Table 6-4 presents results from coupons exposed to the five-step CAN-DEREM™ process.

**Table 6-4**
**Corrosion After Exposure to CAN-DEREM Decontamination Solvent**

| Alloy | Corrosion Film Thickness (mils) |
|---|---|
| NOREM 02 | 0.015 |
| | 0.015 |
| | 0.003 |
| Stellite 6B | 0.017 |
| | 0.017 |
| | 0.016 |

# 7
# MECHANICAL PROPERTIES

Brittle hardfacing alloys show little ability to undergo plastic deformation. Tensile strength and Charpy impact toughness values for the new NOREM compositions are given in Table 7-1. The specimens were machined from undiluted weld deposits. The Charpy specimens were tested in the unnotched condition, The values in this table show improvements over the values measured on earlier heats, suggesting the lower N content of the new variants appears to increase their ductility.

**Table 7-1**
**NOREM Mechanical Properties**

| Alloy | Hardness HRc | Yield Strength (ksi) | Ultimate Tensile Strength (ksi) | Elongation (%) | Reduction in Area (%) | Charpy Energy (ft lb) |
|---|---|---|---|---|---|---|
| NOREM 02 | 39 | 120 | 140 | 0.6 | 1 | NA |
| NOREM 02A | 39 | 128 | 157 | 3 | 6 | 22.7 |
| Stellite 6 | 40 | | 132 | | | 9.4 |

Note: Stellite 6 entries obtained from Deloro Stellite brochure

# 8
# HIGH TEMPERATURE PROPERTIES OF NOREM

Hot hardness measurements on NOREM and Stellite alloys were made by General Electric on small samples. Testing was done under vacuum (~5 torr) using a 1 kg. load. Three indentations were made at each temperature setting. The results from these tests are shown in Figure 8-1. The drop in hardness with temperature is similar for both NOREM and the Stellites.

TurboCare evaluated NOREM as an undercoat for thermal sprayed erosion-resistant chromium carbide coatings. NOREM was welded to a Cr-Mo substrate. Metallographic evaluations were performed on specimens that were exposed to 600°F, 800°F, and 1,000°F steam, each exposure being for 10 days. No difference was observed in a control specimen that did not see elevated temperature and the specimen exposed to steam.

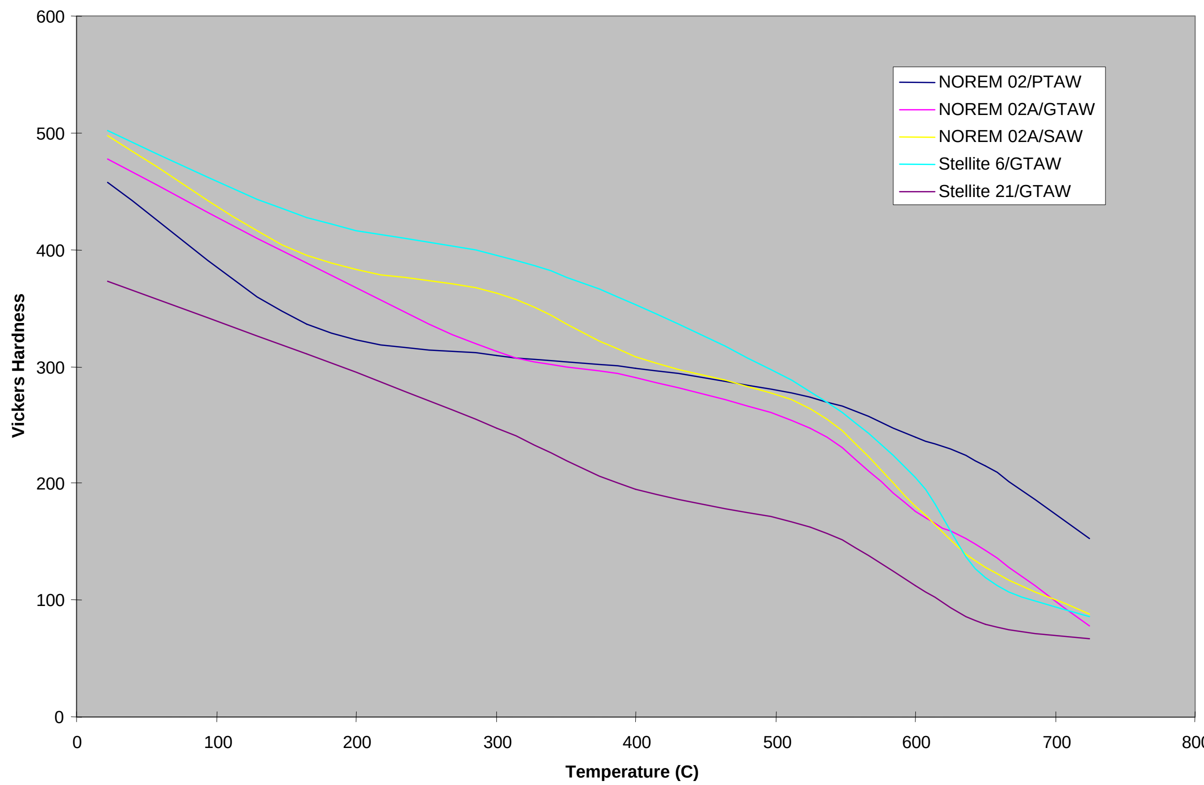


**Figure 8-1**
**Hot Hardness of Hardfacing Alloys**

# 9
# VALVE TESTS IN LOOP FACILITIES

Testing of a component, such as a valve, provides one with the ability to evaluate a number of factors that bear on the performance of a new hardfacing alloys: [1] leak rate measurements provide a more direct measure of the effectiveness of a hardfacing alloy to provide a leak-tight seal than do laboratory measures of galling wear resistance; [2] fabrication of a valve demonstrates the ability of the valve vendor to develop and qualify welding procedures using conventional welding practices and welding consumables produced by suppliers; [3] testing of the valve over comparatively long times provides information about the corrosion resistance of the alloy under representative conditions; and [4] component testing provides the possibility of identifying unexpected synergistic effects that would be difficult to find in laboratory “separate effects” evaluations.

The early laboratory evaluations showing the outstanding galling wear resistance of NOREM 01 and 04 led to a project with AECL to evaluate the performance of 3″ gate valves (manufactured by Velan Valves) that were hardfaced with NOREM. Valves with other promising cobalt-free hardfacing alloys also were evaluated in the program at AECL, together with a valve with Stellite 6 hardfacing that served as a standard. The valves were tested first under simulated PWR primary coolant chemistry conditions [14]. They were then refurbished and tested under simulated BWR coolant chemistry conditions [15]. A subsequent test of a 6″ gate valve (manufactured by Anchor Darling Valve Co., now a division of Flowserve) with NOREM 02 hardfacing was undertaken at facility operated by Electricité de France [16].

## Valve Tests at Atomic Energy of Canada, Ltd.

At AECL the valves were subjected to stroke cycling in a test loop. They were stroked a total of ~2000 times in the PWR tests and ~1000 times in the BWR test. A stroke cycle consisted of the following: close the valve in 2.5 seconds and hold for 7.5 seconds; open the valve in 1.5 seconds and hold for 8.5 seconds. Cycling was performed in blocks of 10 cycles; the rate of cycling was 4 to 5 block cycles for every 7 days of loop operation. Only one block cycle was performed in any 24 hour period. Leak rate tests at elevated and ambient temperatures were performed after each 500 stroke cycles. Visual examinations and profilometry also were performed. Scanning electron microscopy was used to characterize the wear scars at the end of the test.

The valve tests under both PWR and BWR conditions were performed at 570°F. In the PWR phase the dissolved oxygen was 0.01 ppm, boric acid was at 5700 ppm (1200 ppm as B), lithium was at 2 ppm, the conductivity was 20μmho/cm, and the pH at room temperature was 6.5±0.5. In the BWR phase the dissolved oxygen ranged from 100–300 ppb, the pH at room temperature was 5.5±0.5, and the conductivity was <2μmho/cm.

Hot Tests. At the end of each run, hot seat leakage tests were performed. The test valve was closed under full pressure and temperature and the outlet feeder was isolated, blown down and drained. Leakage past the test valve was then collected through a water cooled, copper coil condenser connected to a drain valve located at the outlet end of the test valve. The leakage was collected at five-minute intervals over a total maximum collection period of 45 minutes, and the intergate pressures and valve body temperatures were measured at the same time. The temperature was measured with a thermocouple attached to the surface of the valve body on the inlet side of the crotch between the upper body and the inlet nozzle. This location was felt to best represent cooling due to lack of flow through the body without being greatly influenced by adiabatic cooling which might occur as leakage flashed to steam at the outlet end.

### Leak Rate Test Results

Cold Tests. Cold seat leakage tests were performed at the end of each run and after the valves were reassembled following each interim inspection. For the cold seat leak tests, the loop was pressurized cold to 1850 psig and the test valves were then closed. The outlet feeder was isolated and drained and leakage past the test valve was collected through the downstream drain line. Leakage was collected at 5 minute intervals for up to a total of 45 minutes. The valves were initially leak tested by the manufacturer, Velan Inc. These initial leak rates were less than 0.030 liters/hour indicating that the wedges were correctly fitted and matched to the corresponding seat ring set.

In the PWR tests the valves with NOREM 01 and 04 hardfacing alloys demonstrated steady state leak rates that were significantly lower than those exhibited by the valve with Stellite hardfacing (Tables 9-1 and 9-2). In the BWR tests, the NOREM hardfacing demonstrated leaktightness values that were determined to be generally acceptable but were higher than those of the valves with Stellite hardfacing (Tables 9-3 and 9-4). During these tests, NOREM 04 valve experienced an unexpected high leakage rate. This result was surprising and suspect since the NOREM 04 valve had performed so well in the PWR phase testing. Upon further examination, visual evidence supported the conclusion that there was a dimensional tolerance or fit-up problem, possibly exacerbated when the valve was hot, which resulted in uneven contact around the circumference of the seat and insufficient contact stress to achieve a good seal in the “12 o’clock” area. If this was the case, then the excessive leakage was not due to a failure or breakdown of the hardfacing material but was strictly a mechanical problem that developed with that particular disc/seat ring set. Based on other available data and observations, it was concluded that the observed leakage rate was an anomaly and not indicative of any problems with the hardfacing alloy.

**Table 9-1**
**Seat Leakage of Gate Valves—AECL PWR Tests (Cold Tests)**

| | Cold Leak Rates (liter/hr) | | | |
|---|---|---|---|---|
| **Alloy** | **After 500 Cycles** | **After 1000 Cycles*** | **After 1500 Cycles*** | **After 2000 Cycles*** |
| NOREM 01 | 0 | 0.002 | <0.004 | 0.022 |
| NOREM 04 | 0 | 0.001 | <0.004 | 0.012 |
| Stellite 6 | 0 | 0.056 | 0.210 | 1.00 |

* Leakage calculated from collection over the last 15 minutes of a 30 minute collection period.

**Table 9-2**
**Seat Leakage of Gate Valves—AECL PWR Tests (Hot Tests)**

| | Hot Leak Rates (liter/hr) | | | |
|---|---|---|---|---|
| **Alloy** | **After 500 Cycles*** | **After 1000 Cycles**** | **After 1500 Cycles**** | **After 2000 Cycles**** |
| NOREM 01 | 1.3 | 0.40 | 0.08 | 0.15 |
| NOREM 04 | 0 | 0 | 0 | 0 |
| Stellite 6 | 0.4 | 0.56 | 0.60 | 0.32 |

*Leakage collected over one 15 minute collection period.
**Leakage collected over the last 15 minutes of a 45 minute collection period.

**Table 9-3**
**Seat Leakage of Gate Valves—AECL BWR Tests (Cold Tests)**

| | Cold Leak Rates (liter/hr) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Run 1 Start | | Run 1 Finish | | Run 2 Start | | Run 2 Finish | |
| Alloy | Initial* | Final** | Initial | Final | Initial | Final | Initial | Final |
| NOREM 01 | 0.114 | 0 | 0.048 | 0 | 0 | 0 | 0.034 | 0 |
| NOREM 04 | 0.036 | 0 | 0.062 | 0 | 0.036 | 0 | 0.036 | 0 |
| Stellite 6 | 0.084 | 0 | 0.024 | 0 | 0.018 | 0 | 0.018 | 0 |

* Initial = leakage collected in the first 5 minute interval of a total 45 minute collection period.
** Final = leakage collected in the last 5 minute interval of a total 45 minute collection period.
Run 1 = 500 cycles
Run 2 = 470 cycles
Total = 970 cycles

**Table 9-4**
**Seat Leakage of Gate Valves—AECL BWR Tests (Hot Tests)**

| | Hot Leak Rates (liter/hr) | | | | | |
|---|---|---|---|---|---|---|
| | Run 1 Start | | Run 2 Start | | Run 2 Finish | |
| Alloy | Initial* | Final** | Initial | Final | Initial | Final |
| NOREM 01 | 0 | 0 | 0 | 0 | 0 | 0 |
| NOREM 04# | 2.064 | 0.372 | 0.444 | 0.144 | 0.672 | 0.096 |
| Stellite 6 | 0.024*** | 0.012*** | 0.420 | 0 | 0 | 0 |

*Initial = leakage collected in the first 5 minute interval of a total 45 minute collection period.
**Final = leakage collected in the last 5 minute interval of a 45 minute collection period.
***Result is suspect because the loop lost pressure
#High values likely due to valve fitup problem; indistinct contact witness band seen on both faces of disc and on both seat rings at 12 o'clock position
Run 1 = 500 cycles
Run 2 = 470 cycles
Total = 970 cycles

### *Corrosion Tests*

A black adherent deposit was found on both the hardfacing and the stainless steel substrate of the coupons exposed to both PWR and BWR chemistry conditions. In the PWR phase, the coupon weight gains after run four were more than double the gain measured after run three, indicating an increase in corrosion rate. However, visual and metallographic examination failed to reveal any evidence of selective attack. In the BWR phase the corrosion oxide that formed in the valve on the NOREM trim (and on Stellite 6) was barely discernible at a magnification of 500x.

### *AECL Assessment of NOREM Performance*

AECL concluded that NOREM 01 and 04 met or surpassed the performance of the Stellite 6 standard with respect to corrosion, material loss due to wear, and maintenance of the valve sealing function. The alloys met the acceptance criteria established for the program and could be considered acceptable alternatives to Stellite 6 for PWR and BWR valve hardfacing applications. AECL did not perform valve tests on the NOREM 02 variation that showed evidence of galling in the sliding wear tests performed at BCL.

## Valve Tests at Electricité de France

A valve test using NOREM 02 as the hardfacing alloy recently was conducted at an Electricité de France (EdF). The coolant was deoxygenated water; unlike the AECL valve tests there were no additions of Li or B to the coolant in the EdF test loop. The valve initially was stroked 860 times in ambient temperature (70°F) water. The loop temperature was then raised and the valve stroked for 1500 cycles, opening at a differential pressure of 155 bar (15.5 MPa) and closing at a nominal flow rate of 2.5 m/s at a temperature of 285°C (545°F). The friction coefficient was monitored continuously, which results have been described earlier. Leak rates were measured after 50, 500, 1000, and 1500 opening and closing cycles.

After cycling at ambient temperature the leak rate was 3.8 $cm^3$/hr at 170 bar. There was no galling or significant abrasion of the NOREM surfaces. After cycling at elevated temperature, the valve showed no evidence of galling, but the measured leak rates (Table 9-5) were larger than the internal EdF standard for a 6″ valve. The high leak rates were reported to be the result of damage (“scratches”) on the downstream seating surfaces that apparently resulted from abrasion that occurred shortly after the testing at elevated temperatures began. Some “healing” of the damage took place with continued testing as demonstrated by the fact that lower upstream to downstream leakage rates were measured after 1500 cycles than after 50 cycles. EdF continues to view NOREM as having promise to serve as a replacement for Stellite 6 and plans additional tests of valves with NOREM hardfacing in their loop facilities.

**Table 9-5**
**Seat Leakage of Gate Valves—Electricité de France PWR Tests**

| Test Condition | Strokes | Differential Pressure (bar) | Up to Downstream Leak Rate (liter/hr) | Down to Upstream Leak Rate (liter/hr) |
|---|---|---|---|---|
| Cold (35°C) | 860 | | 3.8 | 1.2 |
| Hot (285°C) | 50 | 170 | 80 | 2 |
| Hot (285°C) | 500 | 170 | 400 | 1.26 |
| | | 260 | 2500 | 0.35 |
| Hot (285°C) | 1000 | 170 | 250 | 0.5 |
| | | 260 | 360 | 0.4 |
| Hot (285°C) | 1500 | 170 | 45 | 1.0 |
| | | 260 | 85 | 1.5 |

# 10
# NUCLEAR PLANT APPLICATIONS

## Nuclear Plant Valves

The first use of NOREM was as a replacement discs in three Chemical Volume Control System isolation valves at Consolidated Edison's Indian Point 2 PWR. These valves were placed in service at the spring 1993 outage. Detailed examinations of these valves have not been performed, but there is no evidence of any problem.

The use of NOREM suffered a potential setback when two 1.5 1500# class globe valves manufactured by Dragon Valve Company and installed in the Chemical Volume Control System at Union Electric's Callaway Nuclear station suffered significant damage following one 18 month operating cycle. The earlier NOREM 01 variant was welded to the forged Type 316 stainless steel seat, disc, and backseat using the manual GTAW process. The function of the valve was to reduce reactor coolant system pressure from 2235 psig to 300 psig and flow from 75 gpm to 11 gpm. Visual examination showed numerous steam cuts on the disc in the direction of flow, and the utility replaced the disc using Stellite 6 as the hardfacing alloy. It is not possible to perform a detailed examination of the discharged disc, but other factors may have contributed to its poor performance.

Orifice plates are installed in the same system, but their effectiveness is problematic because they were reported to be upstream of the valve, where they would create additional pressure drop across the seat. Also, the valve was operating in the partially open position, causing it to operate as a throttle valve, which is not an appropriate application for this type of globe valve.

Valves for use in the same application have been installed at Wolf Creek, Callaway's sister plant. No problems have been encountered after one cycle of operation at Wolf Creek, but the service conditions on the Wolf Creek valves are not as demanding as those at Callaway.

The performance of valves at Callaway should not be considered representative of the overall performance of NOREM hardfacing in nuclear plant valves. Currently, some 30 utilities have purchased or installed over 800 valves with NOREM trim, and those at Callaway are the only ones where problems have been reported. The prime supplier of these valves is the Anchor/Darling Valve Co., although Dragon Valve Co. and Edwards Valves have also provided valves with NOREM trim. Most valve purchases have taken place over the past two years, so little information about the performance of these valves is available.

Comision Federal de Electricidad (Laguna Verde) applied NOREM to the seats and discs of four 4″ gate valves and one 12″ gate valve. The valves normally operate in the open position and have been in service for one fuel cycle. They were inspected during the outage, and NOREM performance was deemed to be satisfactory. The utility plans to use NOREM to repair other valves.

Taiwan Power Co. has specified that cobalt-free hardfacing alloys will be used in valves that will be installed in the two General-Electric-designed BWRs that are now under construction. A number of valve manufacturers will be using NOREM in such valves. Taiwan Power earlier used NOREM on the seats and discs of 20″ double disc gate valves that were installed in recirculation system of the KuoSheng BWR. These valves have been visually inspected at two successive refueling outages and the performance is satisfactory.

Flowserve has built over 800 valves with NOREM trim. Representative examples of the types of valves ordered by nuclear utilities with NOREM are given in Table 10-1. These applications cover a wide range of valve types, valve sizes and ratings, and include purchases by utilities operating both BWRs and PWRs. NOREM has been deposited successfully on cast and wrought stainless and carbon steel materials. Trim for small valves is typically produced as a casting and brazed into place. This supplier has received no reports of problems in the valves with NOREM trim.

The first field application of NOREM was an in-situ repair at Entergy’s Grand Gulf Nuclear Station where Stellite 21 was replaced by the NOREM 01 variant on the seats, guide ribs, and poppets of two 24″ Wm. Powell wye type feedwater check valves. These repairs were performed using small diameter weld wire and the machine GTAW process. The Stellite 21 was removed, and an (intermediate) butter layer of Type 309 stainless steel followed by three layers of NOREM were deposited. Initial problems were encountered with cracking of a guide rib on the first valve as a result of improper preparation of the base material and significant variations in the thickness of deposited NOREM across the width of the guide rib. These problems were easily overcome, and NOREM was successfully deposited on the guide ribs of the first valve and the seats and poppets of both valves. Welding of the guide ribs of the second valve was postponed until the next refueling outage because of time constraints. Leak rate testing of the valves yielded the lowest values recorded by Grand Gulf personnel. However, some of the improvement reflects testing of NOREM in water, whereas earlier tests when these valves were hardfaced with Stellite were performed in air, a more demanding test medium. A review of this project suggests the importance of using personnel trained in all aspects of the work, including welding of hardfacing alloys, machining, and surface finishing. The need to perform preliminary initial evaluations on full-scale mockups was also highlighted [17].

**Table 10-1**
**Replacement Valves with NOREM Trim**

| Utility | Plant (Type) | Valve Type | Size (in.) | Rating (lb.) |
|---|---|---|---|---|
| Taiwan Power | Kuosheng (BWR) | flex wedge gate | 4 | 600 |
| Taiwan Power | Kuosheng (BWR) | swing check | 3 | 600 |
| Taiwan Power | Lungmen (BWR) | flex wedge gate | 14 | 900 |
| Boston Edison | Pilgrim (BWR) | swing check | 18 | 900 |
| Commonwealth Edison | Zion (W—PWR) | in-line check | 3 | 900 |
| CFE | Laguna Verde (BWR) | globe | 4 | 150 |
| Entergy | ANO1 (CE-PWR) | double disc gate | 2 | 1878 |
| Entergy | Waterford (CE-PWR) | flex wedge gate | 3 | 150 |
| Entergy | Waterford (CE-PWR) | flex wedge gate | 3 | 1500 |
| Entergy | Grand Gulf (BWR) | Y-globe | 24 | 900 |
| First Energy | Perry (BWR) | flex wedge gate | 10 | 300 |
| Houston Lighting & Power | South Texas (W-PWR) | double disc gate | 2 | 1888 |
| Illinois Power | Clinton (BWR) | tilt disc check | 12 | 600 |
| Illinois Power | Clinton (BWR) | globe | 4 | 900 |
| Kansas Gas & Electric | Wolf Creek (W-PWR) | globe | 0.75 | 1878 |
| Niagara Mohawk | Nine Mile Point (BWR) | double disc gate | 12 | 900 |
| Niagara Mohawk | Nine Mile Point (BWR) | tilt disc check | 18 | 1500 |
| Public Service Electric & Gas | Hope Creek (BWR) | flex wedge gate | 18 | 300 |
| Omaha Public Power District | Ft. Calhoun (CE-PWR) | globe | 4 | 1740 |
| Southern California Edison | San Onofre (CE-PWR) | slab gate | 1 | 1878 |
| Tennessee Valley Authority | Browns Ferry (BWR) | double disc gate | 2 | 1888 |
| Tennessee Valley Authority | Sequoyah (W-PWR) | swing check | 4 | 150 |

## Reactor Coolant Pump Journals

The Electro-Mechanical Division of Westinghouse Electric evaluated NOREM 02, Tristelle 5183, Colmonoy 84 , and Delchrome 910 cobalt-free hardfacing alloys as potential replacements for the cobalt-base Stellite 12 alloy used in reactor pump journals. Two layers of hardfacing were deposited by PTAW on Type 304 stainless steel specimens. The tests performed included assessments of an alloy's weldability, wear resistance and friction coefficients, and corrosion resistance. Wear tests involved rotating a carbon-graphite ring against a stationary hardfaced specimen. General and crevice corrosion were evaluated in tests performed in an aerated environment at a temperature of 150–200°F. After these early screening tests, better-performing alloys were evaluated in a test simulating a journal operating under abnormal conditions. Here, carbon-graphite pads contacted a hardfaced journal to verify that no catastrophic failure or "explosive disbonding" would occur in the absence of the normal lubricating fluid. The results from these series of tests led Westinghouse to recommend NOREM 02 for this application.

# 11
# NON-NUCLEAR APPLICATIONS OF NOREM

## Repair of Hydroturbine Runners

The outstanding resistance to cavitation erosion wear damage shown in laboratory tests led TVA to include NOREM in a field application of a number of two such alloys. Two small test patches (4 in x 4 in) were deposited by pulsed GMAW in the overhead position on hydroturbine runners made of Type 410 stainless steel at the TVA Raccoon Mountain Station. TVA is also evaluating the Eutectic Castolin Cavitech 914 alloy in these tests. TVA inspected the runner in April, 1998 at Raccoon Mountain that was repaired with NOREM and HQ 914. Both alloys provided similar resistance to cavitation damage based on visual inspections.

A more extensive demonstration of NOREM was undertaken by BC Hydro in June/July 1997 on the Unit #5 turbine runner at the Gordon Shrum Generating Station. This turbine runner is a Francis turbine runner and operates under a 500 foot head of water. It is made of ASTM A-27 carbon steel and rotates at 150 rpm. The runner suffers from leading edge cavitation erosion damage, and during a previous outage in 1995, the cavitated areas of the turbine runner were repaired using a duplex stainless steel overlay. Blades #14 and #16 were both divided into two zones. One zone was repaired using the duplex stainless steel, the other NOREM 4B. Only one layer of NOREM was deposited over the duplex stainless steel, which served as a butter layer. After refurbishing Unit #5 was returned to service in November 1997. The two blades were examined for cavitation damage during a scheduled outage of Unit #5 in March 1999 after ~10,000 hours of operation.

The depth of cavitation erosion on blade #14 and the corresponding band varied from <0.040″ (“frosting” attack) to 3/32″. The blade surface overlaid with NOREM showed slightly deeper cavitation attack than the band area overlaid with the duplex stainless steel. The depth of cavitation attack of blade #16 varied from frosting to 1/8″. The band surface overlaid with NOREM showed frosting damage, but the blade surface overlaid with duplex stainless steel showed cavitation damage up to 1/8″ deep. It was also found that blade surfaces overlaid with NOREM weld metal were more resistant to cavitation than the blade surface overlaid with duplex stainless steel.

The field test did not show the factor of nine reduction in cavitation-induced damage in NOREM as compared with 308 stainless steel (Table 5-2). This discrepancy may be due to dilution of the NOREM 4B overlay. Because only a single layer of NOREM 4B was welded over the duplex stainless steel, it is unlikely the NOREM 4B weld metal met the deposited chemistry specification given in Table 3-1.

## Steam Turbine Blades

Houston Lighting and Power found evidence of cracking in some low pressure turbine blades at its PH Robinson Unit #1 during the 1993 outage. Because the unit is scheduled to remain in service for another 30 years, the utility was amenable to evaluating various thermal spray coatings to provide extra protection. Four coatings were deposited by Praxair Surface Technologies (PST) using its Super D-Gun™ thermal spray technology. Only two blades were coated with NOREM because the as-deposited coating was quite rough and had to be ground to improve the surface finish. PST feels this problem can be overcome in subsequent applications, which would permit more efficient deposition of NOREM. The utility plans to inspect the various coated blades using remote video techniques during routine outages that are scheduled about every two years. More thorough inspections will be performed every six years during major turbine overhauls.

NOREM 02 was included in this evaluation because preliminary development work performed by PST showed that powder produced by vacuum induction melting and argon gas atomization provided sound thermal spray deposits (measured bond strengths were greater than 10,000 psi) and low porosity (<0.5% based on metallographic examinations). Only slight oxidation (<1%) occurred during the coating operation. The cavitation-erosion resistance of the thermal spray coating was measured using a procedure similar to that described in the ASTM G 32-85 standard. A test sample was placed near a horn that sent ultrasonic vibrations through a deionized water bath. A small rectangular coated specimen was placed near the horn. Resistance to cavitation erosion damage was monitored by measuring the initial weight of the coupon and then taking subsequent weight measurements at thirty-minute intervals. The wear resistance compared favorably to that of a Ti-6Al-4V alloy, one of the most cavitation resistant alloys. The corrosion resistance of the thermal spray coating was measured using a potentiodynamic cyclic polarization technique, similar to that described in the ASTM G-61 standard. Current density was measured as a function of applied potential in tests conducted in a 3.56% NaCl solution. The test results show the coating was more resistant to corrosion than 316L stainless steel.

## Fossil Plant Valves

Western Resources welded a turbine throttle valve back seat with a NOREM rod using shielded metal arc welding (SMAW). The backseat operates at 1000°F and 1800 psi. The rod ran well and was readily machined with a carbide lathe tool to a smooth finish. No inspections have been performed since the repair was made, but no indication of leaking or other problems have been noted in the valve after approximately one year of service. The service conditions are such that the likely wear mechanism is fretting wear.

# 12
# CONCLUSIONS

## Nuclear Valve Applications

A substantial development program served to identify alloy compositions and specifications for welding consumables that yield sound weld deposits using standard welding practices with little or no need for preheating when they are deposited on carbon and stainless steel substrates. These developments permit NOREM to be used in the manufacturer’s shop in replacement valves and in the field to refurbish valves that have suffered degradation. Limited studies also show NOREM can be deposited by using thermal spray technology.

The significant body of data obtained from evaluations of the wear and corrosion resistance of the NOREM hardfacing alloys suggests the alloy can serve as a substitute for the cobalt-base Stellites under the wide range of service conditions encountered in the primary circuit of nuclear power plants. NOREM is extremely resistant to both adhesive (galling) wear and cavitation-erosion damage based on information obtained from laboratory evaluations and from valves that have been subjected to stroke cycling in loop facilities designed to simulate conditions found in operating nuclear plants. Limited information obtained from evaluations of valves that have been placed in service in commercial nuclear plants indicates no problems have been reported in valves with NOREM trim.

Only the recent laboratory sliding wear measurements performed at Battelle Columbus Laboratories [13] and the leak rate measurements from a 6″ gate valve with NOREM hardfacing that was tested at a facility operated by Electricité de France [16] suggest the alloy might be inferior to cobalt-base Stellite in some situations. Therefore, caution should be exercised in specifying NOREM for use in gate valves that must meet stringent leakage requirements. Use NOREM hardfacing in gate valves operating at high temperature and high differential pressure service may result in excessive seat leakage. Accordingly, the coolant flow rates and calculated contact stresses should be reviewed carefully if NOREM is proposed for use in gate valves >6″ in size. The loaded stroke length on seats and guides of gate valves is a function of several variables including valve size, flow media (water or steam) and coolant flow velocity. Many gate valves have loaded sliding distances on the seats and guides of less than 0.5 inches and would, therefore, not be susceptible to galling damage with NOREM02 hardfacing. These include gate valves up to 6 inches in size with seat/guide contact stresses less than 15 ksi and water flow velocities less than approximately 15 feet per second. Galling was not observed at applied stress levels of 10 ksi when NOREM 02A was tested against Stellite 6. This result suggests NOREM 02A is acceptable for repair applications of gate valve discs in the field provided that a cobalt-base alloy is retained for use as the hardfacing alloy on the valve seat [18].

Use of NOREM is deemed to be acceptable in all globe, butterfly, and stop and swing check valves. The observed scratching of the seats in the EdF test resulted from sliding contact between the seats; such scratching and associated seat leakage is not expected in valves whose seating process does not involve significant relative sliding motion.

Performance information to be obtained from plant valves with NOREM hardfacing that were installed before the recent information was generated at BCL and EdF will likely provide the best evidence of the ability of the alloy to perform during plant operations than is suggested by the EdF and BCL results.

## Hydroelectric Plant Applications

NOREM has been used to repair runners at two hydroelectric facilities. Sound welds were deposited in different positions, and the alloy could readily be ground to the desired contour. The results from the field are encouraging, although the significant improvements measured in laboratory evaluations of cavitation resistance have not been realized in the field. Dilution in the weld overlays clearly accounted for some of this difference, because only one layer was deposited on the runners tested at BC Hydro’s Gordon Shrum Station.

# 13
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