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FROM: DUE: 02/08/01

EDO CONTROL: G20010024
DOC DT: 12/26/00
FINAL REPLY:

D. C. Agarwal
Krupp VDM Technologies Corp.

TO:

Chairman

FOR SIGNATURE OF : ** GRN ** CRC NO: 01-0040

Kane, NMSS

DESC:

Radwaste Containers for the Yucca Mountain Project: NiDI and Framatome Cogema Sponsored Workshop on the subject at Las Vegas on Oct. 17 and 18, 2000

ROUTING:

Travers
Paperiello
Miraglia
Norry
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Thadani, RES

DATE: 01/19/01

ASSIGNED TO: CONTACT:

NMSS Kane

SPECIAL INSTRUCTIONS OR REMARKS:

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Date Printed: Jan 18, 2001 16:38

PAPER NUMBER:	LTR-01-0040	**LOGGING DATE:**	01/18/2001
ACTION OFFICE:	EDO		
AUTHOR:	D. Agarwal		
AFFILIATION:	TX		
ADDRESSEE:	RICHARD MESERVE		
SUBJECT:	Concerns radwaste containers for the Yucca Mountain Project: NiDI and Framatome Cogema sponsored Workshop on the subject at Las Vegas		
ACTION:	Direct Reply		
DISTRIBUTION:	RF		
LETTER DATE:	12/26/2000		
ACKNOWLEDGED	No		
SPECIAL HANDLING:	SECY TO ACK		
NOTES:	OCM #4862		
FILE LOCATION:	ADAMS		
DATE DUE:	2/8/01 ~~02/01/2001~~	**DATE SIGNED:**	

EDO --G20010024

4862

KRUPP VDM TECHNOLOGIES CORP

11210 Steeplecrest , Suite # 120 , Houston , Texas 77065-4939
Ph: 281-955-6683 or 800-227-8368 / Fax: 281-955-9809
Voice Mail ext.340 e-mail: dcagarwal@pdq.net

December 26, 2000

The Honorable Dr. Richard A. Meserve
Chairman
US Nuclear Regulatory Commission
One White Flint North
11555 Rockville Pike
Rockville, MD 20852-2738 (MS 16C1)

Dear Honorable Dr. Meserve:

Sub: Radwaste Containers for the Yucca Mountain Project : NiDI and Framatome Cogema sponsored Workshop on the subject at Las Vegas on Oct. 17 and 18, 2000.

I received a copy of Dr. B. John Garrick's letter dated December 6, 2000 , addressed to you on the subject of Alloy C-22 Corrosion Studies.

It was suggested that I forward you a copy of my presentation which I gave at the subject workshop in Las Vegas on October 17 – 18 , 2000 on Radwaste Container Material of Construction comparing alloy 22 and alloy 59. This presentation describes the chronology of events since 1995 on the interaction of Krupp VDM, TRW (Framatome), NiDI (Nickel Development Institute) and Lawrence Livermore National Labs (LLNL) on alloy 59.

This alloy 59 is a Ni-Cr-Mo family alloy belonging to the same Ni-Cr-Mo family as alloy 22 but with significantly improved properties over alloy 22. Samples of this alloy were sent to LLNL at the request of TRW (Framatome) during January of this year. Alloy 59 is covered in ASTM and ASME (SC II, Part D for SC VIII, Div.1applications) specifications and has an existing ASME code case N-625 for nuclear applications. Welding filler metal is also covered under American Welding Society specifications A5.11 and A5.14.

The main claim to fame of alloy 59 over alloy 22, is its superior uniform corrosion resistance in a variety of corrosive media , superior localized corrosion resistance (specially crevice corrosion resistance) , better resistance to hot cracking susceptibility during welding and more importantly superior thermal stability. This property of superior thermal stability behavior becomes very important in multi-pass welding of thick sections in maintaining the optimum corrosion resistance of the weldments. The Radwaste container will have thick section multi-pass welding of these Ni-Cr-Mo alloys, hence corrosion resistance of weldments becomes a very critical criteria. Alloy 59 weldments have exhibited superior crevice corrosion resistance characteristics than alloy 22 weldments in various laboratory testing.

In the enclosed package of my presentation in Las Vegas, I want to draw your attention to a letter dated October 6, 1998 by Dr. Stahl of TRW. This letter states that the corrosion resistant material alloy C-22 will henceforth be referred to as alloy 22 and its UNS number, because alloy C-22 is a registered trade mark of a particular supplier and it was never their intention to identify or utilize any one particular supplier for this class of material. This alloy 22 is manufactured by a number of nickel alloy producers including Krupp VDM. Also included are three technical papers on alloy 59 and the data sheet . Of the three papers, two were presented at the NACE International CORROSION / 2000 conference and one will be presented at CORROSION / 2001 conference in Houston , Texas in March, 2001.

Also enclosed is a letter dated November 17, 2000 from Dr. C. William Reamer, Chief, High Level Waste Branch, Division of Wasted Management, Office of Nuclear Material Safety and Safeguards. This letter states that Catholic University presented results on alloy 22 and Ti grade 7 to the Advisory Committee on Nuclear Waste but did not incorporate Alloy 59 results. I would sincerely appreciate receiving the results of Alloy 59 in comparison to alloy 22 and Ti grade 7. May I kindly request your office to send me a complete copy of Catholic University's research on this testing of alloy 22, Ti grade 7 and alloy 59.

As I understand from Dr. Garrick's letter dated Dec. 6, 2000, addressed to you that more corrosion testing of alloy 22 is planned. I request that based on the above mentioned technical merits of alloy 59, this alloy be included in all testing phases to fully ascertain as to which alloy will better fulfil the technical requirements of the Yucca Mountain Radwaste Container Design.

Our company will supply the necessary samples for the laboratory corrosion testing program (both welded and unwelded). Please let us know as to where the samples should be sent and to whose attention.

Dr. Meserve , I further request that your technical experts evaluate the enclosed information. If you wish I could send the same package to other people within your organization. Also if you permit and so desire, I would appreciate the opportunity to come to Rockville , MD and make a presentation to your group on the properties of alloy 59 and its comparison to alloy 22.

Waiting to hear from you,

Sincerely,

D. C. Agarwal
Vice-President, Technical Marketing

CC: Dr. B. John Garrick , Chairman
ACNW
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852-2738 (MS 2 E 26))

DRAFT

Note:

This was a draft response letter drafted by Keith McConnell in the Chairman's office. Use or don't use as you see fit.

D.C. Agarwal
Vice-President, Technical Marketing
Krupp VDM Technologies Corporation
11210 Steeplecrest
Suite #120
Houston, Texas 77065-4939

Dear Mr. Agarwal:

Thank you for your letter of December 26, 2000, concerning materials to be used in waste packages at a potential geologic repository at Yucca Mountain, Nevada. I found your discussion of the merits of alloy 59 versus alloy 22 to be interesting and informative. However, the Department of Energy (DOE) has the responsibility for assessing the various attributes of waste package materials and deciding upon an alloy for use in the potential repository. Although NRC does conduct independent, audit reviews of DOE's repository activities, our efforts are focused more on evaluating DOE's proposed waste package materials rather than identifying specific alternatives. Nonetheless, as mentioned in William Reamer's letter of November 17, 2000, the information you provided was reviewed by NRC staff as well as the staff of our Center for Nuclear Waste Regulatory Analysis. Concerning your request to receive information related to Catholic University's activities in evaluating various alloys, I am told by NRC staff that you were provided all the information that is currently available.

If you have any further questions or comments, please contact me.

Sincerely,

Richard Meserve

cc: Carl Paperiello
William Kane

STARS

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Received Date: 12/27/2000 **Mail Date:** 12/26/2000

To: CHAIRMAN **From:** AGARWAL, D.C.

Assigned To: 0

Subject: RADWASTE CONTAINERS FOR THE YUCCA MOUNTAIN PROJECT: NIDI AND FRAMATOME COGEMA SPONSORED WORKSHOP ON THE SUBJECT AT LAS VEGAS ON OCT. 17, AND 18, 2000 150

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7:44 AM

MEMORANDUM OF CALL

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TO: Chairman

☑ YOU WERE CALLED BY— ☐ YOU WERE VISITED BY—

D.C. Agarwal

OF (Organization) ~~Krupp Groupp~~ VDM

☐ PLEASE PHONE ▶ (Enter area code, if necessary) ☐ DSN

281-955-6683

☐ WILL CALL AGAIN ☐ IS WAITING TO SEE YOU

☐ RETURNED YOUR CALL ☐ WISHES AN APPOINTMENT

MESSAGE

would like to speak w/ you about Fed Ex pkg he sent to you and John Garrick

RECEIVED BY Linda | DATE 1/4 | TIME 3:55

NSN 7540-00-634-4018
50363-111
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OPTIONAL FORM 363 (Rev. 7-94)
General Services Administration

– More important he talks to DOE than NRC

– Corrosion resistance a function of specific environment alloy 59 may or may not be ok.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

November 17, 2000

D. C. Agarwal
Vice-President, Technical Marketing
Krupp VDM Technologies Corp.
11210 Steeplecrest
Suite # 120
Houston, Texas 77065-4939

SUBJECT: OCTOBER 31, 2000, LETTER CONCERNING RADWASTE CONTAINERS FOR THE YUCCA MOUNTAIN PROJECT

Dear Mr. Agarwal:

Thank you for sending the U.S. Nuclear Regulatory Commission the information entitled, "Which Alloy Better Serves the Need of the Rad-Waste Package Alloy 59 or Alloy 22 or both" and the information provided from Corrosion 2000, "Solving Critical Corrosion Problems in Marine Environments by an Advanced Ni-Cr-Mo Alloy 59 UNSN06059" and "Case Histories on Solving Severe Corrosion Problems in the CPO and Other Industries by an Advanced Ni-Cr-Mo Alloy 59 UNSN06059," along with Materials Data Sheet No. 4030.

The staff has reviewed the information provided. I understand that the information on Alloy 59 has been presented to the Center for Nuclear Waste Regulatory Analyses and to TRW, the U.S. Department of Energy's (DOE's) contractor for the proposed repository at Yucca Mountain, Nevada. This is appropriate, since DOE is responsible for the development and testing of any material proposed for use within the repository. Both Catholic University and Lawrence Livermore National Laboratory have evaluated Alloy 59 in side-by-side tests with Alloy 22. Recently, Catholic University presented results on Alloy 22 and Ti grade 7 to the Advisory Committee on Nuclear Waste but did not incorporate Alloy 59 results.

The information provided on corrosion potentials and corrosion rates is sufficiently informative that the staff does not require a presentation at this time. I hope that you will keep the staff informed of any future results of work related to the effect of corrosion, or the thermal stability, of Alloy 59 as it compares with Alloy 22. If you have any questions, or wish to provide additional information, please contact Tamara Bloomer of my staff, at 301-415-6626 or via Internet at TEB@NRC.GOV.

Sincerely,

C. William Reamer, Chief
High Level Waste Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

ACNWR-0161

December 6, 2000

The Honorable Richard A. Meserve
Chairman
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Dear Chairman Meserve:

SUBJECT: ALLOY C-22 CORROSION STUDIES

During its 122nd meeting on October 18, 2000, the Advisory Committee on Nuclear Waste (ACNW) heard presentations on the corrosion resistance of the nickel-based alloy C-22 from consultants to Nevada.[1] The Committee also heard presentations from the Center for Nuclear Waste Regulatory Analyses (CNWRA) and from the Department of Energy (DOE) on their C-22 studies during the 123rd ACNW meeting on November 28, 2000, in San Antonio, Texas. The ACNW has previously reviewed and discussed NRC/CNWRA and DOE studies of the corrosion of C-22 in a June 10–11, 1998, working group meeting on the Near-Field Environment and the Performance of Engineered Barriers at Yucca Mountain.

The longevity of waste packages is a key attribute of DOE's repository safety strategy. According to DOE's current calculations, the putative resistance of C-22 to corrosion will prevent any significant releases of radioisotopes from the waste package to the repository for more than 10,000 years. Thorough study of the alloy's potential degradation modes and corrosion resistance in the Yucca Mountain environment is obviously important to NRC's analyses of a license application for the site.

Conclusions and Recommendations

1. Preliminary experiments conducted by the State of Nevada consultants demonstrated that C-22 corrodes rapidly under extreme conditions. These conditions are not representative of those expected at Yucca Mountain.

2. Neither DOE nor NRC has yet thoroughly investigated the role of trace elements, such as mercury and lead, in the corrosion of C-22.

3. NRC and CNWRA staffs are identifying conditions in which the presence of trace elements could promote corrosion. They should verify that the absence of trace elements in previous work did not bias the conclusions about the susceptibility of C-22 to corrosion.

---

[1] This project is part of Nevada's Oversight Assessment Program of the Engineered Barrier System for the proposed Yucca Mountain high-level waste repository.

4. NRC and CNWRA staffs should proceed with plans to evaluate the performance of C-22 under the full range of conditions that occur or may occur at Yucca Mountain. The ACNW believes that it is essential to understand the mechanisms of corrosion to allow extrapolation of performance over 10,000 years.

Background

A key concern of the Committee, expressed in a 1998 letter, is the need to bound the extreme environments that C-22 may encounter in Yucca Mountain over the long term [Reference1]. More recently the Committee commented on corrosion issues in a letter report on the Importance of Chemistry in the Near Field [Reference 2]. The ACNW noted that pit, crevice, and stress corrosion are still concerns. NRC needs to understand the mechanisms of these corrosion processes better before credit can be taken for the very long-term protection that DOE may postulate in its License Application (LA). The Committee recommended in the letter that the NRC staff continue collecting as much confirmatory data as possible on the corrosion rates and mechanisms over the range of expected conditions. The NRC staff agreed with these recommendations.

Issues from Nevada-Sponsored Research

The State's consultants presented research results of accelerated testing of C-22 corrosion in the presence of minor contaminants (e.g., lead and mercury) known or suspected to cause local corrosion, such as pitting and stress corrosion cracking (SCC). The research, which is being done by chemists and materials scientists from The Catholic University of America and Dominion Engineering, shows that C-22 experiences pitting corrosion and SCC under extreme conditions. One fundamental issue is whether these conditions can be extrapolated to conditions more representative of the waste packages in the repository environment.

Presentations by Geosciences Management Institute addressed the presence of mercury and lead in the geologic strata surrounding the proposed Yucca Mountain high-level waste (HLW) repository site. From the presentations it appears likely that both mercury and lead are present in low concentrations in the rock above the proposed repository. Both of these elements may also be found in the pore water and perched water of the unsaturated zone and in other ground water at the site. It is unknown whether these or other potentially harmful elements exist in either sufficient concentrations or appropriate chemical forms to be detrimental to long-term performance of the waste packages and other engineered barriers in the near-field environment at Yucca Mountain.

Another consultant to Nevada reviewed SCC failures of nickel-based alloys in nuclear power plant steam generators. These failures were caused by small concentrations of lead (a few ppm) in cooling water. He also discussed scenarios that could lead to enhanced corrosion of C-22 and titanium alloys inside the disposal drifts of a Yucca Mountain repository. A key issue is the relevance of the lead-induced corrosion in steam generators to waste package corrosion in the HLW repository. On the basis of these experimental results, the State of Nevada's consultants concluded that the presence of mercury and lead in the Yucca Mountain environment could significantly shorten the period DOE could expect protection from C-22.

It is the opinion of the Committee that the experiments described by the consultants to Nevada were not representative of the conditions likely to occur at Yucca Mountain. Furthermore, the work did not include sufficient control experiments. The experiments showed C-22 corrodes rapidly under extreme conditions and at least suggest that under some conditions mercury, lead, and possibly other minor or trace chemicals can affect corrosion. The Committee concludes that the nature and extent of this effect need to be elucidated under realistic conditions.

The role of stress in the corrosion of C-22 also needs to be studied further. NRC particularly needs to understand the residual stresses on the C-22 waste package and how DOE will ensure that significant tensile stresses are not left on the surface of the finished waste package.

Planned NRC and DOE Activities

On November 28, 2000, the Committee heard from NRC/CNWRA and DOE about planned confirmatory studies to address a number of significant corrosion issues, including those discussed above. The DOE has agreed, as part of the issue resolution process, to do tests to establish the window of susceptibility of C-22 to SCC and to understand the role of trace metals in the corrosion of C-22. The NRC staff has also planned studies to illuminate mechanisms of corrosion of C-22. The Committee strongly supports tests and studies planned by both NRC and DOE.

Sincerely,

/RA/

B. John Garrick
Chairman

References:

1. ACNW letter dated September 9, 1998, to Shirley Ann Jackson, Chairman, U.S. Nuclear Regulatory Commission, from B. John Garrick Chairman, ACNW, Subject: Issues and Recommendations Concerning the Near-field Environment and the Performance of Engineered Barriers at Yucca Mountain
2. ACNW letter dated January 11, 2000, to Richard A. Meserve, Chairman, U.S. Nuclear Regulatory Commission, from B. John Garrick Chairman, ACNW, Subject: Comments on the Importance of Chemistry in the Near-Field to DOE's Yucca Mountain Repository License Application

Fourth Workshop on the Design and Fabrication of the Yucca Mountain Waste Package

<u>Sponsored by NiDI at request of Framatome Cogema Fuels</u>

Which Alloy Better Serves the Need of the Rad-Wsate Package

Alloy 59 or alloy 22 or both

by

D.C.Agarwal

Krupp VDM, Houston

Presented at Las Vegas on Oct. 17 - 18 , 2000

Typical Chemical Composition
Alloy 59 vs. Alloy 22

	Alloy 59	Alloy 22
Ni	59	57
Cr	23	21
Mo	16	13
Fe	<1	3
W	-	3

PRE: Pitting Resistance Equivalent

	Alloy 59	Alloy 22
PRE	76	65

Major difference: Alloy 59 has approximatley 2% more Nickel and Chromium, about 3% more Molybdenum, very low iron and no tungsten & higher PRE number. Tungsten is detrimental for thermal stability.

Uniform Corrosion Resistance of Alloy 59 vs. Alloy 22 in Some Boiling Environments

Media	Corrosion Rate (MPY) Alloy 22	Corrosion Rate (MPY) Alloy 59
• ASTM G28A	36	24
• ASTM G28B	7	4
• Green Death	4	5
• 10% HNO3	2	2
• 65% HNO3	52	40
• 10% H2SO4	18	8
• 50% H2SO4	308	176
• 1.5 % HCl	14	3
• 10% HCl	392	179
• 10% H2SO4 + 1% HCl	354	70
• 10% H2SO4 + 1% HCL*	92	3

*90 Deg. C

Localized Corrosion Behavior
Alloy 59 vs. Alloy 22

CPT and CCT per ASTM G-48
(10% $FeCl_3$ Solution)

Alloy	Cr	Mo	PRE	CPT (deg.C)	CCT (deg. C)
22	21	13	65	>85	58*(ave.)
59	23	16	76	>85	>85

*Round Robin Test conducted on alloy 22 by 6 different laboratories are given below (deg. C):

Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6
50,50 -	50,55 55	50,60 60	67,67 -	No Report	55,55 -

Copy of ASTM G-48 (Table 1 attached)

TABLE 1 Results of Interlaboratory Test Program

NOTE—Minimum temperature (°C) to produce attack at least 0.025 mm (0.001 in.) deep on bold surface of specimen. Edge attack ignored.

Alloy/Laboratory	Method C—CPT Critical Pitting Corrosion Temperature (C)				Method D—CCT Critical Crevice Corrosion Temperature (C)			
	UNS S31603	UNS N08367	UNS S44735	UNS N06022	UNS S31603	UNS N08367	UNS S44735	UNS N06022
1	20/20/20	75/[A]/[A]	85/85/85	>85/>85/>85	<0/<0<0	30/30/30	42/35/42	50/[A]/50
2	20/20/20	70/70/70	80/80/80	>85/>85/>85	<0/<0<0	25/25/25	35/35/[A]	50/55/55
3	20/20/20	85/85/85	75/85/85	>85/>85/>85	<0/<0/<0	25/30/30	35/40/40	55/60/60
4	19/19	75/80	81/81	>85/>85	<0/<0	34/34	40/40	67/67
5	20/20/20	75/75/75	70/70/75	>85/>85/>85	<0/<0/<0	20/20/20	45/45/45	
6	20/20	75/80	75/85	>85/>85	<0/<0	30/30	40/40	55/55

[A] Test run but no attack observed.

examination is required. Photographs of a sample with mass loss less than 0.001 g/cm^2 are unnecessary since no sites of attack will be apparent at low magnification.

NOTE 24—It is often desirable to probe pit sites on the metal surface with a needle to expose subsurface attack. Localized modes of corrosion often result in occluded pits.

NOTE 25—A test shall be discarded if a rubber band or O-ring breaks at anytime during the exposure period.

11.2 Examine specimen faces for pits at low-magnification (for example, 20× magnification). Distinguish between pits on specimen edges and faces, recognizing that edge pits may affect pitting on specimen faces. Edge pits may be disregarded unless of specific interest; for example, in assessing susceptibility to end-grain attack.

11.3 Measure the deepest pits with an appropriate technique; for example, needle point micrometer gage or microscope with calibrated fine-focus knob or calibrated eyepiece. It may be necessary to probe some pits to ensure exposure of the cavity. Measure a significant number of pits to determine the deepest pit (Methods A and C) and the average of the ten deepest pits (Method A). Do not include the depth of pits that intersect the edges of the specimen in the calculated average.

11.4 Count the number of pits on the specimen faces under low-power magnification (for example, 20×) to determine pit density (Method A). A clear plastic grid, divided in centimeters, may be helpful, or the surface can be subdivided by scribing with light lines.

11.5 Visually identify crevice attack under O-rings or rubber bands and TFE-fluorocarbon blocks (Method B) or the multiple crevice assembly (Method D). Measure the greatest depth of attack at the points of contact of the O-rings or rubber bands (open notch), and under the TFE-fluorocarbon blocks or multiple crevice assembly.

12. Report

12.1 Record the test procedure used, specimen size and surface preparation, time of test, temperature, torque used to fasten the crevice assembly (Method D) and the means by which the presence of pits or crevices were assessed for all practices.

NOTE 26—It is important to record the means by which the presence of pits or crevices was assessed, since, for example, small diameter pits (or pits in a region of crevice attack) that were not detected by a needle-point micrometer may be observed with a low-magnification microscope. The latter test would, therefore, be considered more severe than the former.

12.2 Record the maximum pit depth (Methods A and C) and the average of the ten deepest pits in micrometers and pit density in pits per square centimeter for both 25 by 50-mm (1 by 2-in.) faces of the specimen (Method A). Record the maximum pit depth on edges if end grain attack is of interest.

12.3 Record the number of attacked sites on each side of the specimen (Method D), the maximum depth of attack (Methods B and D), and the average depth of attack (Method B) in micrometres under the TFE-fluorocarbon blocks and at the point of contact for the O-rings or rubber bands.

12.4 Calculate the specimen mass loss and record in units of grams per square centimeter for Methods A and B.

NOTE 27—The depth and frequency of attack sites provide a more sensitive criterion than mass loss when assessing resistance to pitting and crevice corrosion (Method A and B). For example, little mass would be lost from a specimen that contained only a few small diameter pits which had penetrated the entire specimen cross section. When attack is significant, mass loss per unit of surface area may provide a rapid means of evaluation.

12.5 Refer to Appendix X1 for a recommended stand. format for the computerization of pitting and crevice corrosion data in ferric chloride solution as generated by this test method, Methods A and B.

13. Precision and Bias

13.1 *Precision*—Precision is the closeness of agreement between test results obtained under prescribed conditions. In the discussion below, two types of precision are described: repeatability and reproducibility. Repeatability is within laboratory variability when the same operator uses the same equipment on identical specimens in sequential runs. Reproducibility refers to the variability that occurs when identical specimens are tested under specified conditions at different laboratories.

13.1.1 The precision of Methods A and B for measuring the pitting and crevice corrosion resistance of stainless steels and related alloys using a ferric chloride solution is being determined.

13.1.2 The precision of Methods C and D for measuring pitting and crevice corrosion temperatures was determined in an interlaboratory test program with six laboratories running triplicate tests on four materials. The results of these tests are given in Table 1. An analysis of the data in the table according to Practice E 691, showed that the results were consistent among laboratories and that there were no significant variations between the materials in either repeatability or reproducibility.

13.1.2.1 The pooled repeatability standard deviation, and 95 % confidence limit, *r*, for Methods C and D for the materials tested was:

Localized Corrosion Behavior
Alloy 59 vs. Alloy 22 in Green Death* Solution

CPT and CCT in Green Death Solution (deg. C)

Alloy (PRE **)	CPT	CCT	Crevice Attack Depth at 105'C
Alloy 22 (65)	120	105	14 mils
Alloy 59 (76)	>120***	110	1 mil

*Green Death: 11.5% H_2SO_4 + 1.2% HCl + 1% $FeCl_3$ + 1% $CuCl_2$

** PRE = %Cr + (3.3) %Mo + 30N

*** Above 120 deg. C, the Green Death solution chemically breaks down.

Thermal Stability Behavior
Alloy 59 vs. Alloy 22

Corrosion of Sensitized Samples (1600 deg. F x 1 hr) of Alloy 22 and Alloy 59 in ASTM G28A and G28B Solution

Corrosion Rate (MPY)

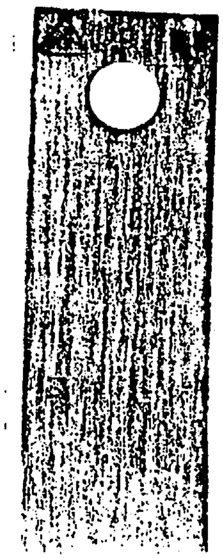
	Alloy 22	Alloy 59
ASTM G28A	>500*	40**
ASTM G28B	>338*	4**

* Alloy 22 showed heavy pitting with grains falling due to deep intergranular attack.

** Alloy 59 was free of any pitting attack

THERMAL STABILITY BEHAVIOR*

Alloy 22



Alloy 59

* Samples sensitized at 1600°F
ASTM G-28 B Solution 23% H_2SO_4 + 1.2% HCl + 1% $CuCl_2$ + 1% $FeCl_3$ - Boiling Solution - 24 hrs.

3M STUDY - HAZARDOUS WASTE INCINERATION SCRUBBER DATA (4798 HRS)*

Alloy	MPY	Remarks
→ 59	1	Clean
654SMo	1	Pitting
622	2	Clean
G-30	3	Rough
686	3	Clean
→ C-22	6	Clean
AL6XN	11	Clean
904L	29	Clean
304SS	170	Clean

*Vic Yanish "Corrosion Testing in a Hazardous Waste Incinerator and Waste Heat Boiler" - Presented at 2nd International Conference on Heat Resistant Materials, Sept. 11-14, 1995

3M STUDY - HAZARDOUS WASTE INCINERATION
SCRUBBER DATA (1991 HRS)*

Alloy	MPY	Remarks
59	1.1	Clean
686	5.4	Clean
C-22	6.7	Clean
31	7.1	Clean
622	12.1	Weld Attack
C-276	35.1	Clean
625	58.6	Rough
825	117	Pitting

*Vic Yanish "Corrosion Testing in a Hazardous Waste Incinerator and Waste Heat Boiler" - Presented at 2nd International Conference on Heat Resistant Materials, Sept. 11-14, 1995

Comparison of Corrosion of Welded Samples of Alloy 59 vs Alloy 22

Base / Filler	ASTM G28A		ASTM G28B		Green Death	
	MPY	IGA mils	MPY	IGA mils	CPT°C	CCT°C
22 / 59 TIG Manual	32	< 4	28	< 2.4	120	115
59 / 59 TIG Manual	24	< 2	8	< 2	> 125	120
22 / 59 electrode	32	< 3	20	< 1.5	120	115
59 / 59 electrode	20	< 2	8	< 1	125	120

Comparison of Corrosion of Welded Samples of Alloy 59 vs Alloy 22 In High Chloride low pH media : 70,000 ppm Cl^- , pH 1 at 105 °C , 21 day test

Base / Filler	Corrosion Rate MPY	Pitting Corrosion	Crevice Corrosion
22 / 22	18	No	Yes
59 / 59	< 0.3	No	No

Chronology of Krupp VDM Interactions on alloy 59 with various NiDi Sponsored Workshops , LLNL and TRW Waste Package Management & Operating Contractor

- First workshop Feb. 1995 : Data on alloy 59 presented
- Second workshop March 1998 : Data on thermal stability of alloy 59 and other alloys presented
- Aug/Sept. 1998 : Letter on alloy 59 superior localized resistance and thermal stability written to LLNL and TRW
- Oct. 1998: Letter from TRW to VDM

  * Alloy C-22 will be referred to as alloy 22 and UNS N06022

  * Initiate testing of alloy 59 at LLNL

  * Initiate ASME code case for SCIII applications

TRW Environmental Safety Systems Inc.
1261 Town Center Drive
Las Vegas, NV 89134
702.295.5400

TRW

WBS: 1.2.2
QA: N/A

Contract #: DE-AC08-91RW00134
LV.WP.DS.10/98-191

October 6, 1998

Dr. D. C. Agarwal
KRUPP VDM
11210 Steeplechase Drive, #120
Houston, TX 77065-4939

Dear Dr. Agarwal:

The letters that you have written to Dr. Daniel McCright and Mr. V. Pasupathi of my staff have been recently given to me. I am happy to respond to your concerns.

Firstly, we have changed our call out of the corrosion-resistant material to Alloy 22 to be more generic. For detailed procurements, we will utilize the UNS number. It was never our intention to identify or utilize any particular supplier for this class of material.

Secondly, in regard to your suggestion that we evaluate Alloy 59, we would certainty like to do that. Please provide fully certified material coupons to Dr. McCright. Contact him directly regarding the details of coupon size, welded versus unwelded specimens, U-bend specimens, etc.

Lastly, in regard to your suggestion that we pursue the ASME code case for Alloy 59, I agree that it would be prudent to initiate that process. Thus, I have asked Mr. Pasupathi to initiate a request to ASME.

I hope that I have adequately responded to your concerns. Please feel free to call me at (702) 295-4383 if you have any additional questions or concerns.

Sincerely,

David Stahl

David Stahl, Ph. D., Manager
Waste Package Materials Department
Management & Operating Contractor

LV.WP.DS.10/98-191
October 6, 1998
Page 2

DS/lk

cc:
H. A. Benton, M&O, Las Vegas, Nevada, M/S 423
W. L. Clark, M&O, Livermore, California, L-217
R. D. McCright, M&O, Livermore, California, L-217
V. Pasupathi, M&O, Las Vegas, Nevada, M/S 423
RPC = 2 pages

Chronology ----- (continued)

- **Third workshop October 1998: Data on Fabrication , Welding and Corrosion resistance of alloy 59 presented**
- **June 1999: After discussions with TRW and LLNL, data on alloy 59 and 22 generated per ASTM G61 Cyclic Potentio - dynamic Polarization Testing in solution chemistry (SAW and SCW) provided by LLNL. Testing done at an independent laboratory, Corrosion Testing Laboratory. *Alloy 59 and alloy 22 performed similarly in these tests. Copy of this report sent to TRW and is attached.***
- **June 25, 1999: Letter fromTRW (Framatome Cogema Fuels) to VDM raising some questions and suggesting a conference call to discuss these questions.**

Test results Summary of the ASTM G61 Test *

(Copy of full report attached - dated June 4, 1999)

Solution (Specification)	SCW (TIP-CM-07)	SAW (TIP-CM-08)
$Ca(NO_3)_2 \cdot 4H_2O$	12.1685	5.8920
$CaCl_2 \cdot 2H_2O$	7.5980	----
$CaCO_3$	37.1173	----
H_2SO_4	0.07679	0.4402
HCl	0.0701	----
KCl	6.2820	6.4828
$KHCO_3$	0.1925	----
$MgSO_4 \cdot 7H_2O$	21.3920	10.1380
$Na_2SiO_3 \cdot 5H_2O$	0.3700	0.3700
Na_2SO_4	12.2545	50.5960
NaCl	----	34.8933
NaF	3.1826	----
$NaHCO_3$	128.2970	----
$NaNO_3$	----	27.2865
Measured pH	8.4	3.0

All values listed are in grams per liter (g/l) of solution.

* Test Parameters provided by LLNL

The following parameters were used for each of the polarization scans:

Temperature	90.0°C
Gas Sparge	Air (150 cm^3/min.)
Initial Potential	-0.100 V from open circuit
Scan Rate	0.17 mV per second

Table 1
Key-Point Electrochemical Data*

Polarization Scan	E_{OC}	E_{corr}	E_{pit}	E_{repas}	I_{corr}	Hysteresis
Alloy 59 in SAW	51	59	617	401	0.09	Yes
Alloy C-22 in SAW	69	84	577	310	0.10	Yes
Alloy 59 in SCW	-247	-246	143	-201	0.25	Yes
Alloy C-22 in SCW	-240	-232	145	-203	0.24	Yes

* NOTE: E-values are in millivolts; and I-values are in micro-amps (10^{-6} amps)

Table 2
Corrosion Rates and Localized Attack Propensity

Polarization Scan	Corrosion Rate (mpy)	Pitting and Crevice Propensity
Alloy 59 in SAW	0.04	Possible
Alloy C-22 in SAW	0.04	Possible
Alloy 59 in SCW	0.10	Possible
Alloy C-22 in SCW	0.09	Possible

Potentiodynamic Polarization
Alloy 59 vs C-22 in SAW and SCW @ 90°C

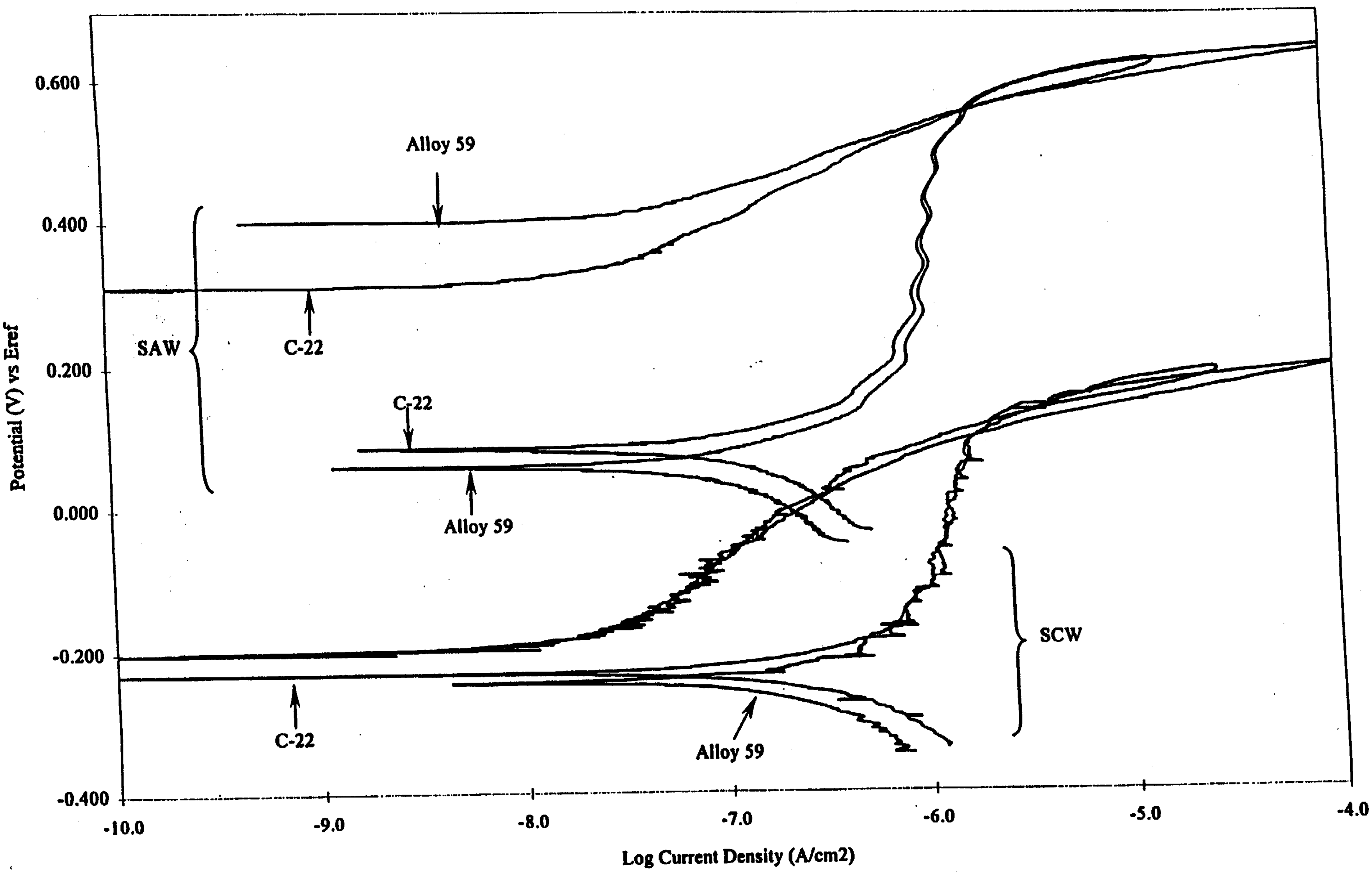


Figure 3

KRUPP VDM

By Federal Express

June 4, 1999

Dr.David Stahl
Manager, Waste Package Materials Dept.
Framatome Cogema Fuels/TRW
1261 Town Center Drive
Las Vegas, NV 89134

Subject: Alloy 59 and C-22 Testing per ASTM G-61 for the Yucca Mountain Project

Dear Dr.Stahl:

As discussed earlier, we got the testing done on the above two alloys at Corrosion Testing Laboratories per parameters discussed at Corrosion/99 conference in San Antonio, Texas, with Drs. Dan McCright and Ajit Roy and further e-mail correspondences.

The attached comprehensive report clearly shows that both alloys performed similiarly in the SAW and SCW test solutions. In fact in the SAW solution, alloy 59 exihibited a significantly nobler (positive) repassivation potential (+401 mv) than alloy C-22 which was at +310 mv.

Also no pits or crevice attack could be seen when examined at a magnification of 40x.

After your experts have examined and evaluated this report, I suggest a meeting at your office to discuss further course of action. We would also like to propose testing in the welded condition on both these alloys.

Waiting to hear from you on the above report and our request for a meeting.

Sincerely,

D.C.Agarwal

11210 Steeplecrest Drive, # 120, Houston, Texas 77065-4939, Tel. (281)955-6683, Fax (281)955-9809

Corrosion Testing Laboratories, Inc.
60 Blue Hen Drive, Newark, DE USA 19713 • (302) 454-8200

CTL REF #15321-1

June 3, 1999

Mr. D. C. Agarwal
National Technical Marketing Manager
Krupp VDM Technologies Corporation
11210 Steeplecrest Drive, Suite 120
Houston, TX 77065-4939

Re: **Alloys 59 and C-22 in Yucca Mountain Project Water Formulations.**
ASTM G 61 Cyclic Potentiodynamic Polarization Testing

Dear Mr. Agarwal:

Presented herein are the results of the above referenced corrosion testing. This work was authorized under your verbal instructions.

BACKGROUND

We understand the corrosion resistance of Alloys 59 for containment of vitrified nuclear waste and spent nuclear fuel has been questioned. Recent testing at the Lawrence Livermore National Laboratory, (LLNL) has shown Krupp VDM Alloy 59 to be susceptible to localized pitting/crevice attack in both alkaline and acidic sodium chloride brines at 90°C. Using Cyclic Potentiodynamic Polarization (CPP) electrochemical techniques, Alloy 59 reportedly showed deep pits after testing while Alloy C-22 showed no evidence of localized attack. Metallographic analysis revealed pits and plastic deformation on the surface of *untested* Alloy 59.

Since these alloys are being considered for nuclear waste containment for the Yucca Mountain Project, any indication of failure in the proposed environment would be grounds for rejection of the candidate alloy. It is therefore most important to test *representative* material slated for this environment. Surface imperfections, however slight, may influence test results, providing erroneous information regarding corrosion susceptibility.

In order to anticipate service performance, simulation of possible service extremes should be considered for testing candidate materials. It is therefore the goal of this test program to define the service environment, and evaluate two candidate alloys (Alloys 59 and C-22) under predicted service extremes.

While the service environment is expected to be dry, and therefore non-corrosive, the possibility exists that these waste containers may periodically experience wet conditions. A worst case scenario would suggest complete immersion of the material to be tested. Based on water samples obtained from the service location, several solution compositions ranging from low ionic content to saturation of ionic species have been proposed for corrosion testing. As well, solution compositions ranging from acidic to alkaline have also been suggested as possible service conditions. For this program, the two most aggressive solutions were chosen. The first solution, Simulated Concentrated Water (SCW), is a nominal 1000× concentration of the chemical composition of the reference water source, J-13 well water (LLNL Procedure TIP-CM-07-0-2). The second solution, Simulated Acidic Concentrated Water (SAW), is based on the acidification of the SCW (LLNL Procedure TIP-CM-08-0-1).

CORROSION AND ELECTROCHEMICAL BASICS

For the purposes of this test program, corrosion is defined as a deterioration of a metal due to its reaction with the surrounding aqueous environment. This reaction is an electrochemical process, where at the anode there is oxidation of the metal to form a corrosion product (i.e., rust) and the release of electrons, and at the cathode there is reduction of dissolved ionic species (i.e., hydrogen or carbonates) and the consumption of electrons. This flow of electrons between the anode and the cathode can be measured by instrumentation (i.e., a potentiostat).

The corrosion reaction has two components: thermodynamics and kinetics.

Thermodynamics is the change in electrochemical potential (voltage), or the electron activity for a corrosion reaction. It is monitored by key-point voltages such as:

- the open circuit potential (E_{OC});
- the polarized null current potential (E_{corr});
- the pitting/crevice breakdown potential (E_{pit}); and
- the repassivation potential (E_{repas}).

In general, the more electro-negative the potential, the more active (or an increased propensity) the corrosion reaction, and an increase in attack propagation once initiated.

Kinetics is the rate at which the corrosion reaction occurs once initiated; and, there is a finite energy, related to each specific metal/environment interaction, required to initiate corrosion. If this energy is not achieved then corrosion will not initiate. Kinetics is monitored by key-point currents such as:

- the corrosion current (I_{corr}) [i.e., the rate of general/uniform attack];
- the presence of a cyclic hysteresis loop upon voltage reversal during the polarization scan [i.e., susceptibility to pitting and/or crevice corrosion]; and
- the relationship of the hysteresis loop to the open circuit potential [i.e., pit initiation].

Specifically, the rate of corrosion is proportional to the increase in current.

The cyclic potentiodynamic polarization technique is used to monitor an electron flow pattern which can be interpreted to qualify and quantify the propensity of a metal to uniformly (generally) corrode and/or be susceptible to localized attack, such as pitting or crevice corrosion.

POTENTIOSTAT CALIBRATION

Calibration of the potentiostat used for this test program was conducted in accordance with ASTM G5 (Standard Reference Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements.) A standard solution of 1.0 N sulfuric acid (H_2SO_4) was prepared by adding 27.8 ml of 98% H_2SO_4 to a 1000 ml volumetric flask and diluting to the mark with de-ionized water. Approximately 900 ml of the solution was added to a test vessel similar to that shown in ASTM G5, Figure 1. The vessel was heated to 30°C. The vessel was fitted with a condenser, two counter electrodes (graphite), a reference electrode (calomel) with a salt bridge filled with test solution, and a sparge tube for bubbling nitrogen (N_2) through the solution. N_2 was bubbled at a rate of approximately 150 cm^3/min and allowed to come to equilibrium for ½ hour.

A 5/8" diameter disc shaped specimen of Type 430 stainless steel (UNS S43000), purchased from ASTM, was prepared by mechanically grinding one face with silicon carbide (SiC) paper to a wet 240 grit finish followed by a wet polish with 600 grit SiC paper. The specimen was degreased using a mild detergent, rinsed with de-ionized water, rinsed with methanol and warm air dried. The specimen was mounted in a specimen holder similar to that described in ASTM G61, Figure 1. The sparge tube was removed and the specimen was introduced to the test vessel within one hour of the grinding and the cell was allowed to equilibrate for 1 hour prior to performing the polarization test.

The following conditions were used for the calibration scan:

Temperature	30.0°C
Initial Potential	0.0 V from open circuit
Scan Rate	0.17 mV per second

The scan was terminated at +1.6 volts and the results compared to the reference scans found in ASTM G 5. The resulting curve was found to be within experimental variance as set forth by ASTM G 5.

TEST PROCEDURE

For each of the solutions tested, the specification cited each chemical weight per 1000 liters. Based on the information provided in LLNL Procedures TIP-CM-07 and TIP-CM-o8, one liter of each solution was prepared using reagent grade chemicals as follows:

Solution (Specification)	SCW (TIP-CM-07)	SAW (TIP-CM-08)
$Ca(NO_3)_2 \cdot 4H_2O$	12.1685	5.8920
$CaCl_2 \cdot 2H_2O$	7.5980	----
$CaCO_3$	37.1173	----
H_2SO_4	0.07679	0.4402
HCl	0.0701	----
KCl	6.2820	6.4828
$KHCO_3$	0.1925	----
$MgSO_4 \cdot 7H_2O$	21.3920	10.1380
$Na_2SiO_3 \cdot 5H_2O$	0.3700	0.3700
Na_2SO_4	12.2545	50.5960
NaCl	----	34.8933
NaF	3.1826	----
$NaHCO_3$	128.2970	----
$NaNO_3$	----	27.2865
Measured pH	8.4	3.0

All values listed are in grams per liter (g/l) of solution.

The solutions were prepared under ambient conditions. Each chemical was weighed to the nearest 0.0001 grams, and added, in no particular order, to a 1 liter volumetric flask with the exception of the sulfuric acid. Each solution was prepared to approximately 90% volume, the sulfuric acid was added, and the solution was heated to accelerate chemical reactions. After dilution to 1 liter, a white precipitate remained at the bottom of each solution due to ionic saturation of chemical added. The solutions were heated to approximately 80°C, agitated, and a 250 ml aliquot poured into a test vessel. The test vessel used was similar to that shown in ASTM G5, Figure 1.

The test vessel was fitted with a condenser, two counter electrodes (graphite), a reference electrode (calomel), and a sparge tube for aeration of the solution. Air was bubbled at a rate of approximately 150 cm^3/min., the solution was heated to 90°C and allowed to come to equilibrium for ½ hour.

For each alloy, a rectangular specimen approximately ½" × ½" × ¼" was prepared by drilling and tapping a hole for mounting and by mechanically grinding each face with silicon carbide (SiC) paper to a wet 240 grit finish followed by a wet polish with 600 grit SiC paper. The specimen was then measured to the nearest 0.01 mm to determine exposed surface area and mounted to the specimen holder similar to that described in ASTM G5, Figure 3. Immediately prior to each test, each specimen was degreased using a mild detergent, and rinsed with de-ionized water. The specimen was introduced to the test vessel and the cell was allowed to equilibrate for 1 hour prior to performing the polarization test.

In the electrochemical technique chosen, cyclic potentiodynamic polarization (CPP) per ASTM G61, a metal specimen (working electrode) is exposed to the solution in a test cell fitted with a reference electrode (saturated calomel) and a counter electrode (graphite). The potentiostat is connected to these three electrodes, and the potential of the working electrode, with respect to the reference, is scanned through a voltage range from negative to positive, and then reversed to its starting potential. The resulting current between the working and counter electrodes is recorded. This scan is then plotted on a semi-log graph, allowing the resulting curve to be analyzed for key-point voltages and currents.

The following parameters were used for each of the polarization scans:

Temperature	90.0°C
Gas Sparge	Air (150 cm^3/min.)
Initial Potential	-0.100 V from open circuit
Scan Rate	0.17 mV per second

RESULTS

The individual curves from each scan are presented in Appendix A. Figure 1 is a composite curve for Alloys 59 and C-22 in Simulated Concentrated Water (SCW), Figure 2 is a composite curve for Alloys 59 and C-22 in Simulated Acidic Concentrated Water (SAW), and a graphical composite of all four curves is shown in Figure 3. The key-point voltage and current data are summarized in Table 1, and calculated corrosion rates and localized attack propensity are presented in Table 2.

Table 1
Key-Point Electrochemical Data *

Polarization Scan	E_{OC}	E_{corr}	E_{pit}	E_{repas}	I_{corr}	Hysteresis
Alloy 59 in SAW	51	59	617	401	0.09	Yes
Alloy C-22 in SAW	69	84	577	310	0.10	Yes
Alloy 59 in SCW	-247	-246	143	-201	0.25	Yes
Alloy C-22 in SCW	-240	-232	145	-203	0.24	Yes

* NOTE: E-values are in millivolts; and I-values are in micro-amps (10^{-6} amps)

Table 2
Corrosion Rates and Localized Attack Propensity

Polarization Scan	Corrosion Rate (mpy)	Pitting and Crevice Propensity
Alloy 59 in SAW	0.04	Possible
Alloy C-22 in SAW	0.04	Possible
Alloy 59 in SCW	0.10	Possible
Alloy C-22 in SCW	0.09	Possible

DISCUSSION

Electrochemical polarization techniques provide a relatively rapid means to experimentally determine the corrosion behavior of a metal in a given environment. The two types of corrosion behavior associated with polarization are activation and concentration. Activation polarization is controlled by the free-energy or driving force at the surface of the metal. Concentration polarization is controlled by the mass transport of reacting species to the metal surface or the reaction/corrosion products away from the metal surface. The shape of a polarization scan, reflected in a plot of potential versus the logarithm of current, will determine which of these two mechanisms are affecting the anodic and cathodic reactions occurring on the metal's surfaces.

Corrosion Rate from Polarization Curves

The corrosion rate of a metal can be estimated from its polarization behavior. To determine the corrosion rate from polarization plot, it is desirable to have both the anodic and cathodic polarization curves. The corrosion rate is determined by extrapolating the anodic and cathodic linear regions (called Tafel Slopes) to the corrosion potential (E_{corr}). At the corrosion potential, the extrapolated anodic and cathodic Tafel slopes should intersect. At this intersection, the rate of the anodic reaction equals the rate of the cathodic reaction, and the value at the intersection is the corrosion current, Icorr. Faraday's Law provides the relationship between current and corrosion rate of a change in thickness per unit time, such as mils per year (mpy), where 1 mil = 0.001 inches.

Pitting and Crevice Corrosion Susceptibility

Cyclic polarization is routinely used to determine pitting and crevice corrosion susceptibility of alloys under controlled conditions. It is often difficult to reproduce actual pitting and crevice attack behavior under service conditions because: a) conditions that initiate these localized corrosion cells are not well-defined and b) the types of surface finishes and crevices that may be present in actual in-plant service is not completely defined and so not reproducible in the laboratory. Even so, the cyclic polarization technique is an extremely powerful tool in defining alloy-environment combinations that may be subject to localized corrosion.

Pitting and crevice corrosion occurs when there is a breakdown in the passive surface film. This localized attack is characterized by a rapid increase in current with only a small change in potential. The potential where this current increase initiates is termed the breakdown potential (E_{pit}). It should be noted that there are other causes for a rapid increase in current, such as oxygen evolution due to hydrolysis or mechanical damage (i.e., a scratch), and the presence of pits or crevice attack must be verified by microscopic examination up to 40X magnification of the test specimen surface upon completion of the polarization experiment.

A fairly sharp break in the polarization curve usually occurs when passivation breaks down. The value selected for this breakdown potential (E_{pit}) is typically well defined. For consistency, the relatively straight portions of the curve before and after breakdown are extrapolated to their intersection point, and this is taken as the breakdown potential. As a general rule of thumb, the differences in breakdown potentials greater than 50 mV between two experiments are considered to be significant. Such that two curves with breakdown potentials within 50 mV of each other would be considered similar unless sufficient reproducibility of the experiments had been made to verify a statistical difference.

A method to determine whether localized attack is occurring on a test specimen during the polarization experiment is to reverse the direction of the scan after a significant current increase (1 to 2 decades of current increase). If hysteresis results, it is very likely pitting or crevice attack has occurred. If no hysteresis results, then some other non-reversible oxidation reaction or transpassive behavior could cause the rapid increase in current to occur. When localized attack occurs, the pits or crevices remain active for some time after reversing the scan direction, resulting in a higher current at potentials where passive behavior (low currents) had previously been observed (producing hysteresis). The repassivation potential, E_{repas}, is that potential where pitting or crevice corrosion ceases activity during the reverse scan, and the current decreases back to, or below the original passive current density. The selection of E_{repas} adopted herein is the potential at which the reverse scan curve changes polarity from anodic to cathodic.

Simulated Concentrated Water (SCW) – pH 8.4
The polarization plots of both alloys (see Figure 1) have been interpreted as showing low active corrosion behavior (a corrosion rate of 0.09 to 0.10 mpy) with the formation of a passive protective film. This is considered to be a low rate for such an aggressive media. However, it is noted that a rapid current increase for both alloys in the potential region of +145 mV occurred. This is usually identified with localized breakdown of the passive film associated with either pitting or crevice corrosion. Both alloys exhibited similar repassivation potentials around –200 mV.

Upon completion of the experiments, both alloy samples were examined microscopically at 40X magnification and no pits or crevice attack under the Teflon gasket were observed.

Simulated Acidic Concentrated Water (SAW) - pH 3.0
The polarization plots of both alloys (see Figure 2) have been interpreted as showing low active corrosion behavior (a corrosion rate of 0.04 mpy) with the formation of a passive protective film. This is considered to be a low rate for such an aggressive media. However, it is noted that a rapid current increase for both alloys in the potential region of +600 mV occurred. This is usually identified with localized breakdown of the passive film associated with either pitting or crevice corrosion. Alloy 59 exhibited a significantly nobler (positive) repassivation potential (+401 mV) than Alloy C-22 (+310mV).

Upon completion of the experiments, both alloy samples were examined microscopically at 40X magnification and no pits or crevice attack under the Teflon gasket were observed.

Comparison of SAW and SCW Solutions
A composite of the polarization curves for SAW and SCW is presented in Figure 3. There is a significant difference between the polarization behavior in these two solutions. Although both alloys behave similarly in each solution, the thermodynamic activity is much greater in the SCW solution. The reason for this does not immediately stand out other than the potential role that the fluoride ion may play in the SCW formulation.

Based on these polarization experiments, Alloy 59 would be expected to perform similarly to Alloy C-22 in both acidic and alkaline concentrated water formulations.

We recommend further testing of these alloys in Simulated Concentrated Basic Water (SBW) as well as testing Alloy 59 and C-22 weldments in all three solutions.

We would recommend future testing to encompass the following

If you have any questions, please feel free to call.

Very truly yours,
Corrosion Testing Laboratories, Inc.

Joseph R. Paller, Jr.
Corrosion Technologist

Approved

Richard A. Corbett
Principal Corrosion Scientist

Policy Statement

This study has been performed and this report was prepared based upon the specific samples provided to Corrosion Testing Laboratories, Inc. (CTL) by Krupp VDM . CTL assumes no responsibility for variations in sample or data quality (composition, appearance, performance, etc.) or any other feature of similar subject matter produced (measured, manufactured, fabricated, etc.) by persons or under conditions over which we have no control.

Corrosion Testing Laboratories, Inc.

CTL REF #15321-1

Potentiodynamic Polarization

Alloy 59 vs. C-22 in SCW @ 90°C

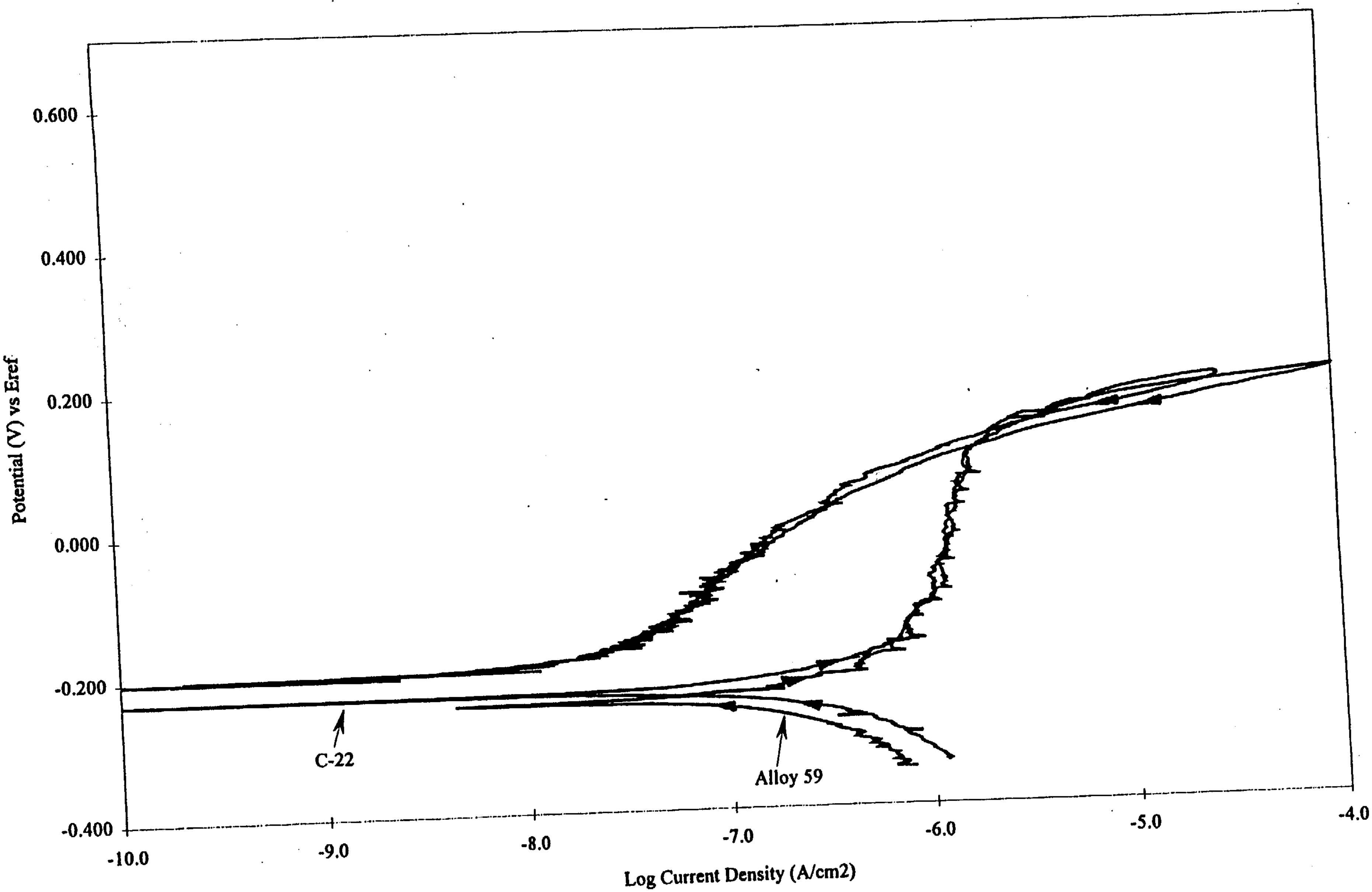


Figure 1

Corrosion Testing Laboratories, Inc.

CTL REF #15321-1

Potentiodynamic Polarization

Alloy 59 vs. C-22 in SAW @ 90°C

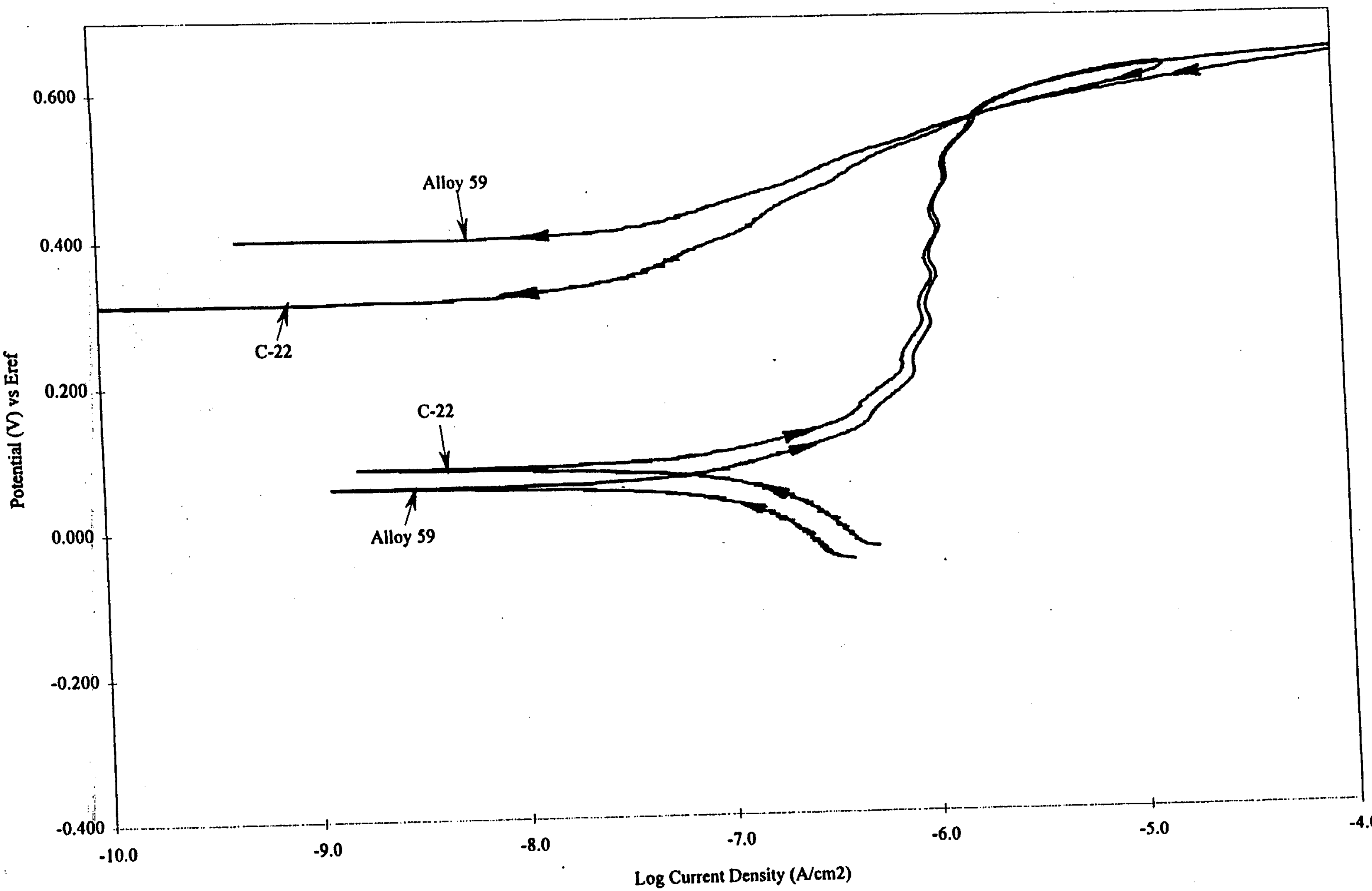


Figure 2

Corrosion Testing Laboratories, Inc.

CTL REF #15321-1

Potentiodynamic Polarization

Alloy 59 vs C-22 in SAW and SCW @ 90°C

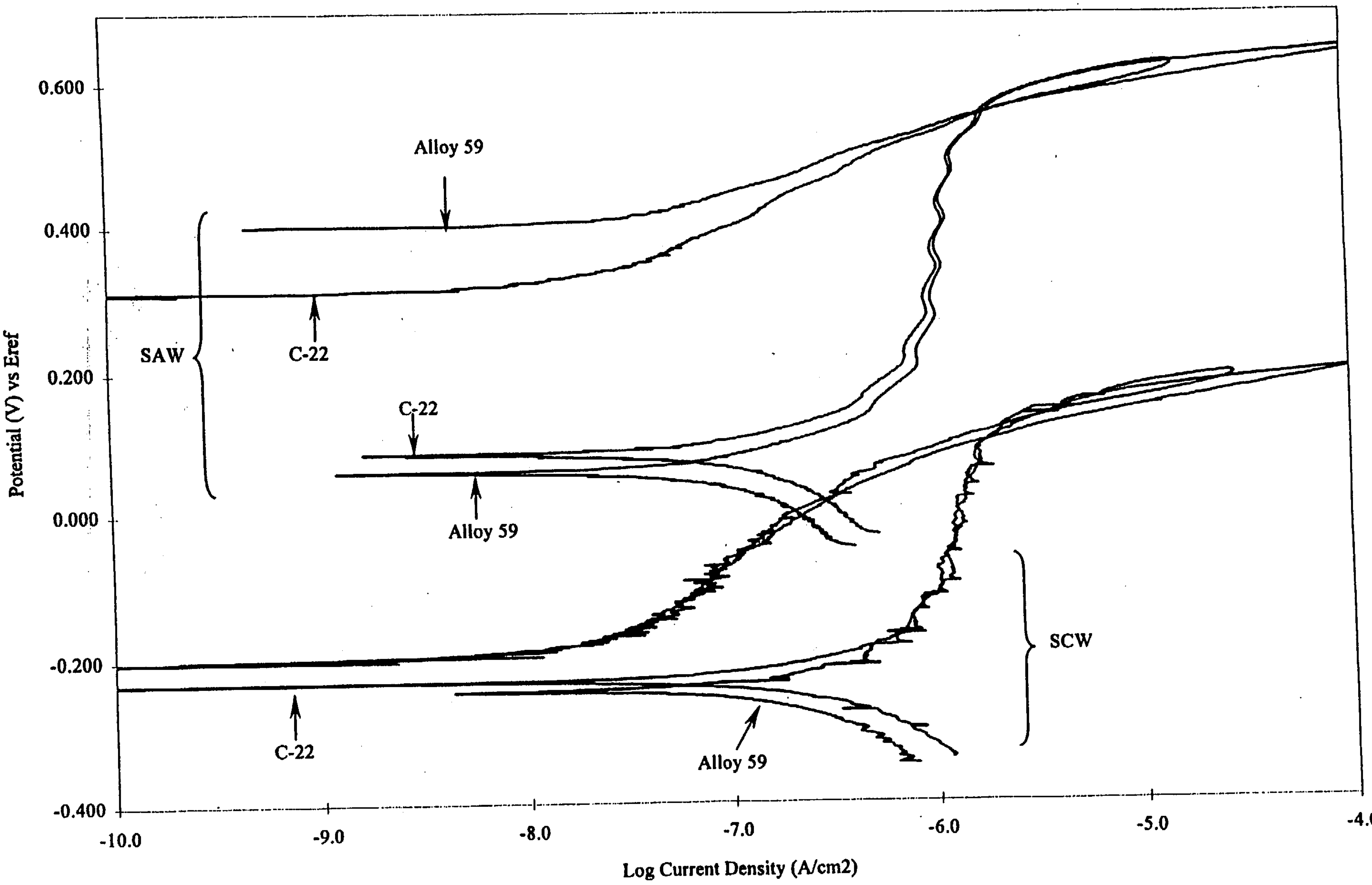


Figure 3

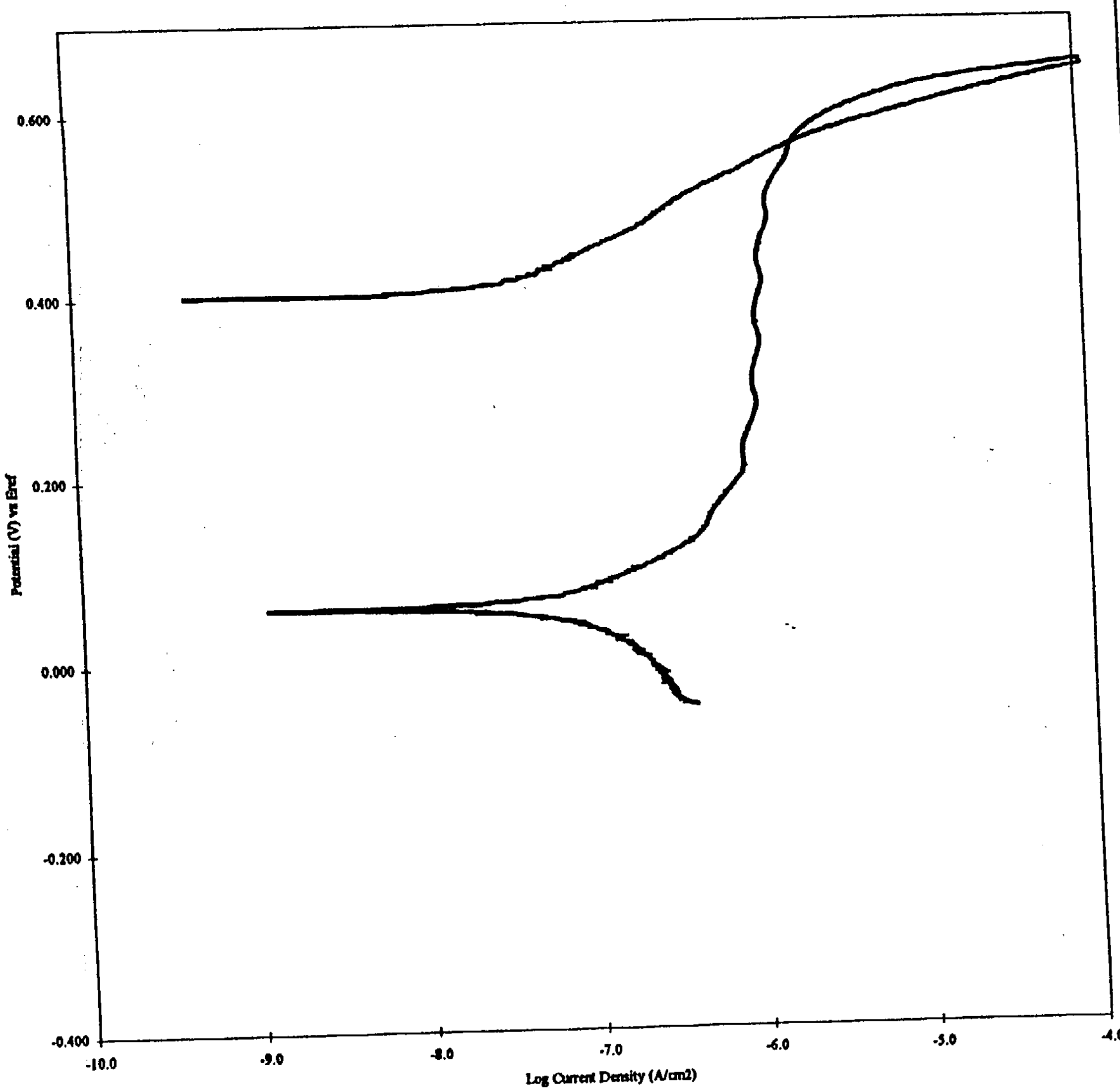
Appendix A

Corrosion Testing Laboratories, Inc.

CTL REF #15321-1R

Potentiodynamic Polarization Scan

Alloy 59 in SAW @ 90°C



Polarization Notes:

Fwd Scan: 0.17 mV/s, 5 s/pt
Rev Scan: 0.17 mV/s, 5 s/pt
EOC: 51 mV
Area: 6 cm2
Electrode: 8.8 gm/cm3, 29 g/Equiv

Notes:

Material: Alloy 59
Solution: SAW
Temperature: 90°C
Agitation: No
Sparge: Air
Reference: SCE
Data File: 15321-4.dta
Epit: 617 mV
Erepas: 401 mV
Epit/Ipit: 0.05

TAFEL RESULTS

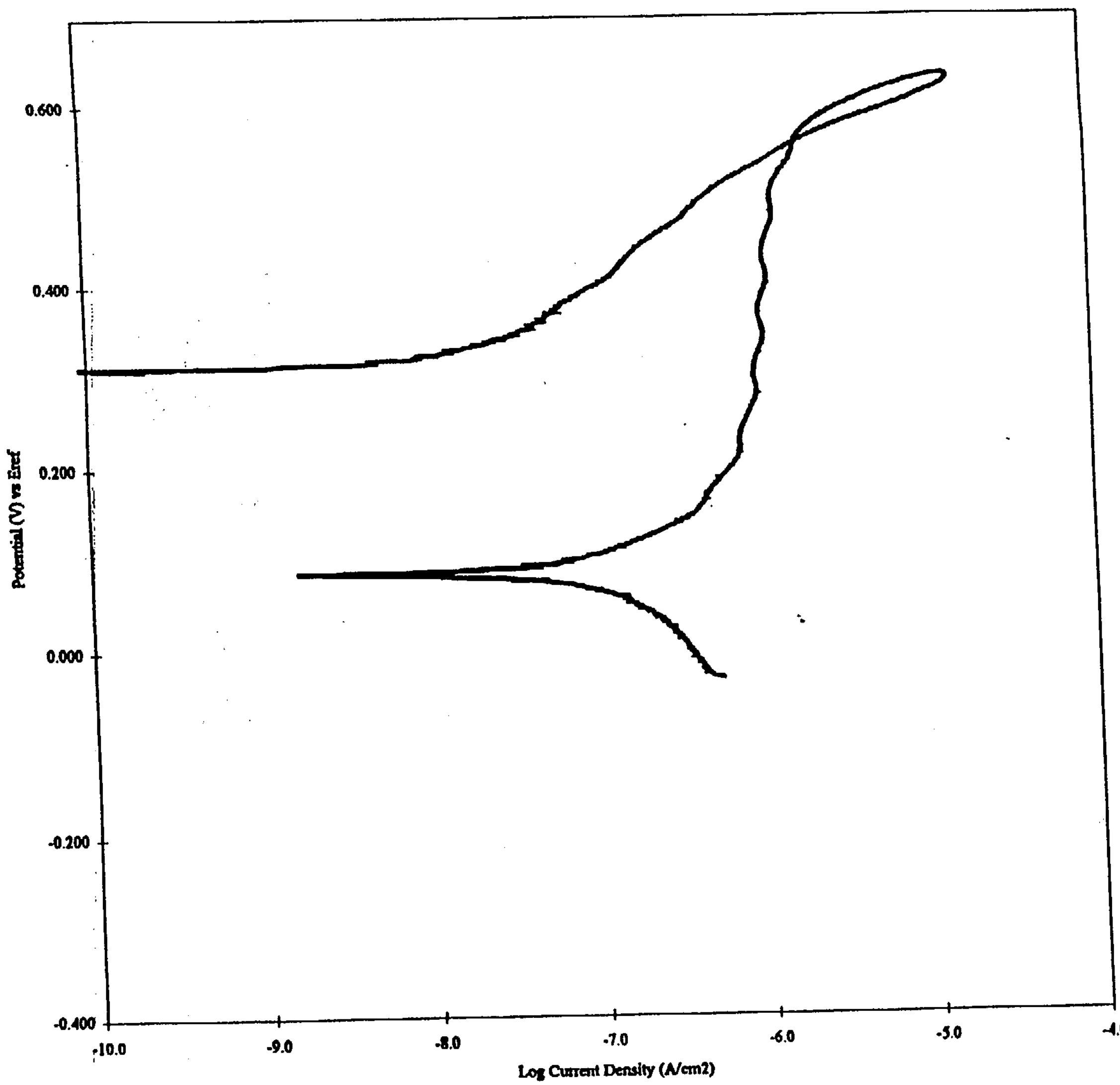
Ecorr = 58.9 mV
Icorr = 0.090 μA/cm2
BetaC = 150.0 mV/Decade
BetaA = 120.0 mV/Decade
Rp = 2.895E+05 Ohm cm2
CorrRate = 0.04 mpy

Corrosion Testing Laboratories, Inc.

Potentiodynamic Polarization Scan

Alloy C-22 in SAW @ 90°C

CTL REF #15321-1R



Polarization Notes:

Fwd Scan: 0.17 mV/s, 5 s/pt
Rev Scan: 0.17 mV/s, 5 s/pt
EOC: 69 mV
Area: 7 cm2
Electrode: 8.69 gm/cm3, 26 g/Equiv

Notes:

Material: C-22
Solution: SAW
Temperature: 90°C
Agitation: No
Sparge: Air
Reference: SCE
Data File: 15321-6.dta
Epit: 577 mV
Erepas: 310 mV
Epit/Ipit: 0.06

TAFEL RESULTS

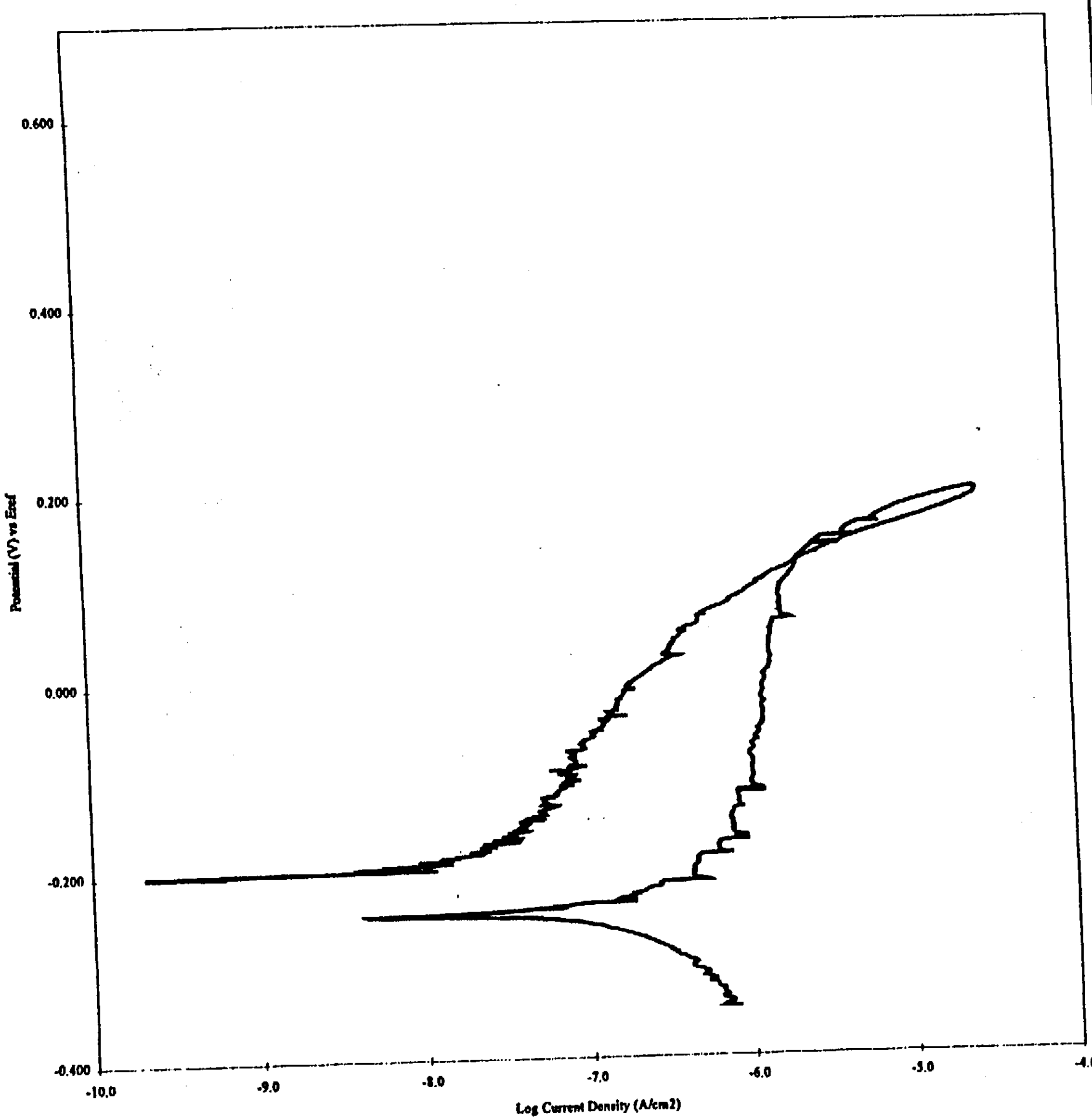
Ecorr = 84.0 mV
Icorr = 0.103 μA/cm2
BetaC = 170.0 mV/Decade
BetaA = 100.0 mV/Decade
Rp = 2.655E+05 Ohm cm2
CorrRate = 0.04 mpy

Corrosion Testing Laboratories, Inc.

Potentiodynamic Polarization Scan

Alloy 59 in SCW @ 90°C

CTL REF #15321-1



Polarization Notes:

Fwd Scan: 0.17 mV/s, 5 s/pt
Rev Scan: 0.17 mV/s, 5 s/pt
EOC: -247 V
Area: 6 cm2
Electrode: 8.8 gm/cm3, 28.98 g/Equiv

Notes:

Material: Alloy 59
Solution: SCW
Temperature: 90°C
Agitation: No
Sparge: Air
Reference: SCE
Data File: 15321-8.dta
Epit: 143 mV
Erepas: -201 mV
Epit/Ipit: 0.06

TAFEL RESULTS

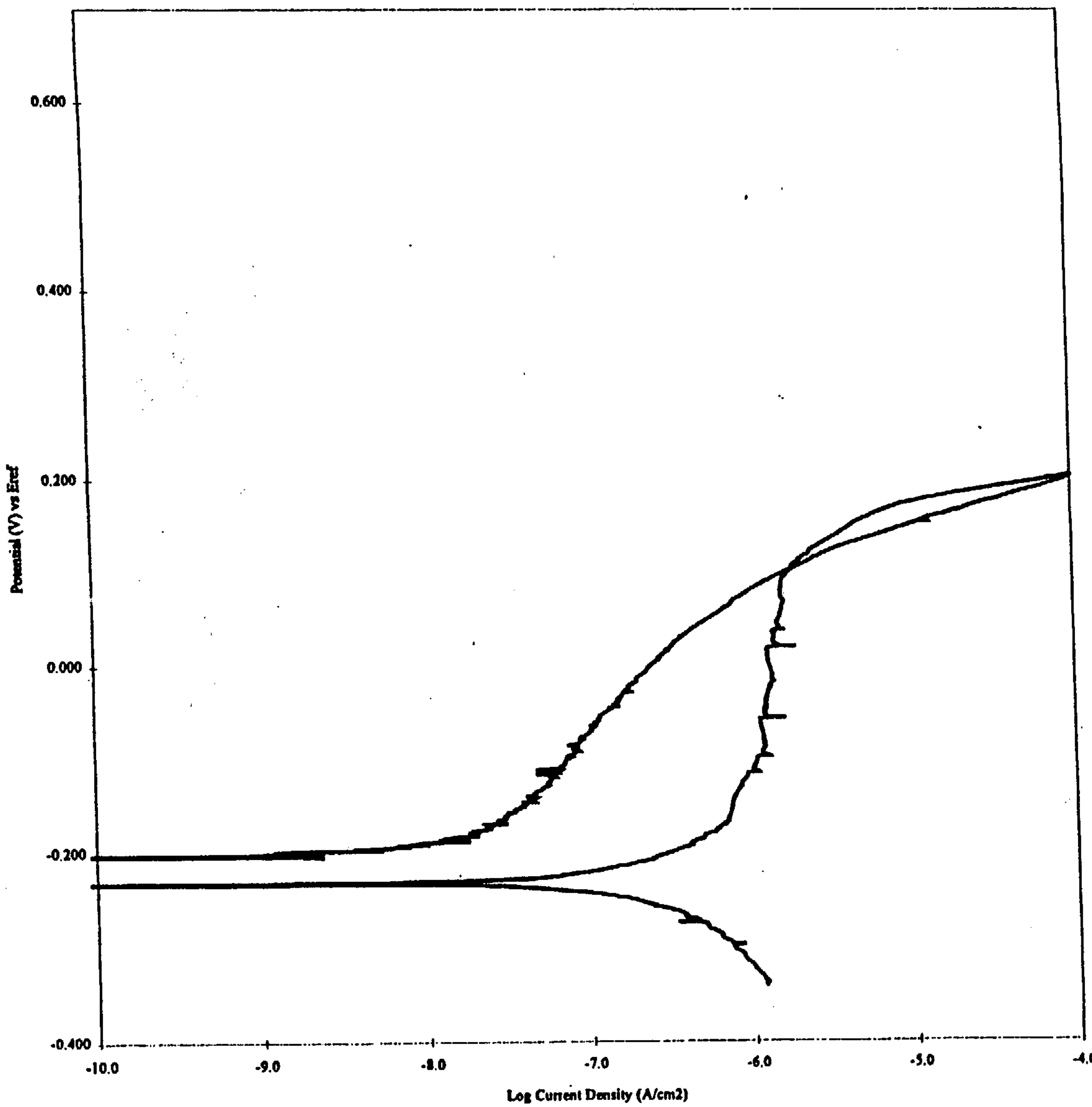
Ecorr = -245.7 mV
Icorr = 0.246 μA/cm2
BetaC = 150.0 mV/Decade
BetaA = 150.0 mV/Decade
Rp = 1.324E+05 Ohm cm2
CorrRate = 0.10 mpy

Corrosion Testing Laboratories, Inc.

Potentiodynamic Polarization Scan

Alloy C-22 in SCW @ 90°C

CTL REF #15321-1



Polarization Notes:

Fwd Scan: 0.17 mV/s, 5 s/pt
Rev Scan: 0.17 mV/s, 5 s/pt
EOC: -240 mV
Area: 7 cm2
Electrode: 8.69 gm/cm3, 26.04 g/Equiv

Notes:

Material: C-22
Solution: SCW
Temperature: 90°C
Agitation: No
Sparge: Air
Reference: SCE
Data File: 15321-10.dta
Epit: 145 mV
Erepas: -203 mV
Epit/Ipit: 0.04

TAFEL RESULTS

Ecorr = -232.0 mV
Icorr = 0.240 µA/cm2
BetaC = 150.0 mV/Decade
BetaA = 120.0 mV/Decade
Rp = 1.206E+05 Ohm cm2
CorrRate = 0.09 mpy

Chronology ----- (continued)

- July 1999: Conference Call held with TRW and LLNL personnel. Additional testing in modified SAW test solution suggested by LLNL using alloy 59, alloy 22 and platinum. Copy of the modified test solution attached

- July 27 1999 : Letter from TRW to VDM

  * Corrosion Testing Laboratory to visit LLNL with their equipment to conduct a *round robin* electrochemical test and compare the results of alloy 59 and alloy 22

  * Explore the introduction of alloy 59 in the test matrix.

- August 1999: The results of testing in the modified SAW solution on alloy 59, alloy 22 and platinum sent to TRW. Both alloys 59 and 22 behaved similarly.Copy of report attached. These results also confirmed results obtained at LLNL.

Corrosion Testing Laboratories, Inc.

60 Blue Hen Drive, Newark, DE USA 19713
(302) 454-8200 • fax (302) 454-8204 • e-mail ctl@corrosionlab.com

CTL REF #15321-3

July 22, 1999

Mr. D. C. Agarwal
National Technical Marketing Manager
Krupp VDM Technologies Corporation
11210 Steeplecrest Drive, Suite 120
Houston, TX 77065-4939

Re: Consultation for the Yucca Mountain Project

Dear D.C.:

We have received an e-mail message from Francis Wang at Lawrence Livermore National Laboratory (LLNL) with a revised recipe for the simulated acidic water (SAW) to be used at 90°C. It is significantly different from the formulation provided originally from Dan McCright. The following is the chemical compositions for the two formulations:

Chemical (g/L)	Original SAW	New SAW
Sodium chloride [NaCl]	34.89	35.59
Sodium nitrate [$NaNO_3$]	27.29	31.94
Sodium sulfate [Na_2SO_4]	50.60	57.27
Sodium metasilicate [$Na_2SiO_3 \bullet 5H_2O$]	0.37	0.38
Magnesium sulfate [$MgSO_4 \bullet 7H_2O$]	10.14	0.52
Calcium nitrate [$Ca(NO_3)_2 \bullet 4H_2O$]	5.89	0.30
Sulfuric acid [H_2SO_4]	0.44 (pH 3.0)	pH=2.7
Potassium chloride [KCl]	6.48	6.61

We will be running the potentiodynamic polarization scans for Alloys 59 and C-22, as well as platinum, in the new solution at 90°C.

I look forward to continuing to be of assistance to you and others at Krupp VDM.

Very truly yours,
Corrosion Testing Laboratories, Inc.

Richard A. Corbett
Principal Corrosion Scientist

TRW Environmental
Safety Systems Inc.

1261 Town Center Drive
Las Vegas, NV 89144-6363
702.295.5400

QA: N/A

Contract#: DE-AC08-91RW00134
LV.WP.DS.07/99-122

July 27, 1999

Dr. D.C. Agrawal
KRUPP VDM
11210 Steeplechase Drive, #120
Houston, TX 77065-4939

Dear Dr. Agrawal:

As a result of the telephone conference call held yesterday, the following actions were identified. Firstly, we agreed that it would be useful for Mr. Corbett of Corrosion Testing Laboratories, Inc. to visit Lawrence Livermore National Laboratory to conduct a round robin electrochemical potential test. Mr. Corbett will provide the specimens. The week of September 20th was suggested. I understand that you would accompany Mr. Corbett on this visit. Please coordinate the visit directly with Dr. McCright. Only social security numbers are needed since you are both U.S. citizens.

Secondly, we agreed that we will explore the introduction of Alloy 59 into our testing program. This will be accomplished in the next few weeks with a meeting between Dr. McCright and Mr. Pasupathi. If advantage can be taken of end-of-year funds, material coupons can be ordered from Metal Samples by the end of August.

I hope that I have captured the near-term actions. Please call me (at 702-295-4383) if you have any corrections or additions.

Sincerely,

David Stahl, Manager
Waste Package materials Department
Management & Operating Contractor

DS/lek

cc:
W. L. Clarke, LLNL
J. C. Farmer, LLNL
R. D. McCright, LLNL
V. Pasupathi

Corrosion Testing Laboratories, Inc.

60 Blue Hen Drive, Newark, DE USA 19713

(302) 454-8200 • fax (302) 454-8204 • e-mail ctl@corrosionlab.com

CTL REF #15321-4

August 9, 1999

Mr. D. C. Agarwal
National Technical Marketing Manager
Krupp VDM Technologies Corporation
11210 Steeplecrest Drive, Suite 120
Houston, TX 77065-4939

Re: **Alloys 59 and C-22 in Yucca Mountain Project Water Formulations**
ASTM G 61 Cyclic Potentiodynamic Polarization Testing
Supplemental Report No. 1

Dear Mr. Agarwal:

Presented herein are the results of additional electrochemical polarization tests performed under your authorization.

BACKGROUND

The background for this project is described in detail in our previous report CTL REF #15321-1, dated June 3, 1999. During a telecommunication conference call on July 19, 1999, between yourself, the principals at Framatome Cogema Fuels/TRW, the principals at Lawrence Livermore National Laboratory (LLNL) and myself, it was revealed that the formulation for SAW (Simulated Acidic Concentrated Water) had been modified. It was suggested by those at LLNL that the insolubility of certain chemicals observed in our test solution was contributing to the different results between their laboratory and CTL. Therefore, a new "recipe" for SAW was provided by LLNL for re-testing Alloys C-22 and 59 (see CTL REF #15321-3 for composition). It was further suggested that a Platinum electrode be tested as a reference material.

TEST PROCEDURE

The same test procedure as previously reported (CTL REF #15321-1) was followed.

RESULTS

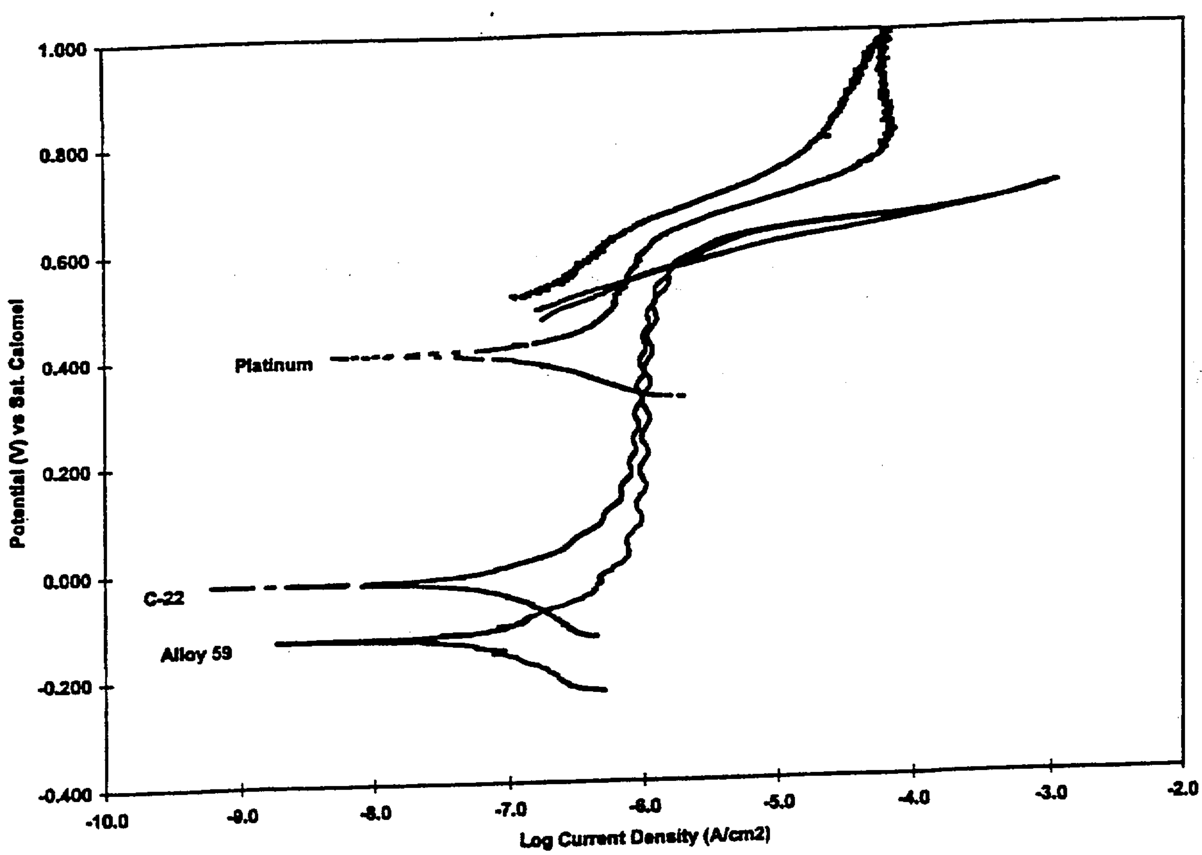
The individual curves from each scan are presented in Appendix A. Figure 1 is a composite curve for Platinum and Alloys C-22 and 59 in modified SAW at 90°C. The key-point voltage and current data are summarized in Table 1, as well as the calculated corrosion rates.

Table 1
Key-Point Electrochemical Data*

Polarization Scan	E_{OC}	E_{corr}	E_{pit}	E_{repass}	I_{corr}	Corrosion Rate (mpy)	Hysteresis Present
Platinum	+414	+404	+620	N/A	0.080	0.047	No
Alloy C-22	-30	-24	+605	+454	0.035	0.013	Yes
Alloy 59	-133	-130	+610	+373	0.031	0.013	Yes

* NOTE: E-values are in volts; and I-values are in micro-amps (10^{-6})

Figure 1
Composite Curves of Platinum and Alloys C-22 and 59
In SAW (modified) Solution at 90°C



DISCUSSION

The polarization curves have been analyzed as showing low active corrosion behavior with the formation of passive protective films. The rapid current increase in the potential range of +600 mV for all three metals is consistent with the transpassive behavior of these alloys in an aqueous environment. This rapid current increase is not consistent with pitting, and this was confirmed by examination at 40X magnification upon completion of the electrochemical scan.

Thermodynamically (i.e., the susceptibility to corrode), Alloy 59 is slightly more active than C-22 owing to its Ecorr being more negative. However, kinetically (i.e., the rate at which corrosion will occur) they both behave identically.

Based upon faxed copies of LLNL test results, Appendix B, it appears for Alloy C-22 (Figure 6-2) there is agreement between our two laboratories. Therefore, for Alloy 59 there should be agreement, and hence LLNL should recognize that Alloy 59 is equally resistant to the SAW solution.

I trust that the foregoing will be of assistance. We remain available should you require further information or clarification.

Very truly yours,
Corrosion Testing Laboratories, Inc.

Richard A. Corbett
Principal Corrosion Scientist

RAC/bec

Policy Statement

This study has been performed and this report was prepared based upon the specific samples provided to Corrosion Testing Laboratories, Inc. (CTL) by Krupp VDM. CTL assumes no responsibility for variations in sample or data quality (composition, appearance, performance, etc.) or any other feature of similar subject matter produced (measured, manufactured, fabricated, etc.) by persons or under conditions over which we have no control.

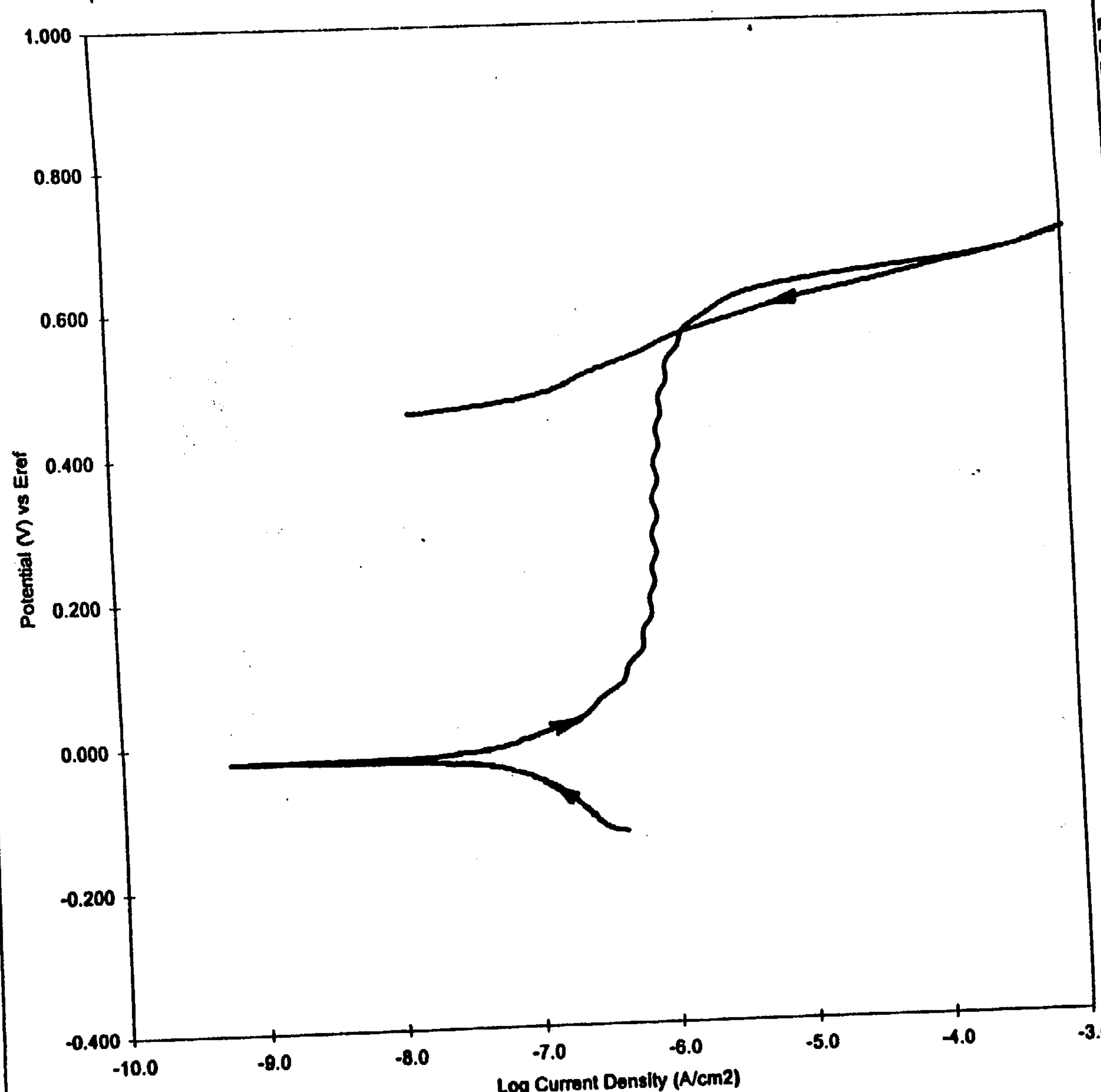
APPENDIX A

Corrosion Testing Laboratories, Inc.

CTL REF #15321

Potentiodynamic Polarization Scan

C-22 in SAW @ 90°C



Polarization Notes:

Fwd Scan: -0.1 V to 1 V, 0.17 mV/s, 5 s/pt
Rev Scan: 1 V to -0.1 V, 0.17 mV/s, 5 s/pt
EOC: -30 MV
Area: 7 cm2
Electrode: 8.69 gm/cm3, 26 g/Equiv

Notes:

Material: C22
Solution: SAW new formula
Temperature: 90°C
Agitation: No
Sparge: Air
Reference: SCE
Data File: 1532122s.dta
Epit: 605 mV
Erepas: 454 mV
Epit/Ipit: 0.026

TAFEL RESULTS

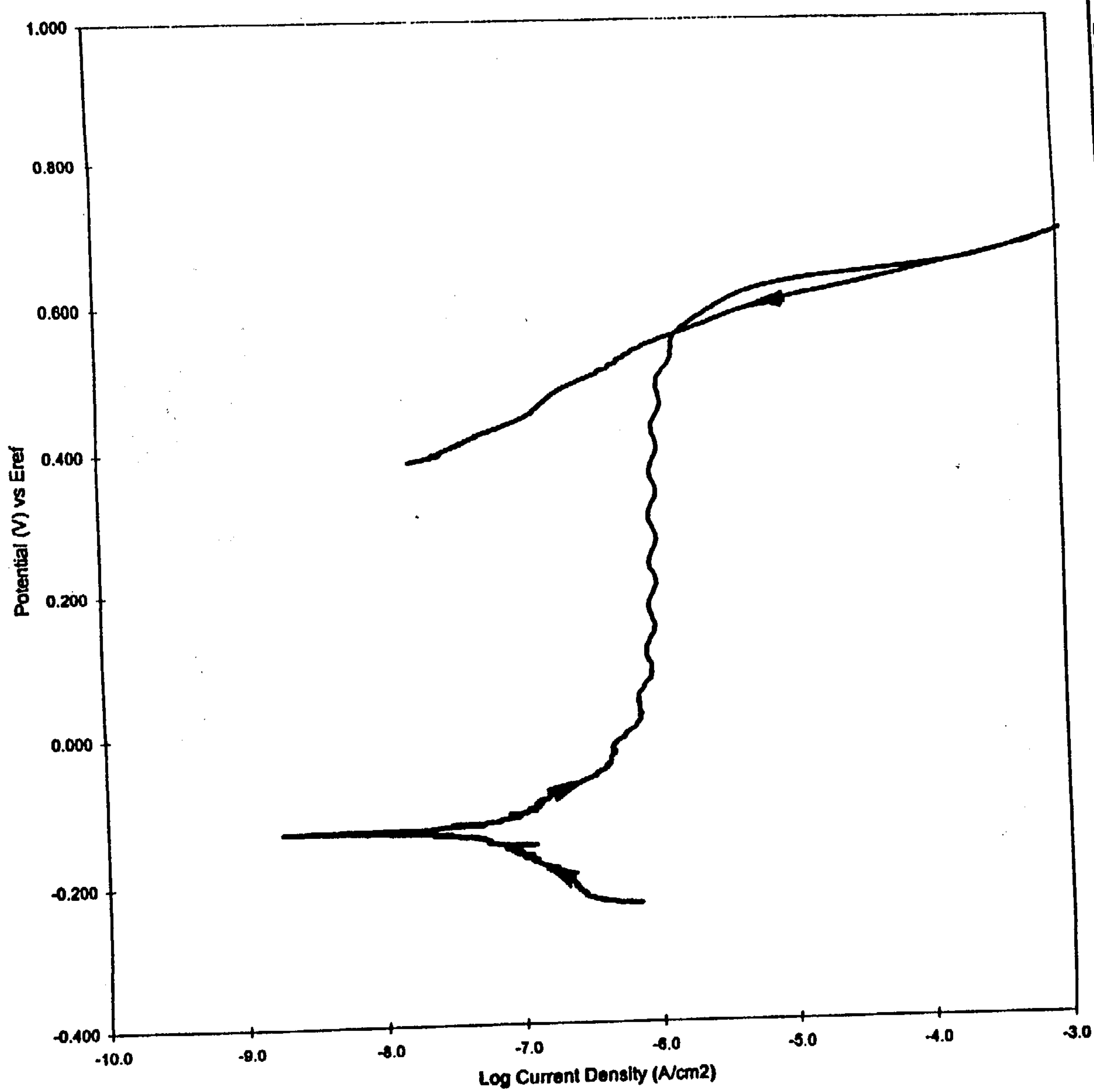
Ecorr = -23.5 mV
Icorr = 3.500E-08 A/cm2
BetaC = 80.0 mV/Decade
BetaA = 80.0 mV/Decade
Rp = 4.254E+05 Ohm cm2
CorrRate = 0.013 mpy

Corrosion Testing Laboratories, Inc.

CTL REF #15321

Potentiodynamic Polarization Scan

Alloy 59 in SAW @ 90°C



Polarization Notes:

Fwd Scan: -0.1 V to 1 V, 0.17 mV/s, 5 s/pt
Rev Scan: 1 V to -0.1 V, 0 17 mV/s, 5 s/pt
EOC: -133 mV
Area: 6 cm2
Electrode: 8.8 gm/cm3, 29 g/Equiv

Notes:

Material: Alloy 59
Solution: SAW new formula
Temperature: 90°C
Agitation: No
Sparge: Air
Reference: SCE
Data File: 1532159s.dta
Eplt: 610 mV
Erepas: 373 mV
Eplt/Iplt: 0.029

TAFEL RESULTS

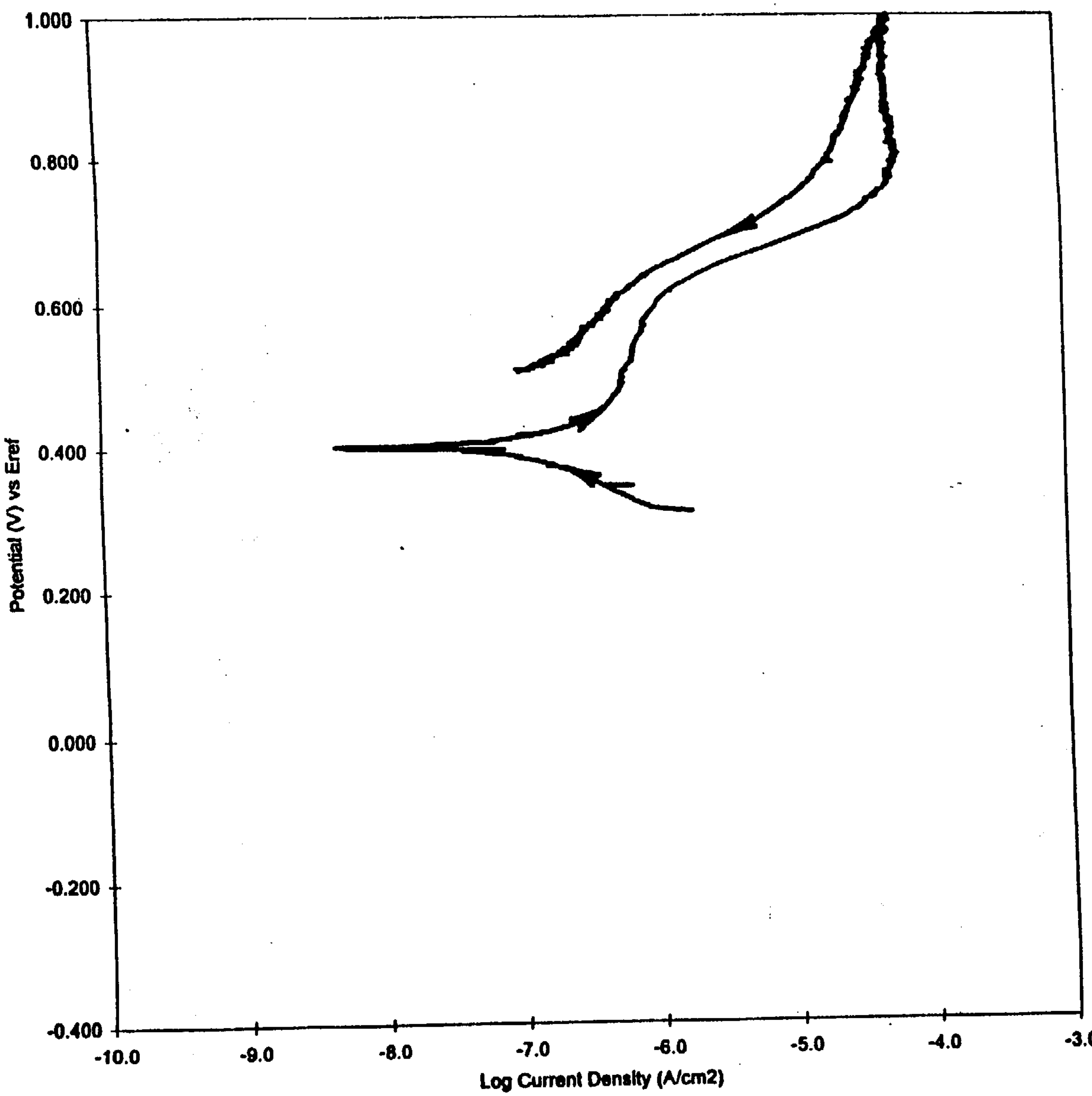
Ecorr = -129.9 mV
Icorr = 3.100E-08 A/cm2
BetaC = 45.0 mV/Decade
BetaA = 58.0 mV/Decade
Rp = 3.495E+05 Ohm cm2
CorrRate = 0.013 mpy

Corrosion Testing Laboratories, Inc.

CTL REF #15321

Potentiodynamic Polarization Scan

Platinum in SAW @ 90°C



Polarization Notes:

Fwd Scan: -0.1 V to 1 V, 0.17 mV/s, 5 s/pt
Rev Scan: 1 V to -0.1 V, 0.17 mV/s, 5 s/pt
EOC: 414 mV
Area: 8 cm2
Electrode: 21.45 gm/cm3, 97.55 g/Equiv

Notes:

Material: Pt
Solution: SAW new formula
Temperature: 90°C
Agitation: No
Sparge: Air
Reference: SCE
Data File: 15321pts.dta
Epit: ----
Erepas: ----
Epit/Ipit: ----

TAFEL RESULTS

Ecorr = 403.8 mV
Icorr = 8.000E-08 A/cm2
BetaC = 50.0 mV/Decade
BetaA = 60.0 mV/Decade
Rp = 1.481E+05 Ohm cm2
CorrRate = 0.047 mpy

APPENDIX B

CHECK COPY

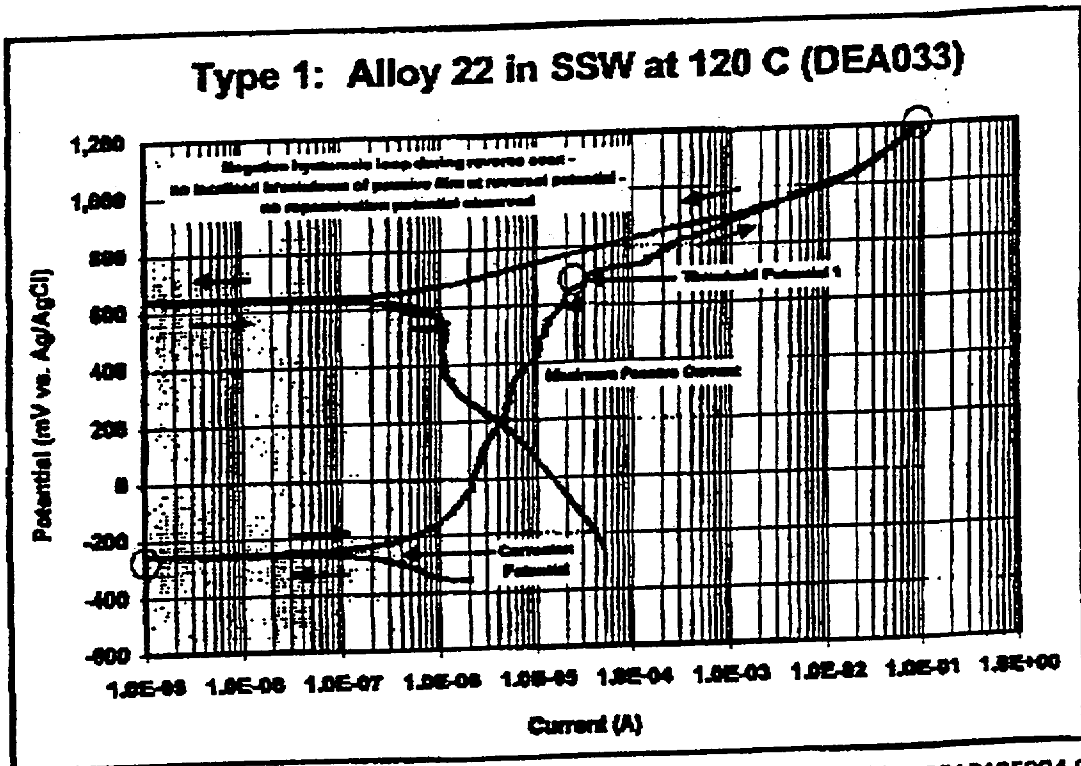


Figure 6 - 1. Type 1 – Alloy 22 in SSW at 120 Centigrade (DEA033) [DTN # LL990610105924.074 308487, DTN # LL990609705924.070 308506]

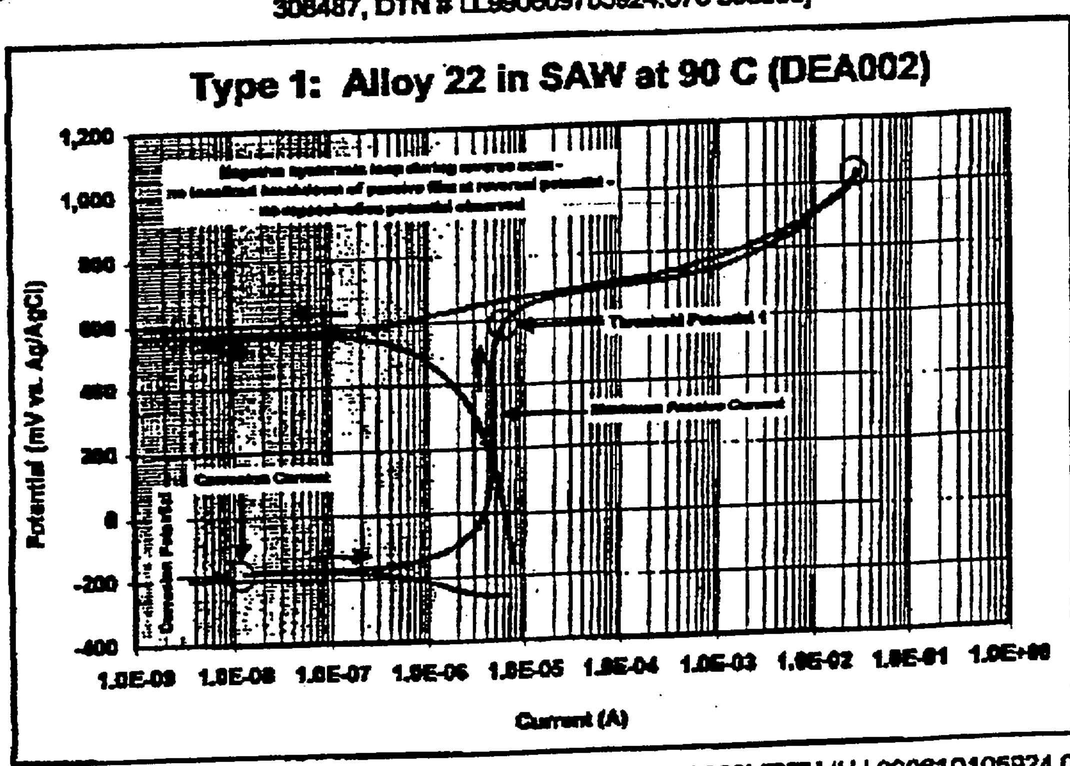


Figure 6 - 2. Type 1 – Alloy 22 in SAW at 90 Centigrade (DEA002) [DTN # LL990610105924.074 308486, DTN # LL990609705924.070 308498]

CHECK COPY

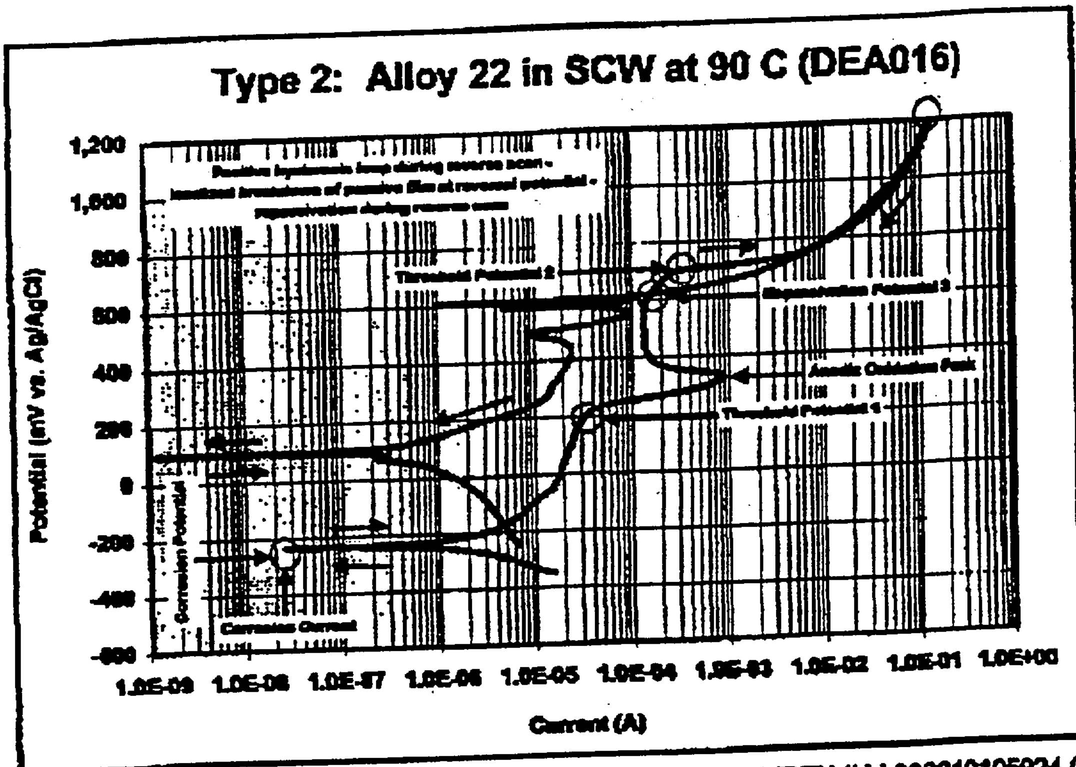


Figure 6 - 3. Type 2 – Alloy 22 in SCW at 90 Centigrade (DEA016) [DTN # LL990610105924.074 308484, DTN # LL990609705924.070 308495]

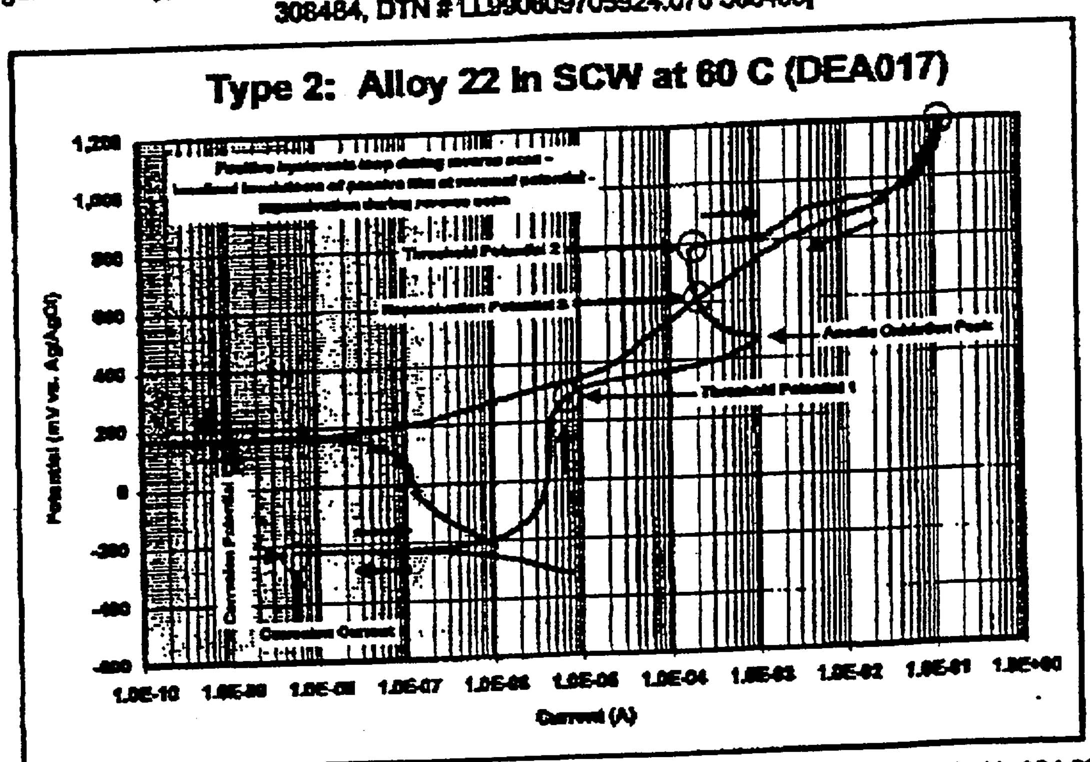


Figure 6 - 4. Type 2 – Alloy 22 in SCW at 60 Centigrade (DEA017) [DTN # LL990610105924.074 308485, DTN # LL990609705924.070 308494]

CHECK COPY

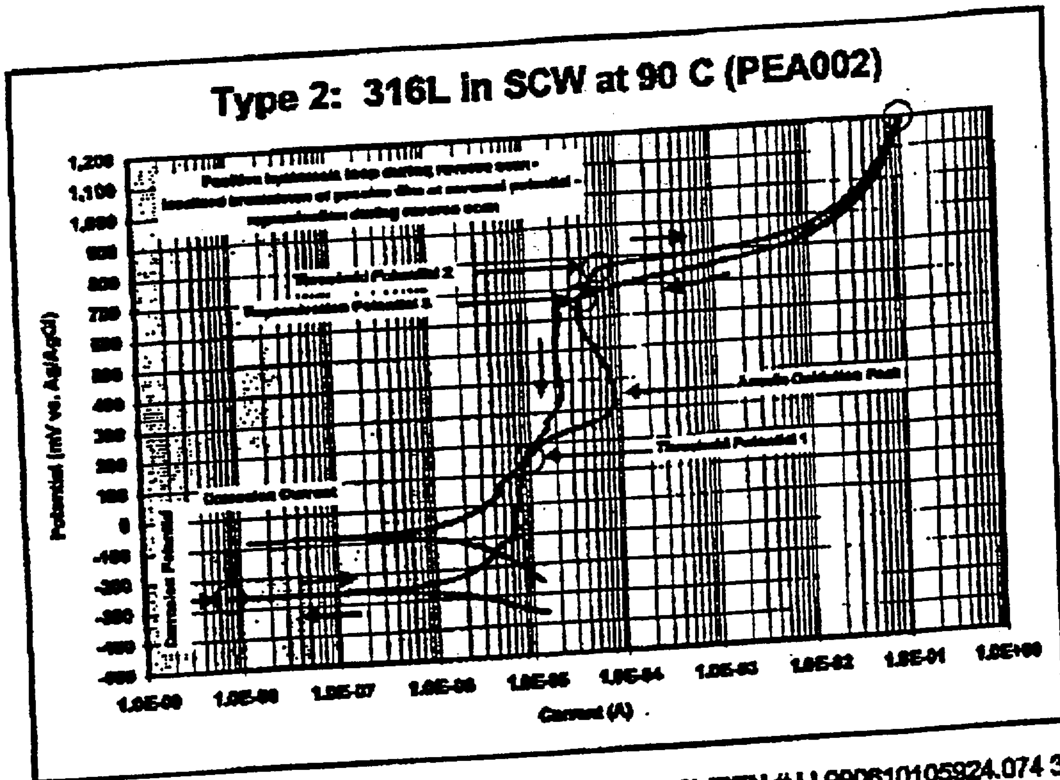


Figure 6 - 5. Type 2 – 316L in SCW at 90 Centigrade (PEA002) [DTN # LL990610105924.074 308482, DTN # LL990609805924.071 308482]

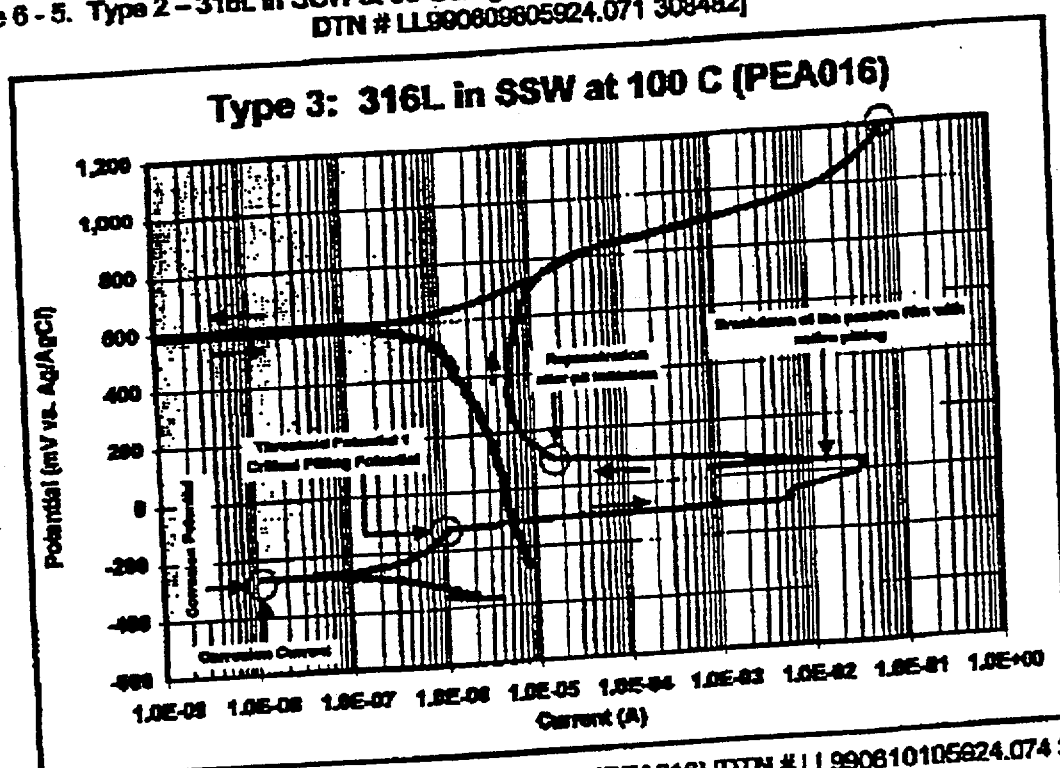


Figure 6 - 6. Type 3 – 316L in SSW at 100 Centigrade (PEA016) [DTN # LL990610105924.074 308483, DTN # LL990609805924.071 308498]

CHECK COPY

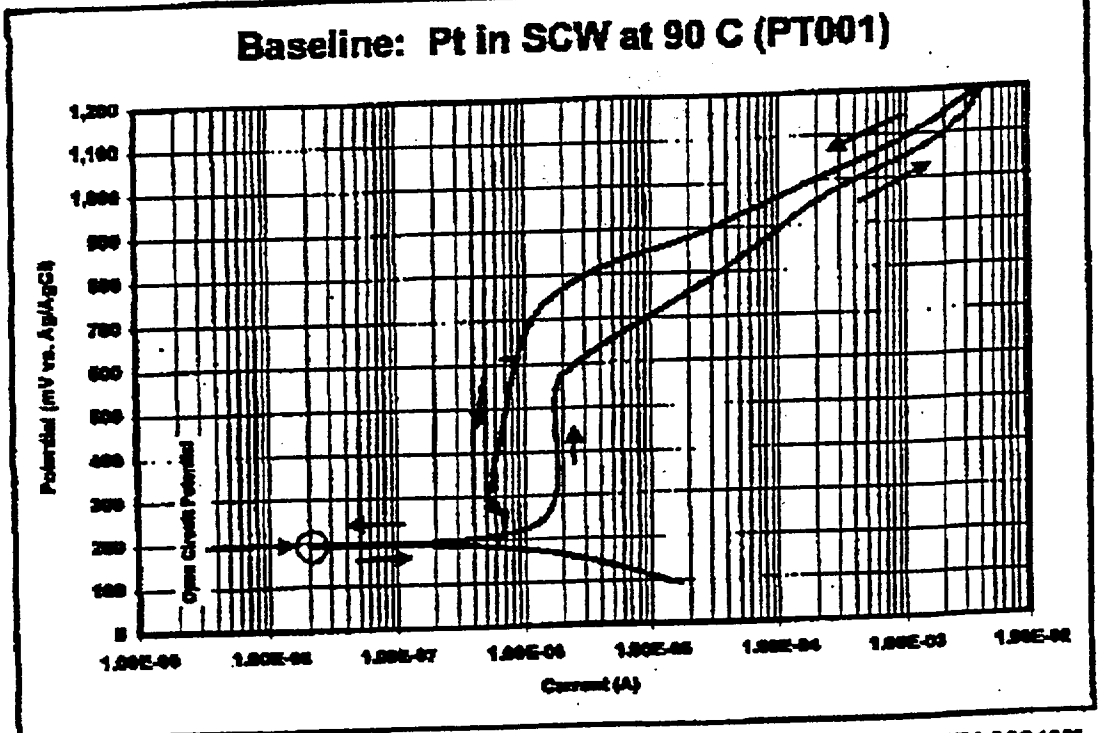


Figure 6 - 7. Baseline – Pt in SCW at 90 C (PT001) [DTN # LL990810105924.074 308489]

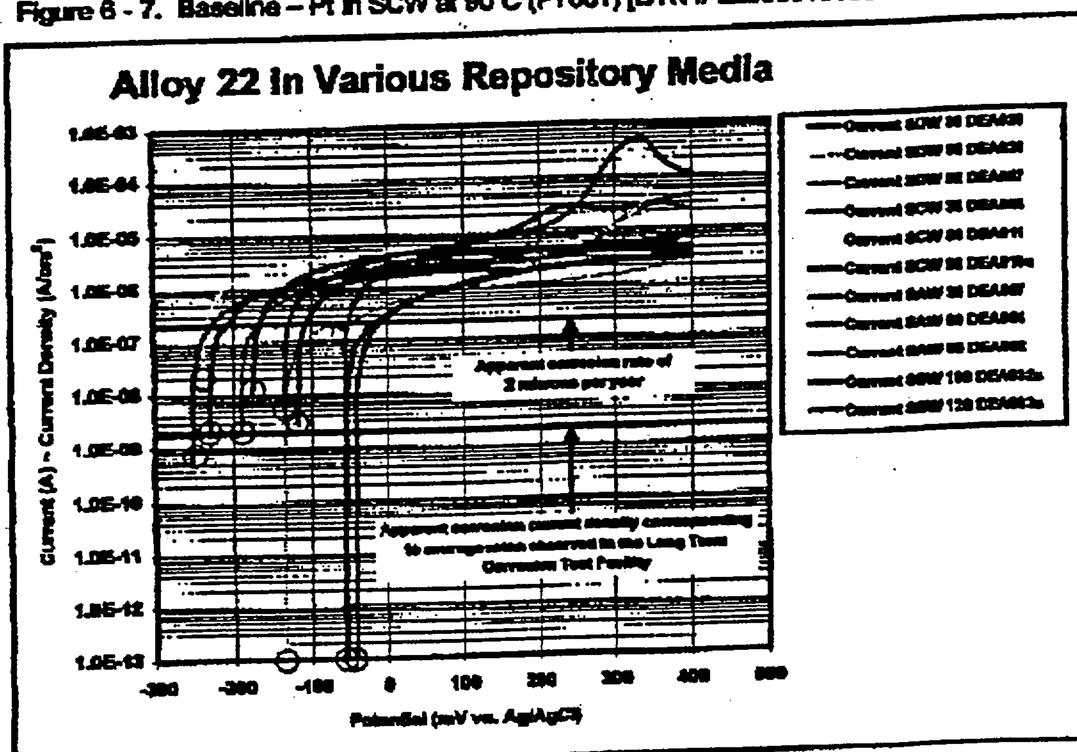


Figure 6 - 8. Alloy 22 in Various Repository Media – Comparison of CP Data [DTN # LL990810205924.075 308483]

Chronology ----- (continued)

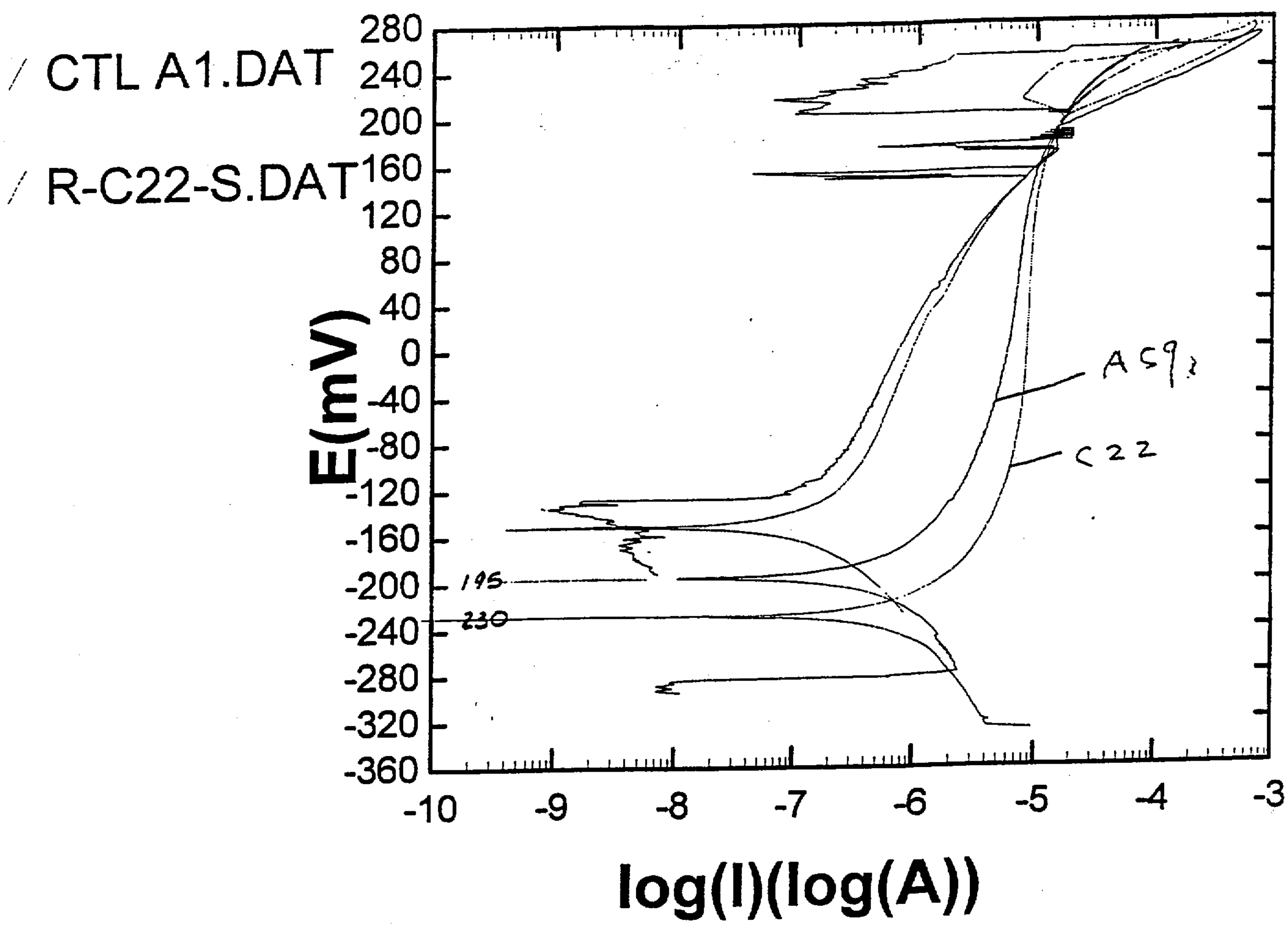
• Sept.20 / 21, 1999 : Round robin tests conducted at LLNL to compare the two machines. Identical results on alloy 59 and alloy 22. Copy of Corrosion Testing Lab. charts attached

• October 14, 1999: Letter from TRW to VDM

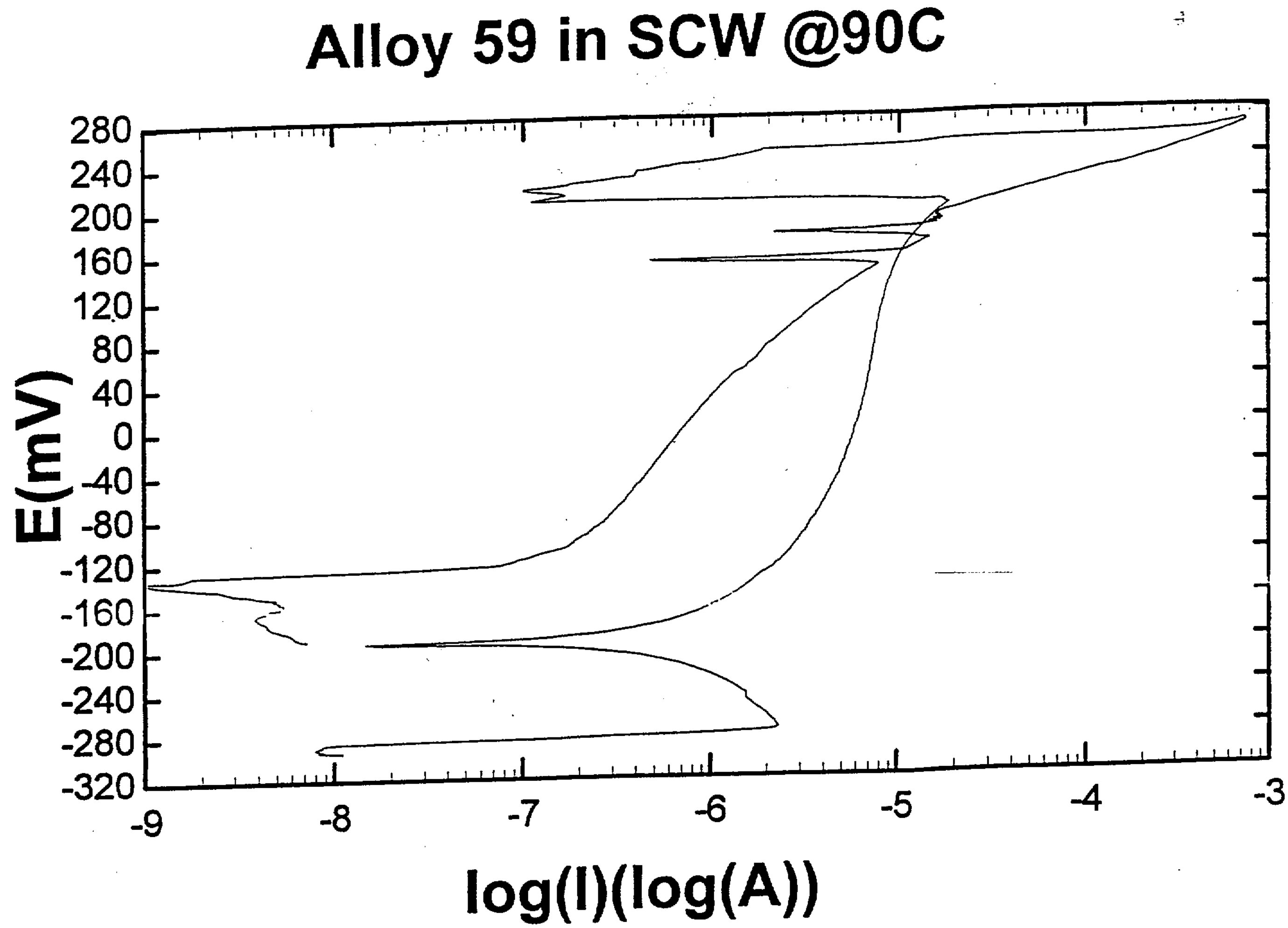
* Continue with additional evaluation of alloy 59 in parallel with alloy 22, the primary candidate material. Copy of the letter attached

• Samples of alloy 59 for thermal aging studies (16mm thick plate specimens) and other sheets for corrosion testing sent to LLNL in Dec. 1999 and Jan. 2000

• VDM initiated its own thermal aging studies on alloy 59 on both welded and unwelded samples at 200, 300 and 427 °C for 10,000 hrs and 20,000 hrs. The 10,000 hr. samples will be available for testing end of 2000 and the 20,000 hr samples available end of 2001 to first quarter of 2002



Tests Run at Lawrence Livermore Lab on 9/20/99 & 9/21/99 to compare the two testing apparatus



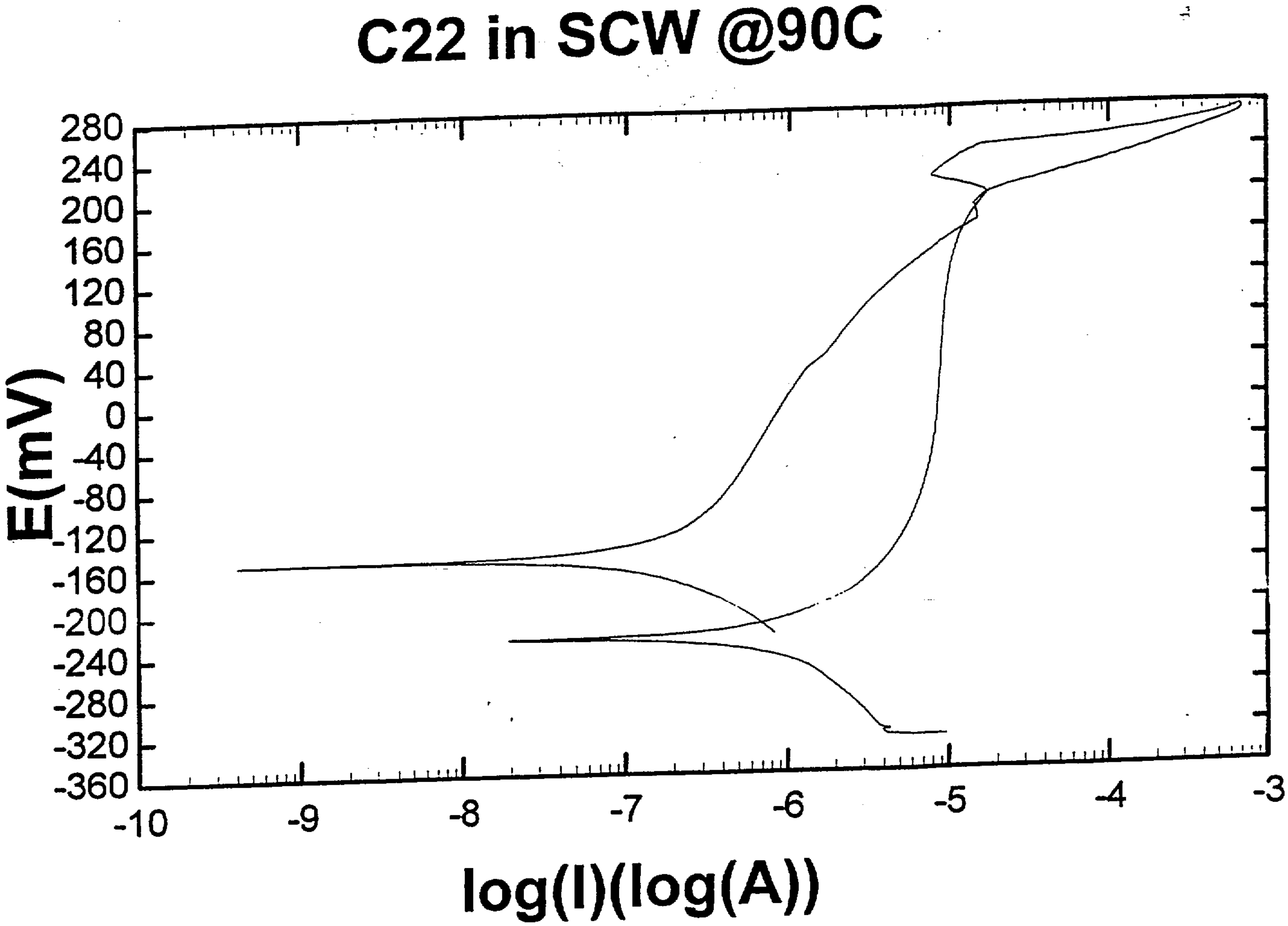
Alloy 59 in SCW @90C
E(mV)
280
240
200
160
120
80
40
0
-40
-80
-120
-160
-200
-240
-280
-320
-9
-8
-7
-6
-5
-4
-3
log(I)(log(A))

Alloy 59 in SCW @ 70 C

352 SoftCorr III Corrosion Measurement Software for Windows, v. 3.03
Filename: A:\CTL_A1.DAT
Pstat: M273 [] Ver 19
CP CYCLIC POLARIZATION
File Status: NORMAL
Date Run: 09-21-99
Time Run: 12:07:53

Cond. Time	CT	pass	s
Initial Pot.	IP	-100.0E-3	V oc
Cond. Pot.	CP	pass	V
Vertex 1 Pot.	V1	0.0000	V
Initial Delay	ID	0	s
I Threshold	IT	738.0E-6	A
Final Pot.	FP	0.0000	V oc
Scan Rate	SR	167.1E-3	mV/s
Curr. Range	CR	Auto	
Scan Incr.	SI	1.000	mV
Step Time	ST	5.983	s
No. of Points	NP	1022	
GI Time Const.	TC	Off	
Line Sync.	LS	yes	
IR Mode	IR	none	
Rise Time	RT	high stability	
Filter	FL	Off	
Working Elec.	WE	Solid	
Ref. Elec.	RE	AgCl 197.0E-3V	
Sample Area	AR	7.380	cm^2
Equiv. Wt.	EW	29.00	g
Density	DE	8.800	g/ml
AUX A/D	AU	no	
Open Circuit	OC	-195.0E-3	V

Comment: Square A - 59 sample from CTL


C22 in SCW @90C
E(mV)
280
240
200
160
120
80
40
0
-40
-80
-120
-160
-200
-240
-280
-320
-360
-10
-9
-8
-7
-6
-5
-4
-3
log(I)(log(A))

C22 in SCWE 90 C

352 SoftCorr III Corrosion Measurement Software for Windows, v. 3.03
Filename: A:\R-C22-S.DAT
Pstat: M273 [] Ver 19
CP CYCLIC POLARIZATION
File Status: NORMAL
Date Run: 09-20-99
Time Run: 15:47:39

Cond. Time	CT	pass	s
Initial Pot.	IP	-100.0E-3	V oc
Cond. Pot.	CP	pass	V
Vertex 1 Pot.	V1	0.0000	V
Initial Delay	ID	3600	s
I Threshold	IT	768.0E-6	A
Final Pot.	FP	0.0000	V oc
Scan Rate	SR	167.1E-3	mV/s
Curr. Range	CR	Auto	
Scan Incr.	SI	1.000	mV
Step Time	ST	5.983	s
No. of Points	NP	1106	
GI Time Const.	TC	Off	
Line Sync.	LS	yes	
IR Mode	IR	none	
Rise Time	RT	high stability	
Filter	FL	Off	
Working Elec.	WE	Solid	
Ref. Elec.	RE	AgCl 197.0E-3V	
Sample Area	AR	7.680	cm^2
Equiv. Wt.	EW	29.00	g
Density	DE	8.610	g/ml
AUX A/D	AU	no	
Open Circuit	OC	-228.0E-3	V

Comment: Square C-22 sample from CTL

TRW Environmental Safety Systems Inc.
1261 Town Center Drive
Las Vegas, NV 89134
702.295.5400

Contract #: DE-AC08-91RW00134
LV.WP.DS.10/99-158

October 14, 1999

Dr. D.C. Agrawal
KRUPP VDM
11210 Steeplechase Drive, #120
Houston, TX 77065-4939

Dear Dr. Agrawal:

Based on our preliminary analyses of the round robin testing performed at LLNL on September 20-22, it is our intent to continue a limited amount of additional evaluation of Alloy 59. This evaluation will be performed in parallel with the on-going evaluation of Alloy 22, which is our primary candidate material for the corrosion resistant barrier of the waste package. As a result of these round robin tests, several actions are planned.

Phase stability software will be utilized to predict the long-term phase structure in Alloy 59, over the range of composition permitted in the UNS specification. A similar analysis is being performed on Alloy 22.

Thermal aging treatments of Alloy 59 will be conducted in parallel to those being performed on Alloy 22 for phase analyses (identification of phase and estimate of volume fraction in the alloy) and production of aged test specimens for corrosion testing. Please call Dr. Tammy Summers of LLNL for the details (e.g., aging temperature and times) should you decide to perform confirmatory testing.

A limited number of corrosion tests will be performed on aged and non-aged specimens of Alloy 59 for comparison with similar specimens of Alloy 22. It is expected that the corrosion testing will begin with short-term testing, such as electrochemical polarization in repository-relevant environments. Please interface directly with Dr. McCright of LLNL for specimen requirements. Future longer-term testing will be based upon the results of these corrosion tests and the aging studies.

I hope that I have captured the near-term actions. Please call me (at 702-295-4383) if you have any corrections or additions.

Sincerely,

David Stahl

David Stahl, Manager
Waste Package Materials Department
Management & Operating Contractor

cc: W. L. Clarke, LLNL
J. C. Farmer, LLNL
A. Lingenfelter, LLNL
R. D. McCright, LLNL
V. Pasupathi
RPC = 2 Pages

Tests on Alloy 22 Conducted at Catholic University <u>Performed for State of Nevada</u>

<u>Report Findings</u>

• 30 day tests on stressed U- Bend samples in J-13 water x1000 at 250 ° C, corrosive attack identified

* Acidified Soln. (pH 0.5) without additives: shallow general corrosion and pitting

* Acidified Soln. with mercury: strong general corrosion, pitting

* Acidified Soln. with lead: Cracking both tranagranular and intergranular mode

Tests on Alloy 22 Conducted at Catholic University Performed for State of Nevada (contd.)

Report Findings

- **Tests on Unstressed Disks: 15 day test in J-13 (conc. x1000) at 163° C , pH 2.5 in presence of lead**
    - * Surface of alloy 22 strongly pitted
    - * Extensive deposit of corrosion products
- **In acidic media, pH 2.5 , both lead and mercury caused extensive dissolution of nickel in alloy 22**
- **In basic concentrated J-13 (pH 13), mercury caused dissolution of chromium and molybdenum**

Tests on Alloy 22 Conducted at Catholic University Performed for State of Nevada (contd.)

Report Findings

Preliminary results indicate small amounts of aggressive spieces that could become available to the repository water, such as lead, mercury can strongly promote localized corrosion (both pitting and crevice) and SCC of alloy 22

Food for Thought

- Lessons from Nuclear Power Plant Experiences over the last 40 years

- Alloy 22 tests on base metal and weldments due to multipass welding of 20mm thick sections and closure plates: Have we generated enough confidence to assure that this is the best alloy for the radwaste containers given the data presented

- It appears that alloy 59, a pure ternary alloy of the Ni-Cr-Mo family may be a better candidate material due to its superior localized corrosion resistance behavior and better thermal stability. It needs to be evaluated similar to tests run on alloy 22 at the Catholic University and at LLNL

QUESTION ??

Which alloy of the Ni-Cr-Mo family will serve and fulfill the needs of the Radwasre container program better ??

Alloy 22 ??

or

Alloy 59 ??

or

Both Equally ??

Paper
01120

CORROSION2001

RESULTS OF VARIOUS TESTS ON WELDED AND UNWELDED ALLOY 59 FOR RAD-WASTE CONTAINERS

D.C. Agarwal and U. Brill
Krupp VDM Technologies
11210 Steeplecrest Drive # 120
Houston, TX 77065-4939

Richard A. Corbett
Corrosion Testing Laboratories
60 Blue Hen Drive
Newark, DE 19713

ABSTRACT

The Nuclear Waste Policy Act of 1982 established an objective of Nuclear Waste disposal in a deep geological repositary. This act was later amended in 1987, and established Nevada as the only site to be characterized. In 1994 a technical decision was made for a multipurpose container consisting of a outer barrier of carbon steel, alloy 400 or Cu-Ni 70/30 and an inner barrier of alloy 825. This concept was later modified to require a more corrosion resistant alloy for the inner barrier i.e., an alloy of the Ni-Cr-Mo family , alloy 22 (UNS N06022) , titanium or a titanium alloy.

Since then many papers[1-6] have been written comparing the corrosion resistant characteristics of alloys 825, 625 , C-276 and alloy 22. The design waste package underwent several iterations with one of the latest design called " Enhanced Design Alternative" (EDA) which will consist of 20 mm thick alloy 22 as the outer container barrier. This will be shrunk fit to a 50mm thick inner barrier fabricated of type 316 nuclear grade or standard 316L SS. This waste package was then to be enclosed by a self-supported 20 mm thick Ti-grade-7 mailbox shaped drip shield. In the authors' opinion this design may be further modified as more comprehensive corrosion characteristics of uniform corrosion, localized corrosion, stress corrosion cracking, thermal stability, microbiological corrosion, galvanic corrosion, intergranular corrosion for both the base metal and more importantly, the weld joints in these waste containers under realistic repository environments are obtained. This paper presents data on a new but well established corrosion resistant alloy 59 (UNS N06059) of the Ni-Cr-Mo family. Alloy 59 appears to have better corrosion resistance , both uniform and localized, and better thermal stability than alloy 22 as measured in standard ASTM laboratory tests. Data from some of these laboratory tests on alloy 59 and 22 along with the various interactions with Lawrence Livermore National Laboratories and the TRW Environmental Safety Systems , Management and Operating Contractor for the waste package design, are discussed.

Key words: crevice corrosion, Yuccaa Mountain Project, rad-waste containers, alloy 22, UNS N06022, alloy 59, UNS N06059 , nuclear waste

INTRODUCTION

The design for containment of spent-fuel and high-level nuclear waste at the proposed geological repositary at the Yucca Mountain, Nevada was a two layer canister. In the previous designs, the inner barrier was to be alloy 825 later changed to alloy 22 with outer barrier of carbon steel , Ni-Cu alloy 400 or Cu-Ni alloy 70/30. This design concept has now been again modified to "Enhanced Design Alternative" (EDA) which will consist of 20 mm thick alloy 22 as the outer container barrier. This will be shrunk fit to a 50mm thick inner barrier fabricated of type 316 nuclear grade or standard 316L SS. This waste package will then be enclosed by a self-supported 20 mm thick Ti-grade 7 mailbox shaped drip shield. It was assumed that the slow uniform corrosion of the 20 mm thick alloy 22 will accomplish containment of the nuclear waste, without degradation of the container, to well beyond 10,000 years. In this latest design assumption has been made that alloy 22 will be immune to localized corrosion, an assumption which is not valid as shown by some of the tests recently conducted. The objective of this paper was to present data on a pure ternary alloy of the Ni-Cr-Mo family, alloy 59, having superior uniform corrosion resistance in a variety of corrosive media , superior crevice corrosion resistance and thermal stability in comparison to alloy 22.

METALLURGY & CORROSION RESISTANCE OF "Ni - Cr – Mo" ALLOY 59

Table 1 gives the basic chemical composition of the various alloys of this family developed in the 20th century. As is evident, the major alloying elements are nickel, chromium and molybdenum with some alloys containing either tungsten or copper, whereas others are of pure Ni-Cr-Mo ternary alloy, such as alloy 59. The alloys developed during the 1960's and later, had very low carbon content due to the improved AOD / VOD melting technology. This overcame the often serious intergranular corrosion attack in heat-affected zone (HAZ) of weldments the first alloy of this family, "Alloy C", UNS N10002, that was developed in the 1930's. Greater details on the physical metallurgy, development of the "C" family of alloys are well documented in the open literature. [7-10]

The next few sections briefly describe the corrosion resistance of alloy 59 in comparison to alloy 22. The dialogue and various interactions and corrosion data generated on the electrochemical testing of alloy 59 and alloy 22 with Lawrence Livermore National Laboratory (LLNL) are presented. The results of these interactions with LLNL and the TRW Environmental Safety Systems , Management and Operating Contractor for the Waste Package Design, finally led to the inclusion of alloy 59 in the test matrix where a parallel evaluation will be done in comparison to alloy 22.

CORROSION RESISTANCE AND WELDABILITY OF ALLOY 59

Uniform Corrosion

Table 2 gives the uniform corrosion rate of the alloys 59 and 22 in some standard and non-standard boiling corrosive media. As is evident, overall alloy 59 appears to have the lowest corrosion rate. The lower iron content of alloy 59 also contributes to its excellent corrosion resistance.

Localized Corrosion Resistance

Table 3A gives the localized corrosion resistance in Green Death , a highly chloridic low pH oxidizing solution. The higher the critical pitting and crevice corrosion temperature (CPT and CCT), the better is the localized corrosion resistance. As is evident alloy 59 was superior to alloy 22. This is easily explained by the fact that the PREN (pitting resistance equivalent number) due to the higher molybdenum and chromium content in alloy 59 is significantly greater than for alloy 22.

Table 3B presents the localized corrosion resistance behavior of alloy 59 and alloy 22 as measured by the CPT (critical pitting temperature) and CCT (critical crevice temperature) in the ASTM G 48 test solution (10% $FeCl_3$). As is evident the lower molybdenum-containing alloy 22 had significantly lower CCT, than the 16% molybdenum Ni-Cr-Mo alloy 59. It has been postulated that ferric chloride may become active in the repositary environment with passage of time. Hence crevice corrosion in this environment takes on an added importance. The ASTM G48 Committee has conducted round robin tests (6 laboratories) on alloy 22 where the critical pitting temperature was > 85 deg. C but the critical crevice corrosion temperature was significantly lower and varied between 50 and 60 degrees C, with only one laboratory reporting at 67 deg. C and one laboratory abstaining from providing the CCT data. This data is currently shown in ASTM Vol. 03.02 under G48[11] specification and is presented in Table 3B.

Thermal Stability

This is an important feature of any alloy system in overlay welding and welding of thick sections, where multiple passes will be required. This will be the case in welding the waste containers which will be 20 mm thick and also in the closure welds which may even be thicker. Table 4 presents the thermal stability data as measured by aging at 1600°F (871°C) followed by corrosion tests in ASTM 28A and 28B test solution. As is clearly evident, the non-tungsten and non-copper containing alloy 59 was the only alloy free of any localized (intergranular) attack. Alloy 22 suffers deep pitting and intergranular attack due to precipitation of detrimental inter-metallic phases during the aging process. Figure 1 shows the extent of the severe pitting attack on the tungsten containing alloy 22 with no attack on alloy 59. This same phenomenon could occur when welding thick sections requiring multiple weld passes, leading to undesirable phase precipitation in the heat-affected zone and thus becoming susceptible to pitting attack in severe corrosive media of the Yucca Mountain Repository environment.

FABRICABILITY AND WELDING CHARACTERISTICS

Fabricability

For alloy 59 the hot working processes like forging, rolling and extrusion, and all cold forming operations like bending, stretching, and drawing, follow the same procedure and experiences established over many years for alloy C-276 and is very similar to that of alloy 22. The same is true for sawing, machining, drilling and chemical milling. The data established for alloy C-276 serves as a equivalent guideline in establishing the optimum parameters for the manufacturing of alloy 59 into various shapes. Heat-treating follows the established rules for the other Ni-Cr-Mo alloys. Solution annealing of alloy 59 is done at 2050°F (1120°C), similar to alloy C-276 / 22. Alloy 59, due to its improved thermal stability, is easier to handle i.e. more forgiving than other alloys of the C family when cooling down from the temperature of solution annealing, followed by water quenching or fast air cooling.

Depending on the hot forming operation, which is generally done in the temperature range of 1175° to 900°C (2150 to 1650°F), the material must be solution annealed followed by water quenching or fast air cooling. A solution anneal is also required after any cold forming operation, when the strain in the outer fiber is equal to or exceeds 15%. Some cases may require a solution anneal even after 10% strain.

Weldability

Welding of alloy 59 follows the same general rules established for welding of high alloyed nickel base materials, where cleanliness is very important and critical. Heat input should be kept low with interpass temperature not exceeding 150°C, preferably 120°C. The use of a matching filler metal is recommended (AWS A5.11 and A5.14, ENiCrMo-13, ERNiCrMo-13). Preheating is not required except to bring the material to room temperature when stored outside in cold weather. Details on welding parameters are given in alloy 59 data sheet from the supplier [12] . In comparison to other Ni-Cr-Mo and some other alloys, the sensitivity to hot cracking, as measured by the Modified Varestraint Test (MVT), alloy 59 exhibits superior behavior. In this test a specimen is melted with a GTAW torch under defined conditions over a specific length as shown in Figure 2 and mechanically bent over a defined radius. The total length of the cracks visible on the surface at a magnification of 25X is measured as a function of the applied bending strain. This measures the sensitivity to hot cracking resistance. Figure 3 clearly shows alloy 59 to be better than many alloys, including alloy 22. Other tungsten containing alloys such as alloy C-276 behaved similar to alloy 22. The only material slightly better than alloy 59 was another tungsten free alloy C-4 in this test.

Corrosion Resistance of Weldments

The corrosion resistance of alloy 59 weldments is essentially similar to that of the base metal without any degradation as shown in Table 5. Corrosion resistance of various Ni-Cr-Mo alloy weldments welded with matching filler metal is shown in Table 6. As is evident, alloy 59 gave the best performance amongst all the Ni-Cr-Mo alloys tested. Both alloy C-276 and 22 not only had significantly higher corrosion rates than alloy 59 but also suffered crevice corrosion attack.

CHRONOLOGY OF VARIOUS INTERACTIONS WITH NiDI , LLNL & WASTE PACKAGE MATERIALS DEPT. OF TRW ENVIRONMENTAL SAFETY SYSTEMS ON ALLOY 59

NiDI Workshops On Radwaste Containers

- NiDI (Nickel Development Institute) sponsored a forum on Radwaste containers – Feb. 25, 1995, Tucson, AZ. [(13)]
  NiDI sponsored another forum on Phase Stability in Nickel Alloys for Radwaste containers – March 19-20 , San Diego, CA [(14)]
- October 6 , 1998 : Letter from Wsate Package Materials Department of TRW Environmental Safety Systems[(15)] indicating that alloy 59 would be tested in this program and that alloy 22 will not be referred to as Hastelloy alloy C-22, since it is a registerd trade mark of a particular company but as alloy 22 (UNS N06022). They also initiated with ASME the request for a nuclear code case for alloy 59. This has already been done. ASME nuclear code case N-625 for alloy 59 was approved on May 7, 1999.
- NiDI sponsored another forum on Fabrication and Welding of Nickel and other materials for the Radwaste containers – Oct. 27-28, Las Vegas, NV [(16)]

Data on alloy 59 was presented at all the workshops showing the superior corrosion resistance of alloy 59 weldments in comparison to alloy 22

Electrochemical Testing Comparing Alloy 22 and 59

After discussions with LLNL and TRW personnel, alloy 59 and 22 were tested per ASTM G 61 Cyclic Potentiodynamic Polarization Testing in solution chemistries supplied by LLNL (SCW – Simulated Concentrated Water and SAW – Simulated Acidic Concentrated Water test solutions). The chemistry of these solutions is shown in Table7 The test parameters were as follows:

Temperature	90.0 deg. C
Gas Sparge	Air (150 cm^3 / min.)
Initial Potential	-0.100 V from open circuit
Scan Rate	0.17 mV per second

The individual curves for each of the 4 scans are presented in Figures 4 through 7 The key-point voltage and current data are summarized below:

Polarization Scan	E_{OC}	E_{corr}	E_{pit}	E_{repas}	I_{corr}	Hysteresis
Alloy 59 in SAW	51	59	617	401	0.09	Yes
Alloy 22 in SAW	69	84	577	310	0.10	Yes
Alloy 59 in SCW	-247	-246	143	-201	0.25	Yes
Alloy 22 in SCW	-240	-232	145	-203	0.24	Yes

* NOTE: E-values are in millivolts; and I-values are in micro-amps (10^{-6} amps)

As is evident both alloys behaved similarly except that in one of the test solutions (SAW), alloy 59 exihibited a nobler (positive) repassivation potential (+ 401 mv) than alloy 22 (+ 310mv). Also no pits or crevice attack could be seen on either alloy when examined at 40x magnification

Corrosion rates and localized attack propensity from this report [17] is presented below:

Polarization Scan	Corrosion Rate (mpy)	Pitting and Crevice Propensity
Alloy 59 in SAW	0.04	Possible
Alloy 22 in SAW	0.04	Possible
Alloy 59 in SCW	0.10	Possible
Alloy 22 in SCW	0.09	Possible

A composite of the polarization curves for SAW and SCW is presented in Figure 8. Based on these results it is clear that alloy 59 and alloy 22 perform similarly. The report dated June 3, 1999 was forwarded to the LLNL and TRW personnel. [17]

After reviewing the results, LLNL provided a new solution recipe on July 22, 1999 for the SAW solution (Table 8) and suggested new tests be done on alloy 59 and 22 as well as on platinum. These were completed and the report [18] dated august 9 , 1999 was forwarded to LLNL and TRW personnel. The composite curves from this report for the platinum and alloys 59 and 22 in the modified SAW at 90 ° C is shown in Figure 9. The key-point voltage and current data are presented below along with the calculated corrosion rates.

Polarization Scan	E_{OC}	E_{corr}	E_{pit}	E_{repas}	I_{corr}	Corrosion Rate (mpy)	Hysteresis Present
Platinum	+414	+404	+620	N/A	0.080	0.047	No
Alloy 22	-30	-24	+605	+454	0.035	0.013	Yes
Alloy 59	-133	-130	+610	+373	0.031	0.013	Yes

* NOTE: E-values are in volts; and I-values are in micro-amps (10^{-6})

These results were in total agreement between the two laboratories of LLNL and Corrosion Testing Laboratories.

Based on these results a decision was made to bring the Corrosion Testing Laboratories equipment to LLNL in Livermore , California to conduct a round robin side by side test on the two machines. These tests were run on September 20 through 22, 1999.The results obtained on the two machines on alloy 59 and alloy 22 were identical. After these extensive testing over the last few months, TRW issued a letter on October 14, 1999 [19] indicating that alloy 59 will evaluated in parallel with the on going evaluation of alloy 22, which was the primary corrosion resistant barrier alloy of the waste package. Several actions were initiated:

- Thermal aging treatments will be conducted in parallel to those being performed on alloy 22 for phase analyses (identification of phases and volume fraction estimate) and production of aged test specimens for corrosion testing in simulated repository test solutions.
- Further electrochemical tests on alloy 59 in comparison to alloy 22.

The necessary samples of alloy 59 were sent to LLNL during end of 1999. KVDM has initiated its own long term aging studies on alloy 59 (both welded and unwelded specimens) up to 20,000 hrs. at 200 , 300, and 427 deg C . Results of this program is not available as yet and will be available during the last quarter of 2001 and first quarter of 2002.

DISCUSSIONS

Alloy 59 in the various tests has clearly proven to be equal if not a better candidate material of construction of the radwaste containers. Its superior crevice corrosion resistance and thermal stability characteristics in comparison to alloy 22 can not be ignored. The extensive side by side electrochemical tests done at LLNL and Corrosion Testing Laboratories show that the alloys behave similarly. A simple question needs to be raised: Is the program of "Radwaste Containers" requiring long term reliability in the extremely harsh and unpredictable conditions over a period of 10,000 years, served better by using alloy 22, the current material of choice or alloy 59 which has shown to be better in many of the tests conducted or a combination of both alloys. This is a vital question needing deep scientific thought with suitable data for both the base metal and weldments.

Recently, a study by Professor Aaron Barkatt of Catholic University [20] and Dr. Jeffery Gorman of Dominion Engineering entiled " Tests to Explore Specific Aspects of the Corrosion Resiatance of Alloy 22", dated August 1, 2000, [14] performed for the state of Nevada, clearly shows failure of alloy 22 when life expectencies of 10,000 years was considered. Alloy 22 corroded after only 30 days of exposure to water samples from the Yucca Mountain ,Nevada containing lead and mercury. Fissure as deep as 0.25" were detected on alloy 22. It is recommended that alloy 59 be tested under similar conditions.

CONCLUSIONS

- Even though alloy 22 is the current material of choice for the radwaste containers for the Yucca Mountain project, data generated on alloy 59 proves that it is superior.
- Even though alloy 59 behaves similarly to alloy 22 in electrochemical tests, its localized crevice corrosion resistance is clearly superior to alloy 22 when measured per ASTM G48 test.
- Alloy 59, in a variety of laboratory and industrial environments , has shown better uniform corrosion resistance than alloy 22.
- Alloy 59 which is a pure ternary alloy of the Ni-Cr-Mo family shows superior thermal stability than the tungsten containing alloy 22.
- Alloy 59 shows better weldability characteristics than alloy 22.

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TABLE 1

TYPICAL CHEMICAL COMPOSITION OF THE "C" FAMILY ALLOYS

Alloy (UNS #)	Decade Introduce	Ni	Cr	Mo	W	Cu	Fe
C (N10002)	1930's	Bal	16	16	4	-	6
C-276 (N10276)	1960's	Bal	16	16	4	-	5
C-4 (N06455)	1970's	Bal	16	16	-	-	2
22 (N06022)	Mid 1980's	Bal	21	13	3	-	3
59 (N06059)	Early 1990's	Bal	23	16	-	-	<1
686 (N06686)	Early 1990's	Bal	21	16	4	-	2
UNS N06200	Mid 1990's	Bal	23	16	-	1.6	2

TABLE 2
TYPICAL CORROSION RATE OF NI-CR-MO ALLOYS IN BOILING CORROSIVE ENVIRONMENTS (MPY)

Media	Alloy C-276	Alloy 22	Alloy 59
ASTM 28A	240	36	24
ASTM 28B	55	7	4
Green Death	26	4	5
10% HNO_3	19	2	2
65%HNO_3	750	52	40
10% H_2SO_4	23	18	8
50% H_2SO_4	240	308	176
1.5% HCl	11	14	3
2% HCl	51	61	3
10% HCl	239	392	179
10% H_2SO_4 + 1 % HCl	87	354	70
10% H_2SO_4 + 1% HCl (90°C)	41	92	3

TABLE 3A

LOCALIZED CORROSION RESISTANCE IN "GREEN DEATH' SOLUTION
(11.4% H_2SO_4 + 1.2% HCL + 1% $FECL_3$ + 1% $CUCL_2$)

Alloy	PREN*	CPT (° C)	CCT (° C)
22	65	120	105
59	76	> 120	110

* PREN = Pitting Resistance Equivalent Number = %Cr + 3.3 (%Mo) + 30N
** Above 120°C the Green Death Solution chemically breaks down.

TABLE 3B

LOCALIZED CORROSION RESISTANCE IN 10% $FECL_3$ SOLUTION (ASTM G-48)

Alloy	PREN*	CPT(°C)	CCT (°C)
22	65	>85 *	58**
59	76	>85	>85

* Above 85°C, the 10% $FeCl_3$ solution chemically breaks down
** Average of the ASTM round robin tests conducted on alloy 22 at the 6 laboratories and is presented below:

Laboratory	1	2	3	4	5	6
CPT	> 85° C	> 85° C	> 85° C	> 85° C	> 85° C	> 85° C
CCT	50 , 50	50,55,55	55,60,60	67, 67	----	55 , 55

TABLE 4

THERMAL STABILITY PER ASTM G-28A AND G-28B AFTER AGING FOR 1 HR AT 1600°F (871°C)
CORROSION RATE (MPY)

Media	22*	59**
ASTM G-28A	> 500*	40**
ASTM G-28B	339*	4**
Pitting Attack	Severe	No attack
Intergranular Attack	Severe	No attack

* Alloy 22 -- Heavy pitting attack with grains falling out due to deep inter-granular attack.
** Alloy 59 No Attack

TABLE 5

CORROSION RESISTANCE OF ALLOY 59 BASE METAL VS. WELDMENT

Media	Unwelded	GTAW*	GPAW**
• H_2SO_4 70,000 ppm Cl^- pH 1, Boiling, 21 days	0.003 mm/y No pitting	0.007 mm/y No pitting	0.003 mm/y No pitting

*GTAW – Gas Tungsten Arc Welding ** GPAW – Gas Plasma Arc Welding

TABLE 6
CORROSION RESISTANCE OF VARIOUS NI-CR-MO ALLOY WELDMENTS IN HIGH CHLORIDE, LOW PH MEDIA *

Sample Base Metal/Filler	Corrosion Rate mm/yr	Pitting Corrosion	Crevice Corrosion
625/625	1.15	No**	No**
C-4/C-4	0.58	No**	No**
C-276/C-276	0.32	No	Yes
22/22	0.44	No	Yes
59/59	0.007	No	No

* 70,000 ppm Cl^-, pH 1, Temperature 105°C, 21 days
** High corrosion rate masks any localized attack

TABLE 7
CHEMISTRY OF SCW AND SAW TEST SOLUTIONS

Solution (Specification)	SCW (TIP-CM-07)	SAW (TIP-CM-08)
$Ca(NO_3)_2 \cdot 4H_2O$	12.1685	5.8920
$CaCl_2 \cdot 2H_2O$	7.5980	----
$CaCO_3$	37.1173	----
H_2SO_4	0.07679	0.4402
HCl	0.0701	----
KCl	6.2820	6.4828
$KHCO_3$	0.1925	----
$MgSO_4 \cdot 7H_2O$	21.3920	10.1380
$Na_2SiO_3 \cdot 5H_2O$	0.3700	0.3700
Na_2SO_4	12.2545	50.5960
NaCl	----	34.8933
NaF	3.1826	----
$NaHCO_3$	128.2970	----
$NaNO_3$	----	27.2865
Measured pH	8.4	3.0

All values listed are in grams per liter (g/l) of solution.

Table 8
Modified SAW Test Solution *

Chemical (g/L)	Original SAW	New SAW
Sodium chloride [NaCl]	34.89	35.59
Sodium nitrate [$NaNO_3$]	27.29	31.94
Sodium sulfate [Na_2SO_4]	50.60	57.27
Sodium metasilicate [$Na_2SiO_3 \bullet 5H_2O$]	0.37	0.38
Magnesium sulfate [$MgSO_4 \bullet 7H_2O$]	10.14	0.52
Calcium nitrate [$Ca(NO_3)_2 \bullet 4H_2O$]	5.89	0.30
Sulfuric acid [H_2SO_4]	0.44	pH=2.7
Potassium chloride [KCl]	6.48	6.61

* All values listed are in grams per liter of solution

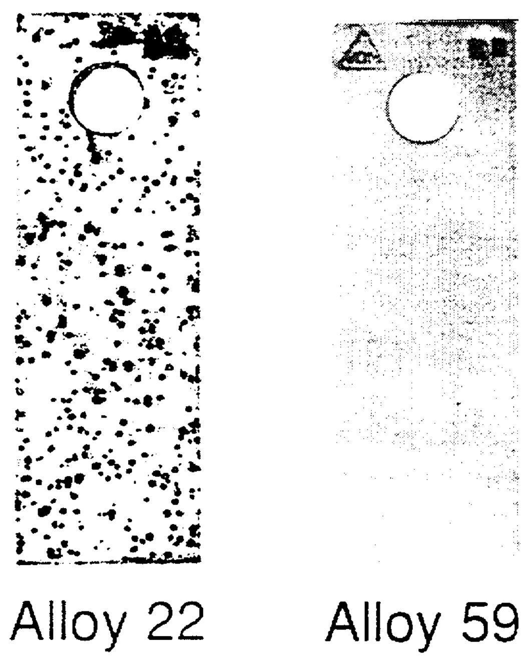


Figure 1 : Influence of Aging on Thermal Stability of Alloy 22 and Alloy 59 as measured after aging at 1600° F for 1 hour and testing in ASTM G-28B Test Solution

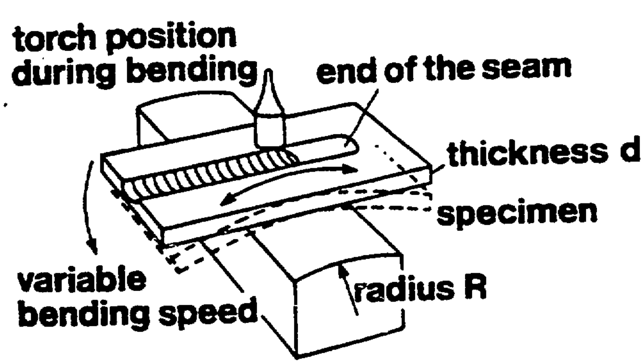


Figure 2: Modified Varestraint Test for evaluation of hot-cracking susceptibility

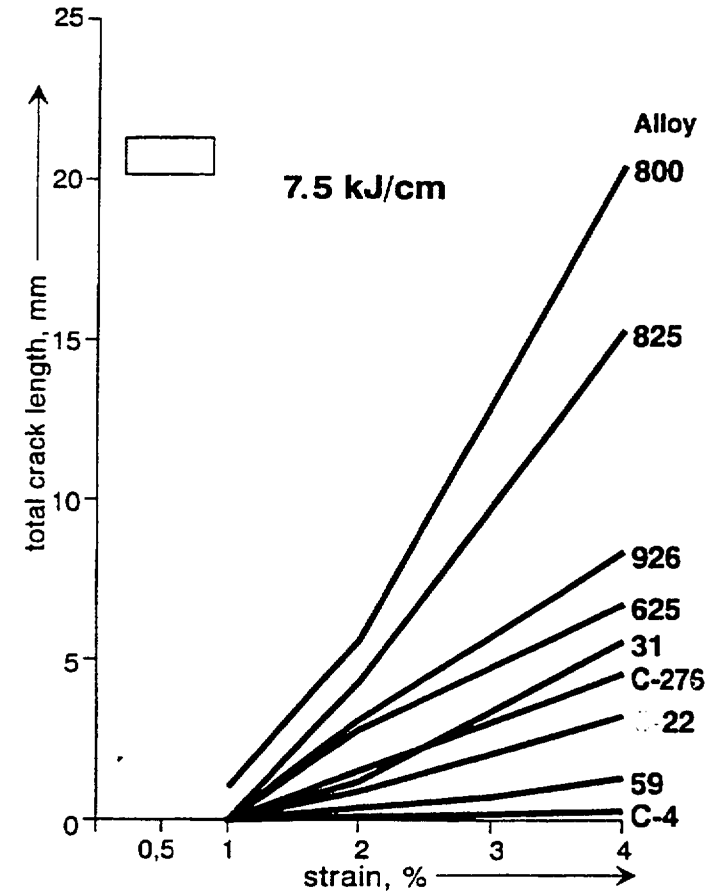


Figure 3 : Hot cracking behavior of various nickel alloys and high stainless steels as evaluated by means of Modified Varestraint Test

01120/12

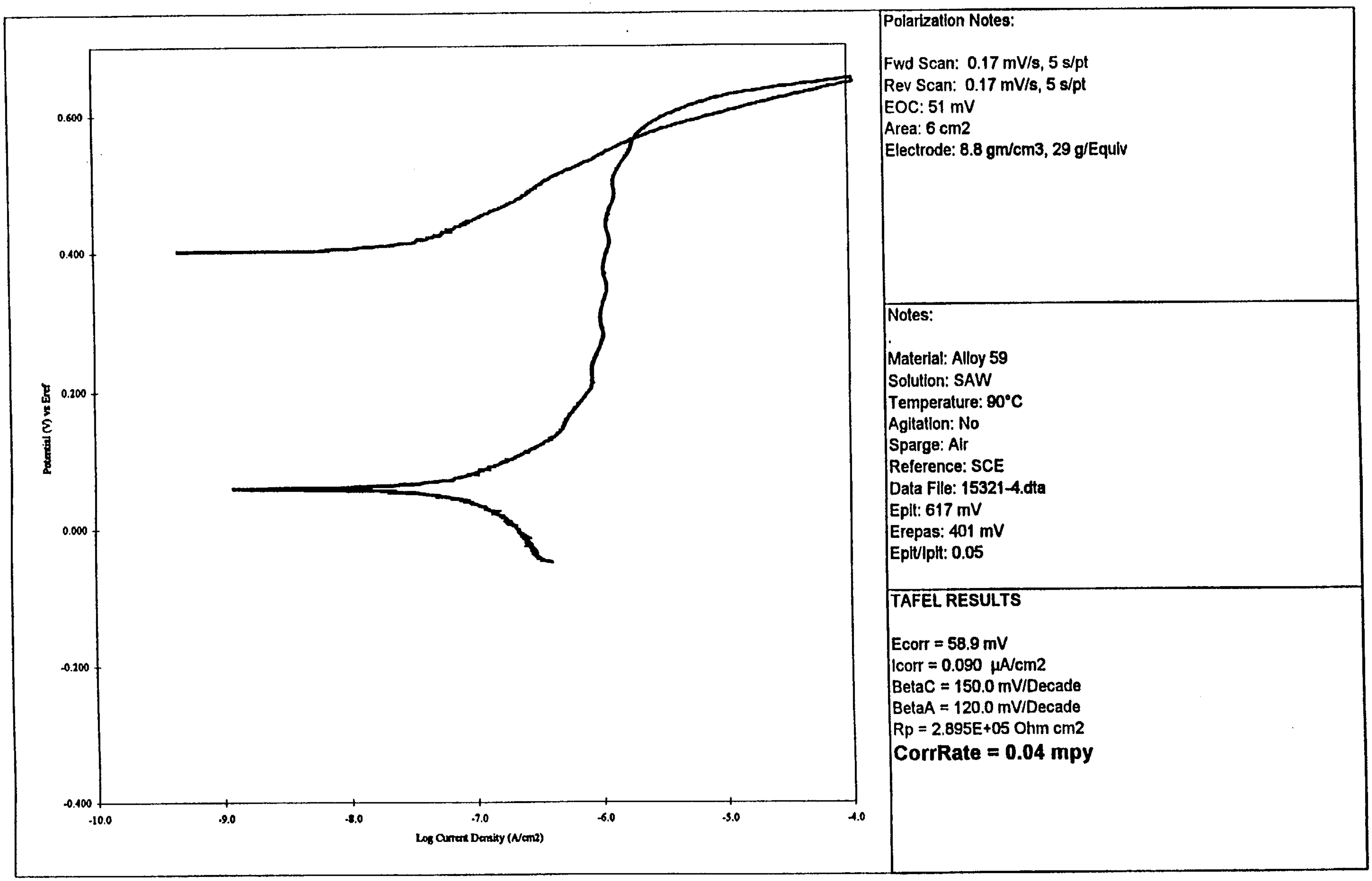


Figure 4 : Potentiodynamic polarization Scan of Alloy 59 in SAW solution at 90 ° C

01120/13

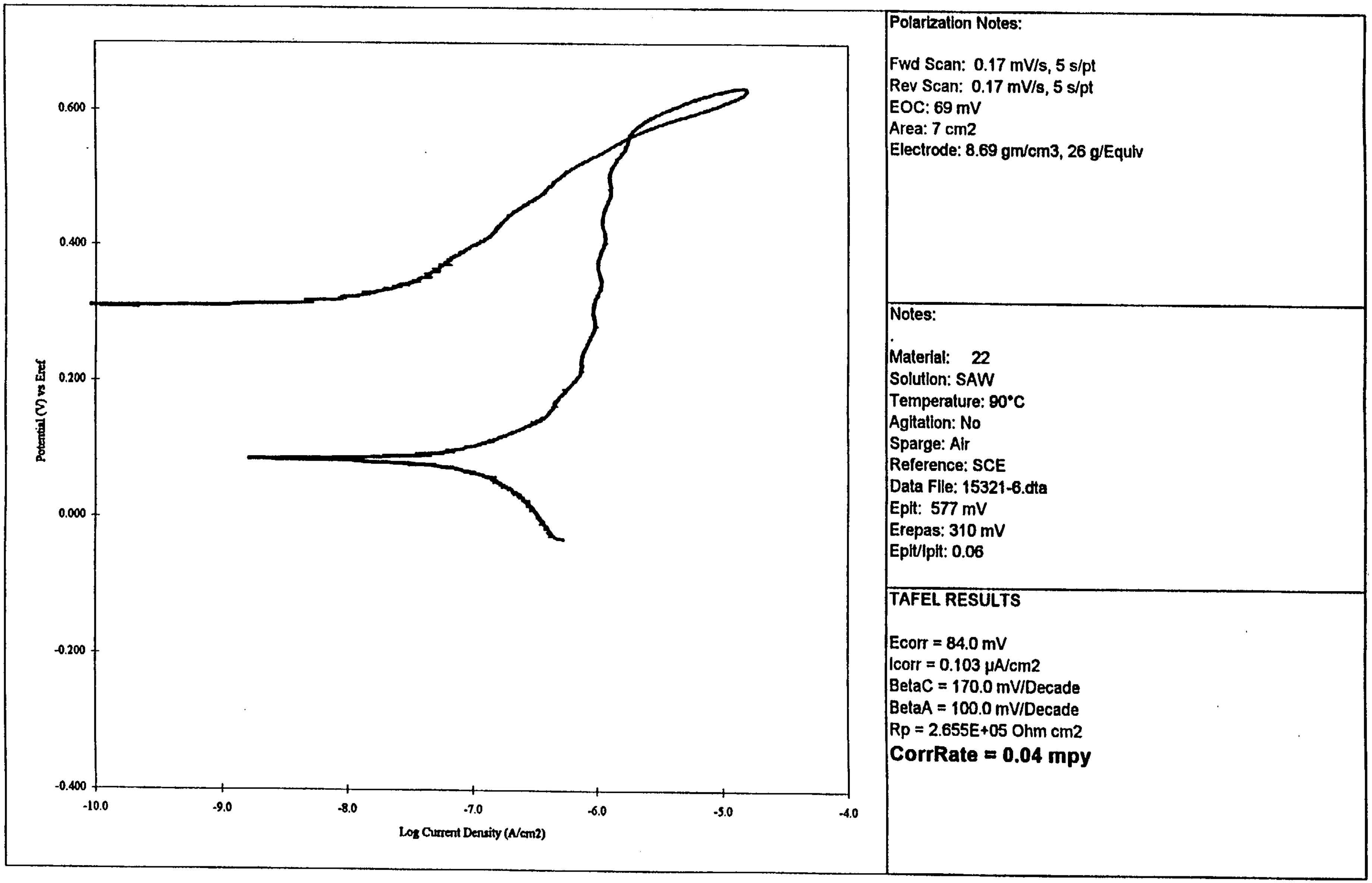
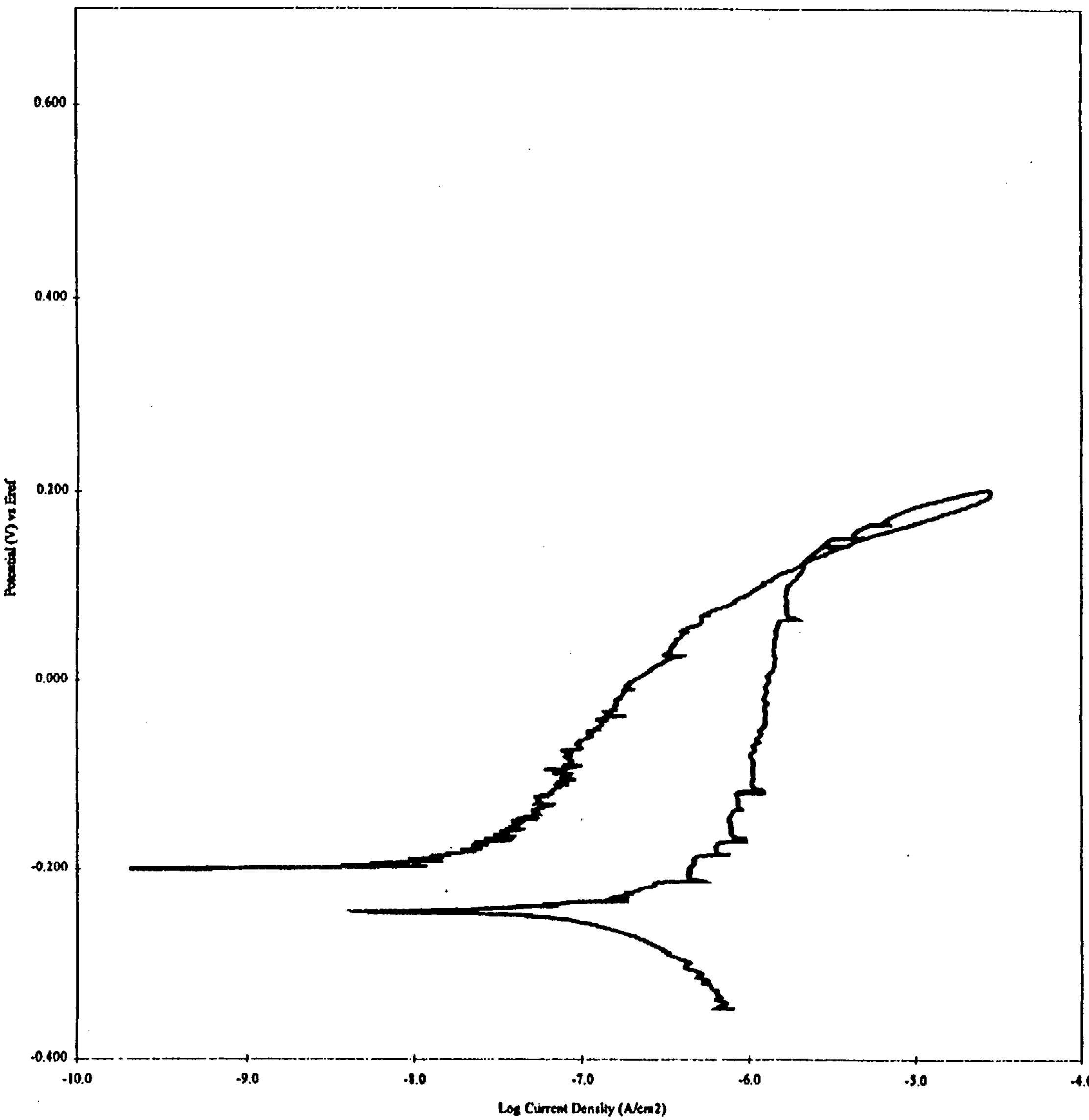


Figure 5 : Potentiodynamic polarization Scan of Alloy 22 in SAW solution at 90 ° C

01120/14



Polarization Notes:

Fwd Scan: 0.17 mV/s, 5 s/pt
Rev Scan: 0.17 mV/s, 5 s/pt
EOC: -247 V
Area: 6 cm2
Electrode: 8.8 gm/cm3, 28.98 g/Equiv

Notes:

Material: Alloy 59
Solution: SCW
Temperature: 90°C
Agitation: No
Sparge: Air
Reference: SCE
Data File: 15321-8.dta
Epit: 143 mV
Erepas: -201 mV
Epit/Ipit: 0.06

TAFEL RESULTS

Ecorr = -245.7 mV
Icorr = 0.246 μA/cm2
BetaC = 150.0 mV/Decade
BetaA = 150.0 mV/Decade
Rp = 1.324E+05 Ohm cm2
CorrRate = 0.10 mpy

Figure 6 : Potentiodynamic polarization Scan of Alloy 59 in SCW solution at 90 ° C

01120/15

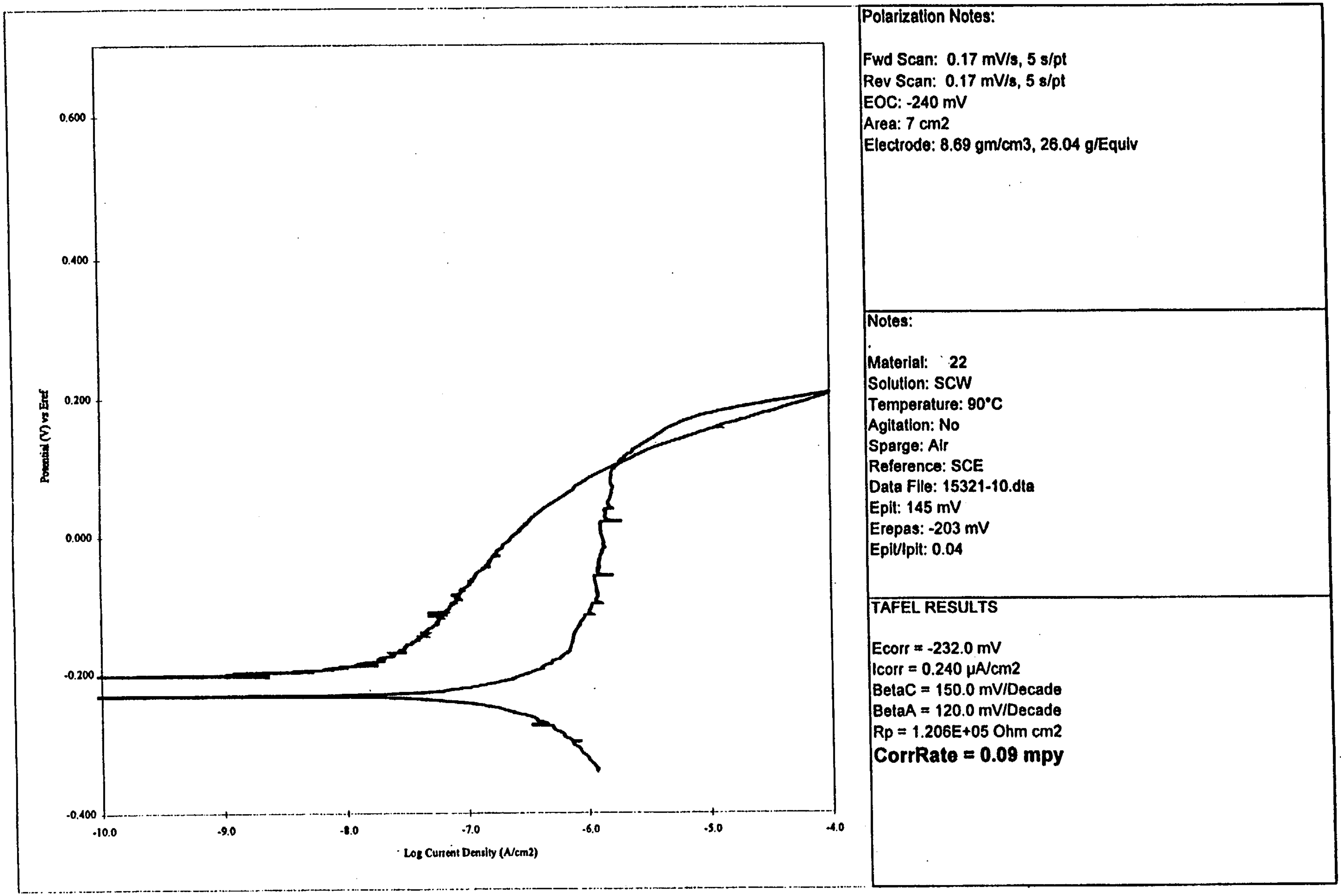


Figure 7 : Potentiodynamic polarization Scan of Alloy 22 in SCW solution at 90 ° C

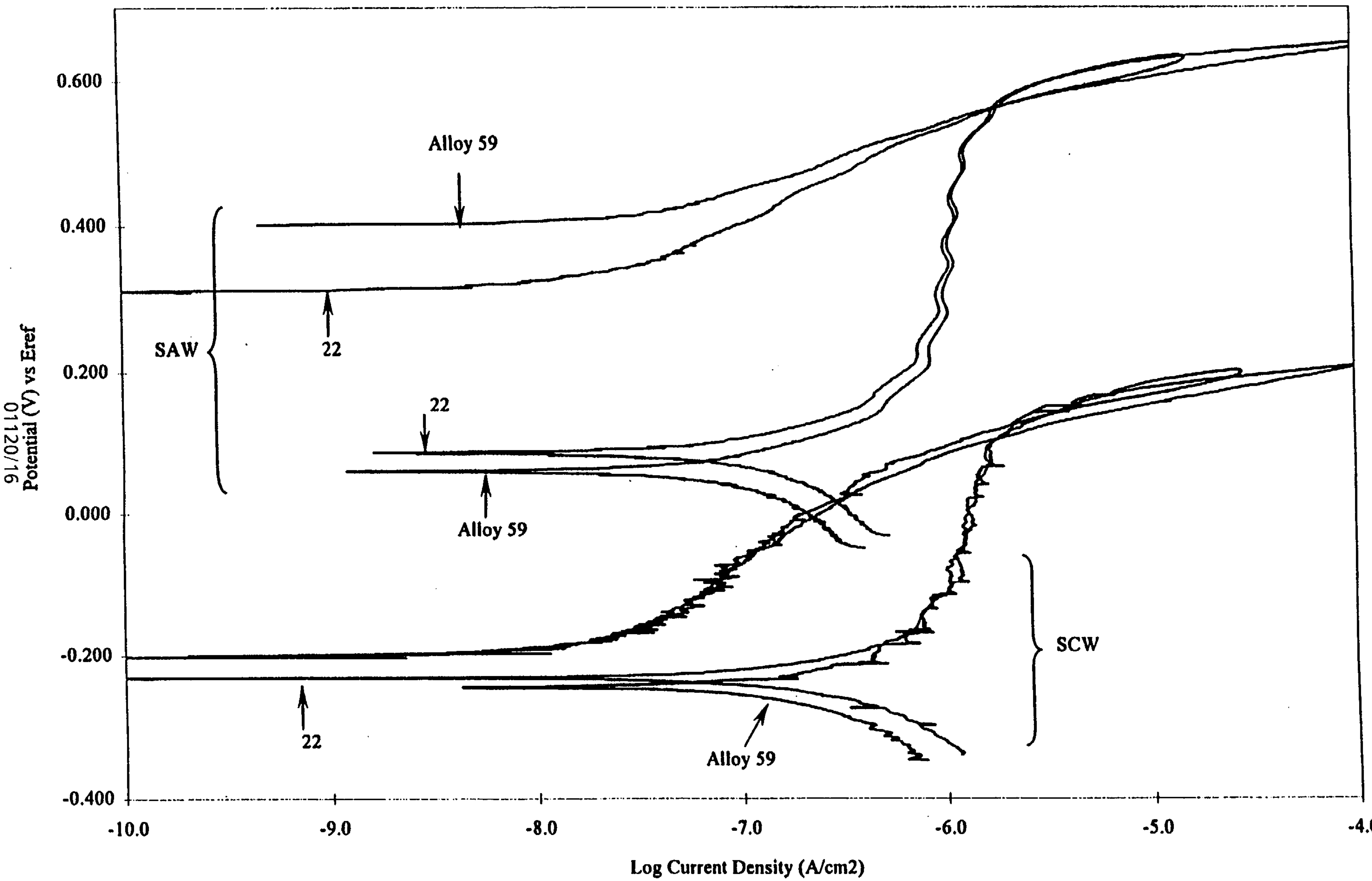


Figure 8 : Composite Potentiodynamic polarization Scans of Alloy 59and Alloy 22 in SAW and SCW solution at 90 ° C

01120/17

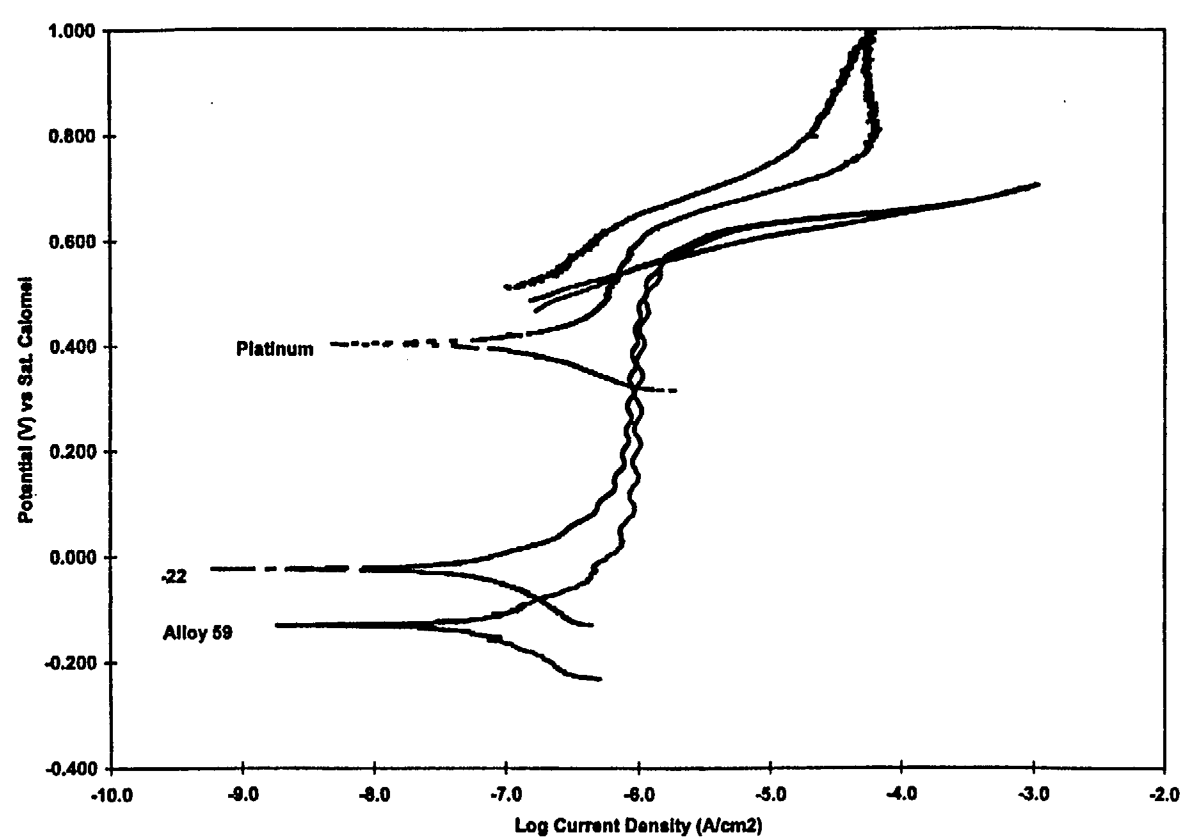


Figure 9 : Composite Potentiodynamic polarization Scans of Alloy 59 , Alloy 22 and Platinum in modified SAW solution at 90 ° C

Paper
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CORROSION2000

CASE HISTORIES ON SOLVING SEVERE CORROSION PROBLEMS IN THE CPI AND OTHER INDUSTRIES BY AN ADVANCED NI-CR-MO ALLOY 59 UNS N06059

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ABSTRACT

At one time one of the major factors in any material selection used to be initial cost with little thought given to maintenance and cost associated with lost production due to unscheduled equipment downtime. In today's economic environment, increased maintenance costs and downtime have placed a greater emphasis on the need for reliable, safe and versatile performance of process equipment, thus requiring improved alloys.

Today's industries not only demand functional and cost effective reliability in operation, but must also possess the necessary versatility to adopt to the changing corrosive environments, imposed by new processes, changing market needs, and lower quality feedstock. This situation will be made more difficult in the upcoming 21[st] century due to the need to comply with regulatory requirements of combating pollution. Hence, process machinery, components (vessels, reactors, heat exchangers, etc.) and other parts must be built of suitable materials of construction possessing adequate mechanical, metallurgical and corrosion resistance characteristics.

This paper presents a chronology of the various corrosion resistant alloys of the "C" family of Ni-Cr-Mo alloys developed in the last 70 years with special emphasis on their applications, particularly alloy 59 (UNS N06059), in CPI and various other industries. Some standard corrosion resistance data comparing the various 'C' family alloys with alloy 59 is also presented along with a section on fabricability/weldability and corrosion resistance of alloy 59 weldments in comparison to the base metal.

Keywords: Ni-Cr-Mo alloys, C-family alloys, Alloy 59, UNS N06059, CPI, Applications, Localized corrosion

INTRODUCTION

The "C" family of Ni-Cr-Mo alloys was an innovative optimization of Ni-Cr alloys having good resistance to oxidizing corrosive media and Ni-Mo alloys with superior resistance to reducing corrosive media. This combination resulted in an alloy family with exceptional corrosion resistance in a wide variety of severe corrosive environments typically encountered in CPI and other industries. The first alloy of this family, known as alloy C (1930's) exhibited excellent resistance to uniform corrosion in many corrosive environments, pitting and crevice corrosion attack in low pH high chloride oxidizing environments, and had virtual immunity to chloride stress corrosion cracking. These properties allowed this alloy to serve the industrial needs for many years, although it had some limitations. The introduction of AOD (argon-oxygen-decarburization) melting technology in the early 1960's and VOD (vacuum – oxygen - decarburization) at a later stage, along with a better understanding of alloy metallurgy and effects of various alloying elements, led to improvements in the original alloy C and development of newer alloys. The decades of the 1960's (alloy C-276), 1970's (alloy C-4), 1980's (alloy 22 and 622) and 1990's (alloy 59, alloy 686 and alloy UNS N06200) saw these newer alloy developments with improvements in corrosion resistance, which not only overcame the limitations of the original alloy C and C-276, but further expanded the horizons of applications as the needs of the CPI and other industries became more critical, more severe and more demanding.

METALLURGY & CORROSION RESISTANCE OF " C " FAMILY NI - CR - MO ALLOYS

Table 1 gives the basic chemical composition of the various alloys of this family developed in the 20^{th} century. As is evident, the major alloying elements are nickel, chromium and molybdenum with some alloys containing either tungsten or copper, whereas others being pure ternary alloy of Ni-Cr-Mo family such as alloy 59. As mentioned, the alloys developed during the 1960's and later, had very low carbon content due to the improved AOD / VOD melting technology and thus overcame the often serious intergranular corrosion attack in HAZ of the first alloy of this family, "Alloy C", UNS N10002, developed in the 1930's.

Greater details [1-4] on the physical metallurgy, development of the "C" family of alloys are well documented in the open literature. The next few sections briefly describe the corrosion resistance, fabricability, and uses of these alloys in various industries with particular emphasis on applications of alloy 59, an advanced alloy of the Ni-Cr-Mo family developed by Krupp VDM in the mid-1980's and commercialized in the early1990's.

CORROSION RESISTANCE

Uniform Corrosion: Table 2 gives the uniform corrosion rate of the various Ni-Cr-Mo alloys in some standard and non-standard boiling corrosive media. As is evident, overall alloy 59 appears to have the lowest corrosion rate. The lower iron content of alloy 59 also contributes to its excellent corrosion resistance and is especially beneficial in overlay welding and welding of dis-similar metals and alloys.

Localized Corrosion Resistance: Table 3A gives the localized corrosion resistance in Green Death Solution , a highly chloridic low pH oxidizing media. The higher the critical pitting and crevice corrosion temperature, the better is the localized corrosion resistance. As is evident, alloy 686 and alloy 59 gave the best results. Alloy N06200, which is basically alloy 59 with addition of 1.6% copper, had a lower localized corrosion resistance to alloy 59, indicating the detrimental effects of copper.
Table 3B presents the localized corrosion resistance behavior of the various alloys as measured by the CPT (critical pitting temperature) and CCT (critical crevice temperature) in the ASTM G 48 test solution (10% $FeCl_3$). As is evident the lower molybdenum-containing alloy 22 had significantly lower CCT, than the 16% molybdenum Ni-Cr-Mo alloys.

Thermal Stability: This is an important feature of any alloy system in overlay welding and welding of thick sections, where multiple passes may be required. Table 4 presents the thermal stability data as measured by aging at 1600°F (871°C) followed by corrosion tests in ASTM 28A and 28B test solution. As is clearly evident, the non-tungsten and non-copper containing alloy 59 was the only alloy free of any localized or inter-granular attack. All others suffered deep pitting and intergranular attack due to precipitation of detrimental inter-metallic phases during the aging process. Figure 1 shows the extent of the severe pitting attack on the tungsten containing alloy 22 with no attack on alloy 59. Similar pitting and inter-granular attack was also observed on alloy C-276 and alloy 686 (both tungsten containing) and alloy UNS N06200 (copper containing). This same phenomenon could occur when welding thick sections requiring multiple weld passes, leading to undesirable phase precipitation in the heat-affected zone and thus becoming susceptible to pitting attack in severe corrosive media.

FABRICABILITY AND WELDING CHARACTERISTICS

Fabricability: For alloy 59 the hot working processes like forging, rolling and extrusion, and all cold forming operations like bending, stretching, and drawing, follow the same procedure and experiences established over many years for alloy C-276. The same is true for sawing, machining, drilling and chemical milling. The data established for alloy C-276 serves as a equivalent guideline in establishing the optimum parameters for the manufacturing of alloy 59 into various shapes. Heat-treating follows the established rules for the other Ni-Cr-Mo alloys. Solution annealing of alloy 59 shall be done at 2050°F (1120°C), similar to alloy C-276. Alloy 59, due to its improved thermal stability, is easier to handle (better thermal stability), i.e. more forgiving than other alloys of the C family when cooling down from the temperature of solution annealing, followed by water quenching or fast air cooling.

Depending on the hot forming operation, which is generally done in the temperature range of 1175° to 900°C (2150 to 1650°F), the material must to be solution annealed followed by water quenching or fast air cooling. A solution anneal is also required after any cold forming operation, when the strain in the outer fiber is equal to or exceeds 15%. Some cases may require a solution anneal even after 10% strain.

Weldability: Welding of alloy 59 follows the same general rules established for welding of high alloyed nickel base materials, where cleanliness is very important and critical. Heat input should be kept low with interpass temperature not exceeding 150°C, preferably 120°C. The use of a matching filler metal is recommended (AWS A5.11 and A5.14, ENiCrMo-13, ERNiCrMo-13). Preheating is not required except to bring the material to room temperature when stored outside in cold weather. Details on welding parameters are given in alloy 59 data sheet from the supplier [5]. In comparison to other Ni-Cr-Mo and some other alloys, the sensitivity to hot cracking, as measured by a modified varestraint test, alloy 59 exhibits superior behavior. Figure 2 clearly shows alloy 59 to be better than many alloys, including alloy C-276. Other tungsten containing alloys such as alloy 22 and 686 behaved similar to alloy C-276. The only material better than alloy 59 was another tungsten free alloy C-4 in this test.

Corrosion Resistance of Weldments: The corrosion resistance of alloy 59 weldments is essentially similar to that of the base metal without any degradation as shown in Table 5. Corrosion resistance of various Ni-Cr-Mo alloy weldments welded with matching filler metal is shown in Table 6. As is evident, alloy 59 gave the best performance amongst all the Ni-Cr-Mo alloys tested. Both alloy C-276 and C-22 not only had significantly higher corrosion rate than alloy 59 but also suffered crevice corrosion attack. Details on the other data on corrosion resistance of weldments is provided elsewhere. [6,11]

APPLICATIONS

The "C" family of alloys have found widespread applications in chemical and petrochemical industries producing various chlorinated, fluorinated and other organic chemicals, agrichemicals, and pharmaceutical industries, producing various biocides, pollution control (FGD of coal fired power plants, waste water treatment, incinerator scrubbers), pulp and paper, oil and gas (sour gas), marine and many others.

As mentioned earlier, the original alloy C is now obsolete, except for use in some castings. In the last thirty-five years, over 60,000 tons of various "C" family alloys have been used in a variety of industries.

The alloy 22 due to its higher chromium content, improved upon the weaknesses of alloy C-276 in highly oxidizing environments, but the industry soon discovered that alloy C-276 was still the better alloy in many of the chemical process environments which were reducing in nature due to use of halogenic acids and proprietary catalysts. Today alloy 22, an alloy of the 80's, has been to a great extent superseded by the "C" family alloys of the 90's, such as alloy 686, alloy UNS N06200 and alloy 59.

Alloy 59 alloy is covered under all appropriate ASTM, AWS, ASME (SC VIII up to 1400°F and SCIII up to 800°F) and NACE MRO-175 specifications in the USA and in most of the European and other international specifications.

Already, alloy 59 with its first commercial introduction in 1990, has found a wide number of applications, and these continue to increase as the "corrosion universe" realizes its superior corrosion resistance behavior in both oxidizing and reducing media, superior localized corrosion resistance, excellent fabricabilty, weldability and thermal stability behavior. Table 7 gives a listing of some applications with a brief description of a few important ones given below.

Pollution Control: The corrosive conditions in scrubbers of coal fired power plants (FGD systems) and in waste incinerators, both for municipal and hazardous waste, have been so severe that only alloys of the Ni-Cr-Mo class have given reliable performance. Combustion gases from fossil fuels or waste incinerators contain sulfur oxide and halogenic acids, which must be scrubbed before gases are released into the atmosphere. Presence of condensates with chloride levels over 100,000 ppm, and fluorides of over 10,000 ppm, very low pH (below 1), sulfuric acid, hydrochloric acid, hydrofluoric acid, various salts and other contaminants, create a situation, where lower alloys have failed in a few days to a few weeks. Many thousands of tons of alloy 59 have been used in recent years in these systems in Europe, USA, and other parts of the world [7-9], giving satisfactory performance.

An independent test program conducted at 3M company's hazardous waste incinerator showed alloy 59 to clearly outperform other alloys of the Ni-Cr-Mo family [10] (Table 8). This company is very satisfied with alloy 59 performance.

In a medical hazardous waste incinerator, scrubbers are used to control acidic emissions. The original scrubber built out of carbon steel (0.5" thick plate) corroded in less than a week. Replacement with alloy 316LSS failed by uniform corrosion, pitting and stress corrosion cracking in less than a month. Table 9 gives the hazardous medical waste liquor analysis, with pH measuring 0.07, a very acidic solution. Laboratory test results in this solution at various temperatures are shown in Table10. Testing with carbon steel and alloys C-276 and 59 in the condensate of this scrubber, showed why the carbon steel failed in less than a week. Of the Ni-Cr-Mo alloys tested, alloy 59 gave the best results.

Petrochemical/Chemical: A major chemical company in Mid-Western USA (3M), producing chlorinated and fluorinated chemicals, had to replace the reactor pressure vessel originally made out of alloy C-276 every 12 to 14 months due to excessive corrosion. The process employed various hydrocarbons, ammonium fluoride, sulfuric acid and a proprietary catalyst in which one atom of chlorine was replaced with one atom of fluorine in the produced chemical compound which is an intermediate for further processing and production of various chlorinated and fluorinated chemicals. Presence of fluorides ruled out the use of tantalum, titanium and glass-lined vessels. Switch to a Ni-Mo alloy B-2 prolonged the life by only 20 to 25%. This was also unacceptable. Extensive tests made with alloy 59 and other alloys over a period of 18 months indicated that with alloy 59 the life of this ASME code reactor vessel could be increased by 250% to 300%. A vessel was built with alloy 59 in 1994. After 27 months of service, a minor repair of the "thermo well" weld had to be performed. It is expected that the life of this vessel will even surpass the original expectations. Since then, two more vessels of alloy 59 have been ordered by this same company and are operating successfully. Figure 3 shows the picture of one of these ASME reactor vessels.

In another application, alloy 625 gave only three years life in a column in a fine chemicals plant. The operating conditions were a temperature of 140°C and a medium consisting of 83.1% water, 14.3% sodium bisulphate, 0.34% sodium sulphate, 0.02% acetone, 0.46% isopropanol, 0.06% copper sulphate, 0.04% DCNB, and 1.5% "various organics". Tests were carried out both at the inlet to the column and at the foot of the column. Based on the results of these tests, an order was issued for a new column to be built in alloy 59. Alloy 59 continues to perform satisfactorily and has already exceeded the life of previously used alloy 625 by a factor of 2 and still performing well.

TDI Production: Heat exchangers are used to reheat TDI (Toluene-di-isocynate) tar residue to 190°C using 18-bar steam. Alloy 600 had a life of about 10 years. A process change led to failure of these tubes in 6 months. Suspect was presence of oxidizing chloride species in the tar residue due to the process change. Testing with alloy 59 led to its selection. Alloy 59 tube heat exchanger is now in service for over 36 months and giving excellent performance.

Herbicide Production: During manufacture, the process media alternates between alkaline and acidic with presence of high chlorides at temperature of 250°C with pressures of 25 bar. The original material of construction failed by pitting corrosion in a very short time and was replaced by alloy 59 after extensive testing. Alloy 59 has been performing well over the last 6 years.

HF Acid Production: Ni-Cr-Mo alloys, such as alloy "C" and later alloy C-276 have been successfully used as a reactor lining since 1960 in the USA. In this service CaF_2 (Fluorspar) and sulfuric acid are reacted to produce calcium sulphate and HF gas. The rotary reactor vessel is heated from outside to about 550°C. Life of alloy C-276 had been about 3 years. Other materials of construction such as alloy 904L and alloy 20, had failed in less than 6 months. A European company initiated a full-scale test with 10-mm plate in various alloys of the "C" family. Alloy 59 was selected due to its superior performance over alloys 686, UNS N06200, 22 and C-276. It is expected that alloy 59 will last at least 5 years or more, a ten-fold improvement over alloy 904L and two-fold over alloy C-276.

Acrylates Production: During manufacture and synthesis of acrylates and methacrylates, a process reaction at 130°C is carried out under oxidizing conditions in presence of acids, fatty alcohols, and paratoluene sulfonic acid. The previous material of construction, alloy 400, had failed rapidly with corrosion rates approaching 0.75 mm/y. A test program with various alloys, including 904L, 28, G-3, 625, C-276, 31 and 59 showed alloy 59 to be totally free from localized attack with a corrosion rate of less than 0.025 mm/yr. Alloy 59 was selected and has operated without any problems for the last 7 years.

Sulfuric Acid Production: In a copper plant, the SO_2 rich gas from the flash smelter furnace is scrubbed with a solution of contaminated 5% H_2SO_4 at a temperature of 45°C-60°C. The produced acid has a concentration of typically 50-55% H_2SO_4 at a temperature of about 75°C. The chloride and fluoride contents of this acid are both high at about 7000 ppm. Previous materials of construction (alloy 20 and rubber lined carbon steel) had failed very rapidly. Tests were carried out using alloy 59, alloy 31 and other alloys. Corrosion rates for both alloys 59 and 31 were below 0.025 mm/y with no localized corrosion. Following these tests, alloy 31 was purchased for the scrubber internals handling the produced acid and alloy 59 for the induced draft fans. These have been in successful operation for the last 5 years with no detectable corrosion. Since then another alloy 59 fan has been placed in service. Due to the excellent performance of the advanced 6 Mo alloy 31 in their process, the plant replaced the other two fans with the lower cost alloy 31. Alloy 31 and alloy 59, both are performing well since 1995.

Citric Acid Production: In citric acid production, a 6% Mo alloy failed rapidly. The reaction was treating calcium citrate with concentrated H_2SO_4 at about 96°C. A test program with alloy 59 led to its selection and since then four reactors have been built. The first one, installed in 1990, continues to operate without any problems. In another citric acid plant, plate heat exchangers of alloy 20 were failing within a period of 6 months. Testing with various alloys led to alloy 59 selection. These alloy 59 plate heat exchangers are giving reliable performance and have been in service for over 4 years.

HCl Production: In a weld overlay of burner bases, where hydrogen and chlorine are burnt to produce hydrochloric acid, a two layer electroslag alloy 59 weld overlay performed significantly better than all previously used materials including alloy 22. In another weld overlay application with alloy 59, superheater tubes in a waste incineration plant extended their life by significantly reducing unusually high fireside surface wastage.

Acetic Acid: In a plant, plate heat exchangers handling acetic acid derivatives effluents were failing rapidly. Corrosion testing at 100°C with alloy C-276 and alloy 59 gave corrosion rates of 0.4 mm/y for alloy C-276 vs. 0.04 mm/y for alloy 59, a ten fold improvement. Hence, alloy 59 was selected. The media consisted of sulfates, acetic acid, phosphates, and chlorides with pH of 1. Alloy 59 plate heat exchangers are in operation since 1995 without any problems.

METAL PROCESSING

Copper Smelters: As mentioned above under sulfuric acid production, alloy 59 induced draft fans and scrubber internals have been operating satisfactorily for the last five years.

Aluminum Refining: When aluminum scrap is remelted, the molten metal is protected from oxidation by a layer of sodium and potassium chlorides. During the refining process this salt layer becomes contaminated with ammonium chloride. These chloride salts then have to be purified and recovered. This is done by dissolving them in water, and then recyrstallizing the solution. In one European plant the solution thus obtained contains 20-25% NaCl, 6-8% KCl and 5-8% NH_4Cl. The pH is in the range 4.5 to 6. The evaporator operates at a temperature of 107°C. The initial plant was built in rubber lined steel, and failed rapidly by cracking of the rubber and subsequent corrosion of the carbon steel. A plant test in 1994 with alloy 59 showed that after some 3800 hours of operating time no corrosion could be detected. The recrystallization plant has since been rebuilt in alloy 59 and is operating successfully since 1995.

Gold Refining: Gold sponge is deposited from an electrolyte of dilute HCl containing impure gold. The deposited spongy cold cathodes are washed in water to remove the HCl and then dried in an oven at 150°C, where the evaporation of remaining dilute HCl electrolyte creates very severe corrosive conditions. After extensive testing alloy 59 was selected for this application and has been performing well since 1990.

Zinc Plating: Electro-galvanizing is used in zinc plating of carbon steel sheets for automotive industry. Zinc plating occurs in a sulphate bath of low pH (2) at 60°C using a current density of 100 amps/dm^2. In the past these electro-galvanizing current carrying rolls were made from clad alloy C-4. Tests with alloy 59 proved its good corrosion resistance and have been used successfully as a superior alternate to alloy 22 and C-4.

Other Applications

There are many other applications of alloy 59, too numerous to mention here. A brief listing is given below:

- Production of Vitamin E products
- Waste water treatment produced from uranium ore leaching process

- Marine application in butterfly valve, where crevice corrosion is a serious problem
- Carbon absorption system for a pharmaceutical process in solvent recovery
- Multistage waste water evaporation
- Flare stacks
- Solvent incinerators
- Pharmaceutical centrifuge
- Medical waste incinerator scrubber
- Electrodes for electrostatic precipitation
- Cross flow glass tube heat exchangers housings in waste incineration plants
- Potential for radioactive waste containers for the Yucca Mountain project. This is a major project where alloy 59 is being considered and tested at Lawrence Livermore National Laboratory as an equal or superior alternate to alloy 22. The electrochemical testing in simulated corrosive test solution showed both alloy 59 and alloy 22 to perform equally well [(11)]. Aging tests at various temperatures are being conducted to prove the better thermal stability of alloy 59 (tungsten free) over alloy 22 (tungsten containing).

A four year US Navy test program conducted at their Key West Test Facilities in search for an alloy which is basically immune to crevice corrosion in critical areas of the navy ships and other testing conducted at Laque Corrosion Testing Laboratories, has led to the selection of alloy 59 pilot testing in valves which see stagnant sea-water, a very severe crevice corrosion causing media. Details on alloy 59 excellent localized corrosion resistance in marine environments are presented elsewhere [(12)]. Alloy 59 continues to be tested and specified for many applications in a wide variety of diverse industries due to its superior corrosion resistance properties.

SUMMARY

This paper has briefly described the chronology of the development of the various alloys of the "C" family over the last 70 years with both their advantages and limitations. The newer alloys such as alloy 59 has shown increased acceptance in the industry due to superior properties over the current workhorse of the Ni-Cr-Mo alloy family, alloy C-276. Alloy 22, an alloy introduced in the 1980's, has now been generally superseded by the newer alloys of the 1990's, i.e. alloy 59, alloy 686 and alloy UNS N06200. Alloy C-4 has found some applications, mostly in European countries. It is likely that alloy C-276 will remain the "work-horse" of the industry for many years to come and well into the 21st century. However, because of its superior overall properties, alloy 59 continues to replace alloy C-276 in media, where alloy C-276 is either inadequate or marginal in nature. As both operating conditions and safety considerations become more demanding, alloy 59 will increasingly be required to fulfill the needs of the industry as has been demonstrated by the many successful and diverse applications.

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Table 1
Typical Chemical Composition of the "C" Family Alloys

Alloy (UNS #)	Decade Introduced	Ni	Cr	Mo	W	Cu	Fe
C (N10002)	1930's	Bal	16	16	4	-	6
C-276 (N10276)	1960's	Bal	16	16	4	-	5
C-4 (N06455)	1970's	Bal	16	16	-	-	2
22 (N06022)	Mid 1980's	Bal	21	13	3	-	3
59 (N06059)	Early 1990's	Bal	23	16	-	-	<1
686 (N06686)	Early 1990's	Bal	21	16	4	-	2
UNS N06200	Mid 1990's	Bal	23	16	-	1.6	2

Table 2
Typical Corrosion Rate of Ni-Cr-Mo Alloys in Boiling Corrosive Environments (MPY)

Media	Alloy C-276	Alloy 22	Alloy 686	Alloy N06200	Alloy 59
ASTM 28A	240	36	103	27	24
ASTM 28B	55	7	10	4	4
Green Death	26	4	8	--	5
10% HNO_3	19	2	--	--	2
65%HNO_3	750	52	231	--	40
10% H_2SO_4	23	18	--	--	8
50% H_2SO_4	240	308	--	--	176
1.5% HCl	11	14	5	2	3
2% HCl	--	--	6	3	3
5% HCl	--	--	244	176	193
10% HCl	239	392	--	--	179
10% H_2 SO + 1 % HCl	87	354	--	--	70
10% H_2 SO + 1% HCl (90°C)	41	92	67	--	3

-- No data available

Table 3A

Localized Corrosion Resistance in "Green Death' Solution
($11.4\% \; H_2SO_4 + 1.2\% \; HCl + 1\% \; FeCl_3 + 1\% \; CuCl_2$)

Alloy	PRE *	CPT(°C)	CCT (°C)
22	65	120	105
C-276	69	110	105
N06200	76	110	100
686	74	>120**	110
59	76	>120**	110

* PRE = Pitting Resistance Equivalent = %Cr + 3.3 (%Mo) + 30N
** Above 120°C the Green Death Solution chemically breaks down.

Table 3B
Localized Corrosion Resistance in 10% $FeCl_3$ Solution (ASTM G-48)

Alloy	PRE *	CPT(°C)	CCT (°C)
22	65	>85 *	58
C-276	69	>85	>85
N06200	76	>85	>85
686	74	>85	>85
59	76	>85	>85

* Above 85°C, the 10% $FeCl_3$ solution chemically breaks down

Table 4

Thermal Stability per ASTM G-28A and G-28B after Sensitization for 1 hr at 1600°F (871°C)

	Corrosion Rate (mpy)				
Media	C-276*	22*	686*	N06200*	59**
ASTM G-28A	>500*	>500*	872*	116*	40**
ASTM G-28B	>500*	339*	17*	>500*	4**
Pitting Attack	Severe	Severe	Severe	Severe	None
Intergranular Attack	Severe	Severe	Severe	Severe	None

* Alloy C-276, 22, C-2000 and 686 – Heavy pitting attack with grains falling out due to deep intergranular attack.
** Alloy 59 No Attack

Table 5

Corrosion Resistance of Alloy 59 Base Metal vs. Weldment

Media	Unwelded	GTAW*	GPAW**
•Green Death	CPT >120°C CCT 110°C	115°C 110°C	>120°C 105°C weld root
• H_2SO_4 70,000 ppm Cl^- pH1, Boiling, 21 days	0.003 mm/y No pitting	0.007 mm/y No pitting	0.003 mm/y No pitting

*GTAW – Gas Tungsten Arc Welding ** GPAW – Gas Plasma Arc Welding

Table 6
Corrosion Resistance of Various Ni-Cr-Mo alloy Weldments
In High Chloride, low pH Media *

Sample Base Metal/Filler	Corrosion Rate mm/yr	Pitting Corrosion	Crevice Corrosion
625/625	1.15	No**	No**
C-4/C-4	0.58	No**	No**
C-276/C-276	0.32	No	Yes
22/22	0.44	No	Yes
59/59	0.007	No	No

* 70,000 ppm Cl^-, pH 1, Temperature 105°C, 21 days
** High corrosion rate masks any localized attack

Table 7
Some Applications of Alloy 59 in Industry

Industry	Remarks
FGD Scrubbers, Incinerator Scrubbers	Acids, H_2SO_4, HCl, HF, Cl^- F^-, others
Multi Stage Waste Water Evaporation	Cl^- , SO_4, Low pH
Halogen Exchange Reactor	Chlorinated / Fluorinated Chemicals
Copper Smelter Scrubbers	Acid, Cl^-, others
Pharmaceutical Products	Solvent recovery, Acid, Cl^-
Activated Carbon Filters	-
HF Acid Production	$CaF_2 + H_2SO_4$, Vapor Phase
Citric Acid Production (4 reactors), Plate Heat Exchangers	Calcium Citrate + H_2SO_4
Metal Sulphates 10 – 15% H_2SO_4	Steam Heating Coil
Acrylate/Methacrylate Reactor and Heating Coil (130°C)	Fatty Alcohols + Acrylic Acid + Sulfonic Acid +Water
Al Refining	Salts, Acids, Cl^-
Acetic Acid Effluent Heat Exchanger pH1, 100°C	Chloride, Low pH
Electrolytic Zinc Plating	H_2SO_4, Cl^-
Gold Production Drying Gold Cathode	HCl Acid/Vapors
Flare Tips	Acid Condensates

(Many other applications in various industries)

Table 8 *
3M study – Hazardous Waste Incineration Scrubber Corrosion Data

Alloy	MPY**	Remarks
59	1.1	Clean
686	5.4	Clean
22	6.7	Clean
31	7.1	Clean
622	12.1	Weld Attack
C-276	35.1	Clean
625	58.6	Rough
825	117	Pitting Attack

* Reference #10
** To convert to mm/y multiply by 0.0254

Table 9

Hazardous Medical Waste Liquor Analysis from the Incinerator

Elements	ppm	Elements	ppm
Br	6	Fe	280
I	53	P	74
Ba	5	Na	2000
Ca	6300		

Chlorides	-	68400 ppm
Fluorides	-	66 ppm
Sulphates	-	6800 ppm
Nitrates	-	<2 ppm

Condensate pH – 0.07

Table 10

Results of 72 Hour Immersion Test at Various Temperatures in the Scrubber Condensate

Corrosion Rate (MPY)

Alloy	150°F	200°F	Boiling
59	<1	<1	<1
C-276	<1	5	14
C-Steel	2120*	4866*	11116*

*Test stopped after 24 hours

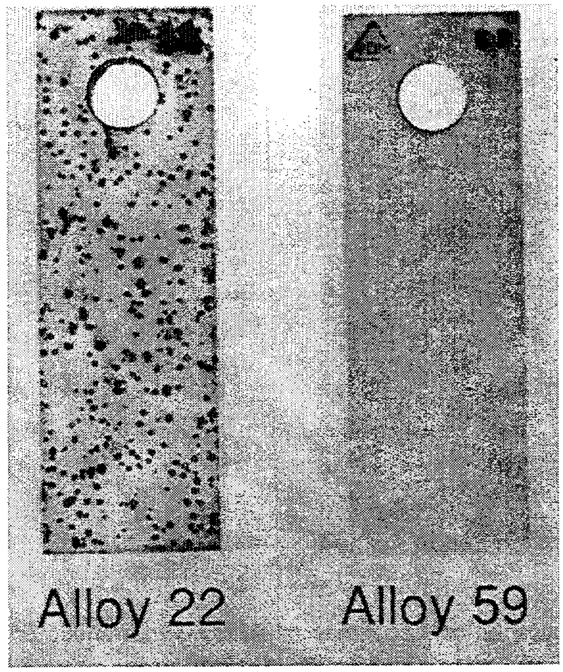

Figure 1: Influence of Thermal Stability on Corrosion of Alloy 22 and Alloy 59 After Aging at 1600°F and Tested in ASTM G-28 B Test Solution

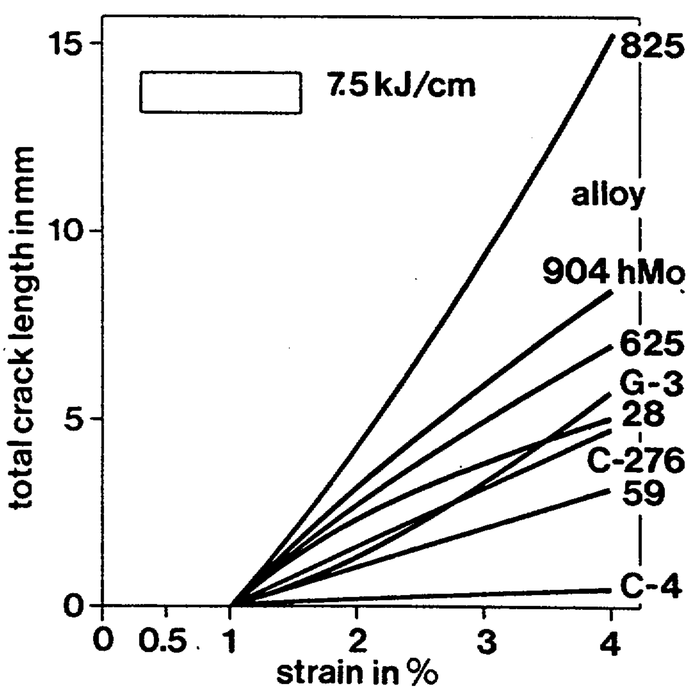

Figure 2: Sensitivity to Hot Cracking of Various Nickel Alloys Measured as Total Crack Length in a Modified Varestraint Test

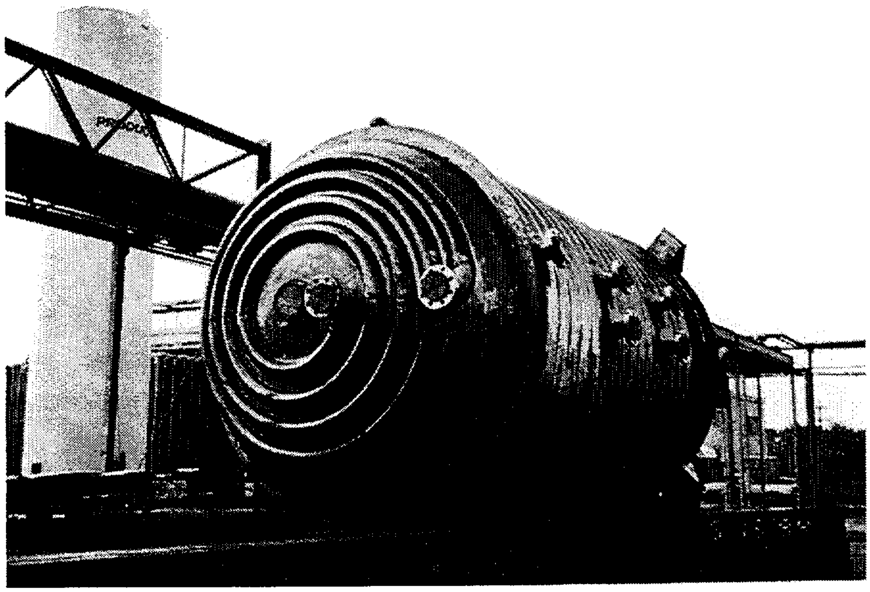

Figure 3: ASME Boiler & Pressure Vessel Constructed of Alloy 59
Producing Chlorinated and Fluorinated Chemicals

Paper
00635

CORROSION 2000

SOLVING CRITICAL CORROSION PROBLEMS IN MARINE ENVIRONMENTS BY AN ADVANCED NI-CR-MO ALLOY 59 UNSN06059

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ABSTRACT

Even though several stainless steels and a few nickel based alloys have shown promise and are used in marine environments, under very severe crevice corrosion conditions, most of these have suffered from localized crevice attack. The search for alloys that are essentially immune to crevice corrosion attack in marine environment led the industry to increase the alloy content of nickel based alloys primarily in chromium and molybdenum. One such alloy, alloy 59 (UNS N06059) having a typical chemical composition of 59% nickel, 23% chromium, 16% molybdenum and iron levels of less than 1%, appears to have fulfilled this need.

Extensive laboratory and field tests by various companies and corrosion laboratories in USA, U.K., Norway, France and the U.S. Navy have shown this alloy to be essentially immune to crevice corrosion attack. Based on the excellent crevice corrosion resistance of alloy 59, the U.S. Navy has selected this alloy for testing a prototype component in a butterfly valve and is conducting further tests for overlay welding application as a superior alternative to alloy 625 and C-276.

This paper presents a brief description of this alloy's development, its physical metallurgical characteristics and localized corrosion data from various test programs. Other companies are also evaluating this alloy for use in a weld overlay application on off-shore platforms.

Keywords: Marine corrosion, seawater corrosion, alloy 59, UNS N06059, crevice corrosion, localized corrosion, applications.

INTRODUCTION

Materials used in the marine industry, such as the U.S. Navy and offshore platforms, encounter numerous corrosion problems. The corrosion problems of primary concern are uniform corrosion, localized corrosion (pitting and crevice), stress corrosion cracking, galvanic corrosion, corrosion fatigue, and erosion corrosion. A large amount of corrosion data has been generated over the last few decades and is well publicized in the technical literature.[1-9] Even though the precise determination of all corrosion variables as related to site specific marine corrosion is not fully categorized, there is ample laboratory, field, and case history experience available to make cost effective and functionally reliable maintenance-free selection. Table 1 lists the various classes of materials, usually specified and used in seawater service, whereas Table 2 lists the nominal chemistry of some of these alloys. Coated carbon steel, along with most of the materials listed in Table 1 and Table 2, have been successfully used in marine applications although in certain very specific severe crevice corrosion conditions, the performance has not been totally satisfactory.

The following sections describe the general metallurgical characteristics, corrosion resistance, mechanical properties and results of marine testing programs conducted at or by various institutions on alloy 59 (UNS N06059) along with a few applications in media with very high chloride contents.

METALLURGICAL AND CORROSION CHARACTERISTICS OF ALLOY 59

Alloys of the Ni-Cr-Mo family, starting with alloy C, date back to the 1930's. Since then improvements in the melting technology and a better fundamental understanding of the role of various alloying elements have led to newer Ni-Cr-Mo alloys. Their typical chemical composition is given in Table 3. The physical metallurgy and corrosion resistance (uniform corrosion, localized corrosion, thermal stability) of Ni-Cr-Mo alloys are very well documented in the open literature, including many applications of alloy 59 in chloride containing environments.[10-12]

Alloy 59 is one of the highest nickel' containing alloy of the Ni-Cr-Mo family without any addition of other alloying elements such as tungsten, copper, or titanium and hence can be classified as the purest ternary form of a "Ni-Cr-Mo" alloy. It also has the highest PRE number (Table 3), which is responsible for its superior crevice corrosion resistance behavior as measured by ASTM G-48, 10% $FeCl_3$ test solution (Table 4). It is evident that a lower molybdenum level in alloy 625 and alloy 22 and hence the lower PRE number is responsible for the lower critical crevice corrosion temperature in comparison to alloy 59. It has been shown by Garner [13] that the ASTM G-48 ferric-chloride test does provide a conservative prediction of crevice corrosion behaviour in ambient sea-water for a wide range of alloys.

Absence of tungsten in alloy 59 is responsible for its excellent thermal stability, a point which becomes very important in overlay welding and multipass welding of thick sections. Alloy 59 was the only alloy without any localized or inter-granular attack as shown by the results in Figure 1 and Table 5. Clearly shown in Figure 1 is the extent of the severe pitting attack on the tungsten containing alloy 22. Alloy 59 was free of any localized attack. Other tungsten containing alloys like C-276 and 686 as well as the copper containing alloy C-2000 behaved similiarly to alloy 22..

CORROSION TESTS ON ALLOY 59 IN MARINE ENVIRONMENTS

I. Laque Center for Corrosoin Technology, Wrightsville Beach, N.C.

a) In 1990 a series of multiple crevice assembly (MCA) corrosion tests in filtered natural seawater at 30°C were conducted on alloy 59 for a period of 90 days. This alloy was totally resistant and no localized attack occurred.[14]

b) In 1992 another series of "joint alloy producer test program" was developed by Laque to study the crevice corrosion in natural seawater of various materials. The test was run in filtered natural seawater for 60 days. Alloy 59 was fully resistant in all the tests with various surface conditions. Even alloy C-276, another high alloy of the Ni-Cr-Mo family with 16% Mo, in one test (surface ground with 120 SiC) showed some crevice attack [15]

c) Another series of severe crevice corrosion testing on alloy 59 tubulars was done in 1993 for a 60 day period in fresh natural strained seawater. The ambient temperature of once through seawater ranged from 26.0°C to 31.3°C. The daily average temperature during the course of 60 day test was 28.6°C. Despite a constant flow rate of 2.4 m/s, accumulation of biofilm developed on tube ID walls, however, no hard shell fouling was observed during the 60 day test period. Tight crevice formers were prepared by cutting a 3 inch (76mm) long segment of vinyl tubing (tygon formulation 3903) and these vinyl sleeves covered approximately 25 mm of the alloy 59 tube. Serrated nylon hose clamps were used to tightly secure the vinyl sleeve to alloy tube assembly. Alloy 59 tubes were totally resistant in this severe crevice test in seawater.[16]

d) In 1998, a series of crevice corrosion tests were run at Laque Center for Corrosion Technology. These tests were sponsored by the U.S. Navy for evaluation of materials for use in a new generation of seawater valves for the U.S. Navy. The 180 days test results in filtered seawater at 85+/-5°F (29.5+/- 2.5°C) on both wrought and cast series of alloys (bronze, copper-nickel, nickel-copper, stainless steels, titanium alloys, nickel base Ni-Cr-Mo alloys and cobalt base alloys) were presented in a Corrosion/99 paper # 329. [17]

The basic conclusion of the results on Ni-Cr-Mo alloys from this study were:

- In wrought condition alloy 59, alloy 22, alloy 686 and alloy UNS N06200 exhibited full resistance in quiescent seawater.
- In flowing seawater – wrought alloy 59 had a minor superficial indication of less than 0.01 mm (0.0004") on two of the 4 exposed sites, whereas wrought alloy 22, UNS N06200 and alloy 686 were totally resistant.
- On cast alloy condition in quiescent seawater only cast 59 was fully resistant to localized corrosion. Cast 625, cast C-276 and cast 22 all showed significant crevice attack.
- On cast alloy condition in flowing seawater, again cast alloy 59 and cast C-276 were the only alloys fully resistant, whereas cast alloy 625 and cast 22 showed significant crevice attack.

Due to the best overall performance in both the wrought and cast condition of alloy 59 taken together, the U.S. Navy has initiated a project to test components in alloy 59 in a butterfly valve application, where severe corrosion conditions exist.

II. Corrosion Test Results at the Navy's , Key West Test Facilities:

Tygon tube test configuration producing a severe crevice test to determine localized corrosion resistance was conducted in a flow loop under two conditions:

a) Continuous chlorination of 0.15 ppm chlorine in natural seawater – test duration up to 1324 days, temperature of natural seawater varied between 21 to 30°C in the sumner and winter,

b) Seawater trough test – unchlorinated continuous refreshed natural seawater – circulating at three gallons/minute – test duration from 92 days to 1324 days.

In the Ni-Cr-Mo alloys the following alloys were tested:

Inco – alloy 686 and alloy 625 (referred as I-686 and I-625)
VDM – alloy 59, C-276, and 625 (referred as V-59, V-C276 and V-625)

The test data was presented by the U.S. Navy personnel at the 1996 Seahorse Institute Conference meeting in Wrightsville Beach, N.C. The major conclusions of this study of 1324 days (approximately 4 years) are presented below:

- Alloy V-C276 showed crevice / pitting attack up to 4 mil (0.1 mm) depth in the trough test (un-chlorinated seawater). In the flow loop test deep etch pitting was observed.
- Alloy V- 59 in the loop test showed some discoloration in two of the loops, etch is one loop and no attack or change in the other three loops after the 1324 days (approx. 4 years) exposure.
- In the trough test there was no indication on alloy V-59 after 876 and 1000 days when the test was stopped. Alloy V-625 showed some etch only in one loop, no damage in the other 5 loops and no damage in the trough test after 1324 and 876 days respectively.
- Alloy I-625 showed etching in three of the loop tests and no damage in other 4 loops, whereas in trough test alloy I-625 showed crevice attack after 180 days.
- Alloy I-686 showed deep etch in the loop test after 229 days.

This report should be available from the U.S. Navy, Key West Facilities, Key West, U.S.A.

III Corrosion Tests in the U.K.

John w. Oldfield[18] showed that over a two year crevice corrosion exposure tests conducted at UK's Defense Research Agency on contract to Cortest in Holten Heath, Poole, U.K. , alloy 59 gave the best performance.

In the 20-25°C range, the predicted alloys ranking order from best to worst was: Alloy 59 > Alloy 22 > Alloy 654SMo > Alloy 625 > Alloy 24. At 50°C the ranking from best to worst changed to: Alloy 59 > Alloy 22 > Alloy 24 > Alloy 625 > Alloy 654SMo. The obtained data from exposure tests, although difficult to generate, did confirm the ranking in resistance to initiation of crevice attack i.e. alloy 59, alloy 22, and 654SMo performed the best (however, a small pit was observed at the crevice edge of both alloy 22 and alloy 654SMo) followed by alloy 24, then alloy 625, with alloy C-276 showing the greatest number of attack initiation sites in the PVC/metal crevice geometry in both natural seawater and chlorinated seawater. Overall alloy 59 gave the best performance, both as predicted per the model and verified by exposure tests.

Agreement with the model predictions of resistance to initiation of attack at ambient temperature showed general agreement in the relative performance of alloy 59, 22 and 654SMo, but agreement was <u>not shown</u> with the results of alloy C-276, which is predicted to be better than alloy 625 due to its significantly higher molybdenum content and higher PRE number. According to the U.S. Navy extensive data base, and other results in the literature, alloy C-276 has outperformed alloy 625 in numerous exposure tests in marine/seawater environments, in agreement with the model's prediction. This discrepancy in this exposure could be explained by the surface roughness of the sample. Finer the roughness of the sample, greater is the severity for crevice corrosion attack. In these tests, the finer surface roughness values on alloy C-276 samples ($R_A \approx 0.47$ microns) in comparison to alloy 625 ($R_A \approx 1.90$ microns), created a much more severe crevice condition on alloy C-276, thus the more severe attack in comparison to alloy 625.

IV Corrosion Tests at SINTEFF Material Technology, Trondheim, Norway

A series of corrosion tests were done on weld overlays of nickel based alloys to determine the localized corrosion behavior. Three types of tests were done:

1) Pitting corrosion test per ASTM G48A
2) Crevice corrosion test per Material Technology Institute. MTI manuel No. 3 procedure MTI-2.
3) Crevice test per SINTEFF's test method.
4)

Various nickel based alloys (alloy 625, 59, C-276, C-4, 22) were overlayed using three welding methods, i.e. GTAW, SMAW, and PTA (Plasma Transferred Arc). The substrate used in all cases was a 6 Mo alloy.

The conclusion from this study was that alloy 59 weld overlay was the best amongst all alloys tested and for all welding processes employed. Details on the test procedures & results obtained were previously presented at Corrosion/98 [7].

V Crevice Corrosion Tests at Cherbourg Naval, France

Various tests were conducted, which involved potentiostatic tests at 300MV vs. SCE, crevice corrosion test assemblies, potentio-dynamic tests, both on cathode and crevice test assemblies testing in natural seawater. One of the conclusions of this study was that alloy 59 was superior to alloy 625 in the various tests conducted.

The other major conclusion of this study was that even though initiation of crevice corrosion under certain conditions can occur on even 16% Mo alloys like alloy 59 and C-276 , the propagation rate is significantly lower than alloy 625. Similar conclusions have also been reached by other researchers and reported elsewhere[22].The details on the various tests were published in Euro Corr'99 Proceedings [23].

VI Corrosion Testing in Natural Seawater with $CO_2 + H_2S$ Addition

Some oil companies were interested in getting corrosion data on various materials on comingled seawater (aerobic and anaerobic) with produced water. Mixing produced water with chlorinated seawater increases the injection teperature and due to chemical reaction with organic material in the produced water, generally all chlorine is removed. Additionally,

H_2S in produced water is oxidized to sulfur in contact with aerobic seawater, potentially intorducing an additional corrodent, which increases the corrosiveness of the media.

Tests in elevated temperature in natural seawater were conducted for a period of 134 days with addition of CO_2 in one test and CO_2 plus H_2S in another test.

The particulars of testing parameters were as follows:

Seawater with CO_2 added
Duration 134 days
Temperature 70-80°C
CO_2 addition pH 4.92 to 5.2
Flow rate - 3m/s
Oxygen 2.6 ppmw

Seawater with CO_2 + H_2S added
Duration 120 days with H_2S, 134 days with CO_2
Temperature 69-75°C
Addition of CO_2 resulted in a pH of 5.0 and H_2S was added to give a residual value of 50 ppmw
Flow rate – approx. 3 m/s
Oxygen – None

No corrosion was observed on alloy 59 tube samples in the flow loops. It was concluded that alloy 59 is totally suitable for marine environment in the presence of H_2S and CO_2.. The details of this test are provided in a private communication with CAPCIS, U.K.

DISCUSSION

Crevice corrosion in marine environments is of significant interest to the U.S. Navy and companies operating off-shore platforms because it has long been recognized as a limiting factor for use of stainless steels. Many researchers such as Lennox and Peterson[19] have concluded the statistical nature of crevice corrosion in higher alloys, i.e. the materials' response to crevice corrosion is unpredictable; it may or may not occur. Extremely small differences in the crevice geometry and/or surface conditions of the materials in a given environment can either lead to crevice corrosion or have immunity to crevice corrosion. The statistical nature of crevice corrosion behavior has also been discussed and argued by the other researchers[20-22] as well some recent data from tests using deeper and tighter crevices has revealed some susceptibility to crevice corrosion initiation for alloys even containing 16% Mo with a high pitting resistance equivalent number of 69 such as alloy C-276. But the research has also shown the very high resistance of the 16% Mo Ni-Cr-Mo alloys to crevice corrosion propagation.

Hence, looking at all the test data on corrosion resistance of Ni-Cr-Mo alloys as presented in this paper and by various other researchers[3,7,8,10-12,14-18], it can be safely concluded that amongst the various alloys of the Ni-Cr-Mo family such as alloy 625, C-276, 22 and alloy 59, the only alloy, which most closely provides total immunity to crevices corrosion in seawater, is alloy 59 (UNS N06059). This alloy is covered in the U.S. in the various specifications such as ASTM, ASME, AWS and NACE (MRO-175, others) and various international specifications.

CONCLUSIONS

- Alloy 59 (UNS N06059) having a typical chemical composition of Ni 59, Cr 23, Mo 16 and Fe <1, is the purest ternary alloy of the Ni-Cr-Mo family.

- It has the highest Pitting Resistance Equivalent number of 76, which accounts for its superior localized corrosion resistance in seawater and other chloride bearing environments.

- The lower iron content, high PRE number and absence of tungsten or copper, makes alloy 59 more thermally stable than alloys like C-276, 22, 686 and UNS N06200. This is critical for overlay welding and multipass welding of thick sections.

- Data generated on localized corrosion behavior at the various test facilities clearly show alloy 59 to be superior to other Ni-Cr-Mo alloys.

- The Navy is evaluating this alloy for butterfly valve components and weld overlay applications due to its excellent thermal stability, a critical point in overlay welding applications and its superior localized corrosion resistance properties.

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Table 1
Various Classes of Materials for Marine Application

Non-Metalllic	Typical Material
• Fire glass reinforced plastic	FRP
• Carbon steel coated with	Epoxy resin/rubber
• Carbon steel coated with	Concrete/cement
Metallic	
• Carbon steel	
• Carbon steel coated with	Zinc
• Copper base alloy	90/10 CuNi, 70/30 CuNi
• Ferritic SS	29-4, 29-4-2
• Ferritic austenitic SS (Duplex)	Alloy 2205, 2506
• Standard austenitic SS	316, 317LMN
• 6Mo super-austenitic SS	Alloy 1925hMo, Alloy 31
• Nickel alloys	Alloy 400, K-500, 825
• Ni-Cr-Mo high performance alloys	Alloy 625, 22, C-276, 59

Table 2
Nominal Composition of Some Marine Alloys

	Nominal Composition				
Alloy/Structure	Cr	Ni	Mo	Fe	Others
Ferritic					
29-4-2	29	2	4	Bal	-
29-4	29	-	4	Bal	-
Austenitic					
904L	20	25	4.5	Bal	Cu
825	22	40	3.2	31	Cu
Ferritic-austenitic (Duplex)					
25Cr	25	6	3	Bal	Cu 1.7
6Mo Superaustenitic					
1925hMo	21	25	6,5	Bal	Cu 0.9, N 0.2
31	27	31	6.5	Bal	Cu 1.2, N 0.2
Copper Alloys					
90/10	-	10	-	1.5	Cu Bal
70/30	-	30	-	0.1	Cu Bal
Nickel Alloys					
400	-	66	-	1	Cu Bal
K-500	-	66	-	1	Al 2.7, Cu Bal
Ni-Cr-Mo Alloys					
625	21	61	9	3	Cb 3.5
C-276	16	58	16	5	W 4
22	21	57	13	3	W 3
59	23	59	16	<1	Al 0.3

Table 3.
Typical Chemical Composition of the "C" Family Alloys

Alloy (UNS #) / Decade Introduced	Ni	Cr	Mo	W	Fe	PRE*
C (N10002) / 1930's Bal	Bal	16	16	4	6	69
625 (N06625) / Late 1950's	62	22	9	-	3	51
C-276 (N10276) / 1960's	Bal	16	16	4	5	69
C-4 (N06455) / 1970's	Bal	16	16	-	2	69
22 (N06022) / Mid 1980's	Bal	21	13	3	3	65
59 (N06059) / Early 1990's	Bal	23	16	-	<1	76

* PRE = Pitting Resistance Equivalent = % Cr + 3.3 (% Mo) + 30 N

Table 4

Localized Corrosion Resistance in 10% $FeCl_3$ Solution (ASTM G-48)

Alloy	Cr	Mo	PRE *	CPT(°C)	CCT (°C)
625	22	9	51	77.5	57.5
22	21	13	65	>85 *	58
C-276	16	16	69	>85	>85
59	23	16	76	>85	>85

* Above 85°C, the 10% $FeCl_3$ solution chemically breaks down

Table 5

Thermal Stability per ASTM G-28A and G-28B after Sensitization for 1 hr at 1600°F (871°C)

Corrosion Rate (mpy)

Media	C-276*	22*	686*	N06200*	59**
ASTM G-28A	>500*	>500*	872*	116*	40**
ASTM G-28B	>500*	339*	17*	>500*	4**
Pitting Attack	Severe	Severe	Severe	Severe	None
Intergranular Attack	Severe	Severe	Severe	Severe	None

* Alloy C-276, 22, N06200 and 686 – Heavy pitting with grains falling due to deep intergranular attack.
** Alloy 59 No Attack

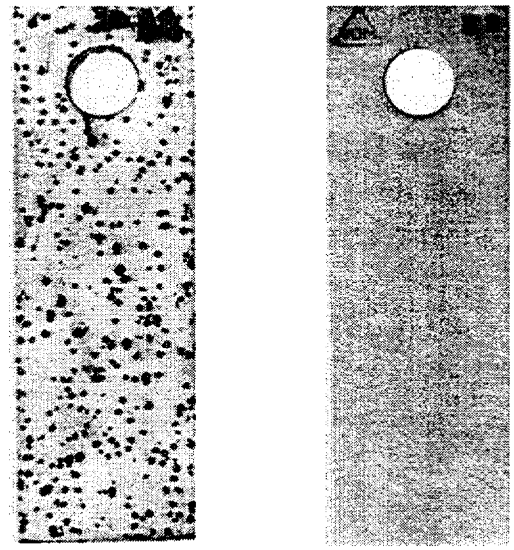

Figure 1 : Influence of Thermal Stability on Corrosion of Alloy 22 and Alloy 59
After Aging at 1600°F and Tested in ASTM G-28B Test Solution

CHAIRMAN REC'D

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KRUPP VDM

Nicrofer® 5923 hMo – alloy 59

Material Data Sheet No. 4030
Edition December 1996

Nicrofer 5923 hMo is a nickel-chromium-molybdenum alloy with an extra-low carbon and silicon content. The alloy was developed by Krupp VDM and has excellent corrosion resistance and high mechanical strength.

Nicrofer 5923 hMo is characterised by:

- outstanding resistance to a wide range of corrosive media under oxidising and reducing conditions
- excellent resistance to pitting and crevice corrosion and freedom from chloride-induced stress-corrosion cracking
- excellent resistance to mineral acids, such as nitric, phosphoric, sulphuric and hydrochloric acids and in particular to sulphuric and hydrochloric acid mixtures
- excellent resistance to contaminated mineral acids
- good workability and weldability without susceptibility to post-weld cracking
- authorisation for pressure-vessel use at wall temperatures of −196 to 450 °C (−320 to 840 °F)

Desigantion and standards

Country / National standards	Material designation	Specification: Chemical composition	Tube and pipe: seamless	Tube and pipe: welded	Sheet and plate	Rod and bar	Strip	Wire	Forgings
F AFNOR									
D	**W.-Nr. 2.4605** NiCr23Mo16Al								
VdTÜV		505			505				
UK BS									
USA	UNS N06059								
ASTM			B 622	B 619/626	B 575	B 574	B 575		B 564
ASME			SB 622	SB 619/626	SB 575	SB 574	SB 575		SB 564
ASME Code Case	SC III		N-625 → ~~2134~~	~~2134~~	~~2134~~	~~2134~~	~~2134~~		2134
ISO									

Table 1 – Designation and standards

Chemical composition

	Ni	Cr	Fe	C	Mn	Si	Mo	Co	Al	P	S
min	bal	22.0					15.0		0.1		
max		24.0	1.5	0.010	0.5	0.10	16.5	0.3	0.4	0.015	0.005

Table 2 – Chemical composition (%)

KRUPP

Nicrofer® 5923 hMo – alloy 59

Physical properties

Density	8.6 g/cm³	0.311 lb/in³
Melting range	1310–1360 °C	2390–2480 °F
Permeability at 20 °C/68 °F (RT)	≤ 1.001	

Temperature T		Specific heat		Thermal conductivity		Electrical resistivity		Modulus of elasticity		Coefficient of thermal expansion between room temperature and T	
°C	°F	J/kg K	Btu / lb °F	W/mK	Btu in / ft² h °F	μ Ω cm	Ω circ mil / ft	kN/mm²	10³ ksi	10⁻⁶/K	10⁻⁶ / °F
20	**68**	414	0.099	10.4	72	126	758	210	30.5		
93	**200**		0.101		83		766		30.0		6.6
100	212	425		12.1		127		207		11.9	
200	392	434		13.7		129		200		12.2	
204	**400**		0.104		96		776		29.0		6.8
300	572	443		15.4		131		196		12.5	
316	**600**		0.106		105		788		28.3		7.0
400	752	451		17.0		133		190		12.7	
427	**800**		0.108		119		800		27.4		7.1
500	932	459		18.6		134		185		12.9	
538	**1000**		0.110		132		806		26.4		7.2
600	1112	464		20.4		133		178		13.1	

*Table 3 – **Typical** physical properties at room and elevated temperatures.*

Mechanical properties

The following properties are applicable to Nicrofer 5923 hMo in solution-treated condition and the indicated size ranges. Specified properties of material outside these size ranges are subject to special enquiry.

Form		Dimensions mm	inches	0.2 % Yield strength N/mm²	ksi	1.0 % Yield strength N/mm²	ksi	Tensile strength N/mm²	ksi	Elongation A5 %
Sheet, strip [1]	cr	0.5– 6.4	0.018–0.25	340	49	380	55	690	100	40
Plate [1]	hr	5.0–30	3/16–13/16							
Rod		≤ 100	≤ 4							
Tube (wall)		0.5– 5	0.02 –0.20							

[1] Mechanical values according to VdTÜV data sheet 505

Table 4 – Minimum mechanical properties at room temperature.

Nicrofer® 5923 hMo – alloy 59

Temperature T °C	°F	0.2% Yield strength 1) N/mm²	ksi	1.0% Yield strength 1) N/mm²	ksi	Tensile strength 2) ( ) N/mm²	ksi	Elongation A5 %
93	200		≥ 43		≥ 48		95 (91)	
100	212	≥ 290		≥ 330		650 (620)		
200	392	≥ 250		≥ 290		615 (585)		
204	400		≥ 36		≥ 42		89 (85)	
300	572	≥ 220		≥ 260		580 (550)		50
316	600		≥ 31		≥ 37		84 (80)	
400	752	≥ 190		≥ 230		545 (515)		
427	800		≥ 26		≥ 32		77 (74)	
450	842	≥ 175		≥ 215		525 (495)		

1) For plates above 30 mm and up to 50 mm ($1^3/_{16}$ to 2 in) thickness the values of yield strengths should be reduced by 20 N/mm² (3 ksi).
2) Values for rods only ( ).

Table 5 – Mechanical properties at elevated temperatures according to VdTÜV data sheet 505 (thickness up to 30 mm/$1^3/_{16}$ in).

Material temperatures °C	°F	Forgings, rod, sheet/plate/strip, seamless tube and pipe N/mm²	ksi
38	100		25.0
93	200		25.0
100	212	172	
149	300		24.7
200	392	161	
204	400		23.3
260	500		22.0
300	572	147	
316	600		20.9
343	650		20.4
371	700		19.8
399	750		19.4
400	752	134	

For welded tube and pipe a factor 0.85 should be applied

Table 6 – Maximum allowable stress values according to code case 2134.

ISO V-notch

Average values at RT: ≥ 225 J/cm²
at –196 °C (–320 °F): ≥ 200 J/cm²

Nicrofer® 5923 hMo – alloy 59

Comparison of **typical** mechanical short-time properties of Nicrofer 5923 hMo (UNS N 06059) ▬▬▬ with similar alloys such as:

alloy 22 (UNS N 06022) ●●●●●●●●

alloy C-276 (UNS N 10276) ▬ ▬ ▬ ▬ ▬

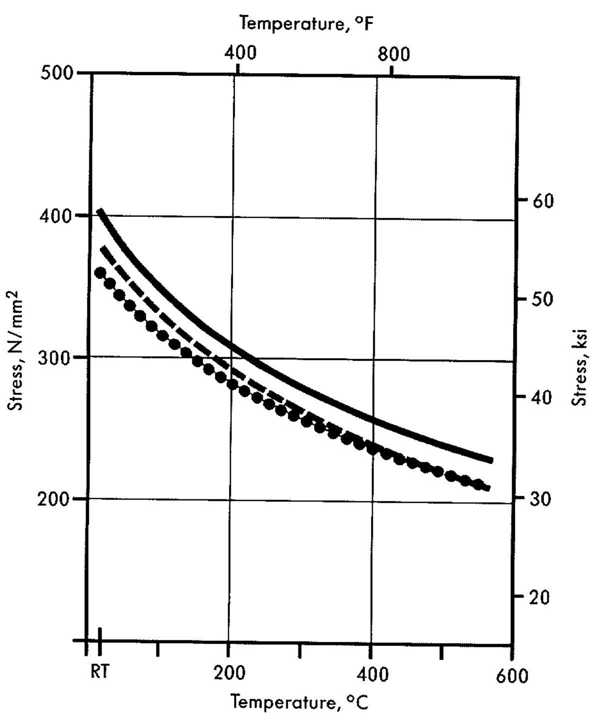

*Fig. 1 – **Typical** short-time 0.2 % yield strengths at both ambient and elevated temperatures.*

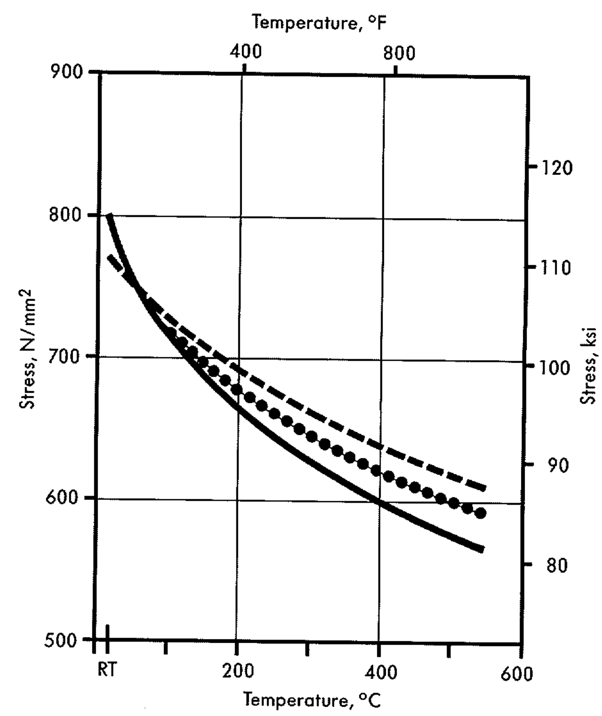

*Fig. 2 – **Typical** short-time tensile strengths at both ambient and elevated temperatures.*

Metallurgical structure

Nicrofer 5923 hMo has a face-centred cubic structure.

Corrosion resistance

The nickel-chromium-molybdenum alloy Nicrofer 5923 hMo with extremely low silicon and carbon content is not prone to grain-boundary precipitation during hot forming and welding. The alloy is therefore suitable for many chemical process applications in both oxidising and reducing media.

Because of its high nickel, chromium and molybdenum contents, the alloy is resistant to attack by chloride ions. Nicrofer 5923 hMo is also one of the few materials that resist wet chlorine gas, hypochlorite and chlorine dioxide solutions as encountered in pulp and paper processing.

The alloy exhibits exceptional resistance to strong solutions of oxidising salts, such as ferric and cupric chlorides. Nicrofer 5923 hMo is also particularly suitable in applications involving hot contaminated mineral acids, solvents and organic acids, such as formic and acetic acid.

Optimum corrosion resistance can be obtained only if the material is in the correct metallurgical condition and clean.

Nicrofer® 5923 hMo – alloy 59

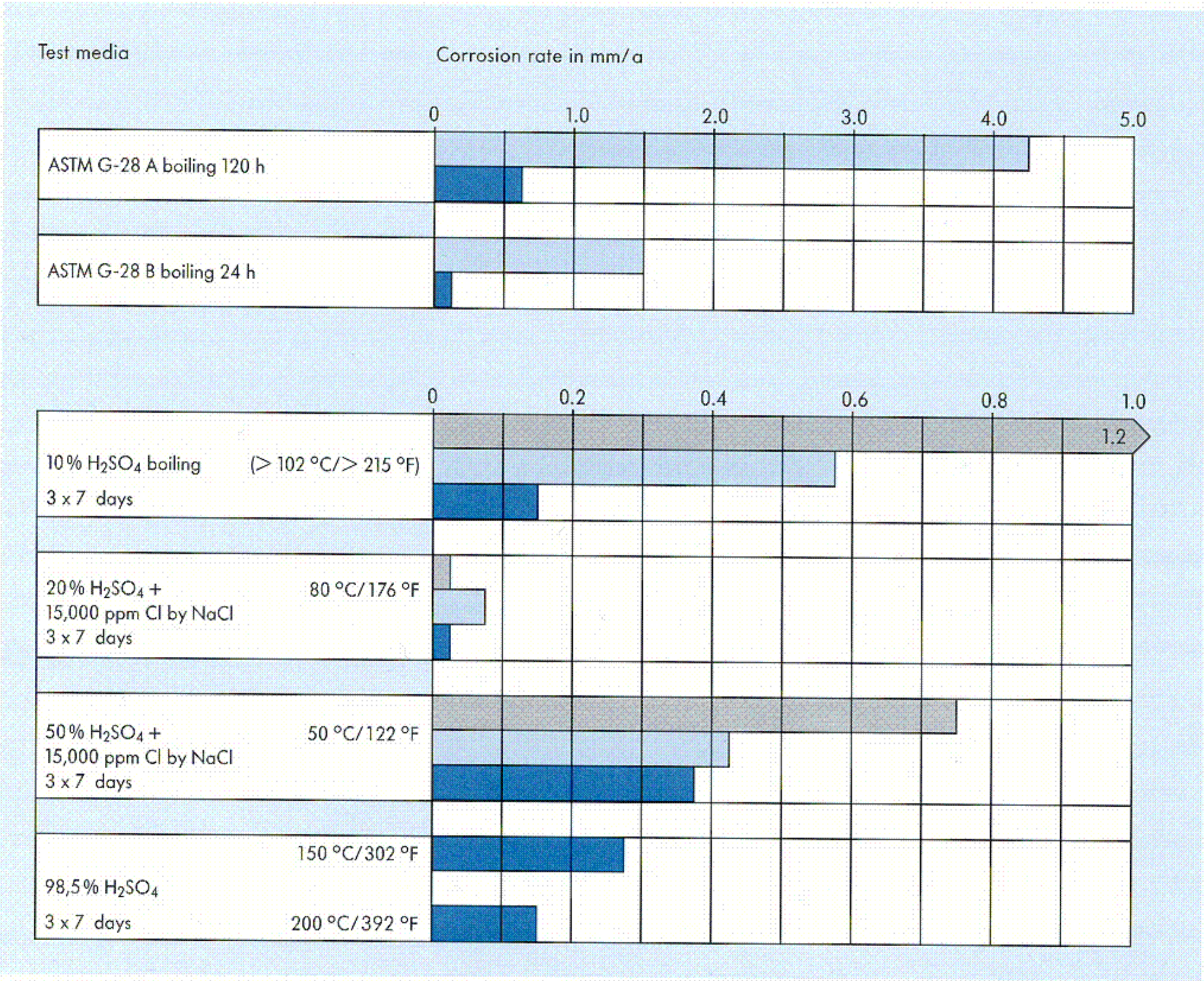

Fig. 3 – Comparison of corrosion rates in a variety of environments: alloy 625 ▭, alloy C-276 ▭ with Nicrofer 5923 hMo – alloy 59 ▬.

Alloy	CPT	CCT
Nicrofer 5923 hMo – alloy 59	> 120 °C/> 248 °F	110 °C/230 °F
alloy C-276	115–120 °C/239–248 °F	105 °C/221 °F
alloy 625	100 °C/212 °F	85 – 95 °C/185–203 °F

Table 7 – Critical pitting temperature (CPT) and crevice corrosion temperature (CCT) in a solution containing: 7 % H_2SO_4 + 3 % HCl + 1 % $CuCl_2$ + 1 % $FeCl_3 \times 6 H_2O$ (Green Death), after ageing for 24 hours per 5 °C (9 °F) increase in temperature.

C01

Nicrofer® 5923 hMo – alloy 59

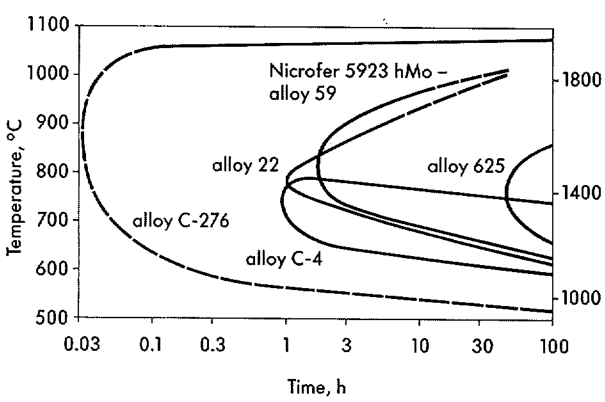

Fig. 4 – Time-temperature-sensitisation-diagrams of the nickel chromium-molybdenum alloys when tested according to ASTM G-28 A.

Applications

Nicrofer 5923 hMo has a wide range of applications in chemicals, petrochemicals, energy production and pollution control.

Typical applications are:

- components in organic processes involving chlorides, particularly when acid chloride catalysts are employed
- digesters and bleaching plants in the pulp and paper industry
- scrubbers, reheaters, dampers, wet fans and agitators for incinerator gas and flue gas desulphurisation (FGD)
- equipment and components in sour gas service
- reactors for acetic acid and acetic anhydride
- sulphuric acid coolers

Fabrication and heat treatment

Nicrofer 5923 hMo is readily fabricated by established industrial working techniques.

Heating

It is very important that the workpiece be clean and free from any contaminant before and during heating.

Nicrofer 5923 hMo may become embrittled if heated in the presence of contaminants such as sulphur, phosphorus, lead and other low-melting-point metals. Sources of contamination include marking and temperature-indicating paints and crayons, lubricating grease and fluids, and fuels. Fuels must be low in sulphur; e.g. natural and liquefied petroleum gases should contain less than 0.1 % by mass and town gas 0.25 g/m³ maximum of sulphur. Fuel oils containing no more than 0.5 % by mass of sulphur are satisfactory.

The furnace atmosphere should be neutral to slightly reducing.

Hot working

Nicrofer 5923 hMo may be hot worked in the range 1180 to 950 °C (2150 to 1740 °F). Cooling should be by water quenching.

Annealing is recommended after hot working to ensure maximum corrosion resistance.

Cold working

Cold working should be carried out on annealed material. Nicrofer 5923 hMo has a much higher work-hardening rate than austenitic stainless steel and the forming equipment must be adapted accordingly.

When cold working is performed, interstage annealing may become necessary, depending on the corrosiveness of the intended application. Consult Krupp VDM for further advice.

Heat treatment

Solution heat treatment should be carried out in the temperature range 1100 to 1180 °C (2010 to 2160 °F), preferably at about 1120 °C (2050 °F).
Water quenching is essential for maximum corrosion resistance.

During any heating operation the precautions outlined earlier regarding cleanliness must be observed.

Nicrofer® 5923 hMo – alloy 59

Descaling
Oxides of Nicrofer 5923 hMo and discoloration adjacent to welds are more adherent than on stainless steels. Grinding with very fine abrasive belts or discs is recommended.

Before pickling in a nitric/hydrofluoric acid mixture, oxides must be broken up by grit-blasting, fine grinding or by pretreatment in a fused salt bath.

Machining
Nicrofer 5923 hMo should be machined in solution-treated condition. The alloy's high work-hardening rate should be considered, i.e. only low surface cutting speeds are possible compared with low-alloyed standard austenitic stainless steel. Tools should be engaged at all times. Heavy feeds are important in getting below the work-hardened 'skin'.

Advice on welding
When welding nickel alloys and high-alloyed special stainless steels, the following instructions should be followed:

Workplace
The workplace should be in a separate location, well away from the areas where carbon steel is worked. Maximum cleanliness, partitions, and avoidance of draughts are required.

Auxiliaries, clothing
Clean fine leather gloves and clean working clothes should be used.

Tools and machinery
The tools should be used only for nickel, nickel alloys and high-alloyed special stainless steels. Brushes, tongs and hammers should be made of rustproof materials. Fabricating and working machinery such as shears, presses or rollers should be equipped with means (felt, cardboard, plastic sheet) of keeping out any ferrous particles which can be pressed into the surface of the material and ultimately lead to corrosion.

Cleaning
Cleaning of the base metal in the weld area (both sides) and of the filler metal (e.g. welding rod) should be carried out with ACETONE.

No trichloroethylene "TRI", no perchloroethylene "PER", no carbon tetrachloride "TETRA".

Edge preparation
Preferably by mechanical means, i.e. turning, milling or planing; plasma cutting is also possible. However, in the latter case the cut edge (the face to be welded) must be clearly finished. Careful grinding without overheating is permissible.

Included angle
The different physical behaviour of nickel alloys and special stainless steels compared with carbon steel generally manifests itself in a lower thermal conductivity and a higher rate of thermal expansion. This should be allowed for by means of, among other things, wider root gaps or openings (2 mm $\pm$ 0.5), while larger included angles (> 70°) should be used for the individual butt joints owing to the viscous nature of the molten metal, in order to counteract the pronounced shrinkage tendency.

Striking the arc
The arc should only be struck in the weld area, e.g. on the faces to be welded, not on the surface of the weldment. Striking marks lead to corrosion.

Postweld treatment (pickling and brushing)
Pickling, if required or prescribed, is generally the last operation performed on the weldment. In such a case, the work should be carried out by specialized firms. Consultation with our specialists is strongly recommended. If the workmanship is of the highest quality, brushing immediately after welding, i.e. while the metal is still hot, can often produce the desired surface condition, i.e. heat tints can be completely removed.

Nicrofer® 5923 hMo – alloy 59

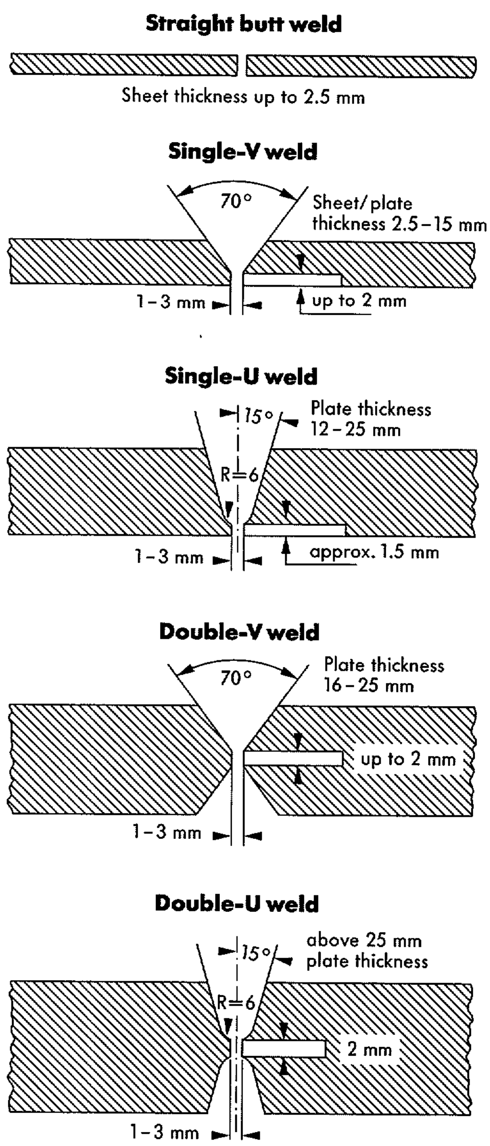

Figure 5 – Edge preparation for welding of nickel, nickel alloys and special stainless steels.

Welding process
Nicrofer 5923 hMo can be welded by all the conventional processes: TIG/GTAW, hot wire TIG/GTAW, plasma arc, manual metal arc and MIG/MAG. Prior to welding, the material should be in solution-treated condition and be free from scale, grease and markings.

Filler metal
The welding filler metal normally used is:

Joint welding
Nicrofer S 5923 – FM 59
W.-Nr. 2.4607
SG-NiCr23Mo16
AWS A5.14 ERNiCrMo-13

Coated stick electrode
W.-Nr. 2.4609
EL-NiCr22Mo16
AWS A5.11 ENiCrMo-13

Overlay welding
Nicrofer S/B 5923
W.-Nr. 2.4607
UP-NiCr23Mo16

Welding parameters and influences (heat input)
Care should be taken to ensure that the work is performed with a deliberately chosen, low heat input, i.e. that an inter-pass temperature of 150 °C is not exceeded and that use of the stringer bead technique is aimed at, regardless of the welding process to be used. Attention is also drawn in this connection to correct selection of the wire and stick electrode diameters (consultation with our Welding Laboratory is advisable).

These instructions result in the energy inputs per unit length shown in Table 9 by way of example. The welding parameters should be monitored as a matter of principle.

Nicrofer® 5923 hMo – alloy 59

Sheet/ plate thick- ness	Welding process	Filler metal Diameter	Speed	Welding parameters Root pass		Intermediate and final passes		Welding speed	Flux/ shielding gas rate	Plasma- gas/rate	Plasma- nozzle diameter
mm		mm	m/min	A	V	A	V	cm/min	l/min	l/min	mm
3.0	Manual GTAW	2.0		90	10	110–120	11	10–15	Ar W3[1] 8–10		
6.0	Manual GTAW	2.0–2.4		100–110	10	120–130	12	10–15	Ar W3[1] 8–10		
8.0	Manual GTAW	2.4		110–120	11	130–140	12	10–15	Ar W3[1] 8–10		
10.0	Manual GTAW	2.4		110–120	11	130–140	12	10–15	Ar W3[1] 8–10		
3.0	Autom. GTAW	1.2	0.5	manual		150	10	25	Ar W3[1] 15–20		
5.0	Autom. GTAW	1.2	0.5	manual		150	10	25	Ar W3[1] 15–20		
4.0	Plasma arc	1.2	0.5	165	25			25	Ar W3[1] 30	Ar W3[1] 3.0	3.2
6.0	Plasma arc	1.2	0.5	190–200	25			25	Ar W3[1] 30	Ar W3[1] 3.5	3.2
8.0	MIG/ MAG[2]	1.0	approx. 8	GTAW		130–140	23–27	24–30	Ar W3[1] 18–20		
10.0	MIG/- MAG[2]	1.2	approx. 5	GTAW		130–150	23–27	20–26	Ar W3[1] 18–20		
12.0	Submerged arc	1.6		and backing GTAW		240–280	28	45–55	highly basic	consult filler metal manufacturer	
20.0	Submerged arc	1.6		and backing GTAW		240–280	28	45–55	highly basic		
6.0	SMAW	2.5		40–70	approx. 21	40-70	approx. 21				
8.0	SMAW	2.5–3.25		40–70	approx. 21	70-100	approx. 22				
16.0	SMAW	4.0				90-130	approx. 22				

1) Argon or Argon + 3% hydrogen
2) MAG welding is to be carried out using the shielding gas Cronigon He30S. We recommend that you consult our welding laboratory.
In all gas-shielded welding operations, ensure adequate back shielding.
These figures are only a guide and are intended to facilitate setting of the welding machines.

Table 8 – Welding parameters (guide values)

Welding process	Energy inputs per unit length KJ/cm	Welding process	Energy inputs per unit length KJ/cm
GTAW, manual, fully mechanised	max 8	Manual metal arc (SMAW)	max 7
Hot wire TIG/GTAW	max 6	Submerged arc	max 10
MIG/MAG, manual, fully mechanised	max 11	Plasma arc	max 10

Table 9 – Energy inputs per unit length (guide values)

Nicrofer® 5923 hMo – alloy 59

Availability
Nicrofer 5923 hMo is available in all standard mill product forms.

Sheet and plate
(for cut-to-length availability, refer to strip)

Conditions:
hot or cold rolled (hr, cr),
solution treated
and pickled

Thickness mm			Width* mm	Length* mm
1.30	< 1.50	cr	2000	6000
≥ 1.50	< 6.0	cr	2400	8000
≥ 6.0	< 10.0	cr	2400	8000
≥ 6.0	< 10.0	hr	2400	8000
≥ 10.0	< 20.0	hr	2400	5000**
≥ 20.0*		hr		

inches			inches	inches
0.050	< 0.060	cr	80	240
≥ 0.060	< 1/4	cr	96	320
≥ 1/4	< 3/8	cr	96	320
≥ 1/4	< 3/8	hr	96	320
≥ 3/8	< 3/4	hr	96	200**
≥ 3/4*		hr		

* other sizes subject to special enquiry
** depending on piece weight

Forgings
Shapes other than discs, rings, rod and bar are subject to special enquiry.

Discs and rings
Conditions:
hot rolled or forged,
solution treated,
descaled or machined

Product	Weight kg	Thickness mm	O D* mm	I D* mm
Disc	≤ 4000	≤ 200	≤ 2000	–
Ring	≤ 3000	≤ 200	≤ 2500	on request

	lb	inches	inches	inches
Disc	≤ 8800	≤ 8	≤ 80	–
Ring	≤ 6600	≤ 8	≤ 100	on request

* other sizes subject to special enquiry

Rod and bar
Conditions:
forged, rolled, drawn,
solution treated,
pickled, machined, peeled or ground

Product		forged* mm	rolled* mm	drawn* mm
round	d	≤ 300	15– 75	12–65
square	a	40–300	15–100	12–65
flat a x b		40– 80 x 200–600	5– 20 x 120–600	10–20 x 30–80
hexagon	s	40– 80	13– 50	12–60

		inches	inches	inches
round	d	≤ 12	5/8– 3	1/2–2 1/2
square	a	1 5/8–12	5/8– 4	1/2–2 1/2
flat a x b		1 5/8– 3 1/8 x 8 –24	3/16– 3/4 x 5 –24	3/8– 3/4 x 1 1/4–3 1/8
hexagon	s	1 5/8–12	1/2– 2	1/2–2 3/8

* other sizes subject to special enquiry

Nicrofer® 5923 hMo – alloy 59

Strip*
Conditions:
cold rolled,
annealed and pickled
or bright annealed**

Thickness mm		Width mm	Coil I D mm			
0.04	≤ 0.10	4 – 200	300	400		
> 0.10	≤ 0.20	4 – 350	300	400	500	
> 0.20	≤ 0.25	4 – 750		400	500	600
> 0.25	≤ 0.60	5 – 750		400	500	600
> 0.60	≤ 1.0	8 – 750		400	500	600
> 1.0	≤ 2.0	15 – 750		400	500	600
> 2.0	- 3.0	25 – 750		400	500	600

inches		inches	inches			
0.0016	≤ 0.004	0.16 – 8	12	16		
> 0.004	≤ 0.008	0.16 – 14	12	16	20	
> 0.008	≤ 0.010	0.16 – 30		16	20	24
> 0.010	≤ 0.024	0.20 – 30		16	20	24
> 0.024	≤ 0.04	0.32 – 30		16	20	24
> 0.04	≤ 0.08	0.60 – 30		16	20	24
> 0.08	- 0.12	1.0 – 30		16	20	24

* cut-to length available in lengths from 500 to 3000 mm (20 to 120 in)
** maximum thickness 3.0 mm (1/8 in)

Wire
Conditions:
bright drawn, 1/4 hard to hard
bright annealed

Dimensions:
0.01 – 12.7 mm (0.0004 – 1/2 in) diameter
in coils, pay-off packs, on spools and spiders

Welding filler metals
Suitable welding rods, wire, strip and wire electrodes and electrode core wire are available in standard sizes.

Seamless tube and pipe
Production of seamless tubes and pipes is carried out at DMV Stainless BV using raw materials supplied by Krupp VDM.

Seam-welded tube and pipe
Seam-welded tubes and pipes are obtainable from renewed manufacturers and are produced from raw materials supplied by Krupp VDM.

Technical publications
The following publications concerning Nicrofer 5923 hMo – alloy 59 may be obtained from Krupp VDM GmbH:

M. Jasner, W. Herda, M. Rockel
"Crevice corrosion behaviour of high-alloyed austenitic steels and nickel-base alloys in seawater, determined under various test conditions"
Applications of Stainless Steel 92, Lohf. Proc., Stockholm, pp. 446 – 457 (1992)

D. C. Agarwal, U. Heubner, R. Kirchheiner, M. Köhler
"Cost-effective solutions to CPI-corrosion problems with a new Ni-Cr-Mo alloy"
Corrosion '91, Paper No. 179, Cincinnati, Ohio, March 11 – 15, 1991

R. Kirchheiner, M. Köhler, U. Heubner
"A new highly corrosion-resistant material for the chemical process industry, flue gas desulfurization and related applications"
Corrosion '90, Paper No. 90, Las Vegas, Nevada, April 23 – 27, 1990

VDM Report No. 17
"Wallpaper installation guidelines and other fabrication procedures for FGD maintenance, repair and new construction with VDM high-performance nickel alloys" – June 1991

VDM Report No. 18
"Corrosion-resistant materials for Flue Gas Desulphurisation systems" – February 1993

VDM Report No. 22
"Behaviour of some metallic materials in sulphuric acid" – August 1994

VDM Report No. 23
"Alloying effects and innovations in nickel base alloys for combating aqueous corrosion" – February 1996

VDM Case History No. 1
"The lining of four flue-gas scrubbers with Nicrofer 5923 hMo – alloy 59 in a German waste incineration plant" – October 1995

Nicrofer® 5923 hMo – alloy 59

We reserve the right to make alterations, especially where necessitated by technical developments or changes in availability.
The information contained in this material data sheet, which in any case provides no guarantee of particular characteristics, has been compiled to the best of our knowledge but is given without any obligation on our part.
Our liability is determined solely by the individual contract terms, in particular by our general conditions of sale.

This issue supersedes data sheet no. 4030, edition of February 1993, and our welding instruction no. 4030/1, edition of December 1994.

Edition December 1996:
Please ask for the latest edition of this data sheet.

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A company of the
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