USEC
A Global Energy Company

January 11, 2006
AET 06-0005

Mr. Jack R. Strosnider
Director, Office of Nuclear Material Safety and Safeguards
Attention: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

American Centrifuge Plant
Docket Number 70-7004
Submittal of Additional Reference Document for the American Centrifuge Plant (TAC Nos. L32306, L32307, and L32308)

Dear Mr. Strosnider:

Pursuant to Reference 1, USEC Inc. (USEC) hereby submits a reference document used within the Integrated Safety Analysis Summary. Enclosure 1 provides KY/L-1990 entitled *The Corrosion of Highly Alloyed Metals by Fluorinating Gases*, dated August 10, 1990.

If you have any questions regarding this matter, please contact Peter J. Miner at (301) 564-3470.

Sincerely,

Steven A. Toelle
Director, Nuclear Regulatory Affairs

cc: Y. Faraz, NRC HQ
E. Smith, NRC HQ

Enclosures: As Stated

Reference:

1. USEC letter AET 06-0004 from S.A. Toelle (USEC) to J.R. Strosnider (NRC) regarding Submittal of Additional Reference Documents for the American Centrifuge Plant (TAC Nos. L32306, L32307, and L32308), dated January 11, 2006

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NMSS01

Enclosure 1 of AET 06-0005

KY/L-1990 entitled *The Corrosion of Highly Alloyed Metals by Fluorinating Gases*, dated August 10, 1990

DATE OF ISSUE: August 10, 1998 DOCUMENT NUMBER: KY/L-1990

The Corrosion of Highly Alloyed Metals by Fluorinating Gases

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Materials Technology Department
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Prepared by
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for the
UNITED STATES ENRICHMENT CORPORATION
Under Contract No. USEC-96-C-0001

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Richard R. Cowell
11 Jan 06

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Executive Summary

The gaseous diffusion plants were built in the 1950s using equipment and materials that had been tested and approved for the intended environment. Many of the original valves and instruments are no longer available because the suppliers are not in business or the tooling is lost or scrapped. Components for maintenance activities and process improvement programs must be obtained through costly rebuilding programs, procurement of limited numbers of custom built parts, or adoption of off-the-shelf commercially available components developed for the chemical industry.

In 1977, a program was initiated to determine if the highly alloyed materials utilized by the chemical industry would be acceptable in the environments of the gaseous diffusion plants. A variety of stainless steels and nickel-based alloys were tested in a range of temperatures and fluorinating environments. The experimental findings indicated that the corrosion rates of many of the highly alloyed materials were low enough to provide long term service in fluorinating environments.

Introduction

The isotopic separation of uranium was developed with processes that utilized the stable, but reactive compound of uranium hexafluoride (UF_6). The gaseous form of UF_6 will rapidly react with common materials of construction, such as alloys of iron, copper, aluminum and nickel, forming a metal fluoride species and a nonvolatile compound of uranium. The ability of nickel, copper, and aluminum to form protective and adherent films of reaction products gave their alloys a degree of passivity that made them acceptable for construction for isotopic separation equipment. However, the reaction rate of alloys can increase if they contain significant quantities of elements that could form volatile or liquid fluorides, or a structural mismatch with the passive film of the base metal.

The large diffusion plants, built in the 1940s and 50s, utilize common materials such as aluminum alloys 1100, 3003 and 214, copper alloys 122, 510 and 955, and nickel alloy 400. Large amounts of low carbon steel were used with the process surface protected with electroplated nickel. The size and the special function of the plants required the establishment of new manufacturing facilities. With the completion of the three-plant complex, some of the special manufacturing facilities were dismantled and the diffusion plants were maintained with either existing supplies of spare components or through expensive and lengthy procurement of specialized hardware.

The scope of the uprating and improvement programs in the 1970s and 80s placed severe pressure on engineering and procurement groups to provide hardware on a timely basis. Some systems could not be brought into operation without the use of instruments and valves that were only available in materials that had not been previously tested. Hardware had to be used on the basis of estimates of corrosion rates or limited laboratory testing. In 1977, the Metallurgy Laboratory made a decision to investigate the corrosion rate of the materials of construction utilized by the manufacturers of chemical processing equipment.

Experimental Program

The materials testing program was developed to obtain corrosion rates that would predict the service behavior of components such as bellows and pressure diaphragms. These mechanically active, thin-wall components are sensitive to low corrosion rates. Not only could the performance of a valve or instrument be affected by corrosion, but penetration of a bellows or diaphragm could result in loss of containment. It was decided that tests would be conducted with thin gage material or thin disks cut from bar stock. Both types of specimens provided a high surface area to weight ratio.

Wrought alloys were purchased in the form of thin stock, usually 0.005 inches thick. The stock was cut into ¾ inch wide and 9 inch long test specimens. Quarter inch holes were drilled in the specimen ends so that numerous strips could be assembled on a test rack. Cast alloys were obtained in the form of keel blocks from a foundry. One-half inch rods were machined from the blocks and cut into 0.015 inches thick disks. The disks were exposed in small metal cups. The soldering and brazing alloys were melted in copper molds which were sectioned and exposed. Figure 1 illustrates this test set-up. A list of all the stainless steel and nickel alloys and their certified chemistries are given in Tables 1 and 2. The soldering and brazing alloys, listed in Table 3, were obtained from plant stock.

The test materials were exposed to corrosive gases in the system shown in Figure 2. Fluorine, chlorine trifluoride and hydrogen fluoride were continuously mixed with nitrogen to a 7% volume concentration, passed through the monel reactors (at a reactant gas constituent flow rate of 20 cc/min.) and vented. This process maintained a fresh supply of the gas mixture. Uranium hexafluoride (as depleted uranium) was recirculated at the rate of 200 cc/min. by a thermal pumping system. The gas flows were continuously monitored with mass flow meters, while the system temperature was monitored with thermocouples attached to the reactor surfaces.

The period of exposure was typically 30 days. The corrosion rates of thin gage material and disks of cast material were calculated from their weight changes. Each reported corrosion rate was based on an average of five specimens. The corrosion rates of the soldering and brazing alloys were determined by metallographically measuring the depth of attack of the alloy deposited in its copper mold.

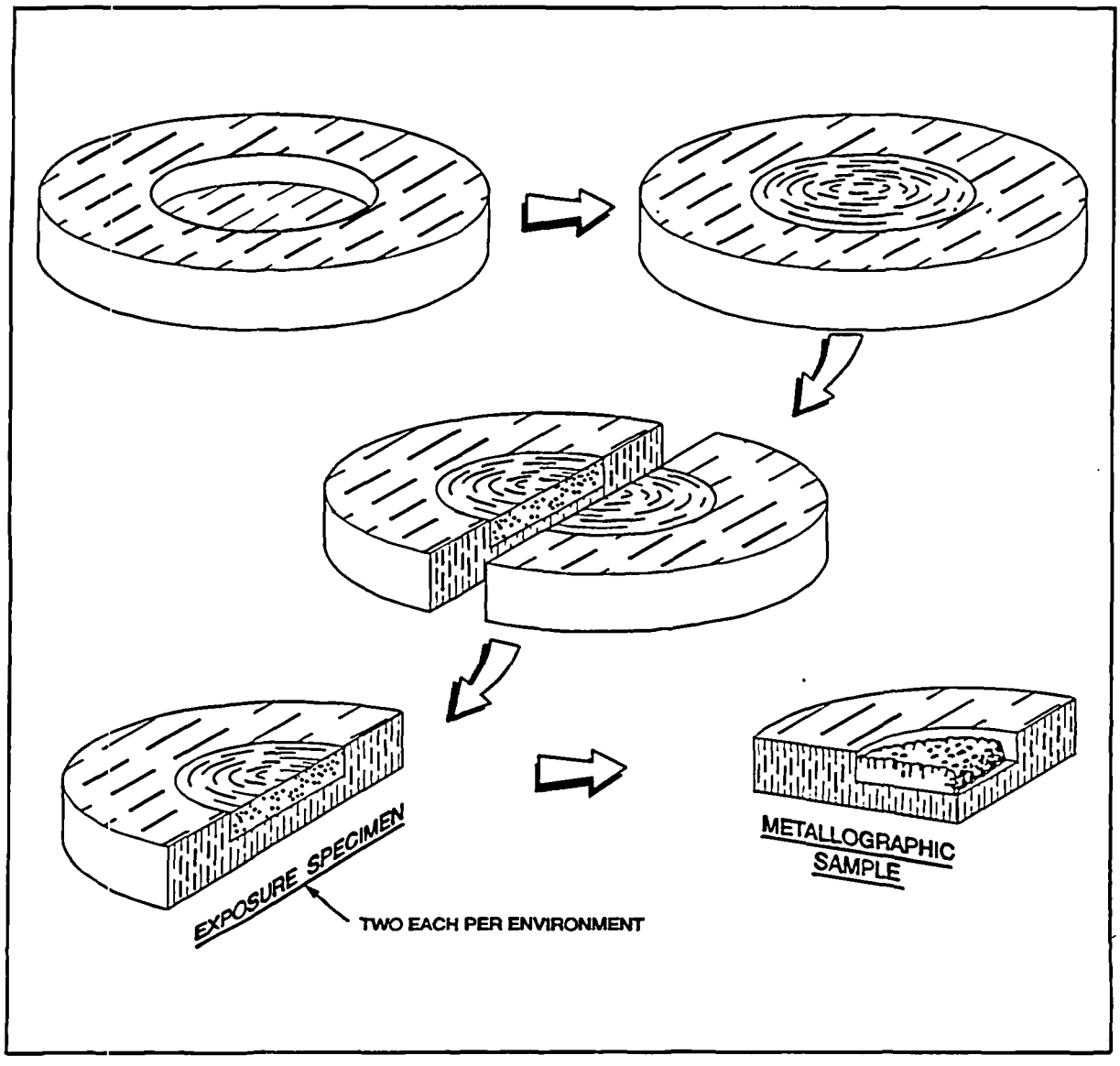

Figure 1. Specimen Design and Test Set-up for Soldering and Brazing Alloy Coupons.

Table 1. Chemical Compositions of Wrought and Cast Stainless Steels[1]

Alloy	C (wt.%)	Mn (wt.%)	Si (wt.%)	P (wt.%)	S (wt.%)	Cr (wt.%)	Ni (wt.%)	Mo (wt.%)	Other (wt.%)
304 SS	0.067	1.18	0.49	0.026	0.009	18.2	8.48	0.28	0.29 Cu
321 SS	0.050	1.71	0.49	0.013	0.004	17.5	9.35	0.13	0.15 Cu, 0.20 Co, 0.15 Ti
316 SS	0.058	1.70	0.32	0.031	0.005	16.8	12.5	2.12	0.43 Cu
316L SS	0.011	1.69	0.58	0.034	0.015	17.1	13.5	2.68	0.19 Cu
310 SS	0.040	1.86	0.59	0.019	0.007	24.7	19.3	0.23	0.17 Cu
AM 350	0.087	0.81	0.33	0.040	0.008	16.7	4.22	2.74	0.089 N
17-7 PH	0.078	0.74	0.38	0.030	0.014	16.4	7.14	NA	1.10 Al
CF8	0.06	0.34	1.19	0.009	0.022	18.9	8.68	0.11	
CF3M	0.02	0.43	0.98	0.019	0.015	18.4	9.14	2.16	
CF8M	0.04	0.49	1.29	0.019	0.010	19.1	9.34	2.16	
CN7M	0.03	0.34	0.78	0.007	0.021	19.2	28.1	2.68	3.10 Cu

[1]All chemical compositions as reported on certificates of test from material suppliers.

Table 2. Chemical Compositions of Wrought and Cast Nickel Alloys[1]

Alloy	C (wt.%)	Mn (wt.%)	Si (wt.%)	P (wt.%)	S (wt.%)	Cr (wt.%)	Ni (wt.%)	Mo (wt.%)	Other (wt.%)
Nickel 200	0.07	0.25	0.02	NA	0.002	NA	99.6	NA	0.01 Cu
Monel 400	0.10	1.06	0.24	NA	0.001	NA	65.4	NA	31.3 Cu, 1.94 Fe, 0.10 Cr
Inconel 600	0.04	0.21	0.22	NA	0.007	15.3	76.6	NA	0.14 Cu, 7.43 Fe
Inconel 625	0.01	0.02	0.21	NA	0.010	21.6	62.5	9.14	0.25 Ti, 0.20 Al, 3.52 Cb+Ta
Inconel 718	0.05	0.10	0.01	0.01	0.003	18.1	53.7	2.95	0.10 Co, 0.98 Ti, 0.003 B, 0.51 Al, 5.27 Cb+Ta
Hastelloy C-276[2]	NA	0.40	0.02	NA	NA	13.0	Major	2.60	0.10 Co, 0.30 Al, 7.0 Fe, 4.0 Co, 4.8 W
Duratherm 600[3]	<0.001	<1.0	<1.0	NA	NA	12.0	Bal. Ni	4.0	41.0 Co, 8.0 Fe, 4.0 W, 2.0 Ti, 0.7 Al
Cast Monel QQN-288. Comp. A	0.12	0.93	1.15	0.009	0.010	NA	Bal. Ni	NA	32.1 Cu, 0.99 Fe
Cast Monel QQN-288. Comp. E	0.16	0.85	0.94	0.011	0.014	NA	Bal. Ni	NA	32.7 Cu, 1.42 Fe, 1.09 Cb
Cabot 214	0.03	0.20	<0.1	<0.005	<0.002	16.0	Bal. Ni	NA	4.65 Al, 2.49 Fe, 0.14 Co

[1]All chemical compositions as reported on certificates of test from material suppliers except [2, 3].
[2]Laboratory Spectrochemical.
[3]Nominal composition communicated by VAC export sales office.

Table 3. Chemical Compositions of Soldering and Brazing Alloys[1]

Alloy	Pb (wt.%)	Sn (wt.%)	Ag (wt.%)	Cu (wt.%)	Zn (wt.%)	Cd (wt.%)	Other (wt.%)
Lead Solder	97.5	NA	2.5	NA	NA	NA	NA
Tin Solder	NA	95.0	5.0	NA	NA	NA	NA
Bag-1a	NA	NA	50.0	15.5	16.5	18.0	NA
Bag-1B	NA	10.0	60.0	30.0	NA	NA	NA
BCuP-5	NA	NA	15.0	80.0	NA	NA	5.0 P
Ney 380	NA	NA	NA	NA	95.0	NA	5.0 Al

[1]Nominal compositions of materials

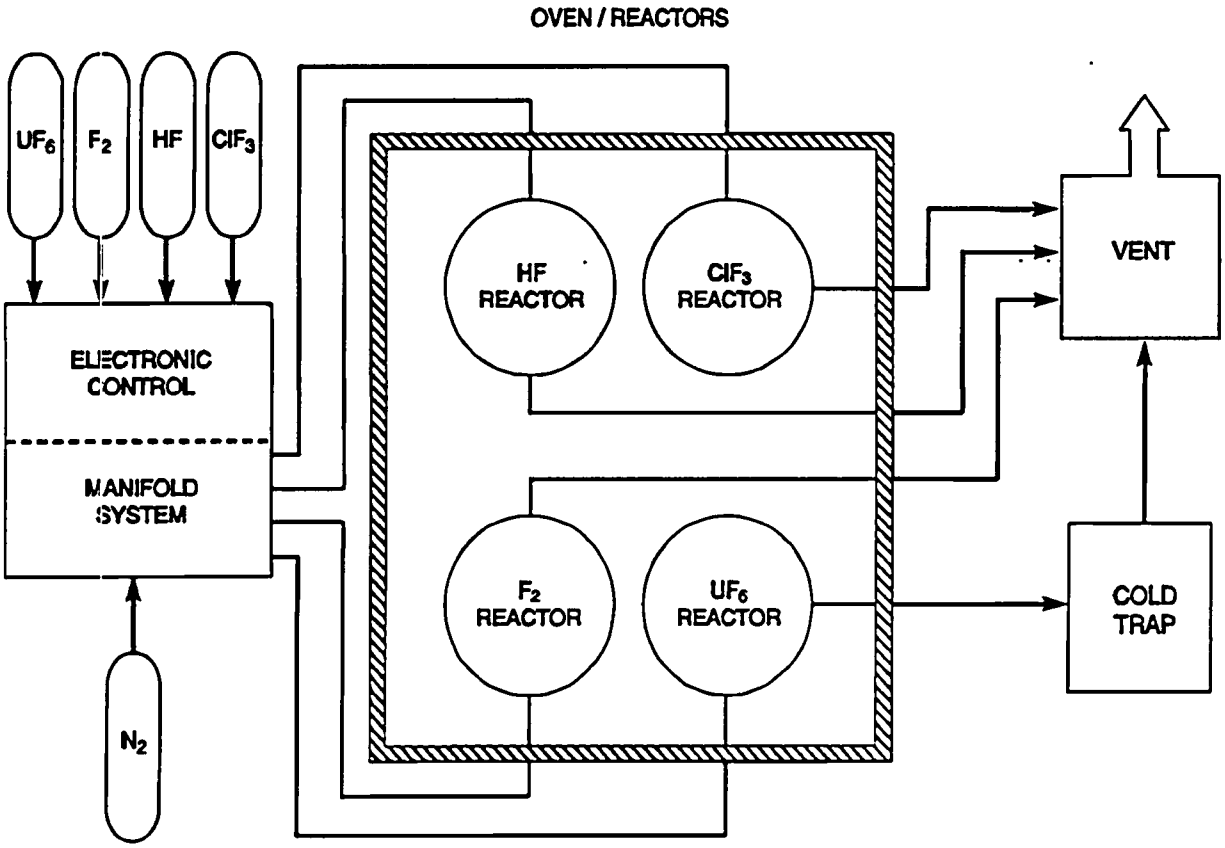

Figure 2. Corrosion Test System

Test Results

The results of the testing program are presented as ranges for temperature intervals and will be referred to as engineering corrosion rates in mils per year (mpy). This format is a useful reference for material selection. The temperature and corrosion ranges were chosen with consideration for potential applications in UF_6 handling and process systems.

The four ranges of corrosion were selected for different applications:

1) <0.01 mpy	Materials with corrosion rates of less than 0.01 mpy are considered to have stable, passivated surfaces. The very thin corrosion product should be adherent and not become a source of process contamination. The materials should be adequate for decades of reliable service.
2) 0.01 - 0.1 mpy	Materials within this corrosion range can be used for years of service if wall thickness and service life are considered.
3) 0.1 - 1 mpy	Materials within this corrosion range may be adopted for testing equipment that has intermittent use. The materials should not be used for process stream if their corrosion products are detrimental to product chemistry or equipment reliability.
4) 1- 10 mpy	This is the upper limit of the testing program imposed by the use of thin (0.005 inch) material.

The temperature ranges were selected to reflect those that are used in or proposed for various plant operations:

1) Room temperature to 200° F.	Many of the gas transfer and process instrument systems will operate in this range.
2) 200° - 300°F	Typical range of plant process temperature.
3) 300° - 400°F	These temperatures could be encountered for transient periods for operations such as trap regenerations.

The assignment of alloys to a specific range of corrosion for a given temperature interval was determined from trends observed when the $\log_{10}$ of the corrosion rate was plotted against the test temperature (degrees Kelvin). Many of these Arrhenius plots exhibited linear plots through the range of test temperatures so that estimates could be made for the specific engineering corrosion range of the alloy. In the presentation of the engineering corrosion rates, the applications engineer is often given several choices for a specific service condition.

The engineering corrosion rates for stainless steels, nickel alloys and soldering and brazing alloys are presented in Figures 3 to 11. The limited data for the cast versions of wrought alloys should not limit their application. It is observed that the data for cast alloys fall within or near the temperature trends of the wrought alloys. For example, the corrosion behavior of cast alloy CF8 is similar to 304 SS, Figure 12. The data collection from the testing program is summarized in Tables 4 to 15. Each corrosion rate is an average of five test specimens.

The materials used in the testing program are identified by nominal designations. Design applications and procurement of these materials would usually require the use of a specification written by an organization such as the American Society for Testing and Materials (ASTM) or the Society of Automotive Engineers (SAE). Three of the materials may not be found in handbook or specification documents. Cabot 214 is a nickel alloy (Cabot Corporation, Kokomo, Indiana) developed for high-temperature oxidation resistance and strength. The Duratherm 600 alloy is a German material (Vacuumschmelze GMBH, Berlin, Germany) consisting of approximately 40 wt.% cobalt, 26 wt.% nickel, 12 wt.% chromium with titanium and aluminum to promote precipitation hardening. Ney 380 (95 wt.% zinc, 5 wt.% aluminum), with a melting point of 380°C, was developed for brazing aluminum.

	<200°	200° - 300°	300° - 400°	400° - 500°
Corrosion Range 1 - 10 (mpy)			AM 350 17-7 PH 304 SS	AM 350
Corrosion Range 0.1 - 1 (mpy)		304 SS AM 350 17-7 PH	321 SS 316 SS 310 SS CF3M CF8 CF8M	310 SS 316L SS
Corrosion Range 0.01 - 0.1 (mpy)	AM 350 17-7 PH	321 SS 316 SS 316L SS 310 SS	316L SS CF7M	CF7M
Corrosion Range <0.01 (mpy)	304 SS 321 SS 316 SS 316L SS 310 SS			

Temperature Range (°F)

Figure 3. Corrosion Rate of Stainless Steel Alloys in Uranium Hexafluoride

	<200°	200° - 300°	300° - 400°	400° - 500°
Corrosion Range 1 - 10 (mpy)			304 SS	AM 350
Corrosion Range 0.1 - 1 (mpy)		304 SS 17-7 PH	321 SS 316 SS 316L SS AM 350 17-7 PH	310 SS
Corrosion Range 0.01 - 0.1 (mpy)	AM 350 17-7 PH	321 SS 316 SS AM 350	310 SS	
Corrosion Range <0.01 (mpy)	304 SS 321 SS 316 SS 316L SS 310 SS	316L SS 310 SS		

Temperature Range (°F)

Figure 4. Corrosion Rate of Stainless Steel Alloys in Fluorine

	<200°	200° - 300°	300° - 400°	400° - 500°
Corrosion Range 1 - 10 (mpy)			AM 350 17-7 PH 304 SS CF8	316L SS 310 SS
Corrosion Range 0.1 - 1 (mpy)	AM 350 17-7 PH	304 SS 321 SS 316 SS AM 350 17-7 PH	316L SS 310 SS CF8M CF3M CN7M	CN7M
Corrosion Range 0.01 - 0.1 (mpy)		316L SS 310 SS		
Corrosion Range <0.01 (mpy)	304 SS 321 SS 316 SS 316L SS 310 SS			

Temperature Range (°F)

Figure 5. Corrosion Rate of Stainless Steel Alloys in Chlorine Trifluoride

	<200°	200° - 300°	300° - 400°	400° - 500°
Corrosion Range 1 - 10 (mpy)				
Corrosion Range 0.1 - 1 (mpy)				Hastelloy C276 Inconel 718 Duratherm 600 Cast Monel-A
Corrosion Range 0.01 - 0.1 (mpy)			Hastelloy C276 Inconel 625 Inconel 718	Nickel 200 Inconel 600 Inconel 625 Monel 400 Cabot 214
Corrosion Range <0.01 (mpy)	Nickel 200 Hastelloy C276 Inconel 600 Inconel 625 Inconel 718	Nickel 200 Hastelloy C276 Inconel 600 Inconel 625 Inconel 718	Nickel 200 Inconel 600	

Temperature Range (°F)

Figure 6. Corrosion Rate of Nickel Alloys in Uranium Hexafluoride

	<200°	200° - 300°	300° - 400°	400° - 500°
Corrosion Range 1 - 10 (mpy)				Inconel 625 Hastelloy C276
Corrosion Range 0.1 - 1 (mpy)				Inconel 718 Duratherm 600 Cabot 214
Corrosion Range 0.01 - 0.1 (mpy)			Inconel 600 Inconel 625 Inconel 718 Hastelloy C276 Duratherm 600	Inconel 600 Cast Monel-A
Corrosion Range <0.01 (mpy)	Nickel 200 Inconel 600 Inconel 625 Inconel 718 Hastelloy C276 Duratherm 600	Nickel 200 Inconel 600 Inconel 625 Inconel 718 Hastelloy C276 Duratherm 600	Nickel 200	Nickel 200 Monel 400

Temperature Range (°F)

Figure 7. Corrosion Rate of Nickel Alloys in Fluorine

	<200°	200° - 300°	300° - 400°	400° - 500°
Corrosion Range 1 - 10 (mpy)				
Corrosion Range 0.1 - 1 (mpy)				Inconel 625 Hastelloy C276 Duratherm 600 Cabot 214
Corrosion Range 0.01 - 0.1 (mpy)		Duratherm 600	Hastelloy C276 Duratherm 600 Cast Monel-A Cast Monel-E	Inconel 600 Cast Monel-A
Corrosion Range <0.01 (mpy)	Nickel 200 Inconel 600 Inconel 625 Inconel 718 Hastelloy C276 Duratherm 600	Nickel 200 Inconel 600 Inconel 625 Inconel 718 Hastelloy C276	Nickel 200 Inconel 600 Inconel 625 Inconel 718	Nickel 200 Monel 400 Inconel 718

Temperature Range (°F)

Figure 8. Corrosion Rate of Nickel Alloys in Chlorine Trifluoride

	<200°	200° - 300°	300° - 400°	400° - 500°
Corrosion Range 1 - 10 (mpy)		Pb Solder Sn Solder	BAg-1a	Ney 380
Corrosion Range 0.1 - 1 (mpy)	Pb Solder	BAg-1a	BAg-18 Ney 380	BAg-18 BCuP-5
Corrosion Range 0.01 - 0.1 (mpy)	Sn Solder BAg-1a BAg-18 BCuP-5 Ney 380	BAg-18 BCuP-5 Ney 380	BCuP-5	
Corrosion Range <0.01 (mpy)				

Temperature Range (°F)

Figure 9. Corrosion Rate of Soldering and Brazing Alloys in Uranium Hexafluoride

Corrosion Range 1 - 10 (mpy)	Pb Solder	Pb Solder BAg-1a	BAg-1a BCuP-5	BCuP-5 Ney 380
Corrosion Range 0.1 - 1 (mpy)	BAg-1a			
Corrosion Range 0.01 - 0.1 (mpy)	Sn Solder BAg-18 BCuP-5 Ney 380	Sn Solder BAg-18 BCuP-5 Ney 380	BAg-18 Ney 380	
Corrosion Range <0.01 (mpy)				
	<200°	200° - 300°	300° - 400°	400° - 500°

Temperature Range (°F)

Figure 10. Corrosion Rate of Soldering and Brazing Alloys in Fluorine

	<200°	200° - 300°	300° - 400°	400° - 500°
Corrosion Range 1 - 10 (mpy)	Pb Solder BAg-1a	Pb Solder BAg-1a		BAg-18 BCuP-5
Corrosion Range 0.1 - 1 (mpy)				
Corrosion Range 0.01 - 0.1 (mpy)	BAg-18 BCuP-5	BAg-18 BCuP-5	BAg-18 BCuP-5	
Corrosion Range <0.01 (mpy)				

Temperature Range (°F)

Figure 11. Corrosion Rate of Soldering and Brazing Alloys in Chlorine Trifluoride

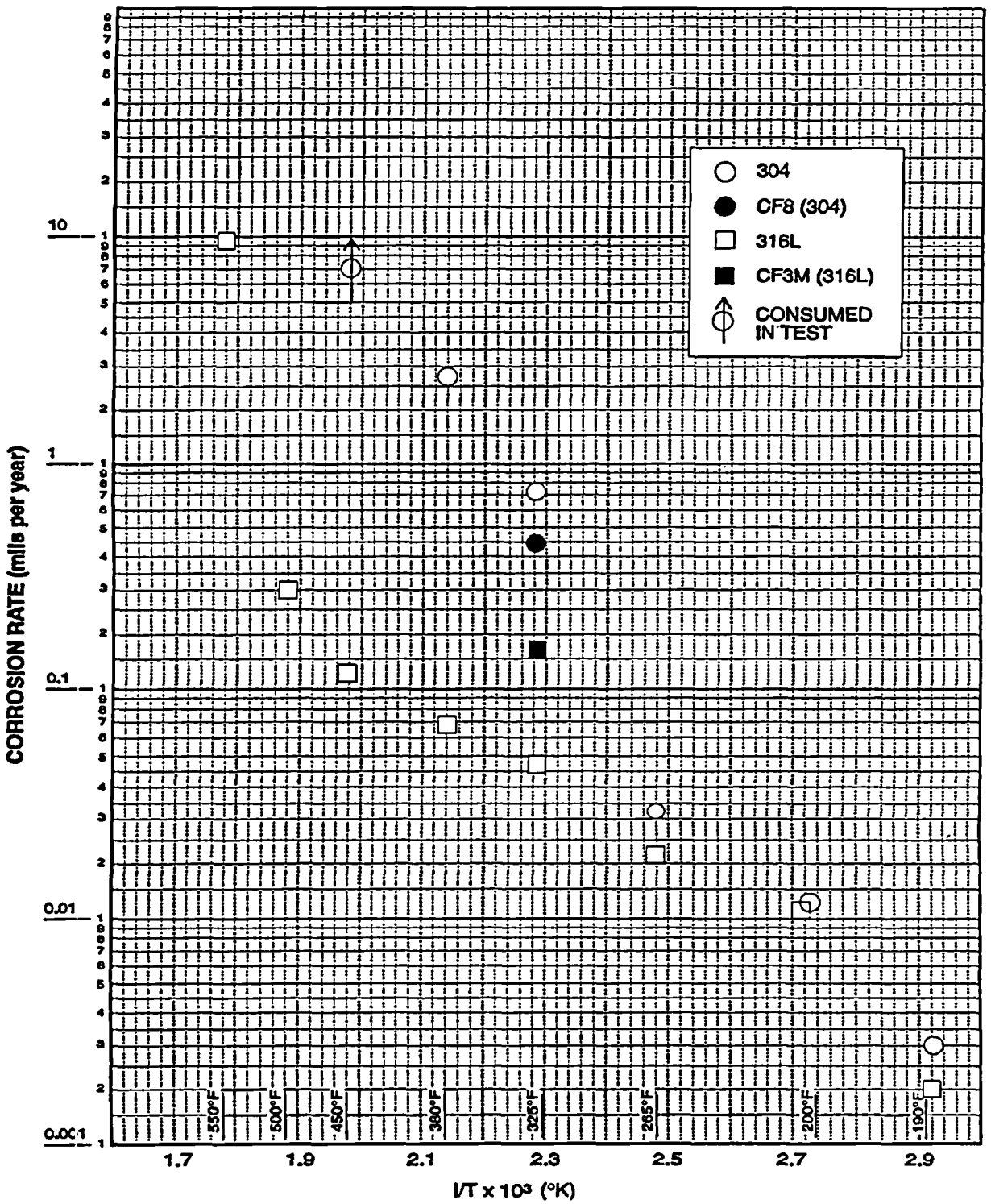

Figure 12. Variation of Corrosion Rate in UF_6 with Temperature

Table 4. Corrosion Rate[1] of Stainless Steels in Uranium Hexafluoride

	Temperature (°F)							
Alloy	160[2]	200	265	325	380	450	500	550
304 SS	<0.01	0.01	0.03	0.75	2.7	D	NT	NT
321 SS	<0.01	0.01	0.03	0.38	0.90	6.2	NT	NT
316 SS	<0.01	0.01	0.02	0.05	0.09	1.86	NT	NT
316L SS	NT	0.01	0.02	0.05	0.07	0.15	0.30	9.9
310 SS	NT	0.01	0.01	0.05	0.31	0.70	0.98	2.0
AM 350	<0.01	NT	0.30	0.53	2.13	NT	4.18	D
PH 17-7	<0.01	NT	0.36	0.23	1.41	10.1	NT	NT
CF8	NT	NT	NT	0.44	NT	NT	NT	NT
CF3M	NT	NT	NT	0.16	NT	NT	NT	NT
CF8M	NT	NT	NT	0.42	NT	NT	NT	NT
CN7M	NT	NT	NT	0.05	NT	NT	0.10	NT

[1]mils per year
[2]The 160 °F test was conducted in liquid UF_6 for 2 months.
D = Destroyed NT = Not Tested

Table 5. Corrosion Rate of Stainless Steels in 7% Fluorine - 93% Nitrogen Mixture

	Temperature (°F)						
Alloy	200	265	325	380	450	500	550
304 SS	<0.01	0.22	1.04	7.9	D	NT	NT
321 SS	<0.01	0.02	0.04	0.18	D	NT	NT
316 SS	<0.01	0.01	0.02	0.05	4.3	NT	NT
316L SS	<0.01	0.01	0.02	0.23	3.5	5.8	8.5
310 SS	<0.01	0.01	0.02	0.07	0.33	0.7	6.0
AM 350	0.03	0.05	0.07	0.17	1.1	1.7	9.1
PH 17-7	0.05	0.24	0.53	NT	2.6	NT	NT
CF8	NT	NT	NT	NT	NT	NT	NT
CF3M	NT	NT	NT	NT	NT	NT	NT
CF8M	NT	NT	NT	NT	NT	NT	NT
CN7M	NT	NT	NT	NT	0.5	NT	NT

D = Destroyed NT = Not Tested

Table 6. Corrosion Rate of Stainless Steels in 7% Chlorine Trichloride - 93% Nitrogen Mixture

	Temperature (°F)						
Alloy	200	265	325	380	450	500	550
304 SS	0.01	0.49	8.3	D	D	NT	NT
321 SS	<0.01	0.33	5.8	D	D	NT	NT
316 SS	0.01	0.01	0.62	4.3	12.6	NT	NT
316L SS	0.01	0.01	0.02	0.27	2.5	9.2	>30
310 SS	0.01	0.01	0.02	0.10	1.8	11.0	34.3
AM 350	0.22	0.58	0.65	5.8	D	NT	D
PH 17-7	0.22	0.69	5.0	16.4	10.6	NT	NT
CF8	NT	NT	2.02	NT	NT	NT	NT
CF3M	NT	NT	0.16	NT	NT	NT	NT
CF3M	NT	NT	0.23	NT	NT	NT	NT
CN7M	NT	NT	0.14	NT	0.3	1.0	NT

D = Destroyed NT = Not Tested

Table 7. Corrosion Rate of Stainless Steels in 7% Hydrogen Fluoride - 93% Nitrogen Mixture

	Temperature (°F)						
Alloy	200	265	325	380	450	500	550
304 SS	<0.01	<0.01	<0.01	0.84	D	NT	NT
321 SS	<0.01	<0.01	<0.01	0.04	10.8	NT	NT
316 SS	<0.01	<0.01	<0.01	NT	NT	NT	NT
316L SS	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.20
310 SS	<0.01	<0.01	<0.01	<0.01	<0.01	0.10	0.20
AM 350	<0.01	<0.01	<0.01	0.03	NT	0.31	1.9
PH 17-7	<0.01	<0.01	0.05	0.23	NT	NT	NT

D = Destroyed NT = Not Tested

Table 8. Corrosion Rate of Nickel Alloys in Uranium Hexafluoride

Alloy	Temperature (°F) 200	265	325	380	450	500	550
Nickel 200	<0.01	<0.01	0.03	<0.01	0.02	<0.01	0.02
Monel 400	NT	NT	NT	NT	NT	0.13	0.20
Inconel 600	<0.01	<0.01	<0.01	<0.01	0.02	0.05	0.06
Inconel 625	<0.01	<0.01	0.02	0.02	0.05	NT	NT
Inconel 718	<0.01	<0.01	0.04	0.02	0.30	0.20	4.1
Hastelloy C276	<0.01	<0.01	0.01	0.02	0.05	0.20	0.80
Duratherm 600	NT	<0.01	0.01	0.07	0.10	NT	NT
Cabot 214	NT	NT	NT	NT	NT	0.10	NT
Cast Monel-A	NT	NT	0.20	NT	NT	0.20	NT
Cast Monel-E	NT	NT	0.20	NT	NT	NT	NT

D = Destroyed NT = Not Tested

Table 9. Corrosion Rate of Nickel Alloys in 7% Fluorine - 93% Nitrogen

Alloy	Temperature (°F) 200	265	325	380	450	500	550
Nickel 200	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
Monel 400	NT	NT	NT	NT	NT	<0.01	<0.01
Inconel 600	<0.01	<0.01	NT	0.01	0.05	0.01	0.04
Inconel 625	<0.01	<0.01	<0.01	0.06	NT	NT	NT
Inconel 718	<0.01	<0.01	<0.01	<0.01	0.10	0.10	4.0
Hastelloy C276	<0.01	<0.01	0.01	0.09	0.40	NT	5.6
Duratherm 600	NT	0.01	0.01	0.04	0.20	NT	NT
Cabot 214	NT	NT	NT	NT	NT	0.10	1.4
Cast Monel-A	NT	NT	NT	NT	0.10	0.03	NT
Cast Monel-E	NT	NT	NT	NT	NT	NT	NT

D = Destroyed NT = Not Tested

Table 10. Corrosion Rate of Nickel Alloys in 7% Chlorine Trifluoride - 93% Nitrogen

Alloy	Temperature (°F) 200	265	325	380	450	500	550
Nickel 200	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.01
Monel 400	NT	NT	NT	NT	NT	0.01	<0.01
Inconel 600	<0.01	<0.01	NT	0.01	0.03	NT	0.06
Inconel 625	<0.01	<0.01	<0.01	<0.01	0.06	NT	NT
Inconel 718	<0.01	<0.01	<0.01	0.05	0.48	0.23	13.2
Hastelloy C276	<0.01	<0.01	<0.01	0.06	0.24	1.09	4.26
Duratherm 600	NT	0.01	0.02	0.04	0.07	NT	NT
Cabot 214	NT	NT	NT	NT	NT	0.16	2.9
Cast Monel-A	NT	NT	0.04	NT	0.1	0.03	NT
Cast Monel-E	NT	NT	0.04	NT	NT	NT	NT

D = Destroyed NT = Not Tested

Table 11. Corrosion Rate of Nickel Alloys in 7% Hydrogen Fluoride - 93% Nitrogen

	Temperature (°F)						
Alloy	200	265	325	380	450	500	550
Nickel 200	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
Monel 400	NT	NT	NT	NT	NT	<0.01	<0.01
Inconel 600	<0.01	<0.01	<0.01	<0.01	0.01	0.02	0.07
Inconel 625	<0.01	<0.01	<0.01	<0.01	<0.01	NT	NT
Inconel 718	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.09
Hastelloy C276	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.04
Duratherm 600	NT	NT	<0.01	<0.01	0.01	NT	NT
Cabot 214	NT	NT	NT	NT	NT	0.01	0.04

D = Destroyed NT = Not Tested

Table 12. Corrosion Rate of Solder and Brazing Alloys in Uranium Hexafluoride

Alloy	Temperature (°F) 200	265	325	380	450
95 Sn - 5 Ag	ND	6.2	19.3	15.6	SM
97½ Pb - 2½ Ag	1.1	6.3	12.9	14.7	59.5
BAg-1a	1.1	ND	3.0	4.1	10.2
BAg-18	ND	ND	ND	1.0	0.3
BCuP-5	ND	ND	0.1	ND	0.8
Ney 380	ND	ND	ND	1.0	6.9

ND = Corrosion Not Detected by Metallographic Examination
SM = Solder Melted

Table 13. Corrosion Rate of Solder and Brazing Alloys in 7% Fluorine - 93% Nitrogen

Alloy	Temperature (°F) 200	265	325	380	450
95 Sn - 5 Ag	ND	ND	ND	SC	SM
97½ Pb - 2½ Ag	1.9	7.6	4.1	21.8	67.4
BAg-1a	0.4	ND	2.3	7.6	8.8
BAg-18	ND	ND	ND	ND	ND
BCuP-5	ND	ND	3.6	3.2	10.7
Ney 380	ND	ND	ND	ND	5.4

ND = Corrosion Not Detected by Metallographic Examination
SM = Solder Melted
SC = Solder Consumed by Test Gas

Table 14. Corrosion Rate of Solder and Brazing Alloys in 7% Chlorine Trifluoride - 93% Nitrogen

Alloy	Temperature (°F) 200	265	325	380	450
95 Sn - 5 Ag	31.5	4.6	50.4	SC	SM
97½ Pb - 2½ Ag	1.5	8.7	13.9	20.7	133.7
BAg-1a	4.0	1.2	4.4	66.9	SC
BAg-18	ND	ND	ND	ND	1.1
BCuP-5	ND	ND	ND	ND	3.2
Ney 380	ND	ND	ND	3.9	19.0

ND = Corrosion Not Detected by Metallographic Examination
SM = Solder Melted
SC = Solder Consumed by Test Gas

Table 15. Corrosion Rate of Solder and Brazing Alloys in 7% Hydrogen Fluoride - 93% Nitrogen

Alloy	Temperature (°F) 200	265	325	380	450
95 Sn - 5 Ag	0.7	12.9	10.3	118.3	SM
97½ Pb - 2½ Ag	3.3	7.6	2.6	6.6	5.8
BAg-1a	ND	ND	ND	1.8	1.4
BAg-18	ND	ND	ND	ND	0.7
BCuP-5	0.4	ND	ND	ND	ND
Ney 380	ND	ND	ND	ND	4.9

ND = Corrosion Not Detected by Metallographic Examination
SM = Solder Melted
SC = Solder Consumed by Test Gas

Corrosion Resistance of Alloy Metals

Many of the alloys tested in the program have demonstrated low corrosion rates even though they contain elements such as iron, chromium, and molybdenum, which form corrosion products that may volatilize or are structurally incompatible with the base constituent. However, the physical distribution and chemical state of these elements may nullify their unfavorable singular chemical reaction with fluorinating gases. The result of scoping tests conducted at the start of the program and special surface chemistry analyses at the end of the studies are informative as to the effect of alloying elements on the observed corrosion rates.

Scoping tests were performed at the start of the study to identify alloys which had potential corrosion resistance to fluorinating gases. The result are shown in Table 15. The test indicated that not only was chlorine trifluoride more corrosive than fluorine, but that there was also greater variation in the corrosion rates. For the purpose of accelerated testing, ClF_3 became the gas of choice. For either gas, the 7-day test was about as informative as the 28-day test. In ClF_3 gas, the comparison of the performance of the 1008 and 1050 steels shows that the corrosion rate of iron is very dependent upon the carbon content. Also, the attack of 430 stainless steel indicates that the addition of 16% chromium rapidly accelerates the corrosion rate of iron. The corrosion rate is reduced when 8-14 percent nickel is added to the iron-chromium formulation. Within the Series 300 stainless steels, the corrosion rates is usually observed to decrease as the nickel content increases in the series.

Toward the end of the testing program, the availability of special analytical equipment was utilized to study the chemistry of fluorinating surfaces. The following paragraphs are the summary by the laboratory at the Oak Ridge Gaseous Diffusion Plant:

> [1]A nickel based alloy, Inconel 600, and two iron based alloys, AM 350 and 316 ELC, were exposed to corrosive halogen environments (e.g. HF, ClF_3 and F_2) for 30 days at 550°F. Visual examination of the as-received corrosion coupons revealed that the ClF_3 was apparently much more corrosive than the other two halogen gases. The corrosion coupons were analyzed by means of electron spectroscopy for chemical analysis (ESCA) in order to determine, 1) how the as-received corrosion products compared to the bulk alloy chemistry, and 2) the structural chemistry of the corrosion products.
>
> ESCA analysis of all three alloys indicates that the halogen gases react to produce a variety of fluorinated products with NiF_2 common to all of the alloys. In addition to the above fluoride products, exposure of Inconel 600 to HF produces CrF_3 and a nickel oxyfluoride compound. Likewise, the exposure of AM 350 and 316 ELC to the three halogen gases also produces the fluoride compounds of nickel and chromium. We observed no significant changes in the nickel:chromium concentration ratios in the Inconel corrosion products as compared with this alloy. This suggests that the halogen gases do not cause preferential corrosion in that specific alloy.

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[1]L. A. Harris and T. L. Hatmaker, The Surface Chemistry of Interfaces between Some Commonly Used Alloys and Halogen Gases

In addition to the ESCA analyses, we obtained X-ray diffraction data from the corrosion products that served to substantiate our principal surface observations.

The findings indicate that the corrosion is general. There is no indication of a selective attack of chromium. The presence of NiF_2 on the exposed surfaces does not necessarily indicate that it is there as a protective film. However, the trend of decreasing corrosion rate with increasing nickel content, may indicate that there is more NiF_2 on the surface and it is imparting protection.

Table 15. Scoping Tests at 325°F with Carbon and Stainless Steels

Alloy	7 Day Corrosion Rate in F_2 (mpy)	28 Day Corrosion Rate in F_2 (mpy)	7 Day Corrosion Rate in ClF_3 (mpy)	28 Day Corrosion Rate in ClF_3 (mpy)
1008 Steel	2.5	5.0	12.1	13.8
1050 Steel	2.4	1.0	60.7	Destroyed
430 SS	0.3	0.1	46.7	Destroyed
304 SS	0.8	2.7	12.4	10.5
321 SS	0.2	0.1	7.2	7.1
316L SS	0.2	0.1	0.1	0.1
AM 350	0.3	0.1	2.3	0.4

Conclusions

Highly alloyed materials have sufficient corrosion resistance to have applications in gaseous diffusion plants and other uses where fluorinating gases are processed or used. The results of this study may not be applicable to applications of mixtures of fluorinating gases or other halogens.

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