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INVESTIGATION OF MATERIALS FOR A WATER COOLED AND MODERATED REACTOR

Louis Scheib

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INVESTIGATION OF MATERIALS FOR A WATER COOLED AND MODERATED REACTOR

by

Louis Scheib
On Special Assignment at the
Oak Ridge National Laboratory from
The American Machine and Foundry Company

Electronuclear Research Division
R. S. Livingston, Director

August, 1954

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ABSTRACT

An investigation of the materials for use in the water-moderated and cooled Army Package Power Reactor (APPR) operating at about 500° F was made. The available literature was analysed, and the results of the different investigators were compared and averaged.

Twenty different materials, including stainless steels, nickel alloys, Stellites and others, were investigated from the point of view of physical properties, susceptibility to radiation damage, and corrosion resistance.

Corrosion rates were established for all the materials under various conditions, such as irradiation, flow, weld, stress, and various water conditions. Type-304 stainless steel was selected as the basic structural material. Operating conditions, to maintain minimum corrosion, were established also.

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Acknowledgement is made also to the many corrosion workers at Argonne, Battelle, WAPD, KAPL, NRL, Hanford, Chalk River, Brookhaven, and others whose investigations and reports have made this report possible.

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1.00 INTRODUCTION

1.10 Basis for Material Selection

In the development of power production equipment often the quality of the materials available has limited the range and efficiency of the equipment produced.

A material investigation was undertaken for the Army Package Power Reactor so that the materials and the operating conditions of the reactor could be established early.

The material requirements for a water-cooled and water-moderated reactor as compared with the needs of either the chemical industry with its high corrosion rates, on one hand, or the aircraft industry with its high temperature requirements, on the other, are not very stringent. The urgency, however, that proper materials be selected is based on the unique combination of the following circumstances:

a. The materials must have the proper physical properties to perform their function over long period of maintenance free periods of time.

b. The materials must perform satisfactorily under irradiation and in contact with transport materials which have been irradiated.

c. The materials must withstand the corrosive action of contact with, and submersion in, water between 450° F and 550° F.

The need for the basic data, to permit the selection of materials, to meet the above requirements, was first felt for the submarine reactor in 1948 and as a consequence, an extensive experimental ivestigation was launched at various research centers, including Oak Ridge, Hanford, Babcock and Wilcox, Westinghouse, General Electric, Battelle Memorial Institute, and others.

It was felt that if this information, in turn, could be tabulated and integrated with other known corrosion data, and then analysed, the following could be accomplished for the Army Package Power Reactor:

a. Eliminate the need for a basic experimental research on materials and so keep the development costs on the package reactor to a minimum.

b. Arrive at proper materials to give trouble-free operation for a minimum of three to five years, on the readily accessible equipment, and to give lifetime operation for the remainder of the equipment.

c. Arrive at the proper operating conditions to enable (b) to be realized.

Accordingly, the literature was carefully combed, symposia were attended, and discussions held with men engaged in current material testing. The criteria which were used in determining the suitability of the materials for a reactor were the physical properties, the effect of irradiation on the physical properties, and the corrosion of the materials.

The amount of effort which was expended on each criteria was based upon the availability of accurate information and the amount of proof necessary to establish tenable conclusions concerning the information.

On the above basis the corrosion resistance of a material was found to be the most important single factor upon which any selection ought to depend. Consequently, much corrosion data were gathered. These data have been tabulated and appear at the end of the report (Appendix C). The data was further averaged and condensed until a single corrosion rate for each material was obtained.

1.20 Materials Selected

The package power reactor plant is composed of two basic components - the reactor itself with its primary loop, and the power plant with its associated equipment; the latter might be considered a secondary loop. This report is mainly concerned with the primary loop, since this loop handles the potentially radioactive liquids and is consequently the most probable source of trouble. The selection of materials for the secondary or steam cycle loop can be handled in the same manner as would any conventional steam turbine plant.

On the basis of the materials selected for testing at the various atomic research centers and on the basis of the general physical and corrosion resistant properties of the materials, the evaluation was confined to the following materials:

Graphitar-14	304L SS
Hastelloy-C	316 SS
Inconel	322W SS
Inconel-X	347 SS
Monel	410 SS
K-Monel	440C SS
A-Nickel	Stellite-3
Armco 17-4 PH	Stellite-6
Armco 17-7 PH	Stellite-12
304 SS	Vascoloy-Ramet 166

As a result of the study, stainless steel AISI 304 was selected as the basic material to be used except in certain special instances. Most of the reactor loops and corrosion loops to date employed 347 SS as the basic corrosion resistant material. The state has been reached in reactor technology where it is becoming more important to select an optimum material rather than just the "best" material. The selection of such an

optimum material is a function of the ability of the material to perform what is required of it based on lowest cost, availability, control, etc. Since 347 SS costs more (about 25%), contains the strategic material columbium, and is only slightly better, under some conditions, than 304 SS, it is felt that the selection of 304 SS is justified. This is particularly true since some of the fears concerning 304 SS which were prevalent have been dispelled by the findings of this investigation.

The suggested materials for the major loop components, including 304 SS, are as follows:

1. Reactor Vessel

   304 SS clad to A.S.M.E. Type SA 212 Grade B fire box quality steel. Gasket - dead soft nickel or Monel. Studs - 304 SS; nuts - 303 SS

2. Piping

   304 SS

3. Fuel elements

   Cladding - 304 SS or 304L; matrix - 304 SS or 304L sintered with suitable fuel

4. Control Mechanisms

   Rack and gear 440C SS Cr plate rack
   Seal - discs Stellite-3; diaphragm - K-Monel
   Shaft - Armco 17-4 PH or 440C chrome-plated
   Bearing - rollers and races - Stellite-3
   Retainers - Armco 17-4 PH
   Springs - Inconel-X or Elgiloy

5. Heat Exchanger

   Tubes and headers - 304 SS

6. Pumps

Canned rotor
Frame, block, and position indicator - 347 SS or 304 SS
Bearing carrier and bracket - 304 SS
Shaft - 410 SS or 440C chrome-plated
Lamination ring - Monel

7. Valves - gate

Body - 347 SS or 304 Stellite-3 runners
Gate - SS 17-4 PH

8. Valves - check

Body - 347 SS or 304 SS
Pin - Stellite-3
Facing - Stellite-3

It should be noted that the AISI 304 stainless steel can be substituted by types 304L, 309, 316, 321, or 347 SS, if it is found propitious to do so.

2.00 PHYSICAL PROPERTIES OF REACTOR MATERIALS

The physical properties of the materials of construction are the first criteria upon which to base the selection of any material. Since it was not the purpose of this report to attempt any detailed design of the reactor, it was considered sufficient to examine enough materials of varying characteristics so that any physical property, such as hardness, ductility, strength, etc., could be obtained by proper selection from the group listed. The analysis of the materials of construction, in light of their physical properties, was limited therefore to an investigation of underwater bearing materials since information on such applications was not normally available elsewhere.

2.10 Wear Tests and Factors

Wear tests were conducted on various materials by Argonne on the Falex machine which rotates a pin against a V-block. Some of the more favorable combinations are listed in Tables I and II.

TABLE I: WEAR RATES AND FRICTION COEFFICIENTS OF MATERIALS AS DETERMINED ON FALEX MACHINE (ONE-HOUR RUNS) (33,6,8)

Water at 500° F

Material	Hardness	Wear	Pressure (psi)	Appearance	Apparent Coefficient of Friction
Pin, Stellite-6 V-block, Stellite-6	Rc 44 Rc 42	0 0.0002	728	Burnished Smooth	0.28
Pin, Stellite-6 V-Block, Stellite-6	Rc 44 Rc 22	0.0001 0.0001	2420	Scratched Some Score	0.21
Pin, Cr plate USS/W V-Block, Stellite-6	R15,N86 Rc 41	0.0001 0.0001	389	Smooth Wear Fine Scratch	0.42
Pin, Cr plate USS/W V-Block, Stellite-6	R15,N86 Rc 41	0.0001 0.0001	707	Smooth Wear Fine Scratch	0.28
Pin, Cr plate USS/W V-Block, Stellite-6	R15,N86 Rc 41	0.0001 0.0003	2380	Smooth Wear Smooth Wear	0.20
Pin, Stellite-6 V-Block, 347 SS	Rc 41 Rc 13	0.0001 0.0009	342	Fine Scratch Deep Scratch	0.71
Pin, Stellite-3 V-Block, USS/W	Rc 53 Rc 46	None 0.0005	398	Burnished Deep Scratch	0.71
Pin, 347 Cr plate (0.0005) V-Block USS/W		None 0.0003	715	Fine Scratch Smooth Wear	0.37

From other tests run on the Falex machine the combinations which showed wear of 0.0005 or less and an apparent friction coefficient of 0.4 or less are listed in Table II.

TABLE II: LOW WEAR AND LOW FRICTION COMBINATIONS[6,7,8]

Water at 500° F

Pin	Hardness		V-Block	Hardness
Stellite-6	Rc 40	vs	Vascoloy-Ramet 166	Rc 55
Stellite-3	Rc 45	vs	Vascoloy-Ramet 166	Rc 54
Vascoloy-Ramet 166	Rc 43	vs	Stellite-3	Rc 52
SS 410 HT	Rc 37	vs	Stellite-3	Rc 49
Stellite-21	Rc 33	vs	Stellite-21	Rc 21
347 SS	R15,N71	vs	Stellite-6	Rc 39
Stellite-12	Rc 40	vs	Stellite-6	Rc 30
USS/W PH	R15,N86	vs	Stellite-6	Rc 41
Stellite-6	Rc 43	vs	Bachrach Alloy	Rc 55
Stellite-3	Rc 53	vs	SS 440C HT	Rc 52
SS 347 CP	R15,N73	vs	Stellite-6	Rc 43
Armco 17-4 CP	R15,N84	vs	Stellite-6	Rc 40

Westinghouse has run wear tests and has evolved a wear factor based on loads per million cycles. Many of the combinations which are of possible interest are listed in Table III.

TABLE III: WEAR FACTORS AT 500° F IN WATER[112]

Weight Loss in Milligrams per Pound Load per Million Cycles

P-C = Piston and Cylinder J-S = Journal and Shaft

Materials	Oxygenated P-C	Oxygenated J-S	Hydrogenated P-C	Hydrogenated J-S
17-4 PH vs 17-4 PH			460	
17-4 PH vs 17-4 PH, Cr plate, honed	20		13	
USS 322W PH vs 322 PH	470			
USS 322W PH vs 304 SS or 347 SS	1040			
USS 322W PH vs 17-4 PH Cr plate	21			
304 SS or 347 vs 17-4 PH	475			
304 SS or 347 vs USS 322W	880			
304 SS or 347 vs 17-4 PH Cr plate, honed	65			
304 SS or 347 vs 304 SS or 347	3200			
17-4 Cr plate vs 17-4 PH		7.8		
17-4 Cr plate vs USS 322W PH		4.7		
Stellite-3 vs 17-4 PH	150	47	25	1.4
Stellite-3 vs USS 322W PH	130	310	11	
Stellite-3 vs 17-4, Cr plate, honed	8.3	6.1	0.3	8.5
Stellite-6 vs 17-4 PH	62	320		100
Stellite-6 vs 17-4 PH Cr plate, honed	65		24	
Haynes 21 PH vs 17-4 PH	25			
Haynes 21 PH vs 17-4 PH Cr plate		80		
S-Monel vs USS 322W PH	340	970		
S-Monel vs 304 or 347 SS	420	180		350
S-Monel vs 17-4 PH Cr plate		420		2
440C SS vs USS 322W PH		59		
440C SS vs 17-4 PH Cr plate, honed	92	47		
Lead vs 304 SS or 347 SS		2730		4.1
USS 322W PH vs Stellite-3	220		136	
17-4 PH nitrided vs 17-4 PH Cr plate	40			
17-4 PH Cr plate, honed vs Stellite-3			37	
17-4 PH Cr plate, honed vs Stellite-6	74		50	
17-4 PH Cr plate, honed vs KR Monel PH	81		1.1	

Materials	Oxygenated P-C	Oxygenated J-S	Hydrogenated P-C	Hydrogenated J-S
Stellite-3 vs Stellite-3	71		34	
Stellite-3 vs Stellite-6	59			
Stellite-3 vs Stellite-12	155			
Stellite-3 vs KR Monel PH	170		31	
Wall Colmonol-6 vs Stellite-3	61		60	
Stellite-3 vs 410 SS	16	140		
Stellite-3 vs Graphitar-14			43	
410 SS vs 410 SS		380		145
416 SS vs 416 SS		165		49
Nitrided CrC_3 vs Nitrided CrC_3	0.0			
Nitrided 17-4 PH vs Nitrided 17-4 PH	9.9			

2.20 Radiation Effect on Physical Properties

The study of radiation damage on materials of construction was investigated extensively at many of the national laboratories. These studies included an investigation of the effect of irradiation on such physical properties as hardness, tensile strength, elongation, ductility, creep strength, and density changes[11,6,57].

The effect of irradiation upon the hardness of the materials selected was investigated at Oak Ridge, Hanford, NRX (Chalk River) and Brookhaven with the results as shown in Table IV.

TABLE IV: EFFECT OF IRRADIATION ON HARDNESS OF MATERIALS[21,11,6,96,69]

Material	Hardness-Rockwell Before	Hardness-Rockwell After	Facility	Irradiation nvtx10^{19} Thermal	Irradiation nvtx10^{19} Fast	Time (hours)	Temp (°F)
304 SS annealed	B72-76	B72-76	ORNL	1	-	3240	500
347 SS annealed	B89-90	B81-90	Hanford	30	-	2065	540
440C SS hardened	A75	A77-79	Hanford	4	5	1800	540
440C SS hardened	C54-55	C53-55	NRX	37	51	3000	70
USS/W hardened	C48-49	C47-49	NRX	37	51	3000	70
17-4 annealed	C33-35	C48-52	Hanford	4	-	4000	540
17-4 hardened	A73	A74	Hanford	3	-	2065	540
17-7 hardened	C50-51	C45-50	Hanford	4	-	4000	540
Hastelloy-C	C16-20	C15-20	Brookhaven	4.8	-	-	270
Stellite-3, cast	A77-78	A78-79	Hanford	1.3	-	-	70-140
A-Nickel	F64-68	F82-91	ORNL	1	-	1800	500
Monel	B81	B95	Hanford	4	5	1080	70-140
K-Monel	C24-28	C25-28	Hanford	4	-	2880	540

In most instances the hardness increased, the nickel-base alloys showing the greatest increase. It is generally believed that the hardness increase was induced by the neutron bombardment. It was shown in other tests run on the 60-inch cyclotron at the University of California[70] that the hardness of 347 SS could be increased (Fig. 1) and then annealed back to about its original hardness by heat treatment.

The welds and the heat-affected zones associated with welds, upon irradiation, showed hardness increases similar to those of the parent metal.

The effect of irradiation on the tensile properties is generally to alter these properties in the same manner that cold working will. Tensile samples irradiated at Oak Ridge were compared with non-irradiated samples as shown in Table V.

TABLE V: EFFECT OF IRRADIATION ON TENSILE PROPERTIES OF STAINLESS STEELS[23,11,6]

Type	Ultimate Strength (psi)	Yield 0.2% Offset (psi)	Elongation (%)
304 irradiated	92,000	43,500	58.5
304 non-irradiated	95,000	48,500	41.0
304 non-irradiated	92,500	44,000	70.8
309 irradiated	99,000	43,500	51.0
309 non-irradiated	95,000	38,500	54.0
316 irradiated	89,500	36,500	66.5
316 non-irradiated	90,000	35,000	70.0
347 irradiated	103,000	42,500	54.5
347 non-irradiated	99,000	37,500	56.6

at 1×10^{19} nvt slow, 3200 hours, 400°-500° F.

Other tensile specimens run at Chalk River and Hanford showed the changes upon irradiation as listed in Table VI.

TABLE VI: EFFECT OF IRRADIATION ON TENSILE PROPERTIES[11,6]

Material	Ultimate Tensile Non-irrad.	Ultimate Tensile Irrad.	Yield 0.2% Offset Non-irrad.	Yield 0.2% Offset Irrad.
316 SS annealed*	79,500	151,000		
USS/W*	113,000	134,500		
440C SS hardened**	199,000	240,000	185,000	205,000
440C SS hardened**	211,000	240,000	185,000	200,000

* 3000 hours 3.7×10^{20} nvt slow, 5.1×10^{20} nvt fast, 75° F Chalk River

** 1800 hours, 4×10^{19} nvt slow, 5×10^{19} nvt fast, Hanford

Nickel-based alloys likewise showed improvement in tensile strength upon irradiation, see Table VII.

TABLE VII: EFFECT OF IRRADIATION ON TENSILE PROPERTIES OF NICKEL-BASE ALLOYS[11,6,8]

Material	Ultimate Strength, psi Non-irrad.	Ultimate Strength, psi Irrad.	Elongation in 2", % Non-irrad.	Elongation in 2", % Irrad.
Monel unnotched	85,000	96,000	33	10
Monel notched	129,000	----	--	--
K-Monel unnotched	123,000	134,000	11	3
K-Monel notched	211,000	226,000	--	--
Inconel unnotched	106,000	116,000	31	29
Inconel-X unnotched	126,000	133,000	20	12
Inconel-X notched	174,000	203,000	--	--

[redacted]

ORNL-LR-Dwg. 7440

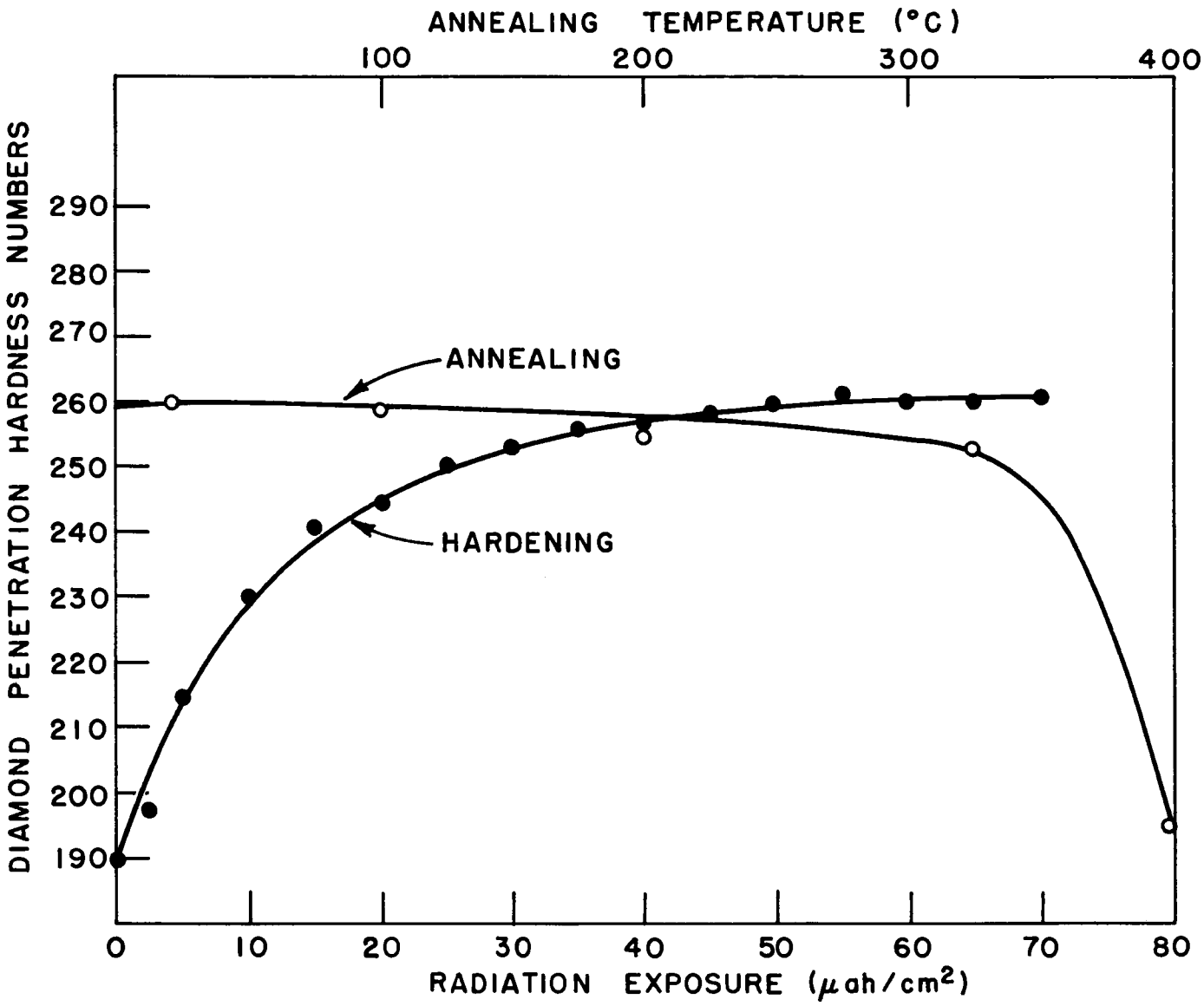

FIGURE 1. CYCLOTRON-IRRADIATED TYPE-347 SS

Tests on springs made of various materials showed minor decreases in free length and some changes in spring constants due to irradiation as shown in Table IX.

The effect of irradiation on the density and the dimensions of most materials was found to be small and often within the measurement error. The results of a typical density investigation are given in Table VIII.

TABLE VIII: EFFECT OF IRRADIATION ON DENSITY OF STRUCTURAL MATERIALS[21]

Exposure 2×10^{20} nvt slow, 3.5×10^{19} nvt fast

Group	Materials	Average Density g/cc Pre-irrad.	Post-irrad. Difference	Average Change (%)
Stainless Steels:				
1	316	7.995	-0.005 ± 0.002	-0.06
2	347	7.938	-0.007 ± 0.002	-0.09
3	347 + Ta	7.942	-0.003 ± 0.001	-0.04
4	410	7.675	-0.004 ± 0.001	-0.05
Nickel Base Alloy:				
5	A-Nickel	8.894	-0.006 ± 0.002	-0.07
6	Monel	8.836	-0.004 ± 0.003	-0.07
Cobalt Base Alloy:				
7	Stellite-3	8.550	0.005 ± 0.002	0.06
8	Stellite-6	8.330	0.009 ± 0.001	0.011
Carbon Steel:				
9	ASME-SA-212	7.850	0 ± 0.003	0

TABLE IX: EFFECT OF IRRADIATION ON CHANGES IN SPRING MEASUREMENTS[11]

Loaded at 55,000 psi

0.058" Diameter wire 0.350" O.D. x 0.200 x 3" L (~)

Material	Change in Free Length (in./3 in.) Irradiated	Change in Free Length (in./3 in.) Unirradiated	Change in Compressed Length under Original Load (in.) Irradiated	Change in Compressed Length under Original Load (in.) Unirradiated	Irrad. (nvt)
Tantaloy	-0.018 to -0.023	0.001 to 0.006	-0.013 to -0.032	0.002 to -0.002	A
Eligiloy	-0.120 to -0.126	-0.006 to -0.025	-0.112 to -0.113	0.005 to -0.006	A
Monel	-0.103 to -0.115	0.007 to -0.007	-0.078 to -0.081	0.005 to -0.002	A
Inconel	-0.020	----	----	----	C
Inconel-X	-0.002	----	----	----	C
Beryllium Cu Loaded 45,000 psi	-0.277	-0.002 to -0.001	-0.267 to -0.011	0.001 to -0.004	B
K-Monel	-0.165 to -0.169	-0.005 to -0.001	-0.149 to -0.170	0.005 to -0.002	B
Type 302 SS	-0.014 to -0.102	-0.006 to -0.030	-0.088 to -0.091	-0.001 to -0.009	A
Type 347 SS	-0.028		-0.033 to -0.096		C
Type 347 SS			-0.026 to -0.038		D

A - 4×10^{19} slow, 6×10^{19} fast, Hanford

B - 5×10^{19} slow, 8×10^{19} fast, Hanford

C - 5×10^{19} slow, 4×10^{19} fast, Hanford

D - 5×10^{19} slow at 450-500° F, Oak Ridge

Changes in electrical resistivity and magnetic susceptibility were found also to be slight with some tendency towards increased values.

Creep tests specimens of stainless steel 347, loaded at 10,000, 15,000, 20,000, and 25,000 psi were irradiated for nine months at Hanford at 1×10^{19} nvt slow and 1.5×10^{20} nvt fast. All changes were within the experimental error. Other tests at ORNL indicate that irradiation may increase the creep rate somewhat.

The effect of irradiation on fatigue strength of various materials is shown in Table X.

TABLE X: EFFECT OF IRRADIATION ON FATIGUE STRENGTH OF MATERIALS[31]

Tested without Failure 10,000,000 cycles

Material	Fatigue Endurance Limit (psi) Unnotched	Fatigue Endurance Limit (psi) Notched	Change percent Unnotched	Change percent Notched	Notch Effect Ratio** (k_f)
ASME-SA-212 Boiler Steel					
Unirradiated	48,000	28,000	-10	+25	1.7
Irradiated*	42,000	35,000			1.2
Type 440C SS hardened					
Unirradiated	76,000	45,000	-10	-30	1.7
Irradiated*	70,000	32,000			2.2
Type 410 SS Malcomized					
Unirradiated	40,000	43,000	20	30	0.9
Irradiated	48,000	56,000			0.9
Type 304 SS as rec'd					
Unirradiated	50,000	20,000	0	5	2.4
Irradiated	50,000	21,500			2.3

* Irradiated at Hanford, dry at 70-140° F at 8×10^{19} nvt slow and 1×10^{19} nvt fast

** Notch effect $k_f = \frac{\text{unnotched}}{\text{notched}}$

In the package reactor it is proposed that the pressure vessel be constructed of ASME-SA-212 Grade B firebox quality steel and clad with 304 SS; the same materials were used in the STR. Irradiation results of this material follow in Table XI.

TABLE XI: EFFECT OF IRRADIATION ON REACTOR PRESSURE VESSEL MATERIAL[11]

SA-212 Grade B Firebox Quality Irradiated at Hanford at 5×10^{19} nvt slow, 4×10^{19} nvt fast

Material	Hardness Rockwell B Before	After
Parent metal	B75	B89
Weld	B65	B89

	Yield (psi)		Ultimate (psi)		Elongation (%)	
	Before	After	Before	After	Before	After
Weld only	43,500	71,000	62,500	75,000	14	6.8
Unnotched	42,000	70,000	64,000	82,000	0	---
Notched			124,000	141,000	19.2	14.5

Specimens of this same material seam welded with E6010 rod and stressed relieved at 620° C were exposed at 4×10^{19} nvt. The samples showed an increase in hardness from 40 to 47 Rockwell A; 63% increase in yield strength, a 20% increase in ultimate, and a decrease in elongation at rupture of 17% to 14%.

The effect of irradiation on fuel elements, particularly hardness changes, is treated under the fuel element section later in the report.

3.00 CORROSION OF REACTOR MATERIALS

3.10 Corrosion Rates

The corrosion behavior of about 1000 specimens of the selected materials was evaluated. Some of the more widely used materials had as many as 150 representative specimens. Individual charts of the various materials were made. The test conditions and the corrosion rates were listed and are included in the report as Appendix C.

These results are summarized under varying conditions in Tables XII through XV, and finally summarized into an over-all corrosion rate appearing in Table XVI.

TABLE XII: AVERAGE CORROSION RATES IN VARIOUS ENVIRONMENTS
(mg/cm^2-mo)

Water at 400° F to 600° F

Material	With Oxygen		With Hydrogen		Degassed		With Alkali		Irradiated	
	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate
304 SS	48	0.04	57	0.03	11	0.09	27	0.03	1	0.02
304L SS	32	0.07	27	0.03	6	0.07				
347 SS	44	0.09	78	0.04			3	0.04	14	0.08
316 SS	63	0.08	24	0.02	14	0.11	18	0.04		
17-4 PH	38	0.09	33	0.17	13	0.27			4	0.05
17-7 PH	29	0.11	8	0.38	15	0.19			9	0.16
440C SS	28	0.41	9	0.66	9	0.41	6	0.48		
410 SS	27	0.63	10	0.52			9	0.23		
Monel	18	1.10	7	0.03	6	0.37	8	0.08	2	0.50
K-Monel	37	0.27	14	0.04			15	0.08	15	0.08
Inconel	51	0.31	39	0.01			11	0.02	1	0.11
Inconel-X	8	0.70	16	0.03	4	0.04	3	0.03	1	0.15
Hastelloy-C	4	0.22			3	0.03			2	0.18
A-Nickel	16	0.27	6	0.02	3	0.19	3		2	0.10
Vascoloy-Ramet 166	7	1.04							2	0.11
Stellite-3	7	0.11	5	0.04			3	0.58	10	0.11
	8	20.60								
Stellite-6	20	0.17			4	0.19	3	0.05	3	0.13
	21	12.13								
Stellite-12	12	0.18			1	0.18				
322W SS	26	0.60	9	0.15	5	0.28			10	0.05
Graphitar-14	5	6.40			3	3.84				

TABLE XIII: AVERAGE CORROSION RATES AT VARIOUS FLOW RATES
(mg/cm^2-mo)

Water at 400° F to 600° F

Material	Fluid Flow 0.01 fps		Fluid Flow 10 fps		Fluid Flow 20 fps		Fluid Flow 30 fps		In Autoclave	
	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate
304 SS	46	0.03	11	0.03	12	0.04	52	0.05	19	0.02
304L SS	24	0.04					31	0.06		
347 SS		0.04	9	0.038	10	0.02	63	0.07	32	0.06
316 SS	43	0.03	3	0.03			49	0.12		
17-4 PH	11	0.12	4	0.02			32	0.22	23	0.12
17-7 PH	15	0.08					15	0.30	14	0.15
440C SS							8	0.29		
410 SS	7	0.14	2	0.23			11	0.26		
Monel	12	0.46					14	1.46		
K-Monel	26	0.16					22	0.20		
Inconel	29	0.06	3	1.20	5	0.052	45	0.12		
Inconel-X	7	0.07					15	0.37		
Hastelloy-C										
A-Nickel	8	0.13					8	0.15		
Vascoloy-Ramet 166									2	0.11
Stellite-3	6	0.20					6	26.84		
Stellite-6			2	0.07			5	0.19	20	0.10
Stellite-12									13	0.18
322W SS	21	0.07					19	0.17		
Graphitar-14										

TABLE XIV: AVERAGE CORROSION RATES AFTER VARIOUS TREATMENTS
(mg/cm^2-mo)

Water at 400° F to 600° F

Material	As Welded		Quenched at 1900°		Machined		Vapor-Blasted		Hardened		Annealed	
	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate
304 SS	20	0.03	10	0.02	12	0.06						
304L SS	3	0.05					10	0.17				
347 SS	28	0.17	27	0.07	44	0.54	5	0.15				
316 SS	14	0.05	12	0.04	4	0.01	20	0.21				
17-4 PH					4	0.07			29	0.14		
17-7 PH									19	0.09		
440C SS									16	0.42		
410 SS									10	0.58	10	1.10
Monel												
K-Monel									14	0.34	21	0.09
Inconel	6	0.15			1	0.07	6	0.19				
Inconel-X												
Hastelloy-C											4	0.21
A-Nickel												
Vascoloy-Ramet 166												
Stellite-3												
Stellite-6	9	0.12										
Stellite-12												
322W SS	4	0.02							12	0.06		
Graphitar-14												

TABLE XV: AVERAGE CORROSION RATES FOR VARIOUS FINISHES
(mg/cm^2-mo)

Water at 400° F to 600° F

Material	Polished		Chrome Plated		Malcomized		Tensile 10,000 psi		Ground		Sensitized	
	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate	Samples	Rate
304 SS	8	0.01			8	0.19					12	0.05
304L SS					10	0.47	1	0.01				
347 SS												
316 SS												
17-4 PH			6	0.04	6	0.16						
17-7 PH					9	0.16						
440C SS									16	0.53		
410 SS			1	0.32					9	0.75		
Monel												
K-Monel												
Inconel							2	0.12	1	0.01		
Inconel-X												
Hastelloy-C			2	0.18								
A-Nickel			1	0.07								
Vascoloy-Ramet 166												
Stellite-3												
Stellite-6	9	0.12										
Stellite-12												
322W SS					7	4.10	2	0.11				
Graphitar-14	6	6.75										

TABLE XVI: GRAND AVERAGE CORROSION RATES FOR CONDITIONS OF TABLES XII THROUGH XV

In water 400° F to 600° F

Material	Number of Samples Averaged	Corrosion Rate (mg/cm^2-mo)
304 SS	116	0.04
304L SS	66	0.05
347 SS	122	0.05
316 SS	101	0.07
17-4 PH	84	0.14
17-7 PH	52	0.17
440C SS	46	0.45
410 SS	37	0.60
Monel	31	0.77
K-Monel	41	0.25
Inconel	80	0.20
Hastelloy-C	7	0.14
Inconel-X	28	0.22
A-Nickel	27	0.18
Vascoloy-Ramet 166	7	1.04
Stellite-3	12	0.08 (no O_2)
Stellite-6	24	0.17 (no O_2)
Stellite-12	13	0.18
322W SS	40	0.46
Graphitar-14	8	4.40

Malcomized samples not included

3.20 Factors Affecting Corrosion

Of the three reactor material selection criteria, the corrosion resistance of the material is the most important; the major effort on materials at AEC installations was directed toward corrosion evaluation. Corrosion is of concern for the following reasons:

a. Corrosion may break down protective clads and coatings, such as the stainless steel cladding on the fuel elements and the chrome plate on other components.

b. Corrosion will damage and shorten the life of moving mechanisms, such as the control rod drives and the break-down seals.

c. Corrosion may form films on heat transfer surfaces to reduce their efficiency.

d. Corrosion may form solid transport materials which may clog passages, hinder operation of fine mechanisms, and differentially coat heat transfer systems to lower the heat transfer efficiency.

e. Corrosion may cause leaks in the high-pressure closed-primary loop.

Although the mechanism of corrosion is generally accepted as an electrochemical process, it is agreed that many variables affect and are in turn affected by the continually changing equilibrium of the corrosion process.

After both a study of the test methods and an analysis of the results determined were made, the various corrosion influences were segregated into the following factors:

1. Effect of dissolved gases (O_2, H_2, CO_2, N_2, degassed).
2. Effect of welding, heat treatment, and sensitizing.
3. Effect of fluid flow, including transfer of corrosion products.
4. Effect of irradiation of materials.
5. Effect of irradiation of water on gases in solution and on corrosion of materials in the water.
6. Effect of water purity.
7. Effect of stress.
8. Effect of pH.
9. Effect of inhibitors and additives.
10. Effect of crevices and galvanic couples.
11. Effect of surface finish.
12. Effect of acid cleaning and passivation.
13. Effect of added poisons.

The evaluation of these effects constitutes the main basis for the corrosion section of the report to follow.

The corrosion behavior of about 1000 specimens of the selected materials was evaluated. Individual charts of the various materials were made; the test conditions and the corrosion rates were listed (Appendix C) so that many of the above effects of the variable conditions could be substantiated with actual corrosion figures.

The results of the tabulation are summarized in Tables XII through XV.

3.201 Effect of Dissolved Gases on Corrosion

The presence of dissolved gases in water has long been known to affect the corrosiveness of the water. Oxygen, nitrogen, carbon dioxide, and hydrogen are normally dissolved in waters obtained from natural sources.

Oxygen and nitrogen are dissolved mostly from the atmosphere. Some of the carbon dioxide is absorbed from the atmosphere, and the remainder obtained from the decompositions of plant and animal life in the water. Hydrogen is probably dissolved from decaying vegetation and is normally present in the water in an non-ionic state to a very small extent. Both the hydrogen and the oxygen in a reactor coolant loop may be augmented by the dissociation of the water caused by irradiation.

Much of the experimental corrosion testing concerned itself with the precise evaluation of the effects of varying quantities of these gases upon corrosion. Of these,the studies of the effect of both hydrogen and oxygen in water, were most significant.

Since most of the products of corrosion are oxides, oxygen is suspected to be the principal corrosive agent. Conversely, since hydrogen is an effective depolarizing agent, its presence should inhibit corrosion. An analysis of data tabulated from many corrosion tests shows that some such general effect is apparent.

The summary of the tabulations appears in Table XII. The values are gross averages in which a large number of samples are employed in order to average out any peculiar results which may be caused by the different techniques of the various investigators. A qualitative evaluation of the

effect of hydrogen and oxygen on the corrosion of sundry materials was made also at Argonne and is shown in Table LXII. In general, the results show that the austenitic stainless steels resist corrosion almost equally well in either medium. The other materials almost always show good corrosion resistance in hydrogenated water. The corrosion rates of the materials, other than the austenitic stainless steels, show a variation depending upon the particular investigation. Most results show a fair corrosion rate for these materials in oxygenated water. Tests at ORNL, however, produced extremely high corrosion rates for the Stellites and for chrome plate, and tests at the Naval Engineering Experimental Station produced high corrosion rates for the high nickel alloys in oxygenated water.

Crevice Corrosion. The corrosion of materials which occurs in close fitting places is potentially serious in systems which contain precision moving parts since the presence of the corrosion products will tend to bind and score the close fitting surfaces of the mechanism. Such binding will take place particularly in machinery which is left idle for periods of time, such as in the control-rod drives. Investigations conducted at Battelle indicate that the presence of oxygen in water promotes the formation of corrosion products at crevices of materials immersed in this water.

In tests run at Battelle, stainless steel 347 was combined with stainless steel 410 and immersed in 600° F degassed water. The crevices between the two materials were made 0.0005, 0.001, and 0.005. After six months no seizing between the two materials was evident. The experiment

was repeated under the same conditions except that 60 cc oxygen/L of water was added. Again no seizing occurred after the same period of time although more rust was apparent. In experiments run at 600° F and 300 cc oxygen/L of water, however, couples of the following materials with 0.0005" clearance, after eight weeks, showed the results given in Table XVII.

TABLE XVII: EFFECT OF OXYGEN ON CREVICE CORROSION[41]
300 cc O_2/L

410 SS	vs	410 SS	Severe seizure
347 SS	vs	347 SS	Slight seizure
430 SS	vs	430 SS	Severe seizure
Armco 17-4	vs	Armco 17-4	No seizure

The same materials run at 600° F, but with 385 cc H_2/L, with the same 0.005" clearance, after twelve weeks submersion, showed the results given in Table XVIII.

TABLE XVIII: EFFECT OF HYDROGEN ON CREVICE CORROSION[41]
385 cc H_2/L

410 SS	vs	410 SS	No seizure
347 SS	vs	347 SS	No seizure
430 SS	vs	430 SS	No seizure
Armco 17-4	vs	Armco 17-4	No seizure

Argonne reported crevice corrosion in tests run in water at 500° F containing 30 cc oxygen/L of water, as shown in Table XIX.

TABLE XIX: EFFECT OF OXYGEN ON CREVICE CORROSION[17]
30 cc O_2/L

Couple			Crevice Width	Comments
410 SS	vs	Stellite-3	0.0027	Partial freezing
Armco 17-4	vs	Stellite-3	0.0024	Frozen
410 SS	vs	Stellite-3	0.0021 to 0.0084	No freezing
Armco 17-4 PH	vs	Stellite-3	0.0028	Frozen

It is apparent that the presence of oxygen promotes the build-up of crevice corrosion products, particularly in some of the less corrosion-resistant materials which may be used. The presence of hydrogen seems to alleviate this condition for long periods of time. Specimens in hydrogenated water at Babcock & Wilcox showed no metal embrittlement attributable to the hydrogen.

The effects of other inhibitors and the effect of crevice width on crevice corrosion are discussed later in the report.

The presence of oxygen in the water also adversely affects the wear rates of bearing surfaces as shown in Table III. The presence of dissolved oxygen favors the formation of hematite (Fe_2O_3) at crevices and so aids in the seizure occurring at mating surfaces. Corrosion products obtained under various gas conditions were x-rayed at Battelle with the results presented in Table XX.

TABLE XX: X-RAY ANALYSIS OF CREVICE CORROSION PRODUCTS[41]
Water at 600° F, 410 SS

Gas in Water	Exposure (wk)	Type of Oxide Film: Exposed Surf.	Mating Surf.	Buildup
385 ml H_2/L	12	Fe_3O_4	Fe_3O_4	None
Degased	26	Fe_3O_4	Fe_3O_4	None
60 ml O_2/L	26	Alpha Fe_2O_3	Fe_3O_4	Alpha Fe_2O_3
300 ml O_2/L	8	Alpha Fe_2O_3	Fe_3O_4	Alpha Fe_2O_3

The results of the tests run in degassed water are erratic, and in many instances they show a higher corrosion rate than similar samples run in oxygenated water. The questionable nature of the results may be attributed to the fact that it is hard to keep a system degassed, particularly in a radioactive zone (see Section 3.205). Some investigators[23,21] have found that the presence of 0.2 cc O_2/L of water has a more corrosive effect than larger concentrations of oxygen, and any attempt at degassification may well lead to this lower oxygen concentration.

The effect of CO_2 in the water is to make it acidic and to promote pitting corrosion (see Section 3.208). Excessive CO_2 is also collected by the deionizer and tends to deplete it.

Nitrogen dissolved in the water is converted to nitrates or nitric acid, which promote corrosion. This occurs to a small extent.

3.202 Effect of Welding and Heat Treatment on Corrosion

The effect of heat applied to engineering materials, as in annealing, tempering, hardening, welding, and the subsequent changes in crystal structure, is of primary concern to us. The effect of welding on the grain structure is of particular concern since the metal is subjected to temperatures varying from that of liquid metal to the cold plate. The unstabilized austenitic stainless steels, when heated in the range between 900° F and 1600° F, tend to precipitate chromium carbide at the grain boundaries. It is postulated that the depletion of chromium from the alloy makes the metal immediately adjacent to the grain boundary susceptible to corrosion. Heating the welded structure to about 1900° F and then quenching, tends to redissolve the chromium and prevent its reprecipitation. In the assembly of large welded pipe sections in the field, however, post-weld heat treatment is not feasible. As a consequence in most AEC installations, the stabilizedstainless steels, such as 347 and 321, have been employed in the pipe lines and the pressure vessels since the presence of columbium and titanium in these alloys prevents the precipitation of chromium carbide. Since a low-cost reactor is sought, the use of the least expensive and most commonly available austenitic stainless steel, namely 304 would be preferred. In a search of the literature, no proof was found that any precipitation of chromium carbide, if it took place, affected the corrosion rate of the 304 stainless steels under APPR operating conditions. Likewise, no correlation was found between any other of the heat treatments and the corrosion rates.

The tests in Table XXI, run at Babcock and Wilcox, indicate that no effect is evident from either welding or sensitizing the materials.

TABLE XXI: WELDED AND SENSITIZED STAINLESS STEEL CORROSION RATES[3]
(mg/cm^2-mo)

Conditions -- 1350 hours
Water at 500° F

Type	pH-10 1.7 cc O_2/L 30 fps	1 fpm	pH-7 2.1 cc O_2/L 30 fps	1 fpm
304	-0.05	0.01	-0.06	0.01
304 welded	-0.04	0.02	--	0.04
304 sensitized at 1250° F	-0.04	0.01	-0.06	0.04
316	-0.07	0.01	-0.04	0.01
316 welded	-0.06	0.00	-0.05	0.02
316 sensitized at 1250° F	-0.05	0.00	-0.04	0.02

Other tests at Argonne show that the effect of quenching to dissolve any precipitated carbides does not give any better corrosion results than the samples left as welded (see Table XXII).

TABLE XXII: WELDED AND QUENCHED STAINLESS STEEL CORROSION RATES[3]
In Water

Type	(°F)	Time (hr)	Conditions	Corrosion Rate (mg/cm^2-mo)	Rating
304 welded to 304, as welded	600	2930	240 cc O_2/L	0.010	Good
304 welded to 304 quenched at 1900° F	600	2930	240 cc O_2/L	0.021	Good
304 welded to 304, as welded	600	2301	70 cc H_2/L	-0.021	Good
304 welded to 304 quenched at 1900° F	600	2301	70 cc H_2/L	0.016	Good
304L welded to 304	600	257	30 cc O_2/L	0.016	Good

Other weldments of 316 SS to 316 SS tested under the same conditions showed similar results. The stabilized stainless steels welded together and corrosion tested, such as 347 and 321,also showed good results. Cross-welding of other dissimilar stainless steels showed no unusual corrosion effects.

Babcock and Wilcox Company, and Westinghouse supplied Argonne with samples of 304 SS of varying carbon content (0.08 to 0.27%) for dynamic corrosion testing in oxygenated water (5-6 cc O_2/L) at 315° C in order to study the extent of intergranular corrosion on samples that were sensitized at 650° C for 2 hours and others at 24 hours. The first test period of 1480 hours was completed with the following results:

a. All samples exhibited an adherent dull bluish tarnish with a yellow-brown discoloration at the edges.

b. The corrosion rates, calculated from the weight changes, were very low, about ±0.04 mg/cm^2-mo, and seemed to have no correlation with the carbon content or the heat treatment.

In his book Metals at High Temperatures, F. H. Clark points out that intergranular corrosion of stainless steels in water does not begin until the water reaches 800° F. The nature of the corrosion at higher temperatures was investigated at Battelle in work on the supercritical reactor. Some of the results of this investigation follow in Table XXIII.

TABLE XXIII: CORROSION OF MATERIALS IN SUPERCRITICAL WATER[39,43]
Degassed

Material	800° F		1000° F		1350° F	
	Days	(mg/cm^2-mo)	Days	(mg/cm^2-mo	Days	(mg/cm^2-mo
17-7 PH	82	0.01	148	0.00	132	0.10
17-4 PH	82	0.03	---	----	132	0.20
302 SS	82	0.03	148	0.19	132	1.00
309 SS	82	0.02	148	0.03	132	0.20
310 SS	82	0.03	148	0.01	132	0.20
347 SS	82	0.00	148	0.02	132	0.20 pits
410 SS	82	0.03	148	0.02	132	0.40
Inconel-X	82	0.00	109	0.25	104	0.95
Hastelloy-F	82	0.00	58	0.07	132	0.13

From these figures, it would appear that the Armco 17-4 and Armco 17-7 as well as Hastelloy-F, 309 SS, and 347 SS offer the best in materials in operations at temperatures above 1000° F. A higher corrosion rate for welded structures becomes apparent at higher operating temperatures as indicated in the tests conducted at Battelle for Pratt and Whitney, and tabulated in Table XXIV.

TABLE XXIV: CORROSION OF WELDED AND UNWELDED METAL IN SUPER-CRITICAL WATER[88]

Degassed and Demineralized

Material	Time (hr)	Temp (°F)	Corrosion Rate (mg/cm^2-mo)	Depth of Pitting (mils)
Armco 17-4 PH, welded, annealed pickled	100	800	-0.01	
Armco 17-7 PH, welded, annealed, pickled	400	800	-0.05	0.3
Armco 17-4 PH, unwelded	100	800	0	
Armco 17-4 PH, unwelded	400	800	0.05	0.5
Hastelloy-C, welded, annealed, pickled	100	1350	0.24	
Hastelloy-C, welded, annealed, pickled	400	1350	0.24	0.5
Hastelloy-C, unwelded	100	1350	0.09	
Hastelloy-C, unwelded	400	1350	0.09	0.02
310 SS welded annealed, pickled	100	1350	0.12	
310 SS welded annealed, pickled	400	1350	0.26	0.1
310 SS unwelded	100	1350	0.09	
3.10 SS unwelded	400	1350	0.11	0.1

3.203 Effect of Fluid Flow on Corrosion

A definite relation between the rates of fluid flow in a water loop and the corrosion rate of the materials composing the loop could not be discerned in the study of the various corrosion testing loops. From the compilations in Table XIII, it may be predicted, in a very general way, that the higher the fluid velocity the greater will be the corrosion rate. This general pattern is illustrated by the typical set of experiments run at Babcock and Wilcox, and enumerated in Table XXV.

TABLE XXV: EFFECT OF FLUID FLOW ON CORROSION[3]
(Water at 500° F)

	Corrosion Rate (mg/cm^2-mo)			
	pH-10		pH-7	
Material	30 fps	1 fpm	30 fps	1 fpm
304 SS	-0.05	0.01	-0.06	0.01
304 SS welded	-0.04	0.02	--	0.04
304 SS sensitized at 1250° F	-0.04	-0.01	-0.06	0.04
Monel	-0.15	-0.01	-0.46	-0.14
440C SS	-0.17	--	-0.09	--
K-Monel annealed	-0.04	0.00	-0.45	0.01
K-Monel hardened	-0.18	0.00	-0.44	-0.05
Inconel	-0.02	0.02	-0.22	0.01
316 SS	-0.07	0.01	-0.04	0.01

From the tabulation of about 120 samples, analysis of the effect of flow upon corrosion of 304 SS with both oxygen and hydrogen dissolved in the water is shown in graphical form in Figure 2. The effect of higher fluid velocities is also apparent in the Argonne Material Evaluation shown in Table LXI. The typical corrosion rate-fluid velocity table above (Table XXV) and all the other compilations show that fluid velocities do not appreciably affect the corrosion rates of the austenitic stainless steels. The corrosion rates of the martensitic and the ferritic stainless steels, and the cobalt and high nickel alloys do show a more marked relation to the fluid velocity changes.

Transfer Products. A secondary effect of fluid flow is the transport of corrosion products from one point in the system to another. This transfer not only bares the corroded surface for renewal attack, but it also affects the remainder of the circuit as follows:

a. Particles may become radioactive and deposit in unshielded areas.

b. Particles may form scale on heat transfer surfaces and so lower the effective heat transfer coefficient.

c. Particles may restrict flow in confined places, such as tubes and orifices.

d. Particles may injure wearing surfaces and precision equipment.

The transport materials may be dispersed for redeposition by traveling in solid particles or floculates, or in solution.

Tests run at Battelle indicate that the solubility of many of the alloy components, and of the corrosion products themselves is not very high in water. This is shown in Table XXVI.

[redacted]

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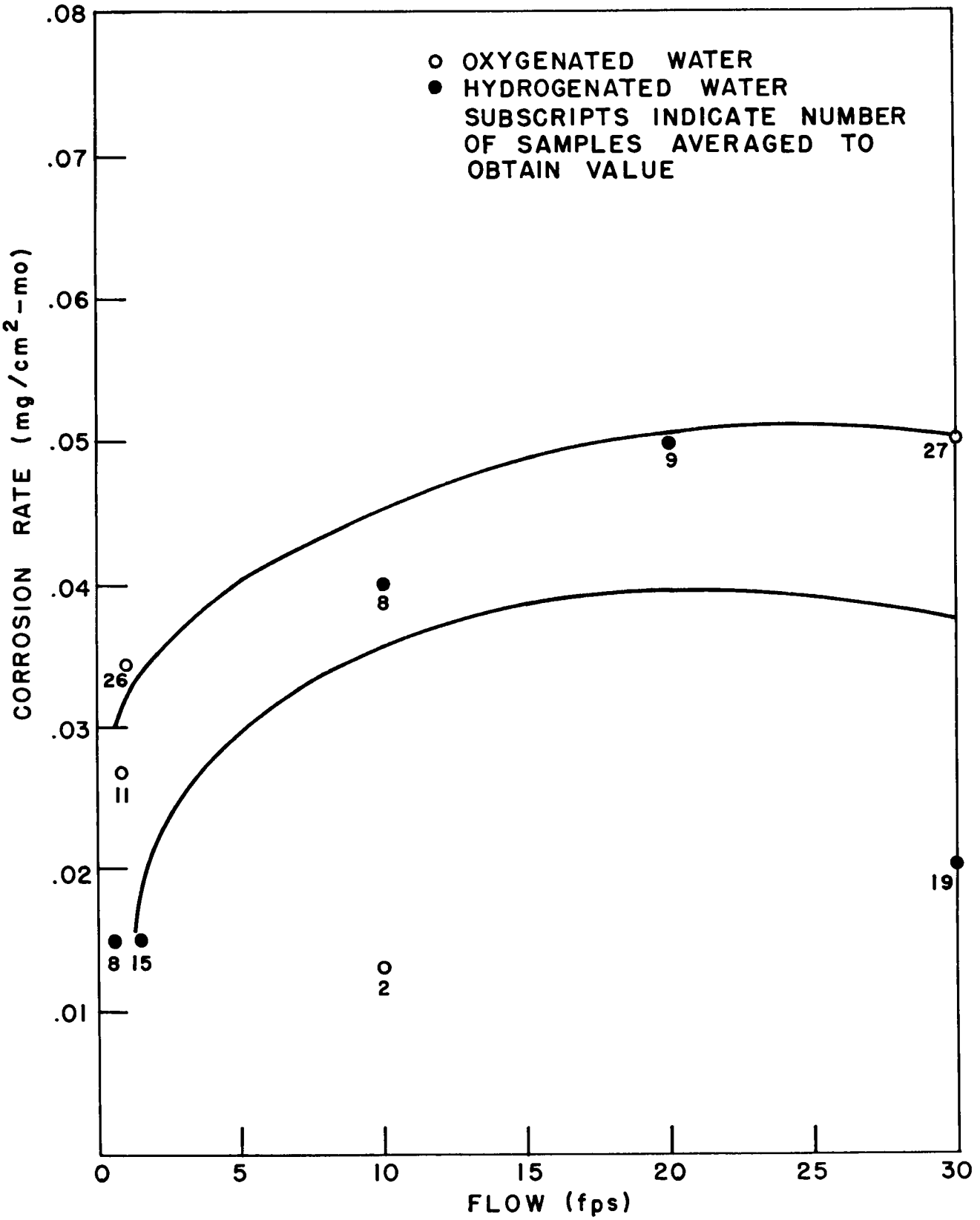

FIGURE 2. CORROSION OF TYPE-304 SS vs FLUID FLOW

TABLE XXVI: SOLUBILITY OF STAINLESS STEEL COMPONENTS[42]
(From Corrosion of 347 SS)

Water, pH 6.9; Resistivity, 1 meg-cm, Originally

Time (hr)	24	100	500	1000	1000	1000	500
Water Conditions	Degas.	Degas.	Degas.	Degas.	200 ml O_2/L	200 ml H_2/L	LiOH pH-10
600° F							
Fe ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Ni ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cr ppm	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Room Temperature							
Fe ppm	<0.03	0.05	<0.03	0.03	<0.03	0.03	<0.03
Ni ppm	<0.03	<0.03	<0.03	0.05	<0.03	0.03	<0.03
Cr ppm	<0.03	0.03	<0.03	0.03	<0.03	0.03	<0.03
Corrosion Rate (mg/cm^2-mo)	0.05	<0.02	0.002	0	0	0	0.003
Iron wire only			0.45				

These solubilities ranged in the neighborhood of 0.03-0.05 ppm for stainless steels so that most of the corrosion products probably were carried in the undissolved state. The presence of loosely adhering corrosion products in nearly all loops suggested the probability that this material was transported by suspension rather than by solution.

At the generally accepted corrosion rate of 0.05 mg/cm^2-mo, the formation of the products of corrosion in the primary loop of the APPR, having a surface area of 4×10^6 cm^2, would be

$0.05\ mg/cm^2\text{-}mo \times 4 \times 10^6\ cm^2$

$= 0.200 \times 10^6\ mg$

= 200 g of corrosion products per month.

If the solubility of the corrosion products is accepted as 0.05 ppm, then the portion of the corrosion products in solution would be

5150 L in system = 5,150,000 ml

or approximately 5×10^6 g of water

$5 \times 0.05 = 0.25$ g of corrosion products in solution in loop.

The greatest portion of the corrosion products apparently is not in solution.

It is rather difficult to estimate what portion of the solid corrosion materials formed enters the water stream and what portion remains on the surface on which it was formed. A study of the corrosion rate charts indicates that a negative corrosion rate, or loss of material, occurs in the more rapidly flowing channels, and a positive corrosion rate, or material buildup, occurs in the more quiescent parts of the currents. If it is assumed that 50% of the corrosion products find their way to the stream, the material introduced into the loop would be

$0.5 \times 200 = 100$ g/mo.

A study of the material deposited on heat transfer surfaces and on fuel elements indicates that corrosion products preferentially coat out on surfaces of high energy exchange. The exact mechanism of such deposition - whether it be from solution or by electrical charge of the solid materials, or both - is in doubt, and is being investigated in some of the laboratories.

At Westinghouse it was found that local boiling or high temperature can cause corrosion deposition, while adjacent cooler areas are free of such deposits. Cooler portions of the hot zone have a less adherent covering of black magnetic oxide, while a brown or red-brown adherent hematite deposit is found in the hotter zones.

It is obvious that the corrosion products must not be permitted to accumulate in the loop. The purification of the water is based on the ionic content of the water, and is described in Section 3.206. In the proposed system, water would be purged from the primary loop at a minimum rate of 18 gph, and the loop replenished with deionized water. This purge and makeup will reduce the amount of transport corrosion products in suspension to one-tenth the value previously given, or 10 g, at any one time in the entire system. This quantity, furthermore, will not be cumulative. The purge system will also effect the removal of corrosion products in solution at the rate of 2.5 g per month.

The effect of the water velocity upon suspended corrosion product deposition was investigated in the Argonne[30] corrosion loop #2. The results seem to indicate a greatest deposition at about 18.5 fps. The deposition is lower for both high and low water velocities. The variation of particle deposition with water velocity is plotted in Figure 3.

At another facility at Argonne, the Component Assembly Test Facility[17], a somewhat different influence of fluid flow on corrosion product deposition was noted. Here the greatest deposition was at low velocity (~5 fps), less at an intermediate velocity (~18 fps), and least at high velocity (~33 fps).

[redacted]

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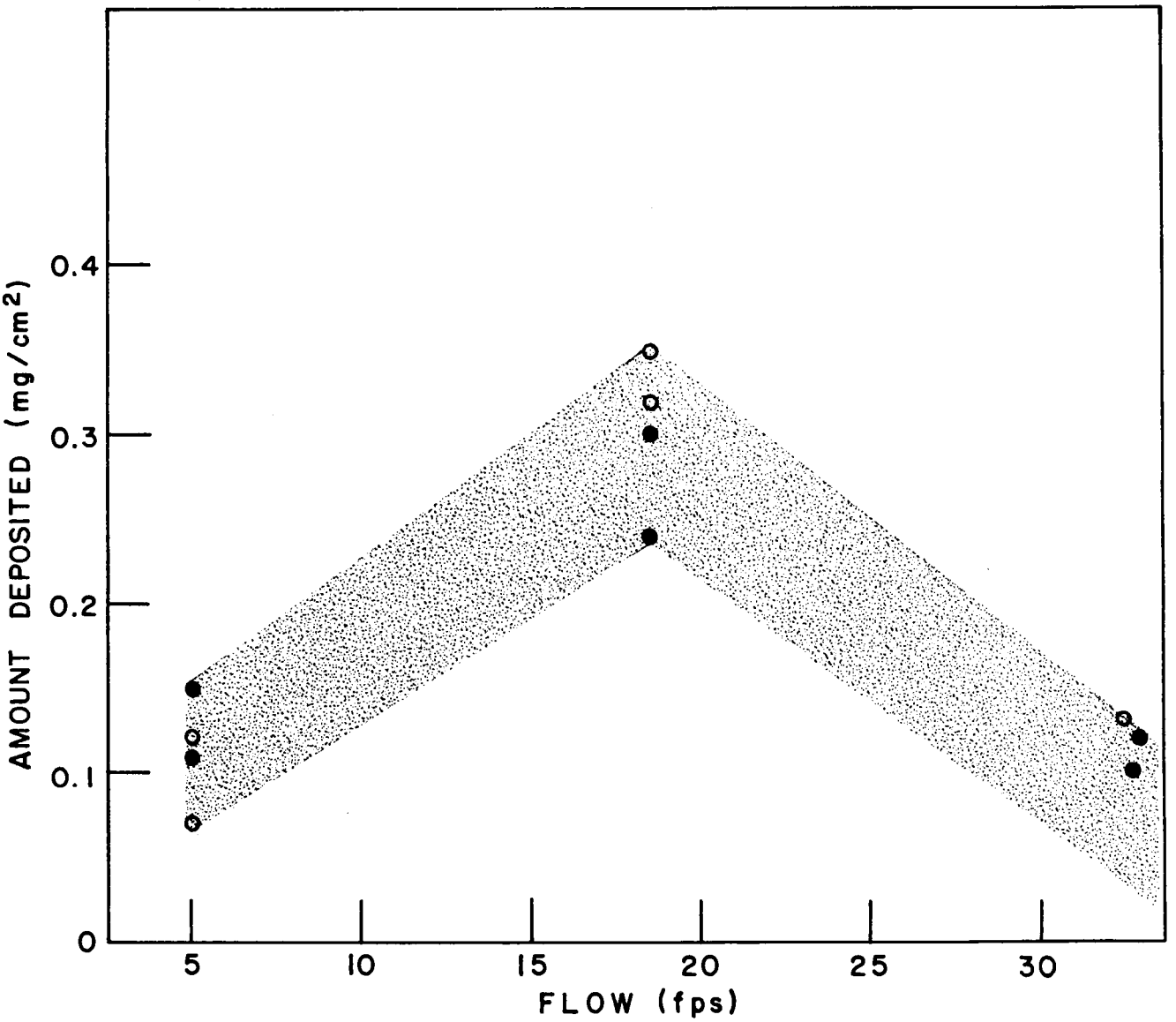

FIGURE 3. FLUID VELOCITY vs DEPOSITION OF CORROSION PRODUCTS

The effect of the solid transport materials can be alleviated further by the consideration of the following additional particle-flow characteristics:

a. At fluid flows of less than 10 fps, it was found that particles less than 0.5 microns to 0.1 microns will deposit out.

b. Fine particles tend to migrate from rapidly flowing streams toward areas of low turbulence. Larger particles remain suspended only in rapidly flowing streams.

c. Irradiation seems to have a coagulative effect on positively charged metal oxide particles.

d. Relatively larger amounts of deposit collect on converging components than on diverging components.

e. Relatively larger amounts of deposit collect at trailing ends than at leading ends on cross-shaped members.

It is therefore possible, by proper flow design, by proper purge outlet location, and by use of filters, to eliminate much of the remaining transport materials.

3.204 Effect of Irradiation of Materials on Their Corrosion Rates

The effect of irradiation of the materials on their corrosion rates, as distinct from the effect of such irradiation on the physical properties, was undertaken at some of the national laboratories. Most data were obtained at Hanford where an irradiated loop was established early. Some of the early results at Hanford as listed in Table XXVII, showed the effects of irradiation on corrosion.

TABLE XXVII: CORROSION OF MATERIALS IN ARGONNE LOOP AT HANFORD[33,12]

Material	Conditions	Irradiation (nvt)	Corrosion Rates (mg/cm^2-mo)
347 SS	25 cc H_2/L	F-1.1 x 10^{19} S-5.5 x 10^{19}	0.078
347 SS	25 cc H_2/L	F-1.8 x 10^{19} S- 9 x 10^{19}	0.105
17-4 PH		S-3.3 x 10^{19}	-0.012
Stellite-3		S-3.33 x 10^{19}	0.006

Later tests at Hanford employed samples which were irradiated, and controls, which were not, to obtain the comparisons listed in Table XXVIII.

TABLE XXVIII: CORROSION OF MATERIALS IN ARGONNE WATER LOOP AT HANFORD[23,12]

6 months at 540° F
1×10^{19} nvt fast 1×10^{20} nvt slow

Material	Flux Capsule 140-16F (mg/cm^2-mo)	Control Capsule 140-16F (mg/cm^2-mo)
347 SS no treatment	0.41	-0.10
347 SS inhibited with Pyrex	0.34	0.05
347 SS machined	0.30	0.09
17-4 PH	0.19	0.07
Stellite	0.03	0.33
17-4 coupled with Stellite-3	0.19	0.09
17-4 coupled with Stellite-3	-0.13	0.14
Monel	0.21	-0.86
Haynes Alloy-25	0.22	0.08
Stellite-6 with USS/W	0.01	0.16
Stellite-6 with USS/W	0.06	0.03

The results are erratic, although the tendency for the irradiated samples to corrode at a higher rate is apparent. An examination of the materials seems to indicate that a fair portion of the weight increases may be attributed to transport corrosion products described earlier in the report.

Other materials run in an ORNL irradiation loop for two weeks at 500° F, and 9 months at 150°-200° C in an integrated flux of 1.5×10^{20} nvt gave less divergent results, as listed in Table XXIX.

TABLE XXIX: IRRADIATION OF MATERIALS IN CORROSION TEST LOOP AT ORNL

Material	Corrosion Rate (mg/cm^2-mo) Irradiated	Non-irradiated
347 SS	-0.014	-0.009
347 SS	-0.017	-0.005
A-Nickel	-0.10	-0.20
A-Nickel	-0.20	-0.14

The corrosion of irradiated and unirradiated zirconium specimens was tested at Hanford with the results listed in Table XXX.

TABLE XXX: EFFECT OF IRRADIATION ON CORROSION OF ZIRCONIUM SPECIMENS AT HANFORD[15]

(Water at 540° F, 2064 hours)

Cartridges 140-B and 140-10

Supplier	Specimen No.	Wt Change (mg/cm^2-mo) Unirradiated	Irradiated
Westinghouse Crystal Bar	26-0	0.02	
	26-1		0.02
	26-2		0.14
Westinghouse Arc melted	27-0	0.01	
	27-1		0.01
	27-2		0.02
Foote Grade-1 Crystal	28-0	0.02	
	28-1		0.04
BM 0.2% Ta	29-0	0.08	
	29-1		0.01
	29-2		0.02
BM 6.2% Sn Arc melted	30-0	0.04	
	30-1		0.01
	30-2		0.01
BM 5.0% Sn Arc melted	31-0	-0.13	
	31-1		0.02
	31-2		0.04

From the results of the irradiated corrosion tests which were investigated, a clear cut pattern or result was not defined, and any difference in the corrosion rates between unirradiated and irradiated samples must be assumed small.

3.205 Effect of Irradiation on Decomposition of Water

Water under irradiation decomposes in part into its elemental components, oxygen and hydrogen. In tests run in an autoclave at Chalk River, with a volume of 1/8 liter at 500° F at 200 psi above saturation pressure, in an irradiated flux of $1.2 \times 10^{12} n/cm^2$-sec fast and $5 \times 10^{12} n/cm^2$-sec thermal, an analysis of previously degassed water showed the following[20]:

	DISSOLVED GAS (cc/L)				
Hours	H_2	O_2	CO_2	Inert	Total
20.5	4.8	0.72	0.4	2.7	8.6

thus, indicating a formation of new gases. The large excess of hydrogen beyond its stoichiometric ratio with oxygen suggests that the oxygen is consumed elsewhere, for example, by combining with the metals to form oxides, with carbonaceous materials to form carbon dioxide, and with nitrogen to form nitrates or nitric acid.

The corrosion products in stainless steel loops were found to contain iron as the major component. The chemical compounding of iron with oxygen is suggested to occur according to the following two formulas[20]:

1. $4\ H_2O + 3\ Fe \longrightarrow Fe_3\ O_4 + 4\ H_2$
2. $2\ O_2 + 3\ Fe \longrightarrow Fe_3\ O_4$

Experiments conducted by Argonne at Chalk River[20] on in-pile, out-of-pile, and pile-down experiments showed evidence that both these reactions occur. One effect of irradiation is then to supply oxygen for corrosion along the lines of Equation 2.

The decomposition of the water under steady-state conditions and 500° F was roughly estimated to vary as the square root of the radiation intensity. This is borne out in part by tests run under different flux densities at Chalk River in which a greater oxygen deficiency was found under a higher integrated neutron flux; Table XXXI illustrates this.

TABLE XXXI: EFFECT OF NEUTRON FLUX ON OXYGEN DEFICIENCY IN WATER[20]

(Test Loop at Chalk River)

Run No.	°F	Neutron Flux (neutrons/cm^2-sec)	Run Time (hr)	O_2 Deficiency cc(STP)
B5-1	500	$2.05 \pm 0.4 \times 10^{12}$ fast $2.7 \pm 0.5 \times 10^{12}$ thermal	5.3	0.09
B5-2	500	$2.05 \pm 0.4 \times 10^{12}$ fast $2.7 \pm 0.5 \times 10^{12}$ thermal	14.7	0.11
B5-3	500	$2.05 \pm 0.4 \times 10^{12}$ fast $2.7 \pm 0.5 \times 10^{12}$ thermal	20.5	0.26
B5-4	500	$2.05 \pm 0.4 \times 10^{12}$ fast $2.7 \pm 0.5 \times 10^{12}$	31.8	0.20
B5-C2	500	$1.2 \pm 0.5 \times 10^{12}$ fast $5.0 \pm 0.2 \times 10^{12}$ thermal	16.7	0.62
B5-1C	500	$1.2 \pm 0.5 \times 10^{12}$ fast $5.0 \pm 0.5 \times 10^{12}$ thermal	20.6	0.80

The irradiation of water, in addition to causing its decomposition, also affects the recombination of the oxygen and the hydrogen, which is dissolved in the water. Such recombination was checked in the previously mentioned Chalk River loop under varying flux densities and different temperatures with the results as shown in Table XXXII.

TABLE XXXII: HYDROGEN AND OXYGEN RECOMBINATION

In Chalk River Loop[20]

Water and Gas Phase Both Present

Run No	Temp (°F)	Initial Gas Concentration cc(STP)	Initial Gas Comb Rate cc(STP)/min	Final Gas Analysis (cc) (STP) H_2	O_2	N_2
Fast Neutron Flux 1 ± 0.5 x 10^{12}n/cm^2-sec						
C3-1	327	182	1.58	0.14	3.9	3.0
C3-2	327	180	1.55	0.20	5.8	3.2
C5-1	501	270	1.65	00	16.8	3.4
Fast Neutron Flux 2.05 ± 0.4 x 10^{12}n/cm^2-sec						
C3-1C	293	185	1.13	26.0	22.4	3.6
C3-2C	345	270	1.86	30.1	0.4	6.5
C5-1C	496	180	1.95	1.2	9.8	1.7
C5-2C	495	320	1.89	2.2	13.7	5.7

The net amount of oxygen and hydrogen released in the water will reach a steady-state quantity equal to the difference between the dissociation of the water and the recombination of the gases. This quantity is a function of temperature, pressure, presence of vapor phase, presence of purities, etc. The above tests seem to indicate that the presence of either an excess of hydrogen or an excess of oxygen will suppress the formation of the other. The tests listed in Table XXXI for the most part showed a suppression of the hydrogen which was attributed to an initial excess of oxygen. In test C3-2C (Table XXXII), the predominance of hydrogen was likewise caused by an initial hydrogen excess.

In a Hanford loop(7) at 540° F, no oxygen was discerned after steady-state conditions were reached. Oxygen was present originally, but its concentration gradually decreased to an immeasurable quantity. The hydrogen concentration reached about 2 cc/L at steady-state conditions in this loop and was as high as 35 cc/L. At Oak Ridge, the hydrogen concentration reached 10 cc/L under steady-state conditions.

The CO_2 concentration at steady-state conditions and 540° F at Hanford(7) reached about 6 cc/L without demineralizer, but went higher if oxygen was introduced into the system.

The quantity of nitric acid formed because of the water irradiation was estimated at 0.06 to 0.09 ppm.

The effect of water irradiation in the package reactor may be summed up as follows:

a. Irradiation of water causes dissociation of the water and its recombination. The rate of these reactions is a function of of the neutron density.

b. An excess of hydrogen in the reactor will inhibit the formation of oxygen. The net quantity of oxygen remaining in a hydrogenated system will be low but finite and will be combined with the materials in the system to form oxides.

c. Some of the gases formed may be transferred to the vapor phase in the pressurizer and from there may be eliminated from the system.

3.206 Effect of Water Purity on Corrosion

The tabulation of the corrosion rates does not correlate the influence of water purity upon corrosion because an insufficient number of samples included data on water purity. It is established, however, that low amounts of total dissolved solids must be maintained in the water to keep the corrosion rates low. In other sections of this report, the effect of undissolved corrosion particles upon the heating surfaces is discussed. It is established also that the corrosion products themselves are not very soluble, but that the effect of certain other ions in the water is to supply an electrolyte which can hasten or abet corrosion.

The water as obtained from outside natural sources may contain as much as 200 ppm of dissolved solids in it. These solids may be removed from solution by distillation or demineralization or both. If distilled water is normally available, as it is in the Army Package Power Reactor, then it would be most economical to use both distilled water and a demineralizer. The distillation process may remove the major portion of the dissolved solids and leave perhaps 5 ppm dissolved solids. The deionizer will then remove the remainder of the solids to the desired purity.

TABLE XXXIII: EFFECT OF ION EXCHANGER ON CORROSION AT ARGONNE[34]

Water at 500° F, 2 cc O_2/L, 500 hours

Material	Without Ion Exchanger (mg/cm^2-mo)	With Ion Exchanger (mg/cm^2-mo)
304 SS	0.17	0.04
316 SS	0.16	0.04
410 SS	0.16	0.34
440C SS	0.24	0.21

Experiments performed at Westinghouse resulted also in improved corrosion rates for materials run in loops with an ion exchanger as shown in Table XXXIV.

TABLE XXXIV: EFFECT OF ION EXCHANGER ON CORROSION AT WESTINGHOUSE[98]

Water at 500° F, 0-1 cc O_2, 1700 hours

Sample Number	Circuit with Ion Exchanger (mg/cm^2-mo)	Circuit without Ion Exchanger (mg/cm^2-mo)
1	-0.05	-0.09
4	-0.06	-0.09
7	-0.05	-0.09
8	-0.05	-0.09
10	-0.06	-0.10

The effect of lessened corrosion is further evidenced in improved heat transfer in loops at Babcock and Wilcox. In Loop "A" an ion exchanger was turned off during the 38th day of operation, and the overall heat transfer was 3,300 Btu/hr-ft^2-°F. On the 39th day the coefficient was reduced to 2,850 Btu/hr-ft^2-°F, and on the 45th day it was further reduced to 1,600 Btu/hr-ft^2-°F, or a decrease slightly over 50% in the overall heat transfer coefficient.

Conversely, Loop "B" started without an ion exchanger, and when an ion exchanger was placed in the circuit the overall heat transfer coefficient began to increase. During the subsequent 10-day operation the coefficient increased from 2,400 to 2,900 Btu/hr-ft^2-°F, from which it varied very little. The increase in this latter loop indicates that not only was the corrosion rate lessened, but that some corrosion products already on the heat transfer surface were either dissolved by the pure water or transported in a solid condition to the ion exchanger where they were filtered out of the circuit.

Similar improvement in the actual reactor at Chalk River (NRX) was observed after the installation of an ion exchanger. Without an ion exchanger it was determined that the resistivity of the water was 0.02 megohm-cm and the rate of decomposition of D_2O was 80 cc D_2/min and 40 cc O_2/min. After the installation of an ion exchanger consisting of two sets of filters and a one-liter mixed-resin bed, the resistivity of the liquid increased to 2 megohm-cm; the decomposition was reduced to 0.4 cc D_2/min and 0.022 cc O_2.min.

The use of ion exchange systems in typical corrosion loops is illustrated in Table XXXV.

TABLE XXXV: ION EXCHANGERS USED WITH VARIOUS TEST LOOPS

At 500° F

Ion Exchanger	Estimated Flow through Ion Arch (gpm)	Total Flow in Loop (gpm)	Flow through Ion Exchanger (%)	Total Water in System (gallons)	Average Resistance (megohm/cm^3)	pH
Argonne						
Loop #1	0.2	30	0.67	6.0	1.8	7.5
Loop #2	0.2	100	0.2	10.0	1.4	5.8
Loop #3	0.2	30	0.67	6.0	1.6	7.3
Component Ass'y Test	0.7-0.8	250	0.3	360.0		
Ball Bearing Lead Screw Assembly	0.1			5.0	0.24	8.5
Babcock & Wilcox						
Corr. Loop #2 (O_2)	0.02	30	0.067	2.96	1.0	6.8
Corr. Loop #3 (H_2)	0.02	30	0.067	2.96	---	6.8
Corr. Loop #4 (Deg)	0.02	30	0.067	2.96	---	6.8
Pilot Channel at ORNL	0.02	30	0.67	13.2	1.5	7.0
At Hanford	0.02	100	0.2	22.2	0.27 to 0.5	7.0

Calculation of Demineralizer. The purity of water may be measured by either its resistivity or its total dissolved solids. Of the two quantities, the resistivity is most easily measured, and will give the best indication of the ionic content of the water from the corrosion point of view. A knowledge of the amount of dissolved solids is helpful, on the other hand, in calculating the amount of demineralization required to effect high purity.

The relation between resistivity and total dissolved solids is not a fixed one since the resistivity is a function of ion activity which may vary from one type of ion to another.

In order, however, to establish a working relation between the two, selected known relations between resistivity and total dissolved solids are plotted on the graph shown in Figure 4. A relation covering the range in which the expected values fall was estimated.

For the package reactor the water in the primary loop will be maintained at 2 ppm (330,000 ohm-cm from the graph). The rate of decrease in resistivity in a system running without demineralizer was selected as a basis for the calculation of the amount of demineralization required. One typical loop at Argonne showed the decrease in resistivity with time as listed in Table XXXVI.

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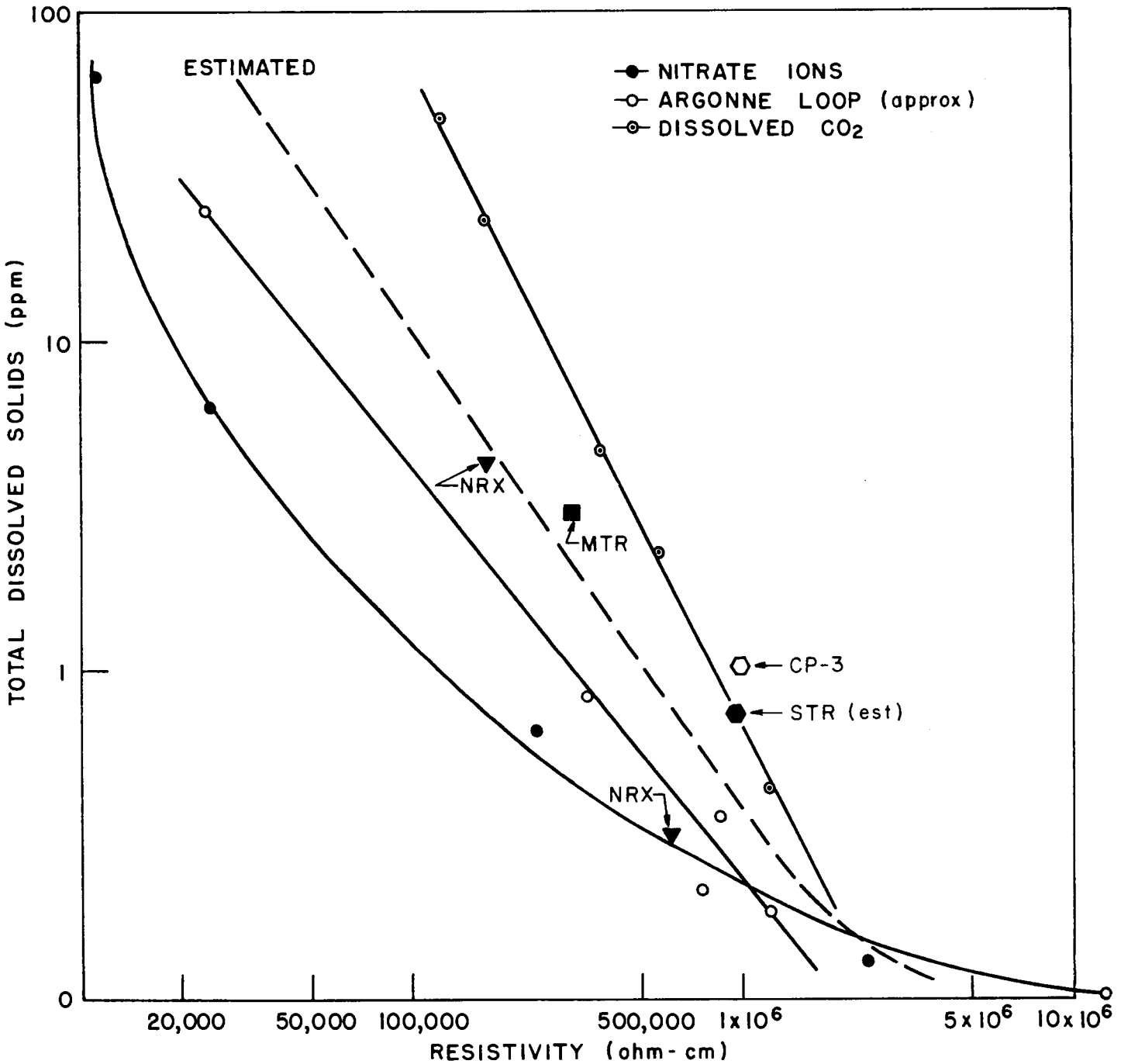

FIGURE 4. TOTAL DISSOLVED SOLIDS vs RESISTIVITY

TABLE XXXVI: EQUILIBRIUM RESISTIVITY WITHOUT DEMINERALIZATION[23]

Loop Condition	5 cc O_2/L 100-150 cc H_2/L Time (hr)	Temp (°F)	Resist (meg-cm)	0.38 cc O_2/L 100-150 cc H_2/L Time (hr)	Temp (°F)	Resist (meg-cm)
Startup	0	150	1.2	0	150	1.3
H_2 added	0.8	150	1.2	0.8	150	1.1
Start of 1st Const Temp Period	1.9	412	0.51	2.1	412	0.61
End of 1st Const Temp Period	2.4	412	0.48	2.8	412	0.57
Start of 2nd Const Temp Period	3.0	500	0.34	3.3	500	0.50
2nd Const Temp Period	3.5	500	0.30	3.7	500	0.50
End of 2nd Const Temp Period	7.2	495	0.30	77.1	500	0.44-0.48

In tests without hydrogen, the resistivity dropped to within less than 0.1 megohm-cm before temperature was reached.

From the above it can be seen that under operating conditions approaching that of our reactor, the resistivity drops from 1.3 megohm-cm to 0.44-0.48 megohm-cm in 77 hours which is seen to be, from Figure 4, equivalent to an increase in solid content of about 1 ppm.

If it is intended that the water be maintained at 2 ppm and if nondeionized water has its impurity increased by 1 ppm in 77 hours, then it would be necessary to completely replace the water in the system with water of 1 ppm purity in 77 hours. Thus the makeup water would have to be:

$$\text{Volume of loop in gallons} = 1365$$

$$\text{Makeup } \frac{1365}{77} = 17.8 \text{ gal/hr}$$

It was estimated by Sevitz and Scheibelhut at Argonne that 1 gram equivalent solids required 1 liter of cation resin and 2 liters of anion resin. The gram equivalent of the total dissolved solids was estimated by calculating the average molecular weight of dissolved solids in a

typical water sample at the Argonne pilot channel at Oak Ridge, as follows:

Material	ppm	Molecular Weight	%	Weighted %
(OH)	1.00	17	34	5.8
SO_4	0.3	80	10	8.0
Cl	0.2	36	7	2.5
NO_3	1.0	62	34	21.0
Ca	0.03	40	1	0.4
K	0.03	40	1	0.4
Mg	0.5	25	17	4.3
Na	0.3	23	10	2.3
Remainder	0.39	50 (assumed)	21	6.5
	3.00			45.2 Average Molecular Weight

Since it is necessary to supply make-up water (a minimum rate of 18 gph) of 1 ppm solid content, it is necessary to remove 4 ppm of the solids from the distilled water containing 5 ppm.

This quantity in terms of equivalents is then

$$\frac{0.004}{45.2} = 8.8 \times 10^{-5} \text{ equivalents/L}$$

$$= 6.0 \times 10^{-3} \text{ equivalents/hr}$$

at 8750 hr/yr

$$= 52.5 \text{ equivalents/yr}$$

The resin required for deionization at 3 L/g equivalent

$$= 157.7 \text{ L/yr}$$

Commercial deionization units may be employed for deionization in which the quantity of resin has already been calculated. One such unit, The Barnstead Model MM-2, will supply the needs of the Army Package Power Reactor as follows:

The unit will provide 1300 gallons of water whose mineral content has been reduced from 10 gr/gal to 10 ppm. The demineralization is therefore

$$10 \text{ gr/gal} = \frac{10}{7000} \times \frac{10^6}{8.3}$$

$$= 170 \text{ lbs}/10^6 \text{ lbs}$$

$$= 170 \text{ ppm.}$$

The net solids removal is then 160 ppm. The equivalent purifying capacity of the deionizer when used on the reactor would be

$$1300 \times \frac{160}{4} = 52{,}000 \text{ gal of water with 4 ppm removal.}$$

At the make-up rate of 18 gal/hr then

$$\frac{52{,}000}{18} = 2900 \text{ hr}$$

$$= 120 \text{ days.}$$

The demineralizer would have to be regenerated every 120 days.

It is of interest to note that the use of a by-pass circulating system would require the removal of 1-2 ppm solids by the demineralizer instead of 4 ppm. This would have the effect of either reducing the size of the demineralizer to almost 1/3 the size or lengthening the period of use of the same demineralizer without regeneration for the longer periods of time - in this instance from 4 months to 1 year. In order to properly compare the recirculating system with the purge-makeup system, other factors, such as the need for cooling, shielding, high pressure, etc., should be considered.

The amount of regenerative chemicals required for the purge-makeup system with the MM-2 demineralizer is 50 pounds of hydrochloric acid and 25 pounds of sodium hydroxide per year.

It should be pointed out that in the discussion on the required capacity of the demineralizer, the following two factors were neglected:

a. The effect of initial dirt in the system.

b. The effect of increasing cleanliness in the system.

The amount of initial dirt in the primary loop may be large. In spite of all the precautions which are taken (see Section 6.00), the large amount of dirt initially removed may well consume several loads of demineralizer before the water attains the desired purity.

It was found that the rate of contamination of the loop water decreased as the loop continued to operate even after the desired purity was attained. Pratt and Whitney determined that the specific resistivity of water in a loop decreased less and less with successive batches of pure water as shown in Figure 5. This same figure also shows the curve drawn from Table XXXV which was used to establish the demineralizer requirements.

The resin bed size in the Chalk River irradiation test loop installation was based upon the corrosion rate of 0.702 mg/cm^2-mo of aluminum which came to about 9 grams of aluminum per month for that system. It was found erroneous to base the ion exchanger size on the corrosion rate since only about 5% of the calculated aluminum was collected by the resin bed.

The operation of Chalk River loop resulted in cation resins carrying practically all the radioactivity. After elution with acid the gamma activity was reduced from 300 to 5 mr/hr at 1 in. The pickup of metal ions that contribute heavily to long-lived activity, such as Co, Cr, Mo, and Mn, was relatively low. The anion resins were in most cases exhausted by CO_2. The resins in general were not harmed by the radioactivity.

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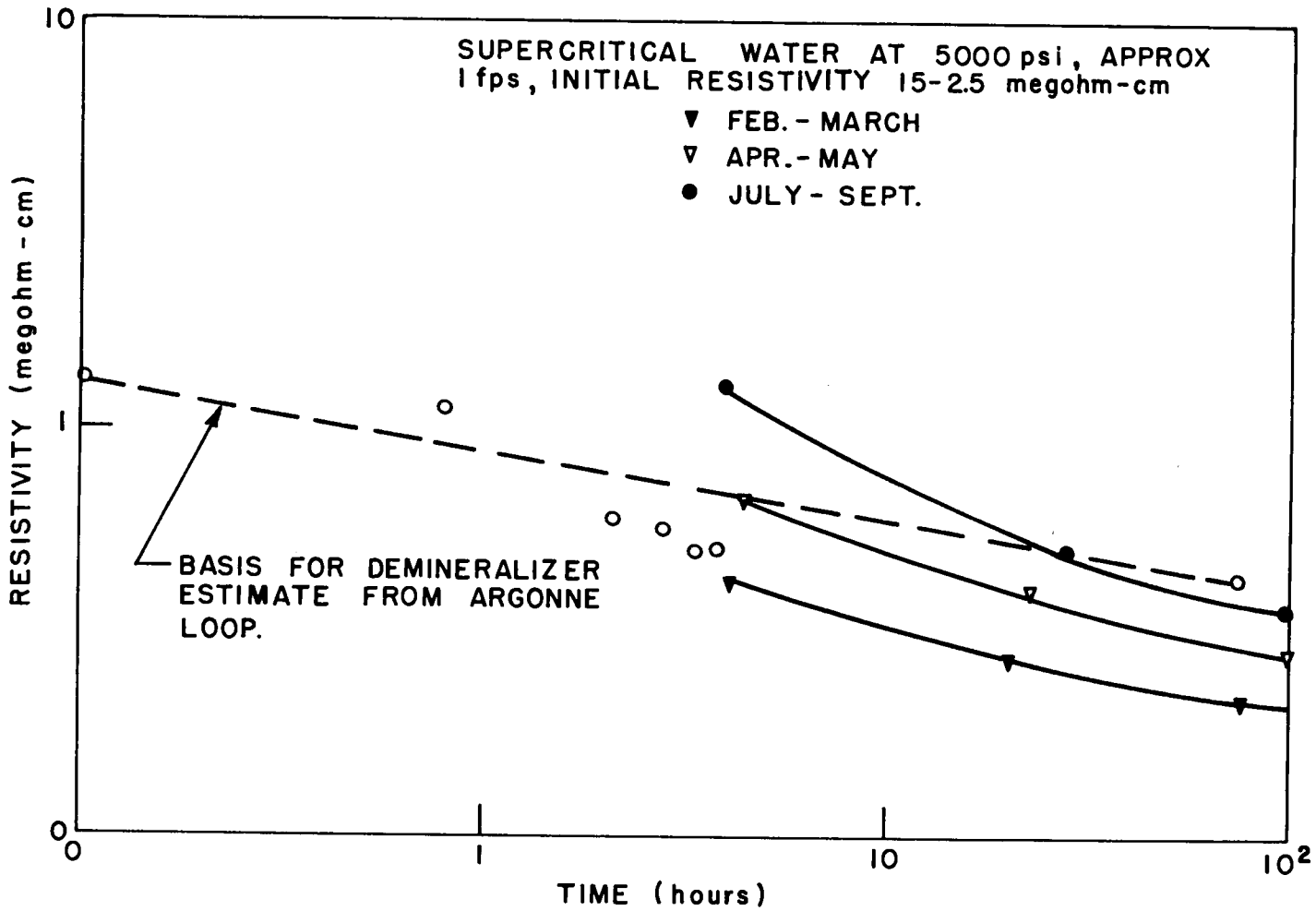

FIGURE 5. CONTACT TIME vs RESISTIVITY

The use of ion exchangers was found useful also in reducing by as much as sixfold both the long-lived gamma activity due to cobalt-60 and the activities other than N^{16} and O^{19} in pumping and heat exchanger areas.

3.207 Effect of Stress on Corrosion

It might be expected that stressing metals would decrease their corrosion resistance, particularly in the instance of welded austenitic stainless steels and other materials subject to carbide precipitation at the grain boundaries. This was not the case for the austenitic stainless steels stressed to 10,000 psi and submerged in 600° F water containing some oxygen in solution. Furthermore, dissimilar stainless steel materials welded together, such as 304 welded to 347 and tested for 1217 hours under the same conditions, showed no excessive corrosion rate. Likewise, 321 SS tested in 600°F water and stressed at 10,000 psi for 3149 hours showed a corrosion rate of 0.084 mg/cm^2-mo. In still another instance, 304 SS was welded to 347 SS and tested in a dynamic loop at 30 fps and 10,000 psi stress for 895 hours; this resulted in a corrosion rate of 0.0028 mg/cm^2-mo. There was no noticeable difference in the stressed and unstressed condition of the Stellites and K-Monel.

Later tests at Argonne showed the effects of stress corrosion testing (see Table XXXVII), in a dynamic loop at 25 to 30 fps, 500° F deionized water, containing 1.2 cc O_2/L and stressed at 10,000 psi.

TABLE XXXVII: CORROSION RATES AND TENSILE PROPERTIES OF STRESSED STAINLESS STEELS[17]

Type	Corrosion Rate (mg/cm^2-mo)	Physical Properties Ultimate(psi)	% Elong
304L, #1	-0.011	85,500	78.8
304L, #2	0.005	86,300	68.2
304L, welded to 304L #1	0.006	83,250	43.6
304L, welded to 304L #2	0.005	82,000	44.7
310 #1	0.004	102,000	36.9
310 #2	-0.039	105,500	42.3

The corrosion rates are low and are comparable to the corrosion rates of unstressed corrosion specimens. The physical properties of the materials themselves likewise do not differ from the normal physical properties expected of these materials.

If 10,000 psi is considered a safe working stress for the materials, then no difficulties should arise due to excessive corrosion on this account. Some indication that much higher stresses can be used without any detrimental corrosion was obtained by tests run at Battelle. Type-347 SS, stressed to 30,000 and 50,000 psi for 16 days, and exposed to degassed, super-heated water at 1000° F showed no cracks, although some permanent set did occur where the yield stress was exceeded.

A working stress of 10,000 psi is a low figure to use on some of the alloys whose yield strength is above 50,000 lbs. Although definite evidence is lacking that a higher working stress value than 10,000 psi may be used, it is felt that a normal conservative factor of safety could be applied in the instances of very high strength materials. The stressing of a material may be likened to the sensitizing of a material discussed earlier in the report, where the grain boundaries became susceptible to

corrosion attack. The fact that the water temperature is not high enough to cause this corrosion should apply also to grain boundary conditions caused by stressing.

Some tests run at Knolls[58] on welded pipe showed fairly high stress rates induced by the welding as seen in Tables XXXVIII and XXXIX.

TABLE XXXVIII: STRESSES IN 5-INCH PIPE[58]

36" long, 1/2" wall

Longitudinally Welded

Location	Circumferential Stress(psi)	Longitudinal Stress(psi)
4" from 1 end	23,000	11,000
4" from other end	27,000	11,800
9" from first end	22,100	22,000
At center	21,000	22,600
347 SS initially stress relieved		

TABLE XXXIX: RESIDUAL STRESSES IN PIPES AFTER LOW TEMPERATURE ANNEAL

Type 347 SS

Pipe	Condition	Outer Surface	Inner Surface
5" O.D.	As welded	14,000	-16,000
1/2" wall	1200° F	12,000	-15,000
9-1/2" O.D.	As welded	18,000	-23,000
1-1/2" wall	1100° F	16,000	-22,000
	1200° F	14,000	-22,500
5" O.D.	1650 - 2 hours	0	0
1/2" wall	1850 - 1 hour	0	0

From Table XXXIX it can be seen that stress relieving at a proper temperature eliminates the internal stresses set up.

It was suggested that the stress relieving of austenitic stainless steels, after welding, is unnecessary[58]. In fact, the stress relieving over 1650° F may lead to stress relief cracking. In order to maintain dimensional stability, lower the stresses, and minimize corrosion in the welded structures, it is suggested that partial annealing in the range of 800°-1000° F for the austenitic stainless steels be used, wherever possible.

Residual stresses form a self-balancing system which in all probability is different from a system of external loads so that they are not additive. As a matter of fact external loads high enough to cause plastic flow would set up a new set of stresses other than those caused by welding.

In an analysis[61] of fatigue stresses in austenitic stainless steels at elevated temperatures the failure due to cyclic stress was determined by the magnitude of the plastic strain and the number of cycles. Thus stress failure and stress corrosion can be expected to occur at points of stress concentration. As in the case of stress fatigue, stress corrosion can be avoided by careful consideration of material variation, temperature variations, and design.

The stresses occurring between the fuel plates in the assembly can be alleviated also by proper design. The net stress in the individual fuel plates is difficult to estimate, but since the fuel plate is under no load other than the internal stresses and since the cladding maintains its elasticity even under irradiation, no serious corrosion consequences are anticipated because of the stresses in the fuel plates.

3.208 Effect of pH on Corrosion

In Section 3.206 it was indicated that the purity of water is measured either by its specific resistivity or by the parts per million of dissolved solids. A third measure of water purity is its hydrogen-ion concentration, or pH. The latter gage of water purity is a very rough yardstick, and, consequently, for very pure water the specific resistivity is determined in preference to the pH.

It is only when large variations from the neutral pH of 7 occur, that it becomes worthwhile to employ pH measurements. This is particularly true if it is necessary to determine whether a solution is acid (low pH) or alkaline (high pH). The determination of the pH of a solution will then help to establish whether excess CO_2 is present, or whether a proper amount of buffers or alkaline inhibitors has been added to the water. In these instances neither the amount of total dissolved solids nor the resistivity of the solution alone would give a true picture of the condition of the water. The effect of dissolved CO_2 in the water on its pH is shown in Table XL.

TABLE XL: EFFECT OF CARBON DIOXIDE IN WATER ON pH AND RESISTIVITY[93]

H_2CO_3 C	CO_2 (ppm)	Hydrogen Ion	pH	Specific Resist. (megohm-cm)
0.5×10^{-1}	2220	1.56×10^{-4}	3.81	0.02
10^{-2}	440	6.7×10^{-5}	4.17	0.04
0.5×10^{-2}	220	4.5×10^{-5}	4.35	0.06
10^{-3}	44	2.1×10^{-5}	4.68	0.12
0.5×10^{-3}	22	1.56×10^{-5}	4.81	0.16
10^{-4}	4.4	6.6×10^{-6}	5.18	0.38
0.5×10^{-4}	2.2	4.5×10^{-6}	5.35	0.55
10^{-5}	0.44	2.1×10^{-6}	6.68	1.2
0	0	1.0×10^{-7}	7.0	18.0

The presence of nitrate ions likewise increases the hydrogen ion concentration to lower the pH as shown in Table XLI.

TABLE XLI: pH AND RESISTIVITY VS NITRIC ACID CONCENTRATIONS[93]

pH	Hydrogen (ppm)	Nitrate Ion (ppm)	Calculated Resistivity (ohm-cm)
7	10^{-4}	0	18,000,000
6	10^{-3}	0.06	2,400,000
5	10^{-2}	0.62	240,000
4	10^{-1}	6.2	24,000
3	1	62	2,400

Both the above relation and the relation between the concentration of CO_2 in the water upon the specific resistivity of the water are graphically charted in Figure 4.

It has been determined also that the presence of either sodium hydroxide or lithium hydroxide in the water will raise the pH to between 9 and 12. This increase in pH will tend to reduce local pitting of the material at some sacrifice to the over-all passivity. The effect of such additions is apparent in the corrosion compilation summaries (Table XII) and is discussed further in Section 3.209. In the areas of water quality determination where its value has some meaning, the pH of a solution is shown to have a definite qualitative correlation to the corrosion potential of the solution. In the near neutral solutions, the approximate nature of the pH value and the small number of samples run in which an accurate

check of the pH was maintained, made it impracticable to arrive at any relation between corrosion rates and pH values. It is possible by using the values in Tables XL and XLI, and Figure 4 to arrive at a very rough qualitative estimate of the influence of pH on corrosion.

3.209 Effect of Inhibitors on Corrosion

Corrosion inhibitors are being used successfully in several water-cooled and moderated reactors at the present time. The Hanford pile utilizes water to which sodium dichromate and sodium silicate have been added. The swimming pool reactor at ORNL uses sodium dichromate. These additives are used to prevent corrosion to materials which are normally much more readily corroded than those being investigated, such as aluminum and carbon steel. The corrosion tabulation includes listings of corrosion tests in which inhibitors were added; in some instances, a definite inhibition trend can be detected. The most promising inhibitor is hydrogen; its effect upon corrosion rates was discussed in Section 3.201. Other additives which will be discussed in this section and which show inhibitive tendencies are sodium hydroxide, lithium hydroxide, and hydrazine hydrate.

The use of hydrazine hydrate has been suggested as an inhibitor and is being tested at Brookhaven. In use, hydrazine decomposes and introduces hydrogen gas into the solution. Initial test results showed that hydrazine at 0.1484 g/L under irradiation gave the following results[121]:

pH	101 - 10.5
Total gas	128 cc/L
O_2	5.49 cc/L
CO_2	2.68 cc/L
H_2	69.95 cc/L
N_2	49.83 cc/L (by difference)

It was determined that some combination of hydrogen with nitrogen occurred to form ammonia. Ammonia in turn was irradiated with the following results:

Conditions	O_2	H_2	N_2	CO_2
1 molar solution at 7-1/2 hours	12%	63%	25%	
2980 cc/L at 120 hours	62 cc/L	2070 cc/L	842 cc/L	6.2 cc/L

The effects of sodium hydroxide in small quantities on the corrosion rate of various materials are illustrated in tests run at Babcock and Wilcox. In these tests 106 mg of NaOH was added to the water to obtain a pH of 10 which resulted in the values shown in Table XLII.

TABLE XLII: EFFECT OF NaOH ON CORROSION (mg/cm^2-mo)(3)

	30 fps		1 fpm	
Material	pH-10 1.7 cc O_2/L	pH-7 2.1 cc O_2/L	pH-10 1.7 cc O_2/L	pH-7 2.1 cc O_2/L
Monel	-0.15	-0.46	-0.01	-0.14
304 SS	-0.05	-0.06	0.01	0.01
440C SS	-0.17	-0.09	--	--
K-Monel, annealed	-0.04	-0.45	0.000	0.01
K-Monel, hardened	-0.18	-0.44	0.00	-0.05
Inconel	-0.02	-0.22	0.02	0.01
316 SS	-0.07	-0.04	0.01	0.01

The addition of lithium hydroxide to the water effected similar corrosion inhibition. It was shown previously that crevice corrosion was most feared because it could cause equipment to bind, and that the addition of H_2 to the water loop minimized this crevice corrosion effect. Additional experiments were reported at Battelle in which small quantities

of LiOH (20 ppm) alleviated the crevice corrosion to some extent as shown in Table XLIII.

TABLE XLIII: EFFECT OF LiOH ON CREVICE CORROSION[41]

Water at 600° F with 300 cc O_2/L

Couple	Clearance mils	No LiOH, Seizure 2 wk	No LiOH, Seizure 6 wk	With LiOH(20 ppm), Seizure 2 wk	With LiOH(20 ppm), Seizure 8 wk
410 SS vs 410 SS	0.5	Severe	Severe	None	Severe
347 SS vs 347 SS	0.5	None	None	None	None
430 SS vs 430 SS	0.5	Slight	Severe	None	Severe
17-4 vs 17-4	0.5	None	None	None	None

Although mitigation of seizure was accomplished in some instances, the alleviation was not quite as complete as when hydrogen was used. Hydrogen additions prevented seizures in all the combinations listed above. The above experiments were run with excess oxygen, however, and the use of LiOH in the water together with degassification might improve the hydroxide's inhibitive qualities.

Lithium hydroxide may be added to the water by means of a LiOH regenerated ion exchanger and was used in the Bettis mock-up of the STR. A tabulation of such a run shows low corrosion rates for the materials as indicated in Table XLIV.

TABLE XLIV: EFFECT OF LiOH ON CORROSION USING REGENERATION ION EXCHANGER[102,103]

Temperature 500° F, pH-10 - 10.5

Material	Corrosion Rate (mg/cm^2-mo) 10 fps	20 fps
347 SS machined	0.0 to -0.01	------
347 SS machined	------	-0.005 to 0.00
347 SS electropolished	------	-0.01
304 SS machined	0.005	0.005
17-4 PH machined	-0.01	-0.02
Inconel machined	------	0.04
Inconel-X machined	0.06	------
410 SS machined	-0.08	-0.09

Still other inhibitors are being investigated. These include sodium diphosphate, sodium arsenate, morpholine, and pertechnetate. The results of some of these inhibitors on ASME A-212B steel are shown in Table XLV.

TABLE XLV: CORROSION INHIBITION IN ASME A-212B STEEL

at 600° F in Water, 0.5 ppm O_2, 6-8 megohm

Inhibition	Gram/L	Time (hr)	pH	Weight Change (gm/dm^2-mo)	Descaled (mg/cm^2-mo)
$NaHPO_4$	5	23	9.7-9	-0.027	-0.90
$NaHPO_4$	10	22	10-9.8	0.063	-0.83
Morpholine	10	8	10.4-9.7	0.005	0.16

Other materials tested with morpholine are listed in Table XLVI.

TABLE XLVI: STATIC TESTS WITH MORPHOLINE

Water at 600° F, 6 days

Concentration 10 g/L initial; 4.7 g/L final

Material	No of Samples Averaged	Corrosion (mg/cm^2-mo)
A-212B	4	0.1
2 1/4% Cr - 1% Mo	4	0.13
1 1/4% Cr - 1/2% Mo	4	0.18
5% Cr - 1/2% Mo	4	0.15
304 SS	4	0.025

Other inhibitors investigated at Argonne included silicon dioxide, zinc dioxide, and germanium dioxide, with the results shown in Table XLVII.

TABLE XLVII: STATIC CORROSION INHIBITOR STUDIES[31]

Initially Demineralized Water Saturated with O_2

Material	Inhibitor	Conc (ppm)	Time (hr)	Weight Change (mg/cm^2-mo)	Appearance
347 SS	GeO_2	2000	166	0.01 -0.01	
347 SS	GeO_2	500	166	-0.006 0.006	
347 SS	GeO_2	100	166	-0.01 0.006	
347 SS	GeO_2	250	502	0.03 0.02	Blue-gray
347 SS	GeO_2	50	502	0.01 0.03	Uniform
347 SS	SiO_2	312			Straw
347 SS	GeO_2	815	162	-0.01 -0.02	Straw
347 SS	SiO_2	157			
347 SS	$Zn(OH)_2$*	500	160	0.014 0.03	Light
347 SS	$Zn(OH)_2$*	50	160	0.06 0.01	Purple
347 SS	ZnO	100	192	0.01 0	Straw
2S Al	GeO_2	2000	162	1.0 1.0	White scale
2S Al	GeO_2	500	162	0.8 0.9	Dull white
2S Al	GeO_2	200	162	2.3 2.5	Dull gray
SAE 1020	$Zn(OH)_2$	1000	161	1.6 1.0	
SAE 1020	$Zn(OH)_2$	250	161	1.4 1.3	
SAE 1020	$Zn(OH)_2$	500-H_2	161	2.5 0.5	
SAE 1020	None	H_2	162	1.0 1.0	Smooth black

* H_2 saturated instead of O_2

Progress is being made on the use of these materials on normal carbon steel; some reactor in the near future may employ an inhibitor which will permit the use of regular carbon steel as the major structural material.

3.210 Effect of Galvanic Couples and Crevices on Corrosion

Any discussion of galvanic couples touches upon what is considered the basic mechanism of corrosion; many of the previously mentioned corrosion factors can probably be shown to either inhibit or promote the formation of galvanic couples. The inhibitors probably attempt to form an irreversible electrode effect, promote anodic or cathodic polarization, alter the current distribution, or increase the resistance in the liquid or metallic circuits.

Crevices, of course, are locations where the galvanic couple gap has been shortened to a point that transmission of ions is relatively easily accomplished. Methods of mitigating crevice corrosion by the use of hydrogen and by the use of hydroxides were discussed in previous sections of this report.

The effect of the crevice width itself was checked in tests run at Argonne. In these tests pistons of mating materials with varying crevice gaps were inserted in Stellite-3 cylinders; assemblies were submerged in water containing 30 cc O_2/L. Some correlation between temperature and gap is readily discernable from the results of these tests given in Table XLVIII.

TABLE XLVIII: COUPLE-CREVICE CORROSION TESTS[17]

Water, 30 cc O_2/L, 421 hours

Couple	Temp(°F)	Crevice Width(in.)	Comments
Stellite-3 with 17-4 PH	200	0.008 one end and 0.0024 other end	No freezing
Stellite-3 with 17-4 PH	200	0.0027	No freezing
Stellite-3 with 17-4 PH	200	0.0022	No freezing
Stellite-3 with 410 SS	200	0.0029	No freezing
Stellite-3 with 410 SS	500	0.0027	Partial freezing
Stellite-3 with 17-4 PH	500	0.0024	Couple froze
Stellite-3 with 410 SS	500	0.0021 one end and 0.0084 other end	No freezing
Stellite-3 with 17-4 PH	500	0.0028	Couple froze

Journal-sleeve type couples were tested at Battelle to determine the clearance under which no seizure would occur, and the results are listed in Table XLIX.

TABLE XLIX: JOURNAL-SLEEVE CREVICE TESTS[41]

Test Conditions	Exposure (wk)	Sleeve Material	Journal Material	Dia (mils)	Seizure (lb to free)	Max Buildup (mils)
500°F H_2O w 30 cc O_2/L	2	17-4 PH	Cr plate 17-4	1.2	50	0.5
500°F H_2O w 30 cc O_2/L	2	347 SS	347 SS	0.9	50	0.5
600°F degassed	2	17-4 PH	Cr plate 17-4 PH	0.6	50	0.5
600°F degassed with 20 ppm LiOH	2	17-4 PH	Cr plate 17-4 PH	2.8	none	0.5
600°F degassed with 20 ppm LiOH	2	347 SS	347 SS	2.1	none	0.5
600°F, 60 cc O_2/L	2	17-4 PH	Cr plate 17-4 PH	2.1	none	0.5
600°F, 600 cc O_2/L	6	17-4 PH	Cr plate 17-4 PH	4.6	none	0.5

Other coupled materials, irradiated in water at Hanford for 6 months at 540° F in an integrated flux of 1×10^{19} nvt (fast) and 1×10^{20} nvt (slow), showed no galvanic corrosion effect. They are:

17-4 PH vs Stellite-3
17-4 PH vs Haynes Alloy-25
17-4 PH vs USS/W
Stellite-6 vs USS/W
Haynes Alloy-25 vs USS/W
Haynes Alloy-25 vs Stellite-3

The position of materials in the electromotive series is of limited assistance in the selection of non-corrosive materials in a reactor loop. Most materials employed are alloys of various elements whose position in the electromotive series may vary with the particular portion of the loop in which they may find themselves.

Argonne[25] has tested externally applied potentials aimed at the prevention of the deposition of the colloidal transport corrosion products onto the fuel plates. The methods being checked, which have met with partial success, employ (a) a charge on the fuel plates the same as that of the transport products so that these materials will be repelled, and (b) an opposite charge on dummy plates so that the colloidal particles will coat out on them and so be removed from the loop. These investigations are continuing.

3.211 Effect of Surface Finish on Corrosion

The surface finish of a material can be divided into two categories:

(a) The first type of finish concerns itself with the smoothness or the irregularity of the surface. This smoothness, which may be measured in micro-inches, is normally a function of the fabricating process. Thus, materials may be ground, machined (turned on lathe, milled, shaped), electropolished, buffed, vapor-blasted, as-cast, as-rolled, etc.

(b) The second type of finish, where the smoothness is normally not measured, consists of coatings and impregnations. This includes electroplated surfaces (such as chrome-plate), and impregnated surfaces (such as anodized, Malcomized, Scottsonized, Parkerized, and Chromallized surfaces).

Smoothness of Surface. It can be generally proven that the finer the finish of the surface, the less it is subject to continued corrosion. In tests at Westinghouse, stainless steel 347 subjected to a 985-hour exposure in 500° F water containing 82-136 cc H_2/L, a water resistivity of 3,000,000 ohm-cm and flowing at 20 fps, showed the following corrosion rates:

Material	Average Corrosion Rate (mg/cm^2-mo)
Machined (12 pieces)	0.05
Electropolished (3 pieces)	0.03

A smooth surface offers less foothold for foreign materials and therefore is less likely to form small galvanic cells. The possibility that small cells can form in what otherwise appears to be a smooth surface is illustrated in tests run at Westinghouse where vapor-blasted surfaces showed aggravated corrosion when compared with machined surfaces (see Table L).

TABLE L: EFFECT OF SURFACE FINISH ON CORROSION[17]

Water at 500° F, 500 hours

Material	Time (hr)	Conditions	Corrosion Rate (mg/cm^2-mo) Machined	Vapor-Blasted
347 TaCb	500	500 cc H_2/L	0.01	-0.13
347 TaCb	1000		0.00	-0.03
347 TaCb welded	500	0.2 cc O_2/L	-0.41	-0.78
347 TaCb welded	500	Degassed	-0.09	-0.33
347 TaCb welded	1000	0.2 cc O_2/L	-0.05	-0.46
347 TaCb welded	1000	2.0 cc O_2/L	0.00	0.01
347 TaCb welded	1000	Degassed	-0.04	-0.17
347 TaCb welded	1500	Degassed	-0.04	-0.13
316 SS	500	500 cc H_2/L	0.00	-0.02
316 SS	500	Degassed	-0.04	-0.35
304L SS	500	0.2 cc O_2/L	0.01	-0.75
304L SS	500	2.0 cc O_2/L	0.04	0.03
304L SS	500	500 cc H_2/L	-0.04	-0.08

Additional tests under the same conditions but at 1 fpm showed similar results.

Surfacing Effect on Corrosion. Most of the special treatment of surfaces has resulted in increased corrosion rates for the materials. This is particularly true of surfaces hardened by a form of carburization, such as Malcomizing or Scottsonizing. Another surface treatment called "Chromallizing" also decreased corrosion resistance.

Some effects of various surface treatments, as determined at Argonne, are summarized in Table LI.

TABLE LI: EFFECT OF SURFACE TREATMENT ON CORROSION[3]

Material	Temp	Time (hr)	Test Conditions	Corrosion Rate (mg/cm^2-mo)
304 SS Chromallized	500	400	30 cc O_2/L	-2.4
304 SS Malcomized	500	1857	30 cc O_2/L	-0.24 to 0.064
304 SS Malcomized	500	1450	30 cc O_2/L	0.048 to-0.41
304 SS Malcomized ground & polished	500	337	Degassed	0.50
440C SS Malcomized ground & polished	500	4475	30 cc O_2/L	-2.2
17-4 PH Malcomized ground	500	3974	30 cc O_2/L	0.79 to 0.041
USS/W Malcomized polished	250	353	Degassed	0.27
302 SS ground & Scottsonized	500	325	Degassed	3.30
302 SS ground & Scottsonized	500	325	30 cc O_2/L	-0.29
347 SS polished & Scottsonized	500	1476	30 cc O_2/L	-0.017 to -0.200

Chrome-plated materials generally showed good corrosion resistance except in certain high-flow rate oxygenated systems.

3.212 Effect of Acid Cleaning and Passivation on Corrosion

It is desirable to be able to clean the primary loop materials with acid for the following reasons:

1. Welds should be cleaned to remove scale and oxidized surfaces which could form nuclei for crevice and pitting corrosion.

2. Strongly irradiated surfaces can be readily decontaminated with an acid bath.

3. Carbon steel materials left on the surface of stainless steels by tool bits, rolls, etc., can be removed by pickling.

4. The surface of many materials undergoes passivation after exposure to acid.

In the section on welding and heat treatment, the corrosion of non-stablized (no Cb or Ti) stainless steels in water was of concern. The investigation proved that undue corrosion did not occur in 304 SS at welds. The treatment of metals with acids may be likened to an accelerated corrosion test; as in the instance of water corrosion, no indication that cleaning with acid will harm any of the 300 series stainless steels has been found.

The effect of acid cleaning on 347 SS was checked at Argonne[8]. Three groups of welded 347 SS channel, after boiling in water to remove soluble alkalis and slag, were treated in the following ways:

(a) Left "as is".

(b) Cleaned for 1 hour in 10% HNO_3 at 170° F.

(c) Cleaned for 1 hour in 15% HNO_3 and 2% HF solution at 170° F.

The samples were then tested in oxygenated water at 500° F for 1800 hours with the following results:

Sample a. Showed dark purplish-brown film with narrow band of loose material at weld.

Sample b. Same as sample (a), but lighter in color.

Sample c. Light blue to silvery color.

These tests indicate that some corrosion inhibition was obtained by the acid cleaning of the specimens.

Tests at Westinghouse on 347 SS in water at 500° F, 100 cc H_2/L of water, 500 hours, and 20 fps showed the results listed in Table LII.

TABLE LII: EFFECT OF ACID CLEANING ON CORROSION[100,102,103]

Material	Corrosion Rates (mg/cm^2-mo) Degassed	Not-degassed
347 SS, as machined	-0.03	-0.03
347 SS, as machined	-0.02	-0.03
Passivated 30% HNO_3	0	-0.03
Pickled 20% HNO_3, HF 5%	0.01	0.01
Pickled 10% H_2SO_4	0	-0.01

A comparison of the effect of molten nitrates with up to 10% excess nitric acid on various types of 300 series stainless steels was made by Mallinkrodt. An average of 25 exposures gave the results shown in Table LIII.

TABLE LIII: CORROSION OF STAINLESS STEELS IN NITRIC ACID (10%)[77]

Penetration (in./mo x 10^{-3})

Form	Condition	Medium	304	304 HC	347	316	317R	309 cb
Sheet	Annealed	Vapor	0.38		0.34	1.07	0.93	0.21
Sheet	Welded	Vapor	0.69		2.40	5.53	6.71	0.23
Sheet	Welded	Liquor	0.99		1.16	3.03	4.27	0.64
Sheet	Unstressed	Liquor						0.16
Sheet	Stressed	Liquor						0.15
Cast		Vapor	0.31	0.69	0.44	0.57		0.30
Cast		Liquor	0.44	1.11	0.52	1.35		0.48

The attack of stainless steels 316 and 317 was greater than the attack of stainless steels 304, 347, or 309 because of the molybdenum in the steel. Stainless steel 309 showed the greatest resistance to corrosion and 304 the next best. The welded 347 sheet showed pitting all over, not just at the weld line.

Many corrosion specimens listed in the gross tabulation were pickled in either nitric acid or nitric acid and hydrofluoric acid prior to testing. This treatment did not seem to increase the corrosion susceptibility of the materials.

3.213 Effect of Added Poisons on Corrosion

Experiments were conducted at Argonne to determine a suitable liquid poison which might be employed in the STR in an emergency. It would be desirable for such a poison not to injure the materials it came in contact with during the time it was in the loop. Of the many solutions investigated, boric acid was found to be the only compound stable at 600°F. The salts considered included LiCl, $LiNO_3$, $Li_2SO_4 \cdot H_2O$, $LiBO_2$, and $LiB_4O_7 \cdot 5H_2O$. In order to make the boric acid more soluble, lithium hydroxide was also added to the solution. The results of corrosion tests run in a boric acid-lithium hydroxide loop are shown in Table LIV.

The corrosion rates were erratic and did not follow the general pattern set by the corrosion rates of specimens in a pure water loop. The corrosion rates were sufficiently low, however, so that no permanent injury resulted to any of the loop components.

The boric acid loop otherwise showed no detrimental effects on the coolant. Additional decomposition of the solution in concentrations of 6.00 and 11.4 g/L at 500° F and a neutron flux of 6×10^{11} nvt, was not observed above that expected for the pure water. The amount of H_3BO_3 required to shut down the Mark I was estimated at 6.4 g/L[15].

None of the poison solution seemed to be permanently trapped in the system after wash down.

TABLE LIV: EFFECT OF SUBMERSION OF MATERIALS IN BORIC ACID POISON LOOP[27]

Demineralized water: 5 g/L H_3BO_3, 0.8 g/L LiOH, 500° F, 1-3 cc O_2/L

pH = 9, velocity 3.1 fps, and 620-hour operation

Material	Corrosion Rate (mg/cm^2-mo)
304L SS	0.088
304 SS	-0.22
309 SS	0.16
316 SS	0.035
USS/W	0.26
347 SS	-1.05
17-4 PH	0.12
17-7 PH	0.42
410 SS	0.07
440C SS	0.0
A-Nickel	0.51
L-Nickel	0.44
K-Monel, aged	0.12
Inconel, aged	0.09
Monel	0.20
Hastelloy-C	0.11
Stellite-3	3.5
Stellite-6	0.63
Vascoloy-Ramet 166	-0.12

4.00 STAINLESS STEEL-CLAD FUEL ELEMENTS

The choice of materials for fuel elements depends on many factors, such as the material cross section, fission products, strength, and heat and corrosion resistance. For the package power reactor, the relative merit of various materials was weighed, and it was decided to use stainless steel as both a cladding material and a bond for the fuel matrix. The fuel plates are to be made in flat strips and brazed together into square cross section boxes with rectangular spaces through which the coolant water can flow.

This general type of fuel element has been made both by Pratt and Whitney for a proposed super-critical water reactor, and by General Electric for another aircraft reactor. The Metallurgy Department at Oak Ridge National Laboratory has also developed a process for the manufacture of these elements using the picture frame technique. In this process the matrix is made 18-30% 93% enriched uranium dioxide mixed with boron carbide and 304L SS powder. The matrix is pressed, sintered, and coined. The resulting tablet is placed in a frame made of rolled 304L SS and sandwiched between top and bottom sheets of rolled 304L SS which are then welded on all sides. The finished sandwich is then hot rolled, cold rolled into flat sheets, cut into uniform sized strips, and brazed into sub-assemblies.

Physical Properties - Unirradiated Elements. The various analyses and tests of the fuel elements in the unirradiated state, run by the ORNL Metallurgy Department on the package reactor fuel elements, and by

General Electric and Pratt and Whitney on the aircraft reactor fuel elements, indicate that both the cladding and the matrix can withstand great stress both individually and sub-assembled.

Pratt and Whitney Fuel Elements. Battelle, who made the fuel element investigations for Pratt and Whitney, made several types of picture frame fuel elements in which both the cladding material and the matrix material were varied. The matrix materials used were electrolytic iron, carbon, nickel, electrolytic chromium, and prealloyed types 347, 302, 316, and 302B stainless steels.

Transverse tests on some of the strips showed the values in Table LV, using 347 cold rolled stainless steel as cladding material.

TABLE LV: EFFECT OF MATRIX COMPOSITION ON TRANSVERSE STRENGTH OF FUEL PLATE[44]

347 SS clad

Matrix	UO_2 in Matrix Wt%	Oxide Particle Size (μ)	Transverse Tensile (psi)	Metallographical Examination
Electrolytic Fe	25	< 53	25,400	Uniform
Electrolytic Fe	25	< 53	31,900	Uniform
Electrolytic Fe	25	< 44	23,200	Uniform
Electrolytic Fe	25	< 3	33,100	Uniform
Prealloyed 347 SS	25	< 53	21,000	Good bond, some stringers
Prealloyed 347 SS	25	< 53	16,350	Good bond, some stringers
Prealloyed 347 SS	25	< 44	24,600	Good bond, some stringers
Prealloyed 347 SS	25	< 3	20,200	Good bond, some stringers
Prealloyed 347 SS	25	< 3	22,900	Good bond, some stringers
Prealloyed 347 SS	25	7-44	28,000	Good bond, some stringers
Prealloyed 347 SS	30	7-44	25,400	Good bond, some stringers
Prealloyed 347 SS	25	44-53	11,200	Good bond, some stringers
Prealloyed 347 SS	25	44-53	15,600	Good bond, some stringers
Prealloyed 302 SS	25	< 53	27,300	Good bond, some stringers
Prealloyed 302 SS	25	< 53	23,200	Good bond, some stringers
Prealloyed 302 SS	25	< 44	26,800	Good bond, some stringers
Prealloyed 302 SS	25	< 3	30,000	Good bond, some stringers
Prealloyed 302 SS	25	< 3	26,500	Good bond, some stringers
Prealloyed 302B SS	25	7-44	27,300	Good bond, some stringers
Prealloyed 302B SS	25	7-44	30,400	Good bond, some stringers
Prealloyed 316 SS	25	7-44	27,800	Good bond, some stringers
Prealloyed 316 SS	25	7-44	29,300	Good bond, some stringers

TABLE LV (Cont.)

Matrix	UO_2 in Matrix Wt%	Oxide Particle Size (μ)	Transverse Tensile (psi)	Metallographical Examination
Elemental 18 Wt% Cr	25	44-53	31,200	Good bond, no stringers
Elemental 18 Wt% Cr	25	44-53	30,500	Good bond, no stringers
Elemental 18 Wt% Cr	25	7-44	22,900	Good bond, no stringers
Elemental 18 Wt% Cr	25	7-44	26,300	Good bond, no stringers
Elemental 18 Wt% Cr	25	< 53	29,900	Good bond, no stringers
Elemental 18 Wt% Cr	25	< 3	29,600	Good bond, no stringers
Elemental 18-9 Wt% Cr and Ni	25	< 53	31,800	Good bond, no stringers
Elemental 18-9 Wt% Cr and Ni	25	< 53	18,200	Good bond, no stringers
Elemental 18-9 Wt% Cr and Ni	25	< 53	24,200	Good bond, no stringers
Elemental 18-9 Wt% Cr and Ni	25	44	23,700	Good bond, no stringers
Elemental 18-9 Wt% Cr and Ni	25	< 3	26,500	Good bond, no stringers
Elemental 22-12 Wt% Cr and Ni	30	7-44	26,000	Good bond, slight stringering
Elemental 22-12 Wt% Cr and Ni	30	7-44	23,000	Good bond, slight stringering
Elemental 25-20 Wt% Cr and Ni	30	7-44	21,000	Good bond, slight stringering
Elemental 25-20 Wt% Cr and Ni	30	7-44	23,600	Good bond, slight stringering
Elemental 25-20 Wt% Cr and Ni	30	7-44	20,400	Good bond, slight stringering

Core 0.008 Clad 0.006

The particle size in the matrix had an unpredictable effect on the strength of the fuel element. The iron matrix and the elemental alloy compositions showed greater strength than the prealloyed powdered matrices. Other fuel elements with varying UO_2 content were made. A marked decrease in strength was evidenced when the core UO_2 content rose to 40%. A similar decrease in ductility was noted with higher UO_2 content as evidenced in bend tests. Bends were made in the iron matirx element about a 1/64" radius without cracking the core and in the alloy matrix element about a 3/32" radius with the 30% UO_2 matrix. These values were somewhat higher for the 40% UO_2 matrix.

The Pratt and Whitney fuel elements used a 0.008" to 0.012" core and a cladding 0.004" to 0.006" thick. These elements were subjected to thermal cycling by heating and cooling between 500° F and 1500° F, at the rate of two cycles per minute. The fuel element with alloy matrices showed no cracking after 1,000 cycles, but those with iron matrices cracked after 250 cycles. A reduction in the maximum temperature to 1300° F increased the life of the iron core fuel plate to approximately 1,000 cycles.

The General Electric fuel elements used 310 SS and 309 SS for both cladding and matrix. It was determined that optimum strength was obtained in the matrix when 10-45 μ- particle size of UO_2 was employed. This strength averaged about 5,000 psi. The ultimate strength of the cladding is about 100,000 psi.

Other properties of the General Electric fuel elements are shown in Table LVI.

TABLE LVI: PHYSICAL PROPERTIES OF TYPE-309 SS-CLAD FUEL ELEMENTS WITH 30% UO_2 IN CORE

Tensile Strength (Parallel to Rolling)

Temp (°F)	Ultimate Tensile (psi)	Elongation %
1500	73,000	10
1650	18,500	11
1800	11,500	12

Creep Strength (Parallel to Rolling)

Temp (°F)	Creep Rate (%/hr)
1500	0.0004
1650	0.001
1800	0.023

Transverse Rupture Strength at 1800° F

% UO_2	Transverse Strength (psi)
0	7000
30	6000
50	2100

Most of the above data concerns itself with fuel elements which will have to withstand much higher temperatures than the package power reactor elements will.

The physical properties of the fabricated fuel plates indicate that they will readily withstand the 500-600°F operation in the Army Package Power Reactor; in fact, it appears that they can withstand temperatures from 800° to 1000°F without decrease in element life.

Irradiated Fuel Elements. From the above, it can be seen that assemblies of stainless steel-clad fuel elements containing a stainless steel matrix and operating at 500° F may well withstand all the stresses to which they may be subjected. The investigations on the matrices to date, however, have been made mostly on unirradiated materials. Recent tests run on Pratt and Whitney specimens at ORNL indicate that the stainless steel matrices containing UO_2 undergo embrittlement upon exposure to neutrons as shown in Table LVII. The cladding itself is not subject to this embrittlement and shows the same improvement in tensile qualities shown by non-cladding stainless steels after irradiation.

In later tests, additional specimens were irradiated up to 11.8% burnup. Some of these showed hardening of the matrix up to DPH 641. The general conclusions drawn from the results are as follows:

1. The core-clad boundary of samples with stainless steel matrix showed greater resistance to separation on bending than the iron matrix.
2. The resistance to intra-core separation was greater in the large particle size range (15-44 μ UO_2) than in the small particle size core ($\approx$ 3μ UO_2).
3. Some radiation damage to the clad due to fission fragments may take place up to 0.0004" penetration.

The embrittlement of the core also drastically affected the radius about which the plate could be bent. However, since the bend test on an unirradiated sample is made to determine the fabrication characteristics of the materials (corrugation, curling, crimping), the reduction

TABLE LVII: EFFECT OF IRRADIATION ON HARDNESS OF FUEL PLATES[84]

Sample Number	Temperature of Irrad (°F)	Clad SS	Hardness of Clad D P H 1 Kg Load Before	Hardness of Clad D P H 1 Kg Load After	Core Material	UO_2 Particle Size (μ)	Hardness of Core D P H 2 Kg Load Before	Hardness of Core D P H 2 Kg Load After
55	166	347	109-124	217-222	90%,18-9	3*	218-266	294-313
56	166	347	103-133	196-220	70%,18-9	3*	177-196	322-342
57	166	347	98-124	205-226	70%,18-9	44-53*	177-196	212-244
58	166	347	93-132	184-255	70%, Fe	3*	162-169	226-234
60	380	347	98-116	181-223	70%,18-9	3	218-232	499-520
61	380	347	109-132	188-222	70%, Fe	3	155-169	500-510
62	380	347	116-132	181-205	70%, Fe	3	143-148	455-463
63	380	347	109-124	171-194	70%,18-9	3	232	480

* Natural Uranium

Capsule #1 206×10^{20} NVT 573 hours #55-#58
Capsule #2 1.5×10^{20} NVT 555 hours #60-#63

in ductility should be of little consequence in the irradiated samples. The effect on the transverse strength of the fuel plates may be great, however, depending on the geometry of the element. For the package power reactor fuel element the transverse strength would be a function of the element's moment of inertia. For a comparison of the strength of the non-irradiated fuel element with the irradiated element, the very worst case was analysed in which the non-irradiated element was considered a homogeneous strip, whereas the irradiated fuel element was considered to have a core that contributed nothing to the strength of the element. The effect on the moment of inertia of the elements is to decrease the strength in the ratio of 1.5 to 1 and 1.3 to 1 on the x-x and the y-y axis respectively, as shown in the calculations in Appendix A.

The flexural strength across the width of the beam would depend upon the pressure differential between adjacent fuel plate channels. In a closed hydraulic system such a differential would be a function of the fluid velocity. High fluid velocity might conceivably cause sufficient pressure differentials to cause vibrations in the plates. It is not expected that such vibrations will occur in the APPR with the low fluid flow of about 4.3 fpm.

Fuel Element Corrosion. The cladding of the fuel element should have the same corrosion resistance as the stainless steels used in other components, since very little change in physical properties of the cladding due to irradiation was noted other than the 0.0004" penetration of fission fragments. This is borne out by corrosion tests run on the fuel plates at Argonne and listed in Table LVIII.

TABLE LVIII: GE - ANP FUEL ELEMENT CORROSION[31]

Fuel Plates Type 310 SS - Cut Edges Sealed with GE-ANL No. 62 Brazing Material and Inconel Wire

		Water Conditions			
		With O_2		With H_2	
Temp (°F)	Time (hr)	(mg/cm^2-mo)	Remarks	(mg/cm^2-mo)	Remarks
500	333	0.481	Adherent, blue-red coating	0.396	Adherent, red-brown tarnish
500	333	0.042	Adherent, blue-red coating	-0.021	Adherent, brown-blue tarnish
500	714	0.059	Adherent, blue-red, black coating	0.012	Adherent, copper, brown coating
600	333	0.069	Adherent, brown-blue tarnish	0.767	Adherent, blue-brown tarnish
600	333	0.021	Adherent, brown-blue tarnish	0.106	Adherent, blue-brown tarnish
600	714	0.022	Adherent, brown-black tarnish	0.025	Adherent, red-brown coating
680	333	-0.027	Adherent, brown tarnish	0.0	Adherent, dark blue-brown tarnish
680	333	0.0	Adherent, brown tarnish	0.0	Adherent, blue and brown tarnish
680	714	0.116	Adherent, dark brown coating	0.15	Adherent, brown-black coating

All samples showed heavy adherent dark or brown coatings on brazed edges.

The corrosion of the matrix itself, however, is of some concern because of the radioactivity which such corrosion may impart to the water. The water may come in contact with the matrix and corrode it, in two ways, (a) after some time pitting corrosion of the cladding may form holes in cladding to expose the core surface, and (b) the cladding may be stripped from the fuel element because of faulty bonding, brazing, assembly, etc.

The corrosion rates of UO_2 determined at Argonne are shown in Table LIX. From this table, it can be seen that UO_2 corrodes moderately in degassed water. From previous experience it may be expected that the corrosion rate may even be lower in a hydrogenated system. The presence of oxygen in the system appears to have a rather erratic effect on the corrosion rates. The corrosion rate figure which was averaged from the table for the proposed conditions is 5 mg/cm^2-mo. The formation of both a vapor phase and a water phase in the presence of exposed UO_2, as might occur in the event of a partial loss of water and some stripping of the cladding, would result in a higher corrosion rate. The negative corrosion rate of most of the specimens on the table indicates that the material chips, flakes off, and is lost to the stream.

The corrosion of the UO_2 in the core may have the following effects:

a. Uranium fuel will be lost from the system.

b. The water may become radioactive because of fission products and recoil fragments.

TABLE LIX: CORROSION OF URANIUM DIOXIDE[19]

Material	Test Conditions	Time (hr)	pH Before	pH After	Resistance (Ohm-cm) Before	Resistance (Ohm-cm) After	Corrosion (mg/cm^2-mo)
Sp gr 10.6, fired at 1750° C	500°F degassed	330	7.1	5.8	195,000	65,000	-4.4
Repeat of above	500°F degassed	333	7.0	5.7	180,000	28,000	-2.4
Sp gr 10.6, fired at 1750° C	500°F oxygenated	330	7.0	5.5	290,000	60,000	0.76
Repeat of above	500°F oxygenated	333	7.0	5.4	210,000	49,000	-15.4
Sp gr 10.3, pressed fired at 1750° C	600°F degassed	358	6.7	6.0	470,000	47,000	0.22
Sp gr 9.3, fired at 1750° C	600°F degassed	358	5.9	5.4	320,000	15,000	-7.05
Sp gr 5.0, extruded, fired at 1700° C	600°F degassed	358	6.4	6.0	140,000	11,000	-0.67
Sp gr 10.6, pressed, fired at 1750° C	600°F oxygenated, steam phase	354	6.9	----	165,000	--	0.00
Sp gr 10.6, pressed, fired at 1750° C	600°F oxygenated, steam phase	400	6.7	6.8	160,000	30,000	-36.9
Repeat of above	600°F oxygenated, water phase						3.38

Some attempt was made by the Army Package Power Reactor Group to evaluate which of the above factors would limit the permissible amount of matrix exposure to corrosion. From rough calculations, it was estimated that the recoil fragments contributed the greatest hazard to matrix exposure and would limit such exposure to 1800 square centimeters with the present shielding.

Effect of Burn-out Poisons

Boron carbide will be used as a burn-out poison in the manufacture of the fuel elements. It will be mixed with the core matrix. In tests run at Knolls[63], boron carbide was found to be very resistant to neutron-induced macroscopic fragmentation. In these tests hot pressed boron carbide bodies withstood 15% atomic percent burnup without physical breakdown.

Argonne has checked the effect of boron directly in the cladding and structural stainless steel material. The effect of such addition on the corrosion rate of the 309 SS is shown in Table LX.

TABLE LX: EFFECT OF BORON AND MISCH METAL ON THE CORROSION OF TYPE-309 SS[31]

In Water at 680° F

Material ANL #	Additives B	Additives Ce+La	Wt Change (mg/cm^2-mo) 333 hrs	Wt Change (mg/cm^2-mo) 761 hrs	Remarks
4005-1	0	0	-0.062	0.082	Lustrous, straw
4005-2	0.05	0	0.062	0.048	Lustrous, straw
4005-3	0.04	0.007	0.047	0.075	Lustrous, straw
4006-1	0	0	0.0	-0.041	Lustrous, straw
4006-2	0.13	0	0.0	0.0	Lustrous, straw
4006-3	0.13	0.051	0.031	0.061	First period, loose Second period, adherent

Micrographic examinations by Carpenter Steel Company who furnished the above material showed that embrittlement occurs when metal is exposed to temperatures of 1200° to 1400° F. This embrittlement is caused by precipitation involving boron rather than embrittlement due to sigma phase formation.

5.00 DISCUSSION OF METHODS USED IN CORROSION MEASUREMENTS

In general, the primary objectives of the Army Package Power Reactor material investigation have been fulfilled insofar as both the missing vital information about materials has been supplied, and the conditions under which the reactor is to run have been determined. Of course, there may be gaps in the continuity of the data, and some information may be of doubtful value. The possibility of such errors prompted the use of large numbers of results, where possible, so that any peculiar result may be leveled by gross averaging.

In most instances, the results of the analysis bore out the conclusions reached in other selection lists, such as the qualitative analysis made by Argonne and partially listed in Table LXI. The actual results of this selection of specific materials were,in some instances, different. The most notable difference, which involved over 80% of the material in the reactor, was the selection of 304 SS in the reactor instead of 347 SS. Graphitar 14, which is used as a bearing material in some of the canned rotor pumps, did not show up too well, and its use augured more frequent pump overhauls than was anticipated for the rest of the system. It may be that a substitute bearing material, liquid bearings, or actualy operational tests of the bearings in existing pumps, would solve this problem.

In the more detailed tabulation shown in Appendix C, the selection and the method of tabulating the information have been made a function of the information available. Many of the factors discussed in the

TABLE LXI: EVALUATION OF REACTOR MATERIALS[17]
Loops 1 and 3 at Argonne

500° F, pH 7, with Mixed Bed Ion Exchanger

Material	Loop 1 100 cc H_2/L 1 fpm	Loop 1 100 cc H_2/L 3 fpm	Loop 3 1-2 cc O_2/L 1 fpm	Loop 3 1-2 cc O_2/L 3 fpm
304 SS	G	G	G	G
304L SS	G	G	G	G
304 SS Malcomized	-	-	-	G
309 SS	G	G	G	G
309 SS Malcomized	-	-	-	D
310 SS	G	G	G	G
316 SS	G	G	G	G
318 SS	G	G	G	G
321 SS	G	G	G	G
347 SS	G	G	G	G
410 SS	-	G	D	D
430 SS	D	G	D	-
440C SS	-	G	-	-
USS/W	G	-	-	-
17-4 PH aged	G	G	D	G
17-7 PH aged	-	G	D	G
17-7 hardened	G	-	D	-
Inconel-X aged	-	G	G	P
K-Monel aged	-	G	G	P
Hastelloy-C	-	D	G	D
L-Nickel	-	-	-	P
Inconel	-	D	G	P
Stellite-3	G	G	G	P
Stellite-6	-	-	-	P

G = Good; D = Doubtful; P = Poor

report do not appear on the forms at all because these phases of the investigation did not lend themselves to quantitative corrosion measurement.

It must be remembered that, although the weight change is an important factor in corrosion evaluation, it can sometimes give an erroneous picture of the corrosion. Thus, a zero weight change can be caused by the formation of an oxide and the loss of some of this oxide by erosion or flaking.

One of the prime factors to be considered in any corrosion analysis is the temper of the corrosion film. If the temper is firm, them it must be assumed that a weight gain is preferable to a weight loss. A weight gain indicates the formation of a metallic compound, usually an oxide whose composition is only partly that of the metal, possibly only 1/3. On the other hand, a weight loss indicates that at least the amount of loss is in actual parent metal. A large loss or a large gain are both objectionable.

A study of the detailed corrosion rates indicated that the corrosion rates of most materials decreased with time. This decreasing corrosion rate was attributed either to a reduction in surface open to attack or to the formation of films which shields the metal from the water. Figure 6 illustrates this reduction in corrosion rate as found for 304 SS in hydrogenated water.

In making the averages of the corrosion rates, the type of corrosion, gain or loss, was ignored. In rating materials on the basis of corrosion, however, some allowance should be made for the fact that a positive corrosion rate is preferable to a negative one. Thus, the corrosion standard

[redacted]

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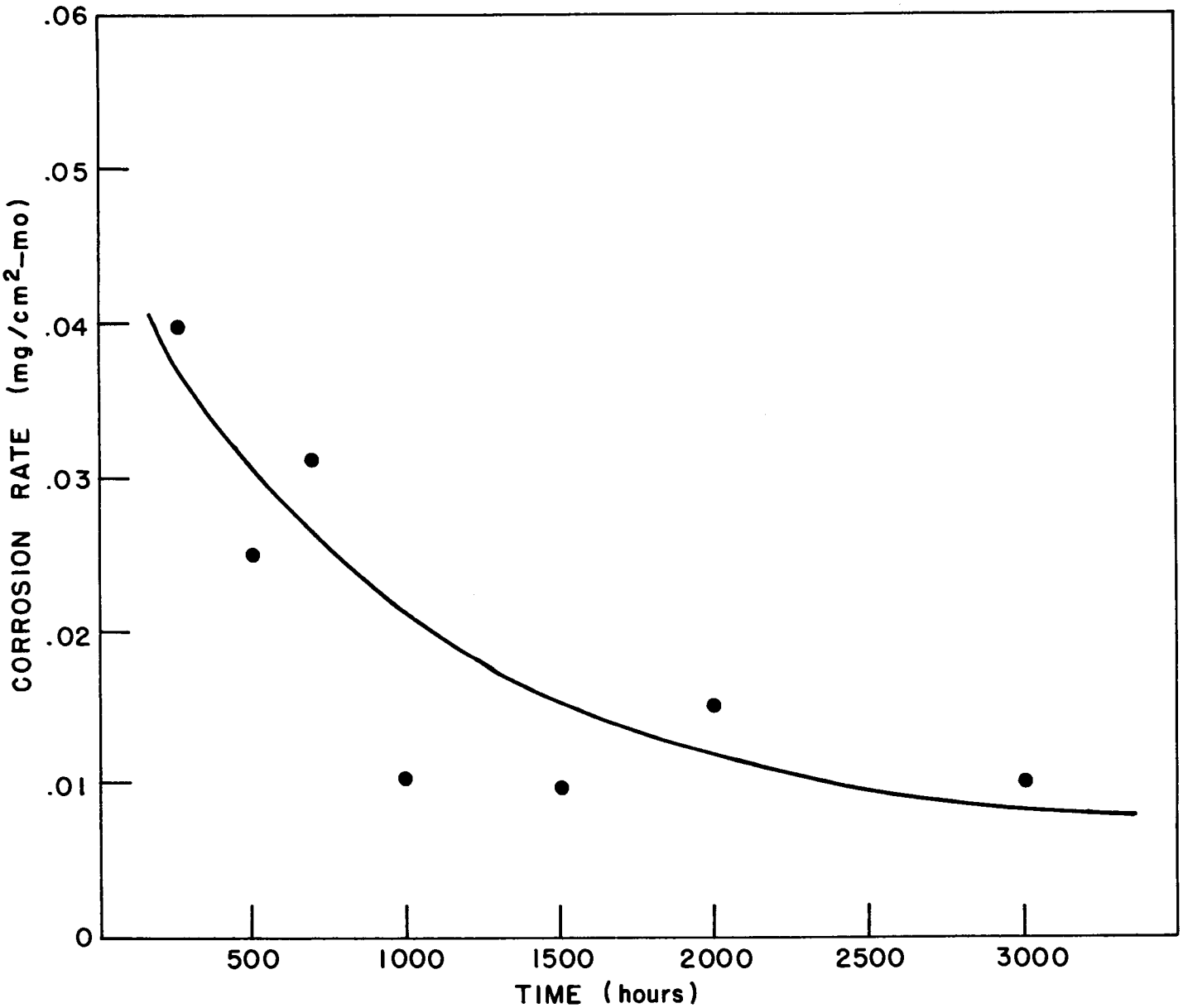

FIGURE 6. CORROSION vs TIME, TYPE-304 SS IN HYDROGENATED WATER

grading as suggested at Argonne should be adjusted for this factor as follows:

Grade I: Uniform, adherent corrosion or temper film; no pits and no weight decrease more than 0.25 mg/cm^2-mo nor weight gain more than 0.15 mg/cm^2-mo.

Grade II: Uniform corrosion and some loose corrosion products; no pits and no weight increase in excess of 2.5 mg/cm^2-mo nor weight loss in excess of 1.5 mg/cm^2-mo.

Grade III: Non-uniform corrosion, pitting, and weight changes in excess of 2.5 mg/cm^2-mo.

It is felt that for the package reactor all the materials, where possible, should fall in Grade I.

Another variation in the test results is caused by different methods of obtaining the corrosion rates for different materials. Some investigators feel that the corrosion product must be stripped from its host in order to obtain the corrosion rate; this is generally shown as a weight loss. The above grading criteria should not be applied in instances where the corrosion rates were established in this manner.

The use of the descaling method offers one means of obtaining more accurate, consistent results. The descaling method, within its accuracy, enables the investigator to determine the portion of the sample which has been lost to corrosion. It eliminates all outside influences, such as the deposition of corrosion products from a different source.

Table LXII shows the relation between corrosion specimens which have been rated "as is" and specimens which have been electrolytically stripped, under various water conditions. A close similarity in corrosion rates is evident between the 30 fps with scale and unscaled conditions, indicating possibly that the 30 fps fluid does its own descaling.

TABLE LXII: EFFECT OF ELECTROLYTIC DESCALING ON CORROSION RATES AT VARIOUS GAS CONCENTRATIONS

H_2O at 500° F

Loop Condition	Time (hr)	Corrosion (mg/cm^2-mo) As Is 30 fps	As Is 1 fpm	Descaled 30 fps	Descaled 1 fpm
SS 304					
0-1 cc O_2/L	500	0	0.01	-0.08	-0.24
	1000	0	0.02	-0.06	-0.08
	1000	0.03	0.06	-0.03	-0.03
	1000	0.02	0.06	-0.03	-0.05
	1500	0.01	0.04	-0.03	0.0
	1500	--	0.02	--	-0.09
1-5 cc O_2/L	500	0.03	0.09	-0.04	0
	500	0.03	0.02	-0.02	-0.12
	1500	0.01	--	-0.03	--
100 cc H_2/L	500	0.02	0	-0.01	0.0
	500	0.03	0	-0.02	-0.02
50 cc H_2/L	500	0.01	-0.01	0	0
	1000	0	-0.01	-0.01	-0.01
25 cc H_2/L	500	-0.02	0.04	-0.04	-0.02
	500	-0.02	0	-0.04	-0.08
SS 304L					
0-1 cc O_2/L	500	--	0.01	--	-0.12
	500	--	0.03	--	-0.23
	1000	0	0.01	-0.02	-0.06
	1000	0.02	--	-0.03	--
	1500	0.01	0.03	-0.03	-0.07
	1500	0.01	0.02	-0.02	-0.10
1-5 cc O_2/L	500	0.01	0.02	-0.04	-0.13
	1000	--	0.03	--	0.05
25 cc H_2/L	500	0.01	0	-0.01	-0.03
	1000	-0.01	--	-0.03	--
50 cc H_2/L	500	--	0	--	0
	1000	0	0	-0.01	-0.01
	1500	0	0	-0.01	0

The greatest disparity in the corrosion results occured in the slow moving stream where higher corrosion rates were obtained for the descaled samples.

The majority of the tests whose results were available did not follow any standarized procedure except such as may have been established within any specific organization. It is felt, however, that the tests as run supplied sufficient accurate data so that the relative merits of the various materials could be gaged. In the investigation of materials which form highly resistant films, particularly most of the austenitic stainless steels, fairly accurate results are obtainable on non-descaled samples when visual inspection augments the weight change.

The many different corrosion rigs prevalent and the varying results obtained accentuate the need for a standard corrosion test procedure which would eliminate much of the blind hunting, permit duplication of results, and make it unnecessary to run numerous tests to establish the accuracy of the results.

It was initially hoped that an analysis, such as was made, might supply information on basic corrosion mechanisms. The erratic results, while valuable for the selection of specific materials, did not make such information available. It is hoped that eventual standardization, particularly in the method of stripping, will permit analysis along more basic trends.

6.00 SOME RECOMMENDATIONS FOR DESIGN AND OPERATION OF REACTORS

Loop Cleanliness. The methods for purifying and maintaining pure water in the primary loop were discussed in another section of the report. Of equal importance in obtaining and maintaining a pure water circuit is the cleanliness of the loop components. The materials undergoing fabrication and assembly often had embedded in them or on their surface, iron, oil, grease, silica, chips, fibers, and other miscellaneous materials. These materials not only contaminated the water, but also provided foci for pitting and crevice corrosion formations. The loop components should be cleaned, and the specific cleaning process either indicated in detail on the component drawings or referred to in an appropriate specification. The suggested cleaning methods follow.

Cleaning Procedures. Oil, grease, paint, dirt, etc., should be removed from all surfaces by detergent, solvent washing, or vapor degreasing. The detergents should not contain borax or chlorides.

Welds should be wire-brushed with a 300-series stainless steel or a silicon oxide grinding wheel, weld film (or flash and splatter) being removed until bright metal is secured. Where exceptional corrosion resistance is desired the ground surfaces should be made even and smooth.

The austenitic stainless steel components should be cleaned in a commercially available pickling solution, such as 10-15% HNO_3 - 2% HF, at 120° - 140° F for 1 1/2 hours. This will remove the embedded iron and scale and will somewhat passivate the surface. The pickled surfaces

should be thoroughly rinsed with distilled or deionized water until no acid reaction is noted with litmus paper. The cleaned surface may be dried with steam or lint-free cloth.

Foundry Products, Pumps, and Valves. The components should be degreased and washed in acid, according to the cleaning procedure above, before assembling the final unit. Castings should be pickled after final heat treatment and prior to final machining. Surfaces to be welded should be wiped free of oil and dirt before welding. Parts fabricated by polishing or lapping should be cleaned with solvents and hot water until all traces of lapping compound or grit have been removed. No acid cleaning should take place after polishing.

Fabricated Piping. Piping should be received from the mill in a pickled condition. The areas adjacent to welds should be wiped free of oil and dirt prior to welding. The finished joint should be clear of all foreign metal, weld splatter, etc. This can be accomplished by wire-brushing and by grinding as previously described. The complete welded component should then be cleaned and washed in acid, whenever possible. It may be difficult to use an acid bath on piping which is jointed in the field, but if efficient rinsing is possible, the acid bath should be considered.

Fabricated Vessels. Vessels, tanks, and columns should be treated the same as the piping. The cleaning and acid bath should be done after the vessel has been pressure tested. Distilled water should be used for pressure testing. The tube side of the heat exchanger should be cleaned and washed in acid in the same manner.

Materials Specifications. Specifications in the materials must be closely followed. Most of the structural components are made of 304 SS, and composition of the specific parts should be accurately ascertained. Bolts made of 304 SS should have nuts of 303 SS.

General Design Considerations. The design of the piping should be such that smooth flow of the water is obtained. Sharp corners and dead spaces should be avoided if possible. The purge-valve outlet should be at a low point in the system and preferably in an area of low turbulance, possibly at the bottom of the reactor. An access hole might be supplied in one of the primary loop pipes to permit the installation of filters and/or magnets for the removal of large particles which may be present initially in the system.

Equipment Exercise. Because of the possible effect of crevice corrosion it is suggested that a schedule of mechanism exercise be worked out for such devices as the control-rod drives and certain valves. Under the operating condition of 50 cc H_2/L of water and a water purity of 2ppm, it would be sufficient to operate the idle equipment once every three months. If the water purity, the hydrogen concentration, or both, should drop then more frequent exercising is indicated. If no hydrogen should be present, the equipment should be exercised about once a week. The extent of exercise must necessarily depend on the reactor operating conditions. Valves may be barely opened several times. The control-rod drives should be run, if possible, to give a complete revolution of the seal rings.

Degassification. The presence of the dissolved gases normally found in water has been found, from a corrosion view, to be undesirable in the primary loop. These gases, which are primarily carbon dioxide, nitrogen, and oxygen, should be kept low. Carbon dioxide forms carbonic acid and lowers the pH and the specific resistivity of the system water. Carbon dioxide can be removed by the anion resin of the demineralizer, but this shortens the effective life of the demineralizer. Nitrogen under irradiation can form either ammonia, if hydrogen is present, or nitrates and nitric acid. All of these compounds will lower the specific resistance of the water and increase the possibility of higher corrosion ratios.

Oxygen is undesirable because it combines with the metals to form oxides, with carbon to form carbon dioxide, and with nitrogen to form nitrates. It is also one of the constituents of water and is therefore difficult to exclude from the water.

Boiling will remove most of the gases dissolved in water. Since the basic water source for the APPR primary loop is the distillate from the evaporator, and is essentially free of dissolved gases, it is necessary to prevent the reabsorption of the undesirable gases in the interim handling between the evaporator and the primary loop. One suggested method of accomplishing this is to maintain an atmosphere of helium above the water during storage in tanks.

Inhibitors. The use of the austenitic stainless steels for any of the vessels or piping should provide ample protection against water corrosion, even in oxygenated systems. The effect of transport corrosion

products and the presence of other materials than austenitic stainless steels indicate that a corrosion inhibitor should be used. For the present, hydrogen in a minimum quantity of 50 cc/L, seems to be the most desirable. Provision should be made on the reactor to permit continual addition of hydrogen to the primary loop to make up for the gas lost through seal water leakage, through the purge of the water, and through the pressurizer venting.

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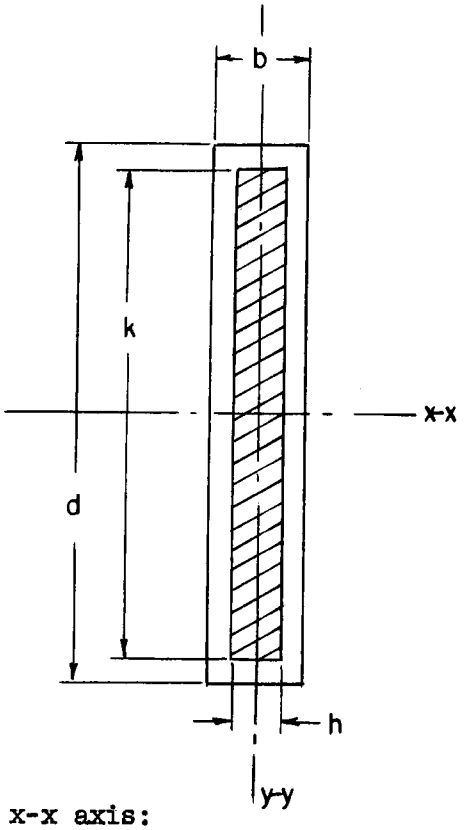
APPENDIX A: MOMENTS OF INERTIA OF FUEL ELEMENTS



If we assume that core contributes nothing to strength of member then

(a) $I = \frac{bd^3 - hk^3}{12}$

If we consider the core as forming a homogeneous mass with the caldding then

(b) $I = \frac{bd^3}{12}$

d = 2-1/2"
k = 2"
h = 0.020
b = 0.030

1. For x-x axis:

(a) $I = \frac{0.030 \times 2.5^3 - 0.020 \times 2^3}{12}$

$= \frac{0.030 \times 15.6 - 0.020 \times 8}{12}$

$= 0.0257$

(b) $I = \frac{0.030 \times 2.5^3}{12} = 0.039$

Ratio $= \frac{0.039}{0.0257} = 1.5:1$

2. For y-y axis:

(a) $I = \frac{2.5 \times 0.030^3 - 2 \times 0.020^3}{12}$

$= 4.3 \times 10^{-6}$

(b) $I = \frac{2.5 \times 0.030^3}{12}$

$= 5.6 \times 10^{-6}$

Ratio $\frac{5.6}{4.3} = 1.3:1$

APPENDIX B: COMPOSITION OF MATERIALS[3]

Weight Percent

Material	Fe	Cr	Ni	C (max)	Co	Cu	Si (max)	Al	Mn	P (max)	S (max)	Mo	W	B
304 SS	Bal	18-20	8-11	0.08			1.0		2.0	0.04	0.03			
304L SS	Bal	18-20	8-11	0.03			1.0		2.0	0.04	0.03			
347 SS*	Bal	17-19	9-12	0.08			1.0		2.0	0.04	0.03			
316 SS	Bal	16-18	10-14	0.10			1.0		2.0	0.04	0.03	2.0-3.0		
17-4 PH	Bal	16-18	3.5-5.0	0.05		4.0	1.0		1.0	0.04	0.03			
17-7 PH	Bal	16-18	6.5-7.8	0.09			1.0	0.8-1.3	1.0	0.04	0.03			
440C	Bal	16-18		1.0-1.2			1.0		1.0	0.04	0.03	0.8 (max)		
410 SS	Bal	12-14		0.15			1.0		1.0	0.04	0.03			
Monel	1.5		67			30			1.0					
K-Monel	1.5		66	0.20		30		3.5						
Inconel	6.5	14.0	78.5	0.08		0.2	0.25		0.25					
Inconel-X**	7.0	15.0	73.0	0.04			0.4	0.7	0.5					

APPENDIX B (Cont)

Material	Fe	Cr	Ni	C (max)	Co	Cu	Si (max)	Al	Mn	P (max)	S (max)	Mo	W	B
Hastelloy-C	4.5-7	15-17	Bal	0.15	3.8-4.8		1.0		1.0			16-18		
A-Nickel	0.15		99.4			0.10	0.10		0.15					
Vascoloy-Ramet 166	2-3	28-29		2-2.5	Bal		0.2-0.3		2-2.5				13-14	0.2
Stellite-3	3.0	29-33	3.0	2.2-2.7	Bal		1.5		0.5				9.5-13.5	.05-.20
Stellite-12	3.0	20.5-32.5	3.0	1-1.1	Bal		1.7		1.0				6-10	
Stellite-6	3.0	26-31	3.0	0.9-1.4	Bal		1.5		1.0				3.5	
322W SS	Bal	17.0	7.0	0.07			0.5	0.02	0.5	0.01	0.01			
ASME SA 212B***	Bal			0.35			.15-.30		0.90 (min)	0.04	0.04			

* Also 8 x C Cb (min)
** Also 1.0 Cb(min) and 2.5 Ti(min)
*** Also 0.7 Ti(min)

APPENDIX C: CORROSION TABLES OF MATERIALS IN WATER

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MATERIAL GRAPHITAR-14

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
1	120	500					8.40														(3)	8.40		ANL-4519	
2	329	250					0.18																	ANL-4519	
3	681	250					2.94																	ANL-4519	
4	375	500	30	12.00																	(3)	12.00		ANL-4519	
5	1212	500	30	-4.20																	(3)	-4.20		ANL-4519	
6	2022	500	30	-5.00																	(3)	-5.00		ANL-4519	
7	2712	500	30	-6.60																	(3)	-6.60		ANL-4519	
8	3517	500	30	-4.30																	(3)	-4.30		ANL-4519	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL HASTELLOY-C

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
1	284	600	30				−0.05	(1)	−0.05		(1)													ANL-4519	
2	790	500	30	−0.05				(1)	−0.05		(1)							(1)	−0.05					ANL-4519	
3	790	500	30	−0.42				(1)	−0.42		(1)							(1)	−0.42					ANL-4519	
4	1503	500	30	0.37				(1)	0.37		(1)							(1)	0.37					ANL-4519	
5	1503	500	30	−0.027				(1)	−0.03		(1)							(1)	−0.03					ANL-4519	
6	620	500	1−3	−2.13						Yes		(2)(3)	9											ANL-5059	
7	4380	540												F = 1 T = 10	0.29								(2)	ANL-5059	
8	4380	540												(a)	0.07								(2)	ANL-5059	
9	168	600					0.02																	See Ref 122	
10	168	600					0.01																	See Ref 122	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Molcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Control

MATERIAL INCONEL

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen									F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.		(fps)	Corr.																
1	895	600	3–5	0.07				(1)	0.07									(a)(b)	–0.07					ANL-4519	Good
2	3149	600	3–5	0.15				(1)	0.15									(a)(b)	0.15					ANL-4519	Good
3	324	500	30	0.26				(1)	0.26															ANL-4519	Good
4	1210	500	30	–0.09				(1)	0.09															ANL-4519	Good
5	1964	500	30	0.08				(1)	0.08															ANL-4519	Good
6	2750	500	30	–0.12				(1)	–0.12															ANL-4519	Good
7	3464	500	30	–0.017				(1)	–0.02															ANL-4519	Good
8	2248	500	30	–0.11				(1)	–0.11															ANL-4519	Good
9	3010	500	30	–0.53				(1)	–0.53															ANL-4519	Good
10	3749	500	30	–0.11				(1)	–0.11															ANL-4519	Good
11	4540	500	30	–0.45				(1)	–0.45															ANL-4519	Good
12	5349	500	30	–0.09				(1)	–0.09															ANL-4519	Good
13	6062	500	30	–0.02				(1)	–0.02															ANL-4519	Good
14	500	500	1.7	–0.04				30	–0.04			(1)	10			(1)	–0.04							ANL-4519	Good
15	500	500	2.1	–0.11				30	–0.11				7			(1)	–0.11							ANL-4519	Good
16	850	500	1.7	0.03				30	0.03			(1)	10			(1)	0.03							ANL-4519	Good
17	850	500	2.1	–0.29				30	–0.29				7			(1)	0.29							ANL-4519	Good
18	1350	500	1.7	0				30	0			(1)	10			(1)	0							ANL-4519	Good
19	1350	500	2.1	–0.22				30	–0.22				7			(1)	–0.22							ANL-4519	Good
20	500	500	1.7	–0.02				30	–0.02			(1)	10											ANL-4519	Good
21	500	500	1.7	0.02				0.01	0.02			(1)	10											ANL-4519	Good
22	500	500	2.1	–0.10				30	–0.10				7											ANL-4519	Good
23	500	500	2.1	0.07				0.01	0.07				7											ANL-4519	Good
24	850	500	1.7	–0.02				30	–0.02			(1)	10											ANL-4519	Good
25	850	500	1.7	0.02				0.01	0.02			(1)	10											ANL-4519	Good
26	850	500	2.1	–0.30				30	–0.30				7											ANL-4519	Good
27	850	500	2.1	–0.02				0.01	–0.02				7											ANL-4519	Good
28	1350	500	1.7	–0.02				30				(1)	10											ANL-4519	Good
29	1350	500	1.7	0.02				0.01	0.02			(1)	10											ANL-4519	Good
30	1350	500	2.1	–0.22				30					7											ANL-4519	Good
31	1350	500	2.1	0.01				0.01	0.01				7											ANL-4519	Good
32		280°C												T = 9	–0.11									ANL-4519	Good
33	1000	500	0–1	–0.14				0.01	–0.14															WAPD-C-110	Good
34	1000	500	0–1	–0.70				30	–0.70															WAPD-C-110	Good
35	1500	500	1	–0.62				30	–0.62	Yes														WAPD-C-110	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE
(a) Tensile
(b) 10,000

MATERIAL INCONEL (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
36	1500	500	1	−0.18				0.01	−0.18	Yes														WAPD-C-110	
37	1000	500	4.5		200	0				Yes											(4)	0		WAPD-C-110	
38	500	500			40	0		30	0	Yes														WAPD-C-110	
39	500	500			40	0.01		0.01	0.01	Yes														WAPD-C-110	
40	500	500			40	0		30	0	Yes														WAPD-C-110	
41	500	500			40	0.02		0.01	0.02	Yes														WAPD-C-110	Thin, loose
42	1500	500			200	0		30	0	Yes														WAPD-C-110	Good
43	500	500			2	0.08		20	0.08			(2)	10											WAPD-C-122	Black film
44	500	500			2	0.08		20	0.08			(2)	10											WAPD-C-122	Black film
45	1900	500			200	0		30	0															WAPD-C-122	Good
46	500	500			100	−0.01		20	−0.01															WAPD-C-125	Light
47	1000	500			100	−0.02		20	−0.02															WAPD-C-125	Light
48	3000	500			200	−0.01		30	−0.01												(4)	−0.01		WAPD-C-135	Light
49	1000	500			50	0		30	0															WAPD-C-135	Good
50	580	500						20	0.07	Yes		(2)	10.5								(2)	0.07		WAPD-C-141	Black
51	3600	500			200	0.01		30	0.01	Yes														WAPD-C-141	Good
52	1500	500			50	−0.01		30	−0.01	Yes														WAPD-C-141	Good
53	500	500	1	−0.35				30	−0.35															WAPD-C-141	
54	1000	500	1	−0.12				30	−0.12															WAPD-C-141	
55	1500	500	1	−0.48				30	−0.48															WAPD-C-141	
56	500	500	1	0.21				0.01	0.21															WAPD-C-141	
57	1000	500	1	−0.14				0.01	−0.14															WAPD-C-141	
58	1500	500	1	−0.06				0.01	−0.06															WAPD-C-141	
59	500	500			25	0		30	0															WAPD-C-141	
60	500	500			25	0.01		0.01	0.01															WAPD-C-141	
61	500	500			50	−0.01		30	−0.01															WAPD-C-141	
62	500	500			50	−0.01		0.01	−0.01															WAPD-C-141	
63	1000	500			50	0		30	0															WAPD-C-141	
64	1000	500			50	−0.01		0.01	−0.01															WAPD-C-141	
65	1500	500			50	0		30	0															WAPD-C-141	
66	500	500			100	0		30	0															WAPD-C-141	
67	500	500			100	0		0.01	0															WAPD-C-141	
68	702	500			100	−0.01		10	−0.01												(2)	−0.01		WAPD-C-137	Golden
69	500	500	0.2	−0.67				30	−0.67	Yes														ANL-5011	
70	500	500	0.2	−0.11				0.01	−0.11	Yes														ANL-5011	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL INCONEL (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
71	500	500			50	0		30	0	Yes														ANL-5011	
72	500	500			50	0		0.01	0	Yes														ANL-5011	
73	500	500					−0.03	30	−0.03	Yes														ANL-5011	
74	500	500					−0.03	0.01	−0.03	Yes														ANL-5011	
75	1000	500			50	0		30	0	Yes														ANL-5011	
76	1000	500			50	−0.01		0.01	−0.01	Yes														ANL-5011	
77	1500	500					−0.07	30	−0.07	Yes														ANL-5011	
78	1500	500					−0.03		−0.03	Yes														ANL-5011	
79	250	500	2.4		200	−0.04		30	0.04															ANL-5011	Aerated
80	250	500			200	0																	(a)	ANL-5011	Deaerated
81	500	500	2	−0.52				30	−0.52	Yes											(1)	0.52		ANL-5011	
82	500	500	2	−0.27				0.01	−0.27	Yes											(1)	−0.27		ANL-5011	
83	500	500			500	−0.06		30	−0.06	Yes											(1)	−0.06		ANL-5011	
84	500	500			500	−0.08		0.01	−0.08	Yes											(1)	−0.08		ANL-5011	
85	500	500					−0.14			Yes											(1)	−0.14		ANL-5011	
86	500	500					−0.08			Yes											(1)	−0.08		ANL-5011	
87	620	500	1−3	0.09								(2)(3)	9											ANL-5059	
88	620	500	1−3	0.27								(2)(3)	9											ANL-5059	
89	1500	500			50	0.01		30	0.01	Yes	0.5−1.7		6.6−7.4											ANL-5059	Good
90	500	500					−0.03	30	−0.03	Yes														ANL-4950	
91	1500	500					−0.03	0.01	−0.03	Yes														ANL-4950	
92	1500	500					−0.07	30	−0.07	Yes														ANL-4950	
93	1500	500					−0.03	0.01	−0.03	Yes														ANL-4950	
94	500	500			100	0		30	0	Yes														ANL-4950	
95	500	500			100	0		0.01	0	Yes														ANL-4950	
96	500	500			50	0		30	0	Yes														ANL-4950	
97	500	500			50	0		0.01	0	Yes														ANL-4950	
98	1000	482	1200	3.40																				ORNL-1605	
99	1000	482			1200	0																		ORNL-1605	
100	2160	500	30	−1.88				10	−1.88	Yes	14.3		6.15											See Ref 52	
101	1440	500	30	0.12				0.01	0.12	Yes	14.3		6.15											See Ref 52	
102	2160	500	30	−1.72				10	−1.72	Yes	14.3		6.15			(1)	−1.72							See Ref 52	
103	1440	500	30	0.03				0.01	0.03	Yes	14.3		6.15			(1)	0.03							See Ref 52	
104	250	500			230	−0.15				Yes														See Ref 52	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Pickled

MATERIAL INCONEL-X

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
1	353	500	30	0.17				(1)	0.17									(a)	0.17					ANL-4519	Good
2		280°C												9	−0.15									RH-3	
3	1000	500	4.5		200	0				Yes														WAPD-C-110	Good
4	1500	500			200	0.02		30	0.02	Yes														WAPD-C-115	Good
5	1900	500			200	−0.01		30	−0.01	Yes														WAPD-C-122	Good
6	836	500	0.1		2	−0.01		10	−0.01				10.5											WAPD-C-125	Straw
7	836	500	0.1		2	0		10	0				10.5											WAPD-C-125	Straw
8	500	500					−0.06	30	−0.06															WAPD-C-129	Good
9	500	500					−0.03	0.01	−0.03															WAPD-C-129	Good
10	500	500	1	−0.35				30	−0.35	Yes														WAPD-C-129	Doubtful
11	500	500	1	0.01				0.01	0.01	Yes														WAPD-C-129	Good
12	3000	500			200	−0.01		30	−0.01	Yes														WAPD-C-135	Good
13	500	500			100	0		10	0															WAPD-C-141	
14	500	500						10	0.06	Yes		(2)	10.5											WAPD-C-141	
15	3600	500			200	0		30	0	Yes														WAPD-C-141	Good
16	500	500			50	−0.02		30	−0.02	Yes														WAPD-C-141	Good
17	1500	500	1	−0.30				30	−0.30															WAPD-C-141	Doubtful
18	1500	500	1	−0.06				0.01	−0.06															WAPD-C-141	Good
19	1000	500					−0.04	30	−0.04															WAPD-C-137	Doubtful
20	1000	500	1	−0.35				30	−0.35															WAPD-C-137	
21	250	500			200	−0.08		30	−0.08															ANL-5011	
22	250	500			200	−0.10		0.01	−0.10															ANL-5011	
23	500	500			50	0.02		30	0.02	Yes	0.5–1.7		6.6–7.4											ANL-5059	Good
24	1000	500			50	−0.04		0.01	−0.04	Yes	0.5–1.7		6.6–7.4											ANL-5059	Good
25	250	500			200	−0.08		30	−0.08															ANL-4950	
26	250	500			200	−0.10		0.01	−0.10															ANL-4950	
27	1000	482	1300	4.30				31	4.30															ORNL-1605	
28	1000	482			1200	0		31	0															ORNL-1605	
29	720	600	64	−0.06																				See Ref. 122	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Cold drawn

MATERIAL MONEL

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
1	500	500	1.7	−0.27				30	−0.27		(1)	(1)	10											ANL-4519	
2	500	500	1.7	0.04				0.01	0.04		(1)	(1)	10											ANL-4519	
3	500	500	2.1	−0.76				30	−0.76		(1)		7											ANL-4519	
4	500	500	2.1	−0.03				0.01	−0.03		(1)		7											ANL-4519	
5	850	500	1.7	−0.09				30	−0.09		(1)	(1)	10											ANL-4519	
6	850	500	1.7	−0.04				0.01	−0.04		(1)	(1)	10											ANL-4519	
7	850	500	2.1	−0.29				30	−0.29		(1)		7											ANL-4519	
8	850	500	2.1	−0.22				0.01	−0.22		(1)		7											ANL-4519	
9	1350	500	1.7	−0.15				30	−0.15		(1)	(1)	10											ANL-4519	
10	1350	500	1.7	−0.01				0.01	−0.01		(1)	(1)	10											ANL-4519	
11	1350	500	2.1	−0.46				30	−0.46		(1)		7											ANL-4519	
12	1350	500	2.1	−0.14				0.01	−0.14		(1)		7											ANL-4519	
13	349	500	30	−0.27				(1)	−0.27		(1)													ANL-4519	
14	3000	500			200	−0.01		30	−0.01	Yes														WAPD-C-135	Good
15	500	500						20	0.03	Yes		(2)	10.5											WAPD-C-141	Dull
16	500	500						10	−0.09	Yes		(2)	10.5											WAPD-C-141	Dull
17	500	500	0.1		100	0		10	0	Yes														WAPD-C-141	Bright
18	3600	500			200	0.01		30	0.01	Yes														WAPD-C-141	
19	250	500			200	0.21		30	−0.21	Yes														ANL-5011	
20	250	500			200	0.03		0.01	−0.03	Yes														ANL-5011	Aerated
21	500	500	0.2	−12.50				30	−12.50	Yes														ANL-5011	
22	500	500	0.2	−2.10				0.01	2.10	Yes														ANL-5011	
23	500	500	2	−3.70				30	−3.70	Yes														ANL-5011	
24	500	500	2	2.30				0.01	2.30	Yes														ANL-5011	
25	500	500			500	0.02		30	0.02	Yes														ANL-5011	
26	500	500			500	−0.01		0.01	−0.01	Yes														ANL-5011	
27	500	500					−1.83	30	−1.83	Yes														ANL-5011	
28	500	500					−0.19	0.01	−0.19	Yes														ANL-5011	
29	620	500	1−3	0.20						Yes		(2)(3)												ANL-5059	
30	4380	540												F = 1	0.23									ANL-5059	
														T = 10											
31	4380	540												(a)	−0.80									ANL-5059	
32	250	500			200	−0.21		30	−0.21															ANL-4950	
33	250	500			200	−0.03		0.01	−0.03															ANL-4950	
34	1032	600					−0.05																	See Ref. 122	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivoted

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Control

MATERIAL MONEL (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
35	720	600					0.13																	See Ref. 122	
36	720	500					−0.02																	See Ref. 122	
37	168	600					0.02																	See Ref. 122	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Molcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL K-MONEL

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
1	5970	500	30	−0.21							(1)													ANL-4519	
2	895	600	3–5	−0.056				30	−0.056									(a)		(b)				ANL-4519	Good
3	6301	500	30	−0.03																				ANL-4519	S-Monel
4	850	500	2.1					30	0.40			(1)	10					(1)	0.40					ANL-4519	
5	1350	500	2.1					30	0.45				7					(1)	0.45					ANL-4519	
6	895	600	3–5	0.24																				ANL-4519	S-Monel
7	500	500	1.7	−0.33				30	−0.33			(1)	10					(2)	0.33					ANL-4519	
8	1350	500	1.7					30	−0.04			(1)	10											ANL-4519	
9	1350	500	1.7					0.01	0			(1)	10											ANL-4519	
10	1655	540												T = 3.33	0.03			(2)	0.03					ANL-4795	
11	1655	540												T = 3.33	0.01			(1)	0.01					ANL-HE-1101	
12	1655	540												T = 3.33	0.05			(1)	0.05					ANL-HE-1101	
13	1655	540												T = 3.33	0			(2)	0					ANL-HE-1101	
14	324	500	30	0.15				(1)	0.15		(1)													ANL-4519	Poor
15	652	500	30	0.22				(1)	0.22		(1)													ANL-4519	
16	1393	500	30	−0.54				(1)	0.54		(1)													ANL-4519	
17	2111	500	30	−0.89				(1)	0.89		(1)													ANL-4519	
18	2895	500	30	0.31				(1)	0.31		(1)													ANL-4519	
19	3605	500	30	−0.15				(1)	0.15		(1)													ANL-4519	
20	4493	500	30	0.09				(1)	0.09		(1)													ANL-4519	
21	5234	500	30	−0.84				(1)	0.84		(1)													ANL-4519	
22	500	500	1.7	−0.06				30	−0.06			(1)	10					(1)	0.06					ANL-4519	
23	500	500	1.7	0.05				0.01	0.05			(1)	10					(1)	0.05					ANL-4519	
24	500	500	2.1	−0.56				30	−0.56				7					(1)	−0.56					ANL-4519	
25	500	500	2.1	0.04				0.01	−0.04				7					(1)	−0.04					ANL-4519	
26	850	500	1.7	−0.03				30	−0.03			(1)	10					(1)	−0.03					ANL-4519	
27	850	500	1.7	−0.04				0.01	−0.04			(1)	10					(1)	−0.04					ANL-4519	
28	850	500	2.1	−0.01				0.01	−0.01				7					(1)	−0.01					ANL-4519	
29	1350	500	1.7	−0.04				30	−0.04			(1)	10					(1)	−0.04					ANL-4519	
30	1350	500	1.7	0				0.01	0			(1)	10					(1)	0					ANL-4519	
31	1350	500	2.1	0.01				0.01	0.01				7					(1)	0.01					ANL-4519	
32	500	500	1.7	0.04				0.01	0.04			(1)	10					(2)	0.04					ANL-4519	
33	500	500	2.1	−0.54				30	−0.54				7					(2)	−0.54					ANL-4519	
34	500	500	2.1	−0.01				0.01	−0.01				7					(2)	−0.01					ANL-4519	
35	672	500					−0.02			Yes														ANL-4519	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODES

(a) Cold drawn
(b) 10,000

MATERIAL K-MONEL (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
36	1032	500					–0.04			Yes														ANL-4519	
37	2160	500	30	–2.47				10	–2.47		14.3		6.15					(2)	–2.47					See Ref 52	
38	1440	500	30	–0.40				0.01	–0.40		14.3		6.15					(2)	–0.40					See Ref 52	
39	1350	500	1.7	–0.04				30	–0.04			(1)	10					(1)	–0.04					ANL-4519	
40	1350	500	1.7	0				0.01	0	(1)		(1)	10					(1)	0					ANL-4519	
41	1350	500	2.1	–0.45				30	–0.45	(1)			7					(1)	–0.45					ANL-4519	
42	1350	500	2.1	0.01				0.01	0.01	(1)			7					(1)	0.01					ANL-4519	
43	1350	500	1.7	–0.18				30	–0.18	(1)		(1)	10					(2)	–0.18					ANL-4519	
44	1350	500	1.7	0				0.01	0	(1)		(1)	10											ANL-4519	
45	1350	500	2.1	–0.44				30	–0.44	(1)			7					(2)	–0.44					ANL-4519	
46	1350	500	2.1	–0.05				0.01	–0.05	(1)			7					(2)	–0.05					ANL-4519	
47	620	500	1–3	0.12				3.1	0.12	(1)		(2)(3)	9											ANL-5059	
48	250	500			200	–0.04		30	–0.04	Yes														ANL-4950	
49	250	500			200	–0.08		0.01	–0.08	Yes														ANL-4950	
50	2000	540												T = 3	0.02			(1)	0.02					ANL-4795	
51	2000	540												T = 3	0.05			(1)	0.05					ANL-4795	
52	250	500			200	–0.04	Yes	30	–0.04	Yes														ANL-5011	
53	250	500			200	–0.08	Yes	0.01	–0.08	Yes														ANL-5011	
54	250	500	2.4		200	–0.03	No	30	–0.03	Yes														ANL-5011	
55	1655	540												T = 3.33	0.05			(1)	0.04					ANL-5011	
56	1655	540												T = 3.33	0.03			(2)	0.03					ANL-5011	
57		280°C												T = 9	–0.33									RH-3	
58		280°C												T = 8	0.03			(1)	0.03					RH-3	
59		280°C												T = 9	–0.23			(1)	–0.23					RH-3	
60		280°C												T = 8	0.02			(2)	0.02					RH-3	
61		280°C												T = 9	–0.27			(2)	–0.27					RH-3	
62	1000	500	4.5		200	0				Yes														WAPD-C-110	Fair
63	1500	500			200	0.01		30	0.01	Yes														WAPD-C-115	Good
64	1900	500			200	–0.02		30	–0.02	Yes														WAPD-C-122	Good
65	3000	500			200	–0.01		30	–0.01	Yes														WAPD-C-135	Good
66	3600	500			200	0.03		30	0.03	Yes														WAPD-C-141	Good
67	250	500			200	–0.04		30	–0.04	Yes														ANL-5011	
68	250	500			200	–0.08		0.01	–0.08	Yes														ANL-5011	Deaerated
69	250	500	2.4		200			30	–0.03															ANL-5011	Aerated
70	2000	500												T = 3	0.04									ANL-5011	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL K-MONEL (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen																				
			(cc/L)	Corr.	(cc/L)	Corr.		(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
69	2000	500												T = 3	0.01									ANL-5011	
70	168	500					0.02																	See Ref 122	
71	168	500	33	0.23												(1)	0.23							See Ref 122	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL A-NICKEL

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
1	324	500	30	0.20				(1)	0.20															ANL-4519	
2	353	500	1500	1.40				(1)	1.40			(1)	9											ANL-4519	
3	353	500	1500	0.20				(1)	0.20			(1)	10											ANL-4519	
4	353	500	1500	0.16				(1)	0.16			(1)	11											ANL-4519	
5	350	600					0.37	(1)	0.37															ANL-4519	
6	895	600	3–5	0.12				(1)	0.12															ANL-4519	
7		280°C												T=8	0.07								(2)0.07	RH-3	
8		280°C												T=9	–0.13									RH-3	
9	500	500	0.2	–0.06				30	–0.06	Yes														ANL-5011	
10	500	500	0.2	–0.07				0.01	–0.07	Yes														ANL-5011	
11	500	500	2	–0.48				30	–0.48	Yes														ANL-5011	
12	500	500	2	–0.37				0.01	–0.37	Yes														ANL-5011	
13	500	500			500	0.03		30	0.03	Yes														ANL-5011	
14	500	500			500	0		0.01	0	Yes														ANL-5011	
15	1000	500	0.2	–0.06				30	–0.06															ANL-5011	
16	1000	500	0.2	–0.10				0.01	–0.10															ANL-5011	
17	1000	500	2	–0.39				30	–0.39															ANL-5011	
18	1000	500	2	–0.32				0.01	–0.32															ANL-5011	
19	1000	500			500	0.03		30	0.03															ANL-5011	
20	1000	500			500	0		0.01	0															ANL-5011	
21	1500	500	2	–0.16				30	–0.16															ANL-5011	
22	1500	500	2	–0.18				0.01	–0.18															ANL-5011	
23	1500	500			500	0.02		30	0.02															ANL-5011	
24	1500	500			500	–0.01		0.01	–0.01															ANL-5036	
25	1032	600					0.18																	See Ref 122	
26	168	600					0.01																	See Ref 122	
27	336	300	24	0.02																				See Ref 122	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 17-4 PH

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen																				
			(cc/L)	Corr.	(cc/L)	Corr.		(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
1	7785	500	30	0.04				(1)			(1)	(4)						(2)(b)	0.04		(5)	0.04		ANL-4519	Good
2	338	500					0.31	(1)										(1)	0.31					ANL-4519	Good
3	338	500					0.08	(1)										(2)(c)	0.08					ANL-4519	Good
4	338	600					0.28	(1)										(2)-850	0.28					ANL-4519	Good
5	2000	540												T = 3	0.01									ANL-4795	
6	500	500	0.2	0				30	0	Yes														ANL-4950	
7	500	500	0.2	0.02				0.01	0.02	Yes														ANL-4950	
8	500	500	2	0				30	0	Yes														ANL-4950	
9	500	500	2	0.06				0.01	0.06	Yes														ANL-4950	
10	500	500					-0.59	30	-0.59	Yes														ANL-4950	
11	500	500					0.46	0.01	0.46	Yes														ANL-4950	
12	1000	500	0.2	0				30	0	Yes														ANL-4950	
13	1000	500	0.2	0				0.01	0	Yes														ANL-4950	
14	1000	500					-0.30	30	-0.30	Yes														ANL-4950	
15	1000	500					-0.02	0.01	-0.02	Yes														ANL-4950	
16	1500	500	0.2	0				30	0	Yes														ANL-4950	
17	500	500			50	-0.86		3.1	-0.86			(2)(3)	9											ANL-4950	
18	500	500			50	0.15		0.01	0.15															ANL-4950	
19	620	500	1-3	0.12				3.1	0.12			(2)(3)	9											ANL-5059	
20	500	500	0-1	0.01				30	0.01															WAPD-C-110	
21	500	500	0-1	-0.17				0.01	-0.17	Yes														WAPD-C-110	
22	1000	500			200	0.03		30	0.03	Yes														WAPD-C-110	Good
23	1500	500			200	0.02		30	0.02	Yes													(2) 0.02	WAPD-C-110	Good
24	500	500	2	0.13				30	0.13	Yes													(1) 0.01	WAPD-C-120	Good
25	1500	500	0.2	-0.01			0	0.01	0.01	Yes														ANL-5011	
26	1500	500	0.2	0			-0.23	30		Yes														ANL-5011	
27	1655	540												T = 3.3	-0.01									ANL-HE-1101	
28	1000	482	1300	0.80	1200	0.45		31										(2)	0.45					ORNL-1605	
																			0.80						
29	1000	482	1300	0.03	1200	0.19		31																ORNL-1605	
30	4380	540												F = 1	0.17									ANL-5059	
														T = 10											
31	4380	540												(a)	0.07									ANL-5059	
32	500	500	0-1	0.01				30	0.01															WAPD-C-110	
33	324	500	30	0.20				(1)			(1)							(2)(a)	0.20		(5)	0.20		ANL-4519	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Control
(b) R_C43
(c) R_C44

MATERIAL 17-4 PH (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen									F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.		(fps)	Corr.																
34	1184	500	30	0.02				(1)			(1)							(2)(a)	0.02		(5)	0.02		ANL-4519	
35	1950	500	30	0				(1)			(1)							(2)(a)	0		(5)	0		ANL-4519	
36	2688	500	30	−0.10				(1)			(1)							(2)(a)	−0.10		(5)	−0.10		ANL-4519	
37	3429	500	30	−0.15				(1)			(1)							(2)(a)	−0.10		(5)	−0.10		ANL-4519	
38	4147	500	30	−0.25				(1)			(1)							(2)(a)	−0.25		(5)	−0.25		ANL-4519	
39	4931	500	30	0.23				(1)			(1)							(2)(a)	0.23		(5)	0.23		ANL-4519	
40	5641	500	30	−0.01				(1)			(1)							(2)(a)	−0.01		(5)	−0.01		ANL-4519	
41	6335	500	30	0.03				(1)										(2)(a)	0.03		(5)	0.03		ANL-4519	
42	7073	500	30	0.19				(1)										(2)(a)	0.19		(5)	0.19		ANL-4519	
43	7785	500	30	0.04				(1)										(2)(a)	0.04		(5)	0.04		ANL-4519	
44	324	500	30	0.36				(1)										(2)(b)	0.36		(5)	0.36		ANL-4519	
45	1950	500	30	−0.03				(1)										(2)(b)	0.03		(5)	0.03		ANL-4519	
46	3429	500	30	0.05				(1)										(2)(b)	0.05		(5)	0.05		ANL-4519	
47	4217	500	30	−0.11				(1)										(2)(b)	−0.11		(5)	−0.11		ANL-4519	
48	5001	500	30	0				(1)										(2)(b)	0		(5)	0		ANL-4519	
49	5711	500	30	0.04				(1)										(2)(b)	0.04		(5)	0.04		ANL-4519	
50	6405	500	30	0.21				(1)										(2)(b)	0.21		(5)	0.21		ANL-4519	
51	7143	500	30	0.05				(1)										(2)(b)	0.05		(5)	0.05		ANL-4519	
52	7715	500	30	0.09				(1)										(2)(b)	0.09			0.09		ANL-4519	
53	1000	500	4.5		200	−0.03				Yes								(2)	−0.03					WAPD-C-110	Good
54	1000	500	4.5		200	−0.03				Yes													(2) −0.03	WAPD-C-110	Fair
55	1500	500			200	−0.04		30	−0.04	Yes								(2)	−0.04					WAPD-C-115	Good
56	1500	500			200	0.02		30	0.02	Yes													(2) 0.02	WAPD-C-115	Good
57	500	500	2	0.13				30	0.13	Yes													(1) 0.13	WAPD-C-120	Good
58	1900	500			200	0		30	0	Yes								(2)	0					WAPD-C-122	Good
59	1900	500			200	−0.02		30	−0.02	Yes													(2) −0.02	WAPD-C-122	Doubtful
60	1000	500	2	−0.06				0.01	−0.06															WAPD-C-122	Good
61	836	500	0.1		2	−0.02		10	−0.02				10.5											WAPD-C-125	Tarnished
62	836	500	0.1		2	−0.01		10	−0.01				10.5											WAPD-C-125	Tarnished
63	836	500	0.1		2	−0.02		10	−0.02				10.5										(2) −0.02	WAPD-C-125	
64	836	500	0.1		2	−0.01		10	−0.01				10.5										(2) −0.01	WAPD-C-125	
65	1000	500					−0.87																	WAPD-C-129	Doubtful
66	1000	500					0.08	0.01	0.08															WAPD-C-129	Good
67	3000	500			200	−0.04				Yes														WAPD-C-129	Good
68	3000	500			200	0																	(2) 0	WAPD-C-129	Doubtful

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) R_C43
(b) R_C50

MATERIAL 17-4 PH (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
69	1000	500			50	−0.53		30	−0.53															WAPD-C-129	Doubtful
70	1000	500			50	0.01		0.01	0.01															WAPD-C-129	Good
71	508	500	0.1		100	−0.26				Yes	3–4										(2)	−0.26		WAPD-C-141	Purple
72	500	500						20	0	Yes		(2)	10.5								(2)	0		WAPD-C-141	Black
73	500	500						10	−0.01	Yes		(2)	10.5								(2)	−0.01		WAPD-C-141	Gold
74	500	500						20	−0.02	Yes		(2)	10.5								(2)	−0.02		WAPD-C-141	Gold
75	3600	500			200	0		30	0									(2)						WAPD-C-141	Good
76	3600	500			200	−0.04		30	−0.04														(2) −0.04	WAPD-C-141	Doubtful
77	2100	500			200	−0.03		30	−0.03															WAPD-C-141	Doubtful
78	1500	500			50	−0.05		0.01	−0.05	Yes														WAPD-C-141	Good
79	1500	500					0	0.01	0	Yes														ANL-5011	
80	1000	500					−0.30	30	−0.30															ANL-5011	
81	1000	500					−0.02	0.01	−0.02															ANL-5011	
82	250	500			200	−0.36		30	−0.36															ANL-5011	
83	250	500			200	−0.52		0.01	−0.52															ANL-5011	
84	250	500			200	−0.09		30	−0.09														(2) −0.04	ANL-5011	
85	2000	540												T − 3	0									ANL-4795	
86	1500	500			50	0.50		30	0.50		0.5–1.7		6.6–7.4											ANL-5059	Doubtful
87	1500	500			50	0.05		0.01	0.05		0.5–1.7		6.6–7.4											ANL-5059	Good
88	1500	500	0.2	−0.01				0.01	−0.01	Yes														ANL-4950	
89	1000	500	0.2	0.02				30	0.02	Yes														ANL-4950	
90	500	500	0.2	−0.16				30	−0.16	Yes													(1) −0.16	ANL-4950	
91	500	500	0.2	−0.04				0.01	−0.04	Yes													(1) −0.04	ANL-4950	
92	500	500					−0.49	30	−0.49														(1) −0.49	ANL-4950	
93	500	500					−0.17	0.01	−0.17														(1) −0.17	ANL-4950	
94	500	500			50	−0.86		30	−0.86															ANL-4950	
95	500	500			50	0.15		0.01	0.15															ANL-4950	
96	500	500			50	−0.79		30	−0.79															ANL-4950	
97	500	500			50	0.08		0.01	0.08															ANL-4950	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 17-7 PH

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
1		280°C												T = 9	−0.71									RH-3	
2		280°C												T = 8	−0.01			(2)						RH-3	
3		280°C												T = 9	−0.14			(2)						RH-3	
4		280°C												T = 8	−0.07								(1)−0.07	RH-3	
5		280°C												T = 9	−0.40								(1)−0.40	RH-3	
6	349	500					−0.11	(1)			(1)							(2)(a)	−0.11					ANL-4519	Good
7	353	500	1500	−0.14				(1)			(1)		9					(2)	−0.14					ANL-4519	
8	353	500	1500	0.03				(1)			(1)		10					(2)	0.03					ANL-4519	
9	340	600					−0.15	(1)			(1)							(2)(a)	−0.15					ANL-4519	
10	358	500	30	−0.75				(1)			(1)					(2)	−0.75							ANL-4519	
11	324	500	30	0.36				(1)			(1)							(2)(a)	0.36		(5)	0.36		ANL-4519	
12	1184	500	30	0.15				(1)			(1)							(2)(a)	0.15		(5)	0.15		ANL-4519	
13	1950	500	30	−0.03				(1)			(1)							(2)(a)	0.03		(5)	−0.03		ANL-4519	
14	2688	500	30	0.09				(1)			(1)							(2)(a)	0.09		(5)	0.09		ANL-4519	
15	3429	500	30	0.05				(1)			(1)							(2)(a)	0.05		(5)	0.05		ANL-4519	
16	4147	500	30	−0.11				(1)			(1)							(2)(a)	0.11		(5)	−0.11		ANL-4519	
17	4931	500	30	0				(1)			(1)							(2)(a)	0		(5)	0		ANL-4519	
18	5640	500	30	0.04				(1)			(1)							(2)(a)	0.04		(5)	0.04		ANL-4519	
19	6334	500	30	0.21				(1)			(1)							(2)(a)	0.21		(5)	0.21		ANL-4519	
20	7072	500	30	0.05				(1)			(1)							(2)(a)	0.05		(5)	0.05		ANL-4519	
21	7784	500	30	0.09				(1)			(1)							(2)(a)	0.09		(5)	0.09		ANL-4519	
22	500	500					−0.16	0.01	−0.16	Yes														WAPD-C-110	
23	500	500	1	−0.09				30	−0.09	Yes													(1)−0.09	WAPD-C-110	
24	1000	500					−0.84	30	−0.84	Yes														WAPD-C-110	
25	1000	500					−0.08	0.01	−0.08	Yes														WAPD-C-110	
26	1000	500	2	0.02				30	0.02	Yes														WAPD-C-120	Good
27	1000	500	2	0.04				0.01	0.04	Yes														WAPD-C-120	Good
28	500	500	2	−0.08				0.01	−0.08	Yes													(1)−0.08	WAPD-C-120	Doubtful
29	1500	500	2	0.02				0.01	0.02	Yes														WAPD-C-122	Good
30	1500	500	2	0.01				30	0.01	Yes														WAPD-C-122	Good
31	1000	500					−0.36	30	−0.36															WAPD-C-129	Doubtful
32	1655	540												T = 3.33	−0.03									ANL-HE-1101	
33	1655	500												T = 3.33	−0.07								(1)−0.07	ANL-HE-1101	
34	1000	500	0.2	0.02				30	0.02	Yes														ANL-5011	
35	1000	500	0.2	0.02				0.01	0.02	Yes														ANL-5011	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Molcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) $R_C 50$

MATERIAL 17-7 PH (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
36	1000	500					−0.07	30	−0.07	Yes														ANL-5011	
37	1000	500					−0.07	0.01	−0.07	Yes														ANL-5011	
38	1500	500	0.2	0.01			−0.08	30	−0.08	Yes														ANL-5011	
39	1500	500	0.2	−0.01			−0.07	0.01	−0.07	Yes														ANL-5011	
40	500	500	0.2	−0.16				30	−0.16	Yes													(1)−0.16	ANL-5011	
41	500	500	0.2	−0.04				0.01	−0.04														(1)−0.04	ANL-5011	
42	500	500					−0.49	30	−0.49														(1)−0.49	ANL-5011	
43	500	500					−0.17	0.01	−0.17														(1)−0.17	ANL-5011	
44	2000	540												T = 3	−0.02			(2)	−0.02					ANL-4795	
45	2000	540												T = 3	−0.01			(2)	−0.01					ANL-4795	
46	260	500			2−3		−0.07			No			7−8											ANL-4641	
47	310	500			16	−0.58				Yes			7											ANL-4641	
48	290	500			1300	−0.28				Yes			7											ANL-4641	
49	620	500	1−3	0.42				3.1	0.42			(2)(3)	9											ANL-5059	
50	1000	500	0.2	0.02				30	0.02															ANL-4950	
51	1000	500	0.2	0.02				0.01	0.02															ANL-4950	
52	1000	500					−0.07	30	−0.07															ANL-4950	
53	1000	500					−0.07	0.01	−0.07															ANL-4950	
54	500	500			100	−0.88		30	−0.88															ANL-4950	
55	500	500			100	0		0.01	0															ANL-4950	
56	500	500			100	−0.72		30	−0.72															ANL-4950	
57	500	500			100	−0.02		0.01	−0.02															ANL-4950	
58	500	500			100	−0.70		30	−0.70															ANL-4950	
59	500	500			100	−0.01		0.01	−0.01															ANL-4950	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 304 SS

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen									F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.		(fps)	Corr.																
1	720			0.01		0	−0.06																	ANL-4300	No quanity given
2	336	500	30	0.09				(1)			(1)	(4)												ANL-4519	Good
3	334	600					−0.08	(1)			(1)	(4)												ANL-4519	Good
4	400	500	30	−2.40				(1)			(1)	(4)											(b)−2.40	ANL-4519	Poor
5	2930	600	240					(1)			(1)	(4)				(1)	−0.01							ANL-4519	Good
																(2)	−0.02								
6	2301	600			70			(1)			(1)	(4)				(1)	−0.01							ANL-4519	Good
																(2)	−0.02								
7	1350	500	1.7					30	−0.05		(1)	(1)	10											ANL-4519	Good
8	1350	500	1.7					0.01	0.01		(1)	(1)	10											ANL-4519	
9	1350	500	2.1					30	−0.06		(1)		7											ANL-4519	
10	1350	500	2.1					0.01	0.01		(1)		7											ANL-4519	
11	1350	500	1.7					30	−0.05		(1)	(1)	10			−0.05								ANL-4519	
12	1350	500	1.7					0.01	0.02		(1)	(1)	10			0.02								ANL-4519	
13	1350	500	2.1					0.01	0.04		(1)		7			0.04								ANL-4519	
14	1350	500	1.7					30	−0.04		(1)	(1)	10					(a)	−0.04					ANL-4519	
15	1350	500	1.7					0.01	0.01		(1)	(1)	10					(a)	0.01					ANL-4519	
16	1350	500	2.1					30	−0.06		(1)	(1)	7					(a)	−0.06					ANL-4519	
17	1350	500	2.1					0.01	0.04		(1)	(1)	7					(a)	0.04					ANL-4519	
18	3200	450		0.02										T = 1	0.02		−0.02							ANL-4537	
19	500	500	0.2					30	0.03	Yes														ANL-4950	
20	500	500	0.2					0.01	0.01	Yes														ANL-4950	
21	500	500			100	0.03		30	0.03	Yes														ANL-4950	
22	500	500			100	0		0.01	0	Yes														ANL-4950	
23	500	500			50	0.01		30	0.01	Yes														ANL-4950	
24	500	500			50	−0.02		0.01	−0.02	Yes														ANL-4950	
25	500	500	0.2	0				30	0	Yes														ANL-5011	
26	500	500	0.2	0.01				0.01	0.01	Yes														ANL-5011	
27	500	500			50	0.01		30	0.01	Yes														ANL-5011	
28	500	500			50	−0.01		0.01	−0.01	Yes														ANL-5011	
29	500	500					−0.20	30	−0.20	Yes														ANL-5011	
30	500	500					0.06	0.01	0.06	Yes														ANL-5011	
31	1000	500			50	0		30	0	Yes														ANL-5011	
32	1000	500			50	−0.01		0.01	−0.01	Yes														ANL-5011	
33	250	500			200	−0.87		30	−0.87															ANL-5011	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODES

(a) Sensitized
(b) Chromallized

MATERIAL 304 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
34	250	500			200	–0.04		0.01	–0.04															ANL-5011	
35	1000	482	1300	0.08				30	0.08	Yes														ORNL-1605	
36	1000	482	1300	0.04				30	0.04	Yes														ORNL-1605	
37	1000	482			1200	0.17		30	0.17	Yes														ORNL-1605	
38	620	500	1–3	0.02				3.1	0.02			(2)(3)	9											ANL-5059	
39	653	600	240					(1)			(1)	(4)				(1)	0.02							ANL-4519	Good
																(2)	0.04								
40	1481	600	240					(1)			(1)	(4)				(1)(2)	0							ANL-4519	Good
41	2180	600	240					(1)			(1)	(4)				(1)(2)	0.04							ANL-4519	Good
42	2930	600	240					(1)			(1)	(4)				(1)	–0.01							ANL-4519	Good
																(2)	–0.02								
43	789	600			70			(1)			(1)	(4)				(1)	0.01							ANL-4519	Good
																(2)	0.02								
44	1551	600			70			(1)			(1)	(4)				(1)	–0.03							ANL-4519	Good
																(2)	0								
45	2301	600			70			(1)			(1)	(4)				(1)	0.01							ANL-4519	Good
																(2)	–0.02								
46	2160	500	30	–0.01				10	–0.01		0.07		6.15											See Ref 52	
47	1440	500	30	0				0.001	0.00		0.07		6.15											See Ref 52	
48	2160	500	30	–0.02				10	–0.02		0.07		6.15			(1)	–0.02							See Ref 52	
49	1440	500	30	–0.03				0.001			0.07		6.15			(1)	–0.03							See Ref 52	
50	2160	500	30	0.02				10										(a)	0.02				(1)–0.40	See Ref 52	
51	1440	500	30	0.06				0.001	0.07									(a)	0.06				(1)–0.19	See Ref 52	
52	334	500	30	–0.24				(1)				(4)											(1)–0.24	ANL-4519	Doubtful
53	1072	500	30	–0.04				(1)				(4)											(1)–0.04	ANL-4519	Doubtful
54	1857	500	30	0.06				(1)				(4)											(1)–0.06	ANL-4519	Doubtful
55	334	500	30	0.05				(1)				(4)											(1) 0.05	ANL-4519	Poor
56	688	500	30	–0.12				(1)				(4)											(1)–0.12	ANL-4519	Poor
57	1450	500	30	–0.41				(1)				(4)											(1)–0.41	ANL-4519	Poor
58	500	500	1.7	–0.11				30	–0.11			(1)	10											ANL-4519	
59	500	500	1.7	0.04				0.01	0.04			(1)	10											ANL-4519	
60	500	500	2.1	–0.17				30	–0.17				7											ANL-4519	
61	500	500	2.1	0.04				0.01	0.04				7											ANL-4519	
62	850	500	1.7	–0.02				30	–0.02			(1)	10											ANL-4519	
63	850	500	1.7	–0.01				0.01	–0.01			(1)	10											ANL-4519	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Sensitized

MATERIAL 304 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
64	850	500	2.1	0.01				30	0.01				7											ANL-4519	
65	850	500	2.1	–0.01				0.01	–0.01				7											ANL-4519	
66	500	500	1.7	–0.09				30	–0.09			(1)	10			(1)	–0.09							ANL-4519	
67	500	500	1.7	0.06				0.01	0.06			(1)	10			(1)	0.06							ANL-4519	
68	500	500	2.1	0.08				0.01	0.08				7			(1)	0.08							ANL-4519	
69	850	500	1.7	–0.02				30	–0.02			(1)	10			(1)	–0.02							ANL-4519	
70	850	500	1.7	–0.01				0.01	–0.01			(1)	10			(1)	–0.01							ANL-4519	
71	850	500	2.1	0.01				0.01	0.01				7			(1)	0.01							ANL-4519	
72	500	500	1.7	–0.07				30	–0.07			(1)	10					(a)	–0.07					ANL-4519	
73	500	500	1.7	0.05				0.01	0.05			(1)	10					(a)	0.05					ANL-4519	
74	500	500	2.1	–0.16				30	–0.16				7					(a)	–0.16					ANL-4519	
75	500	500	2.1	0.08				0.01	0.08				7					(a)	0.08					ANL-4519	
76	850	500	1.7	–0.01				30	–0.01			(1)	10					(a)	–0.01					ANL-4519	
77	850	500	1.7	–0.01				0.01	–0.01			(1)	10					(a)	–0.01					ANL-4519	
78	850	500	2.1	0				30	0				7					(a)	0					ANL-4519	
79	850	500	2.1	0.01				0.01	0.01				7					(a)	0.01					ANL-4519	
80	1000	500	1	0				30	0															WAPD-C-110	
81	1000	500					–0.17	30	–0.17															WAPD-C-110	
82	1000	500	1	0.02				0.01	0.02															WAPD-C-110	
83	1000	500					–0.04	0.01	–0.04															WAPD-C-110	
84	500	500	1	0.02				30	0.02															WAPD-C-110	
85	500	500						0.01	0.07	Yes														WAPD-C-110	
86	1000	500	1	0.03				30	0.03	Yes														WAPD-C-110	
87	1000	500	1	0.06				0.01	0.06	Yes														WAPD-C-110	
88	1500	500	1	0.01				30	0.01	Yes														WAPD-C-110	
89	1500	500	1	0.04				0.01	0.04	Yes														WAPD-C-110	
90	500	500					–0.11	30	–0.11	Yes														WAPD-C-110	
91	1500	500					–0.11	30	–0.11	Yes														WAPD-C-110	
92	1500	500					–0.03	0.01	–0.03	Yes														WAPD-C-110	
93	1000	500			200	0				Yes														WAPD-C-110	
94	500	500			40	0		30	0	Yes														WAPD-C-110	
95	500	500			40	0		0.01	0	Yes														WAPD-C-110	
96	500	500			40	0.02		30	0.02	Yes														WAPD-C-110	
97	500	500			40	0.04		0.01	0.04	Yes														WAPD-C-110	
98	500	500			25	–0.01		30	–0.01		1													WAPD-C-115	Good

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcamized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Sensitized

MATERIAL 304 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated F&T (10^{19} nvt)	Irradiated Corr.	Welded Type	Welded Corr.	Heat Treatment Type	Heat Treatment Corr.	Stress (psi)	Surface Finish Type	Surface Finish Corr.	Treatment Type	Reference	Remarks
99	1500	500			200	0		30	0															WAPD-C-115	Good
100	500	500	2	0.03				30	0.03															WAPD-C-120	Good
101	500	500	2	0.09				0.01	0.09															WAPD-C-120	Good
102	1000	500					−0.08	30	−0.08															WAPD-C-120	Good
103	1000	500			25	−0.02		30	−0.02	Yes														WAPD-C-122	Good
104	500	500			25	0		0.01	0	Yes														WAPD-C-122	Good
105	500	500	2	0.03				30	0.03	Yes														WAPD-C-122	Good
106	500	500	2	0.06				0.01	0.06	Yes														WAPD-C-122	Good
107	836	500			2	0		10	0	Yes			10.5											WAPD-C-125	
108	836	500			2	−0.01		20	−0.02				10.5											WAPD-C-125	
109	836	500			2	0.03		10	0.03				10.5											WAPD-C-125	
110	836	500			2	−0.02		20	−0.02				10.5											WAPD-C-125	
111	1500	500					−0.05	30	−0.05	Yes														WAPD-C-125	
112	1500	500				−0.01		0.01	−0.01	Yes														WAPD-C-125	
113	500	500			100	−0.08		10	−0.08	Yes											(2)	−0.08		WAPD-C-129	
114	500	500			100	−0.08		20	−0.08	Yes											(2)	−0.08		WAPD-C-129	
115	500	500			100	0.01		10	0.01	Yes											(3)	0.01		WAPD-C-129	
116	500	500			100	0		20	0	Yes											(3)	0		WAPD-C-129	
117	500	500						20	0			(2)	10								(2)	0		WAPD-C-135	
118	500	500						20	0.01			(2)	10								(2)	0.01		WAPD-C-135	
119	500	500						10	0			(2)	10								(2)	0		WAPD-C-135	
120	3000	500			200			30	−0.01	Yes											(3)	−0.01		WAPD-C-135	
121	702	500			100	0		10	0	Yes	2–4		7								(3)	0		WAPD-C-137	
122	702	500			100	0.01		20	0.01	Yes	2–4		7								(3)	0.01		WAPD-C-137	
123	702	500			100	−0.11		10	−0.11	Yes	2–4		7								(2)	−0.11		WAPD-C-137	
124	702	500			100	−0.10		20	−0.10	Yes	2–4		7								(2)	−0.10		WAPD-C-137	
125	1500	500	1	0.01				30	0.01															WAPD-C-137	
126	1500	500	1	0.04				0.01	0.04															WAPD-C-137	
127	1500	500	5	0.01				30	0.01															WAPD-C-137	
128	500	500			100	0.02		30	0.02															WAPD-C-137	
129	500	500			100	0		0.01	0															WAPD-C-137	
130	500	500			100	0.03		30	0.03															WAPD-C-137	
131	500	500			100	0		0.01	0															WAPD-C-137	
132	500	500			50	0.01		30	0.01															WAPD-C-137	
133	500	500			50	−0.01		0.01	−0.01															WAPD-C-137	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 304 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
134	1000	500			50	0		30	0															WAPD-C-137	
135	1000	500			50	–0.01		0.01	–0.01															WAPD-C-137	
136	500	500			25	–0.02		30	–0.02															WAPD-C-137	
137	500	500			25	–0.04		0.01	–0.04															WAPD-C-137	
138	508	500			100	–0.10		10	–0.10	Yes	3–4										(2)	–0.10		WAPD-C-141	
139	508	500			100	–0.13		20	–0.13		3–4										(2)	–0.13		WAPD-C-141	
140	508	500			100	–0.08		20	–0.08		3–4										(2)	–0.08		WAPD-C-141	
141	508	500			100	0.01		10	0.01		3–4										(3)	0.01		WAPD-C-141	
142	508	500			100	0.01		20	0.01		3–4										(3)	0.01		WAPD-C-141	
143	500	500						20	0.01			(2)	10								(2)	0.01		WAPD-C-141	
144	500	500						10	0.01			(2)	10								(2)	0.01		WAPD-C-141	
145	3600	500			200	0		30	0															WAPD-C-141	Good
146	1500	500			50	0		30	0															WAPD-C-141	Good
147	1500	500			50	–0.01		0.01	–0.01															WAPD-C-141	
148	750	500			200	–0.20		30	–0.20															ANL-4950	
149	750	500			200	–0.27		0.01	–0.27															ANL-4950	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 304L SS

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated F&T (10^{19} nvt)	Irradiated Corr.	Welded Type	Welded Corr.	Heat Treatment Type	Heat Treatment Corr.	Stress (psi)	Surface Finish Type	Surface Finish Corr.	Treatment Type	Reference	Remarks
1	324	500	30	0.12				(1)	0.12		(1)													ANL-4519	Good
2	401	500	30	0.19				(1)	0.19		(1)													ANL-4519	Good
3	330	600					-0.15	(1)			(1)					(1)	-0.15							ANL-4519	Good
																	to 304								
4	4584	500	1-2	-0.01				30	-0.01	Yes										(a)				ANL-4898	
5	4584	500	1-2	0.01				30	0.01	Yes														ANL-4898	
6	4584	500	1-2	0.01				30	0.01	Yes						(1)	0.01							ANL-4898	
7	4584	500	1-2	-0.01				30	-0.01	Yes						(1)	-0.01							ANL-4898	
8	500	500	0.2	0.01				30	0.01	Yes											(2)	0.01		ANL-4898	
9	500	500	0.2	-0.75				30	-0.75	Yes											(1)	0.75		ANL-4898	
10	500	500	2	0.04				30	0.04	Yes											(2)	0.04		ANL-4898	
11	500	500	2	0.03				30	0.03	Yes											(1)	0.03		ANL-4898	
12	500	500			500	-0.04		30	-0.04	Yes											(2)	-0.04		ANL-4898	
13	500	500			500	-0.08		30	-0.08	Yes											(1)	-0.08		ANL-4898	
14	1000	500	0.2	-0.47				30	-0.47	Yes											(1)	-0.47		ANL-4898	
15	1000	500	2	0.04	500	-0.03		30	0.04	Yes											(1)	0.04		ANL-4898	
16	500	500	0.2	0.01				0.01	0.01	Yes											(2)	0.01		ANL-4898	
17	500	500	2	0.01	500	-0.05		0.01		Yes											(2)			ANL-4898	
18	500	500	0.2	-0.16				0.01	-0.16	Yes											(1)	-0.16		ANL-4898	
19	500	500	2	0.08	500	-0.06	-0.04	0.01		Yes											(1)			ANL-4898	
20	1000	500	0.2	-0.08				0.01	-0.08	Yes											(1)	-0.08		ANL-4898	
21	1000	500	2	0.01	500	-0.01	-0.04	0.01		Yes											(1)			ANL-4898	
22	500	500	0.2	0.01				30	0.01	Yes											(1)	0.01		ANL-5011	
23	500	500	0.2	0.03				0.01	0.03												(1)	0.03		ANL-5011	
24	500	500			50	0		0.01	0												(1)	0		ANL-5011	
25	1500	500			50	-0.01		30	-0.01		0.05-1.7		6.6-7.4											ANL-5059	Glossy
26	1500	500			50	0.15		0.01	0.15		0.05-1.7		6.6-7.4											ANL-5059	Glossy
27	1000	500			25	-0.01		30	-0.01		0.9-3.0		6.4-7.7											ANL-5059	Straw
28	500	500			25	0		0.01	0		0.9-3.0		6.4-7.7											ANL-5059	
29	620	500	1-3	0.09				3.1	0.09			(2)(3)	9											ANL-5059	
30	1000	482	1300	0.08				30	0.08															ANL-5059	
31	1000	482	1300	0.17	1200	0.17		30																ANL-5059	Cast
32	1000	500	0-1	0				30	0															WAPD-C-110	
33	1000	500	0-1	0.01				0.01	0.01															WAPD-C-110	
34	1500	500	1	0.01				30	0.01	Yes														WAPD-C-110	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsanized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) 10,000

MATERIAL 304L SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated F&T (10^{19} nvt)	Irradiated Corr.	Welded Type	Welded Corr.	Heat Treatment Type	Heat Treatment Corr.	Stress (psi)	Surface Finish Type	Surface Finish Corr.	Treatment Type	Reference	Remarks
35	1500	500	1	0.02				0.01	0.02	Yes														WAPD-C-110	
36	1500	500	1	0.03				0.01	0.03	Yes														WAPD-C-110	
37	500	500	1	-0.11				30	-0.11	Yes													(1) -0.11	WAPD-C-110	Good
38	500	500	1	-0.53				0.01	-0.53	Yes													(1) -0.53	WAPD-C-110	Fair
39	500	500					-0.12	30	-0.12	Yes														WAPD-C-110	
40	500	500			40	0.01		30	0.01	Yes														WAPD-C-110	
41	500	500			40	0		0.01	0	Yes														WAPD-C-110	Thin, loose
42	500	500			40	0.01		30	0.01	Yes														WAPD-C-110	Thin, loose
43	500	500			25	-0.01		30	-0.01	Yes														WAPD-C-115	
44	500	500			25	-0.01		30	-0.01	Yes														WAPD-C-115	Good
45	500	500			25	-23.2		30	-23.2	Yes													(1) -0.23	WAPD-C-115	
46	500	500	2	0.16				30	0.16	Yes													(1) -0.16	WAPD-C-120	Good
47	500	500	2	0.01				0.01	0.01	Yes													(1) 0.01	WAPD-C-120	Doubtful
48	1000	500			25	-0.01		30	0.01	Yes														WAPD-C-122	
49	1000	500			25	-1.65		30	-1.65	Yes													(1) -1.65	WAPD-C-122	Good
50	500	500			25	0		0.01	0	Yes														WAPD-C-122	Doubtful
51	500	500	2	0.01				30	0.01	Yes														WAPD-C-122	Good
52	500	500	2	0.08				0.01	0.08	Yes														WAPD-C-122	Good
53	1500	500					-0.06	30	-0.06	Yes														WAPD-C-125	Loose, good, blue
54	1500	500					-0.01	0.01	-0.01															WAPD-C-125	Good
55	500	500			25	-0.01		30	-0.01															WAPD-C-129	
56	1000	500			25	-0.01		30	-0.01															WAPD-C-129	
57	1000	500			25	0		0.01	0															WAPD-C-129	
58	1000	500			50	0		30	0	Yes														WAPD-C-135	Good
59	1000	500			50	0		0.01	0	Yes														WAPD-C-135	Good
60	1500	500			50	-0.01		30	-0.01															WAPD-C-141	Good
61	1500	500			50	-0.01		0.01	-0.01															WAPD-C-141	Good
62	500	500	0.2	-0.16				30	-0.16	Yes													(1) -0.16	ANL-4950	
63	500	500	0.2	-0.20				0.01	-0.20	Yes													(1) -0.20	ANL-4950	
64	500	500					-1.29	30	-1.29														(1) -1.29	ANL-4950	
65	500	500					-0.36		-0.36														(1) -0.36	ANL-4950	
66	1000	482	1300	0.16				30	-0.16															ORNL-1605	
67	1000	482	1300	0.08				30	-0.08															ORNL-1605	
68	1000	482			1200	0.16		30	-0.16															ORNL-1605	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 316 SS

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
1	500	500	1.7	−0.10				30	−0.10			(1)	10											ANL-4519	
2	500	500	1.7	0.05				0.01	0.05			(1)	10											ANL-4519	
3	500	500	2.1	−0.17				30	−0.17				7											ANL-4519	
4	500	500	2.1	0.04				0.01	0.04				7											ANL-4519	
5	850	500	1.7	−0.04				30	−0.04			(1)	10											ANL-4519	
6	850	500	1.7	−0.01				0.01	−0.01			(1)	10											ANL-4519	
7	850	500	2.1	0.04				30	0.04				7											ANL-4519	
8	850	500	2.1	−0.01				0.01	−0.01				7											ANL-4519	
9	1350	500	1.7	−0.07				30	−0.07			(1)	10											ANL-4519	
10	1350	500	1.7	0.01				0.01	0.01			(1)	10											ANL-4519	
11	1350	500	2.1	−0.04				30	−0.04				7											ANL-4519	
12	1350	500	2.1	0.01				0.01	0.01				7											ANL-4519	
13	500	500	1.7	−0.09				30	−0.09			(1)	10			(2)	−0.09							ANL-4519	
14	500	500	1.7	0.05				0.01	0.05			(1)	10			(2)	0.05							ANL-4519	
15	500	500	2.1	−0.18				30	−0.18				7			(2)	−0.18							ANL-4519	
16	500	500	2.1	0.05				0.01	0.05				7			(2)	0.05							ANL-4519	
17	850	500	1.7	−0.03				30	−0.03			(1)	10			(2)	−0.03							ANL-4519	
18	850	500	1.7	−0.02				0.01	0.02			(1)	10			(2)	0.02							ANL-4519	
19	850	500	2.1	0.05				30	0.05				7			(2)	0.05							ANL-4519	
20	850	500	2.1	0				0.01	0				7			(2)	0							ANL-4519	
21	1350	500	1.7	−0.05				30	−0.05			(1)	10			(2)	−0.05							ANL-4519	
22	1350	500	1.7	0				0.01	0			(1)	10			(2)	0							ANL-4519	
23	1350	500	2.1	−0.04				30	−0.04				7			(2)	−0.04							ANL-4519	
24	1350	500	2.1	0.02				0.01	0.02				7			(2)	0.02							ANL-4519	
25	500	500	1.7	−0.11				30	−0.11			(1)	10			(1)	−0.11							ANL-4519	
26	500	500	1.7	0.03				0.01	0.03			(1)	10			(1)	0.03							ANL-4519	
27	500	500	2.1	−0.19				30	−0.19				7			(1)	−0.19							ANL-4519	
28	500	500	2.1	0.05				0.01	0.05				7			(1)	0.05							ANL-4519	
29	850	500	1.7	−0.05				30	−0.05			(1)	10			(1)	−0.05							ANL-4519	
30	850	500	1.7	−0.02				0.01	−0.02			(1)	10			(1)	−0.02							ANL-4519	
31	850	500	2.1	0.03				30	0.03				7			(1)	0.03							ANL-4519	
32	850	500	2.1	0				0.01	0				7			(1)	0							ANL-4519	
33	1350	500	1.7	−0.06				30	−0.06			(1)	10			(1)	−0.06							ANL-4519	
34	1350	500	1.7	0				0.01	0			(1)	10			(1)	0							ANL-4519	
35	1350	500	2.1	−0.05				30	−0.05				7			(1)	−0.05							ANL-4519	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 316 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated F&T (10^{19} nvt)	Irradiated Corr.	Welded Type	Welded Corr.	Heat Treatment Type	Heat Treatment Corr.	Stress (psi)	Surface Finish Type	Surface Finish Corr.	Treatment Type	Reference	Remarks
36	1350	500	2.1	0.02				0.01	0.02				7			(1)	0.02							ANL-4519	
37	500	500					−0.09	30	−0.09	Yes														WAPD-C-110	
38	500	500					−0.03	0.01	−0.03	Yes														WAPD-C-110	
39	1000	500					−0.06	30	−0.06	Yes														WAPD-C-110	
40	1000	500					−0.08	0.01	−0.08	Yes														WAPD-C-110	
41	500	500			40	0.01		30	0.01	Yes														WAPD-C-110	
42	500	500			40	0.02		30	0.02	Yes														WAPD-C-110	
43	1500	500	2	0.02				30	0.02	Yes														WAPD-C-120	Glossy, good
44	1500	500	2	0.03				0.01	0.03	Yes														WAPD-C-120	Violet, good
45	500	500			50	0		0.01	0	Yes														WAPD-C-129	
46	500	500			50	−0.01		30	−0.01	Yes														WAPD-C-129	
47	1500	500	1	0				30	0															WAPD-C-137	
48	1500	500	5	0.02				30	0.02															WAPD-C-137	
49	500	500			500	0.01		30	0.01															WAPD-C-137	
50	500	500			500	0.01		0.01	0.01															WAPD-C-137	
51	500	500	0.2	0.02				30	0.02	Yes														ANL-5011	
52	500	500	2	0.02				30	0.02	Yes														ANL-5011	
53	500	500	2	0.08				0.01	0.08	Yes														ANL-5011	
54	500	500			500	0.02		30	0.02	Yes														ANL-5011	
55	500	500			500	0.01		0.01	0.01	Yes														ANL-5011	
56	500	500					−0.04	30	−0.04	Yes														ANL-5011	
57	500	500					0	0.01	0	Yes														ANL-5011	
58	500	500	0.2	−0.85				30		Yes											(1)	−0.85		ANL-4898	
59	500	500	0.2	−0.74				30		Yes											(1)	−0.74		ANL-4898	
60	500	500	0.2	−0.75				30		Yes											(1)	−0.75		ANL-4898	
61	1000	500	0.2	−0.48				30		Yes											(1)	−0.48		ANL-4898	
62	500	500	2	0.02				30		Yes											(1)	0.02		ANL-4898	
63	1000	500	2	−0.01				30		Yes											(1)	−0.01		ANL-4898	
64	500	500			500	0		30		Yes											(1)	0		ANL-4898	
65	500	500			500	−0.02		30		Yes											(2)	0		ANL-4898	
66	1000	500			500	0.02		30		Yes											(1)	0.02		ANL-4898	
67	500	500					−0.04	30		Yes											(2)	0.02		ANL-4898	
68	500	500					−0.35	30		Yes											(1)	−0.04		ANL-4898	
69	500	500					−0.34	30		Yes											(1)	−0.35		ANL-4898	
70	1000	500					−0.17	30		Yes											(1)	−0.34		ANL-4898	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 316 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
71	1500	500					−0.11	30		Yes											(1)	−0.11		ANL-4898	
72	500	500	0.2	−0.11				0.01	−0.11	Yes											(1)	−0.11		ANL-4898	
73	500	500	2	0.02				0.01	0.02	Yes											(1)	0.02		ANL-4898	
74	500	500			500	0.01		0.01	0.01	Yes											(2)	0.01		ANL-4898	
75	500	500			500	−0.07		0.01	−0.07												(1)	−0.07		ANL-4898	
76	500	500					0	0.01	0												(2)	0		ANL-4898	
77	500	500					−0.13	0.01	−0.13												(1)	−0.13		ANL-4898	
78	1000	500	0.2	−0.04				0.01	−0.04												(1)	−0.04		ANL-4898	
79	1000	500	2	0.03				0.01	0.03												(1)	0.03		ANL-4898	
80	1000	500			500	−0.03		0.01	−0.03												(1)	−0.03		ANL-4898	
81	1000	500					−0.06	0.01	−0.06												(1)	−0.06		ANL-4898	
82	620	500	1–3	0.04				3.1	0.04			(2)(3)	9											ANL-5059	
83	500	500			100	0.02		30	0.02	Yes														ANL-4950	
84	500	500			100	−0.01		0.01	−0.01	Yes														ANL-4950	
85	500	500			100	0.01		30	0.01	Yes														ANL-4950	
86	500	500			100	0		0.01	0	Yes														ANL-4950	
87	500	500			50	0		30	0	Yes														ANL-4950	
88	500	500			50	−0.01		0.01	−0.01	Yes														ANL-4950	
89	500	500			50	−0.01		30	−0.01	Yes														ANL-4950	
90	500	500			50	0		0.01	0	Yes														ANL-4950	
91	1000	482	1300	0.03																				ORNL-1605	
92	1000	482	1300	0																				ORNL-1605	Cast
93	1000	482			1200	0.12																		ORNL-1605	
94	1000	482			1200	0.03																		ORNL-1605	Cast
95	2160	500	30	−0.03				10	−0.03		14.3		6.15											See Ref. 52	
96	1440	500	30	−0.00				0.01	0		14.3		6.15											See Ref. 52	
97	2160	500	30	−0.03				10	−0.03		14.3		6.15			−0.03								See Ref. 52	
98	1440	500	30	−0.05				0.01	−0.05		14.3		6.15			−0.03								See Ref. 52	
99	2160	500	30	−0.01				10	−0.01		14.3		6.15			(a)	−0.01							See Ref. 52	
100	1440	500	30	−0.01				0.01	−0.01		14.3		6.15			(a)	−0.01							See Ref. 52	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Sensitized

MATERIAL 322W SS

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
1	500	500	1	−0.05				30	−0.05	Yes													(1)−0.05	WAPD-C-110	
2	500	500	4.5		200	−0.04												(2)	−0.04					WAPD-C-110	Fair
3	500	500			25	−21.60																	(1)−21.6	WAPD-C-115	Doubtful
4	1500	500			200	−0.02		30	−0.02									(2)	−0.02					WAPD-C-115	Good
5	500	500	2	0.16				30	0.16														(1)0.16	WAPD-C-120	Good
6	1900	500			200	−0.02		30	−0.02									(2)	−0.02					WAPD-C-122	Doubtful
7	500	500					−0.71	30	−0.71															WAPD-C-125	Doubtful
8	500	500					0.11	0.01	0.11															WAPD-C-125	Doubtful
9	500	500					−0.28	30	−0.28															WAPD-C-129	Grey, good
10	500	500	1	0.05				30	0.05	Yes														WAPD-C-129	Good
11	500	500	1	0.06				0.01	0.06	Yes														WAPD-C-129	Good
12	3000	500			200	−0.03		30	−0.03									(2)	−0.03					WAPD-C-135	Doubtful
13	3600	500			200	−0.03		30	−0.03	Yes								(2)	−0.03					WAPD-C-141	Doubtful
14	500	500			50	−0.26		30	−0.26	Yes														WAPD-C-141	Doubtful
15	1500	500	1	0.02				30	0.02															WAPD-C-141	Good
16	1500	500	1	0.03				0.01	0.03															WAPD-C-141	Good
17	1500	500					−0.30	30	−0.30	Yes														WAPD-C-137	Doubtful
18	1500	500					−0.01	0.01	−0.01	Yes														WAPD-C-137	Good
19	1000	500	1	0.02				30	0.02															WAPD-C-137	Glossy
20	1655	500												T = 3.3	−0.02			(2)	−0.02					ANL-HE-1101	
21	1655	500												T = 3.3	−0.03			(2)	−0.02					ANL-HE-1101	
22	2000	540												T = 3	−0.01			(2)	−0.01					ANL-4795	
23	2000	540												T = 3	0			(2)	0					ANL-4795	
24	625	500	1−3	0.26				3.1	0.26			(2)(3)	9											ANL-5059	
25	500	500			50	−0.26		30	−0.26	Yes	0.5−1.7		6.6−7.4											ANL-5059	Doubtful
26	1500	500			50	−0.30		0.01	−0.30	Yes	0.5−1.7		6.6−7.4											ANL-5059	
27	4380	540												F = 1	0.12									ANL-5059	Cpld. to 17-4
														T = 10											
28	4380	540												(a)	0.01									ANL-5059	Cpld. to 17-4
29	4380	540												F = 1	0.06									ANL-5059	Cpld. to Stellite-6
														T = 10											
30	4380	540												(a)	0.03									ANL-5059	Cpld. to Stellite-6
31	4380	540												F = 1	0.16									ANL-5059	Cpld. to Haynes 25
														T = 10											
32	4380	540												(a)	0.07									ANL-5059	Cpld. to Haynes 25

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Control

MATERIAL 322W SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
33	500	500	0.2	−0.17				30	−0.17	Yes													(1)−0.17	ANL-4950	
34	500	500	0.2	−0.20				0.01	−0.20	Yes													(1)−0.20	ANL-4950	
35	1000	482	1300	0.08				30																ORNL-1605	
36	1000	482	1300	0.12				30										(2)	0.12					ORNL-1605	
37	1000	482	1300	3.00				30															(1)3.00	ORNL-1605	
38	1000				1200	0.34		30																ORNL-1605	
39	1000				1200	0.41		30										(2)	0.41					ORNL-1605	
40	1000				1200	3.50		30															(1)3.50	ORNL-1605	
41	340	500	30	0.01				(1)										(2)(a)	0.01		(5)	0.01		ANL-4519	
42	1200	500	30	0.017				(1)										(2)(a)			(5)			ANL-4519	
43	1966	500	30	−0.037				(1)										(2)(a)			(5)			ANL-4519	
44	2704	500	30	−0.034				(1)										(2)(a)			(5)			ANL-4519	
45	3421	500	30	0.03				(1)										(2)(a)			(5)			ANL-4519	
46	4139	500	30	−0.11				(1)										(2)(a)			(5)			ANL-4519	
47	4875	500	30	0.12				(1)										(2)(a)			(5)			ANL-4519	
48	5614	500	30	−0.01				(1)										(2)(a)			(5)			ANL-4519	
49	6308	500	30	0.13				(1)										(2)(a)			(5)			ANL-4519	
50	7046	500	30	0.07				(1)										(2)(a)			(5)			ANL-4519	
51	7782	500	30	0.08				(1)										(2)(a)			(5)			ANL-4519	
52	334	500	30	−0.04				(1)								(1)	−0.04							ANL-4519	Welded to 347
53	334	500	30	0.01				(1)								(1)	0.01							ANL-4519	Welded to 347
54	1144	500	30	0.01				(1)								(1)	0.01							ANL-4519	Welded to 347
55	1144	500	30	0				(1)								(1)	0							ANL-4519	Welded to 347

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) $R_C 43$

MATERIAL 347 SS

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated F&T (10^{19} nvt)	Irradiated Corr.	Welded Type	Welded Corr.	Heat Treatment Type	Heat Treatment Corr.	Stress (psi)	Surface Finish Type	Surface Finish Corr.	Treatment Type	Reference	Remarks
1	720	500					–0.04	(1)	–0.04															ANL-4300	
2	5000	500			25	–0.01		30	–0.01		(1)													ANL-HE-1478	
3	5000	600			25	–0.01		30	–0.01		(1)													ANL-HE-1478	
4	2500	500			25	–0.05		30	–0.05		(1)													ANL-HE-1478	
5	2832	540			25–39	0.08		10.5	0.08					T = 5.5	0.08									ANL-HE-1478	
														F = 1.1											
6	4800	540			25–39	0.11		10.5	0.11					T = 9	0.11									ANL-HE-1478	
														F = 1.8											
7	7762	500	30	0.02				(1)			(1)													ANL-4519	Good
				to 0.00																					
8	353	500	1500	–0.12				(1)			(1)	(1)	11											ANL-4519	Good
9	400	500	30	0.00	18	0.10	0.04	(1)			(1)													ANL-4519	Cladding
10	2930	600	240					(1)			(1)					(1)(2)	–0.01				(5)(b)			ANL-4519	Good
																	–0.02								
11	2301	600			70			(1)			(1)					(1)(2)	0.02				(5)(b)			ANL-4519	Good
																	–0.00								
12	331	600	30					(1)			(1)					(1)	–0.10							ANL-4519	Good
																	–0.27								
13	331	600	30					(1)			(1)					(1)	–1.20							ANL-4519	Good
																	–2.50								
14	895	600	3–5					30	–0.05		(1)								–0.05	(a)				ANL-4519	Good
15	5503	500					–0.01	(1)			(1)					(2)	–0.01				(5)(b)			ANL-4519	TS347A
16	5471	500	30	0.01				(1)			(1)					(2)	0.01				(5)(b)			ANL-4519	TS347A
17	5000	500	30	–0.02			Yes	30			(1)													ANL-4519	
18	2500	600	30	0.01				30			(1)													ANL-4519	
19	700	500	0.02	0				28																ANL-4519	
20	3200	450												T = 1.2	0.00	(2)	0.00							ANL-4537	
21	260	500			2–3		0.31			None			7–8											ANL-4641	
22	310	500			16	–0.46				Yes			7											ANL-4641	
23	290	500			1300	0.04				Yes			7											ANL-4641	
24	2000	540												T = 3	0.01									ANL-4795	TS347A
25	500	500	2	–0.09	500	0.01		30		Yes											(2)	0.01		ANL-4898	
26	500	500	2		500	–0.13		30		Yes											(1)	–0.13		ANL-4898	
27	500	500	2	0.08	500	–0.01		0.01		Yes											(2)	–0.01		ANL-4898	
28	500	500			500	–0.21		0.01		Yes											(1)	–0.21		ANL-4898	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODES

(a) 10,000

(b) HNO_3

MATERIAL 347 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
29	1000	500	2	−0.04	500	−0.03		30		Yes											(1)	−0.03		ANL-4898	
30	1500	500	2	−0.04	500	0.00		30		Yes											(2)	0		ANL-4898	
31	500	500	2	−0.01	500	0.00	−0.09	30		Yes							Yes				(2)	0		ANL-4898	
			0.2	−0.41																					
32	1000	500	2	0.00	500	0.01	−0.04	30		Yes							Yes				(2)	0.01		ANL-4898	
			0.2	−0.50																					
33	1500	500	2	0.00	500	0.00	−0.04	30		Yes							Yes				(2)	0		ANL-4898	
			0.2	−0.39																					
34	500	500	2	0.08	500	−0.01		0.01		Yes											(2)			ANL-4898	
35	1000	500	2	0.06	500	0.00		0.01		Yes											(2)			ANL-4898	
36	1500	500	2	0.05	500	−0.01		0.01		Yes											(2)			ANL-4898	
37	500	500	2	0.03	500	0.00	−0.04	0.01		Yes						(2)	Yes				(2)			ANL-4898	
			0.2	0.03																					
38	1500	500	2	−0.04	500	0.00	0.00	0.01		Yes						(2)	Yes				(2)			ANL-4898	
			0.2	0.02																					
39	1000	500	2					0.01	0.01	Yes														ANL-5011	347A
								30	−0.01																
40	1000	500			50			0.01	−0.01	Yes														ANL-5011	347A
								0.30	−0.01																
41	1500	500	0.2					30	−0.40	Yes														ANL-5011	
								0.01	−0.02																
42	1500	500	2					30	0.01	Yes														ANL-5011	
								0.01	0.03																
43	1500	500			500			30	0.00	Yes														ANL-5011	
								0.01	0.00																
44	1500	500					Yes	30	−0.03	Yes														ANL-5011	
								0.01	0.04																
45	1500	500	0.2					30	−0.39	Yes						(1)	Yes							ANL-5011	
								0.01	−0.04																
46	1500	500	2					30	0.00	Yes						(1)	Yes							ANL-5011	
								0.01	0.02																
47	1500	500			500			30	0.00	Yes						(1)	Yes							ANL-5011	
								0.01	0.00																
48	1500	500				Yes		30	−0.04	Yes						(1)	Yes							ANL-5011	
								0.01	0.00																

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 347 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
49	1000	482	1300	0.07				30		Yes														ORNL-1605	
50	1000	482			1200	0.10		30		Yes														ORNL-1605	
51	1655	540								Yes				F = 3.3	−0.02									ANL-HE-1101	347A
															−0.01										
52	1655	540												F = 3.3	0.05								(2)	ANL-HE-1101	
															0.04										
53	1500	500			50	0.00		30			0.5–1.7		6.6–7.4			(1)	0.00							ANL-5059	
54	1000	500			25	0.02		30			0.9–3.0		6.4–7.7			(1)	0.02							ANL-5059	
55	4380	540												T = 1	0.41									ANL-5059	
														F = 10											
56	4380	540												F = 10	0.10									ANL-5059	Control
57	161	500						(1)	0.00			(b)												ANL-5059	
58	161	500						(1)	0.03			(b)												ANL-5059	
59	161	500						(1)	0.01			(b)												ANL-5059	
60	161	500						(1)	0.01			(b)												ANL-5059	
61	161	500						(1)	0.01			(b)												ANL-5059	
62	161	500						(1)	0.09			(a)												ANL-5059	
63	161	500							0.04			(a)												ANL-5059	
64	161	500						(1)	0.03			(a)												ANL-5059	
65	620	500	1–3	−1.50				3.1	−1.50			(2)(3)	9											ANL-5059	Poison loop
66	985	500			100	0.04		20			3										(3)	0.04		WAPD-C-110	
67	985	500			100	0.00		20													(2)	0.00		WAPD-C-110	
68	653	600	240					(1)			(1)					(1)	0.01				(c)			ANL-4519	Good
																(2)	0.02								
69	1418	600	240					(1)			(1)					(1)	0.02				(c)			ANL-4519	Good
																(2)	0.00								
70	2180	600	240					(1)			(1)					(1)	0.02				(c)			ANL-4519	Good
																(2)	0.03								
71	2930	600	240					(1)			(1)					(1)	−0.01				(c)			ANL-4519	Good
																(2)	−0.02								
72	789	600			70			(1)			(1)					(1)	0.03				(c)			ANL-4519	Good
																(2)	0.02								
73	1551	600			70			(1)			(1)					(1)	−0.03				(c)			ANL-4519	Good
																(2)	−0.01								

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) $MgFlSiO_2$
(b) $Zn\ FlSiO_2$
(c) HNO_3

MATERIAL 347 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
74	2301	600			70			(1)			(1)					(1)	0.02				(a)			ANL-4519	Good
																(2)	−0.00								
75	1500	500					−0.33	30	−0.33												(1)	−0.33		ANL-4519	
76		280°C												T = 9	−0.13									RH-3	
77		280°C												T = 8	0.08								(2)	RH-3	
78	1000	500					−0.31	30	−0.31															WAPD-C-110	347A
79	1000	500					−0.03	0.01	−0.03															WAPD-C-110	
80	1500	500	0–1	0.01				30	0.01															WAPD-C-110	
81	1000	500	4.5		200	0				Yes														WAPD-C-110	
82	1000	500	4.5		200	−0.01				Yes														WAPD-C-110	
83	500	500			40	0.01		30	0.01	Yes														WAPD-C-110	
84	500	500			40	0.01		0.01	0.01	Yes														WAPD-C-110	
85	500	500			25	−0.03		30	−0.03	Yes						(1)	−0.03							WAPD-C-110	
86	500	500			25	−0.03		30	−0.03	Yes														WAPD-C-115	Doubtful
87	1500	500			200	0.01		30	0.01	Yes														WAPD-C-115	Good
88	500	500			100	−0.01		20	−0.01	Yes														WAPD-C-115	
89	1000	500	2	0.02				30	0.02	Yes											(2)	−0.01		WAPD-C-120	
90	1000	500	2	0.05				0.01	0.05	Yes														WAPD-C-120	Good
91	1500	500					−0.22			Yes														WAPD-C-120	Good
92	500	500	0.08		2	0.02		20	0.02				10											WAPD-C-120	Nicrobraze
93	1900	500			200	−0.01		30	−0.01	Yes											(2)	0.02		WAPD-C-122	Black film
94	1900	500			200	−0.01		30	−0.01	Yes														WAPD-C-122	Good
95	1000	500			25	−0.02		30	−0.02	Yes														WAPD-C-122	Good
96	1000	500			25	−0.02		30	−0.02	Yes						(1)	−0.02							WAPD-C-122	
97	1500	500	2	0.02				30	0.02	Yes						(1)	−0.02							WAPD-C-122	
98	500	500			100	−0.03	0																	WAPD-C-122	347A
99	500	500	0.1		2	0.02							10.5								(5)	0		WAPD-C-125	
100	836	500	0.1		2	0		10	0				10.5											WAPD-C-125	
101	836	500	0.1		2	−0.01		20	−0.01				10.5								(2)	0		WAPD-C-125	
102	836	500	0.1		2	−0.10		10	−0.10												(2)	0.01		WAPD-C-125	
103	836	500	0.1		2	−0.02		20	−0.02												(2)	−0.10		WAPD-C-125	
104	836	500	0.1		2	0.01		10	0.01												(2)	−0.02		WAPD-C-125	
105	836	500	0.1		2	−0.05		20	−0.05												(2)	0.01		WAPD-C-125	
106	500	500					−0.07	30	−0.07	Yes											(2)	−0.05		WAPD-C-125	
107	500	500			100	−0.03	Yes	10	−0.03															WAPD-C-125	Good
																					(2)	−0.03		WAPD-C-129	Brown

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) HNO_3

MATERIAL 347 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
108	500	500			100	−0.05	Yes	20	−0.05												(2)	−0.05		WAPD-C-129	Brown
109	500	500			100	0.01		10	0.01												(3)	0.01		WAPD-C-129	Bright
110	500	500			100	0.01		20	0.01												(3)	0.01		WAPD-C-129	Bright
111	500	500			100	0.01		20	0.01												(a)	0.01		WAPD-C-129	Shiny
112	1000	500			500	0		30	0															WAPD-C-129	H_2 added cold
113	500	500			500	0.12		30	0.12															WAPD-C-129	H_2 added hot
114	100	500			500	0.05		30	0.05															WAPD-C-129	H_2 added hot
115	1500	500			500	0		30	0															WAPD-C-129	H_2 added hot
116	2000	500			500	0.01		30	0.01															WAPD-C-129	H_2 added hot
117	500	500					−0.06	30	−0.06							(1)	−0.06							WAPD-C-129	Good
118	500	500					0.01	10	0.01			(2)	10.5											WAPD-C-135	Dull, dark
119	500	500					0	20	0			(2)	10.5											WAPD-C-135	Dull, dark
120	3000	500			200	−0.01				Yes														WAPD-C-135	Good
121	3000	500			200	−0.01				Yes														WAPD-C-135	Good
122	500	500	0.1		100	−0.04					3–4													WAPD-C-141	Brown
123	500	500			100	−0.06					3–4													WAPD-C-141	Brown
124	3600	500			200	0.01		30	0.01	Yes														WAPD-C-141	Good
125	1500	500			50	0		30	0	Yes						(1)	0							WAPD-C-141	Good
126	702	500			100	0		10	0	Yes	2–4		6–7								(3)	0		WAPD-C-137	Bright
127	702	500			100	0.01		20	0.01	Yes	2–4		6–7								(2)	0.01		WAPD-C-137	Bright
128	1000	500	1	0.03				30	0.03															WAPD-C-137	Good
129	1584	540												T = 3	0.05									ANL-HE-1101	Good
														F = 6											
130	1584	540												(b)	0.03									ANL-HE-1101	Control
131	250	500			200	−0.18		30	−0.18	Yes														ANL-5011	
132	250	500			200	−0.12		0.01	−0.12	Yes														ANL-5011	
133	250	500			200	−0.10		30	−0.10	Yes														ANL-5011	
134	250	500			200	−0.11		0.01	−0.11	Yes														ANL-5011	
135	250	500			200	−0.11		30	−0.11	Yes														ANL-5011	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODES

(a) HNO_3
(b) Control

MATERIAL 410 SS

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen																				
			(cc/L)	Corr.	(cc/L)	Corr.		(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
1	280	500	2300	2.00				(1)			(1)							(1)	2.00		(3)	2.00		ANL-4519	
2	101	500	1500	1.60				(1)			(1)	(1)	10											ANL-4519	
3	353	500	30	−0.32				(1)			(1)												(2) −0.32	ANL-4519	
4	375	500	30	−0.22				(1)			(1)							(1)			(4)	0.32		ANL-4519	
5	775	500	30	0.12				(1)			(1)							(1)			(4)	−2.20		ANL-4519	
6	1126	500	30	−0.03				(1)			(1)							(1)			(4)	0.12		ANL-4519	
7	1839	500	30	−1.50				(1)			(1)							(1)			(4)	−0.03		ANL-4519	
8	2599	500	30	−0.95				(1)			(1)							(1)			(4)	−1.50		ANL-4519	
9	3335	500	30	−1.30				(1)			(1)							(1)			(4)	−0.95		ANL-4519	
10	4071	500	30	0.03				(1)			(1)							(1)			(4)	−1.30		ANL-4519	
11	4781	500	30	−0.42				(1)			(1)							(1)			(4)	0.03		ANL-4519	
12	5475	500	30	−2.60				(1)			(1)							(1)			(4)	−0.42		ANL-4519	
13	500	500	1.7	−0.15				30	−0.15		(1)	(1)	10											ANL-4519	
14	500	500	1.7	−0.01				0.01	−0.01		(1)	(1)	10											ANL-4519	
15	500	500	2.1	−0.17				30	−0.17		(1)		7											ANL-4519	
16	500	500	2.1	−0.02				0.01	−0.02		(1)		7											ANL-4519	
17	850	500	1.7	−0.04				30	−0.04		(1)	(1)	10											ANL-4519	
18	850	500	1.7	−0.04				0.01	−0.04		(1)	(1)	10											ANL-4519	
19	850	500	2.1	−0.01				30	−0.01		(1)		7											ANL-4519	
20	850	500	2.1	0.01				0.01	−0.01		(1)		7											ANL-4519	
21	1350	500	1.7	−0.08				30	−0.08		(1)	(1)	10											ANL-4519	
22	1350	500	1.7	−0.03				0.01	−0.03		(1)	(1)	10											ANL-4519	
23	1350	500	2.1	−0.07				30	−0.07		(1)		7											ANL-4519	
24	1350	500	2.1	0				0.01	0		(1)		7											ANL-4519	
25	1000	500	4.5		200	−0.08												(2)	−0.08					WAPD-C-110	Fair
26	1500	500			200	−0.08		30	−0.08									(2)	−0.08					WAPD-C-115	
27	1900	500			200	−0.05		30	−0.05									(2)	−0.05					WAPD-C-122	Good
28	3000	500			200	−0.08		30	−0.08									(2)	−0.08					WAPD-C-135	Doubtful
29	500	500			100	−0.39		10	−0.39		3–4							(1)	−0.39					WAPD-C-141	Purple
30	500	500						10	−0.07			(2)	10.5					(2)	−0.07					WAPD-C-141	Purple
31	500	500						20	−0.08			(2)	10.5					(2)	−0.08					WAPD-C-141	Purple
32	3600	500			200	−0.06		30	−0.06	Yes														WAPD-C-141	Doubtful
33	250	500			200	−2.12		30	−2.12									(2)	−2.12					ANL-5011	
34	250	500			200	−0.84		0.01	−0.84									(2)	−0.84					ANL-5011	
35	310	500			16	−0.68							7											ANL-4641	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Molcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 410 SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
36	290	500			1300	-0.84						(2)(3)	7											ANL-4641	
37	620	500	1-3	0.07				3.1				(2)(3)	9											ANL-5059	
38	1000	482	1300	1.00														(2)	1.00					ORNL-1605	
39	1000	482			1200	1.40												(2)	1.40					ORNL-1605	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL 440C SS

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen																				
			(cc/L)	Corr.	(cc/L)	Corr.		(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
1	664	500					0.10	(1)																ANL-4424	
2	187	500			25	0.25		(1)																ANL-4424	
3	170	500	30	−1.42				(1)																ANL-4424	
4	664	500					0.10	(1)			(1)							(2)	0.10		(4)	0.10		ANL-4519	
5	341	500					0.19	(1)			(1)							(2)	0.19		(4)	0.19		ANL-4519	
6	5496	500	30	−0.18				(1)			(1)							(2)	−0.18					ANL-4519	
7	4710	500	30	0.23				(1)			(1)							(2)	0.23					ANL-4519	
8	187	500			30	0.14		(1)			(1)							(2)	0.14		(4)	0.14		ANL-4519	
9	335	500					3.00	(1)			(1)	(c)	12					(2)	3.00		(4)	3.00		ANL-4519	
10	335	500					0.55	(1)			(1)	(a)	10					(2)	0.55		(4)	0.55		ANL-4519	
11	335	500					1.50	(1)			(1)	(b)	11					(2)	1.50		(4)	1.50		ANL-4519	
12	280	500	3000	0.03				(1)			(1)							(2)	0.03		(4)	0.27		ANL-4519	
13	3149	600	3–5	−0.14					−0.14		(1)							(2)	−0.14		(4)	0.14		ANL-4519	
14	260	500			2–3		0.19	30	0.19	Yes	0.25–0.10		7–8.8							(d)				ANL-4641	
15	310	500			16	−0.62				Yes			7											ANL-4641	
16	290	500			1300	0.84				Yes			7											ANL-4641	
17	1000	482	1300	0.80				30	0.19									(2)	0.80					ORNL-1605	
18	1000	482	1300	0.30				30	0.30															ORNL-1605	
19	1000	482			1200	1.60		30	1.20									(2)	1.60					ORNL-1605	
20	1350	500	1.7	−0.17				30	−0.17			(1)	10											ANL-4519	
21	1350	500	2.1	−0.09				30	−0.09				7											ANL-4519	
22	850	500	1.7	−0.14				30	−0.14			(1)	10											ANL-4519	
23	850	500	2.1	−0.02				30	−0.02				9											ANL-4519	Poison loop
24	620	500	1–3	0				3.1	0			(2)(3)	9											ANL-5059	
25	401	600					−0.57											(2)	−0.57		(4)	−0.57		ANL-4519	
26	363	600					0.28					(a)	10					(2)	0.28		(4)	0.28		ANL-4519	
27	363	600					0.22						10					(2)	0.22		(4)	0.22		ANL-4519	
28	375	500	30	−3.00							(1)										(5)	3.00		ANL-4519	
29	775	500	30	−0.09							(1)													ANL-4519	
30	1126	500	30	0.17							(1)													ANL-4519	
31	1863	500	30	−0.01							(1)													ANL-4519	
32	2623	500	30	0.04							(1)													ANL-4519	
33	3359	500	30	−0.21							(1)													ANL-4519	
34	4095	500	30	−0.21							(1)													ANL-4519	
35	4805	500	30	−0.12																				ANL-4519	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODES

(a) Buffer
(b) KOH
(c) Phosphorus
(d) 10,000

MATERIAL 440C SS (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated F&T (10^{19} nvt)	Irradiated Corr.	Welded Type	Welded Corr.	Heat Treatment Type	Heat Treatment Corr.	Stress (psi)	Surface Finish Type	Surface Finish Corr.	Treatment Type	Reference	Remarks
36	328	500	30	−2.80				(1)			(1)										(3)(4)	−2.80		ANL-4519	
37	1045	500	30	−0.37				(1)			(1)										(3)(4)	−0.37		ANL-4519	
38	1763	500	30	−0.84				(1)			(1)										(3)(4)	−0.84		ANL-4519	
39	2547	500	30	0.43				(1)			(1)										(3)(4)	0.43		ANL-4519	
40	3257	500	30	0				(1)			(1)										(3)(4)	0		ANL-4519	
41	3969	500	30	0.09				(1)			(1)										(3)(4)	0.09		ANL-4519	
42	1000	482			1200	1.00																		ORNL-1605	
43	2160	500	30	−0.11				10	−0.11		14.3		6.15					(2)	−0.11					See Ref 52	
44	1440	500	30	−0.09				0.01	−0.09		14.3		6.15					(2)	−0.09					See Ref 52	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

MATERIAL STELLITE-3

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
1	6942	500	30	0				(1)			(1)														
2	353	500	~1800	0.06				(1)			(1)	(1)	9								(4)	0		ANL-4519	Good
3	353	500	~1800	-0.55							(1)	(1)	11											ANL-4519	Good
4	3149	500	3-5	-0.21				30	-0.21		(1)													ANL-4519	Good
5	2000	540												T = 3	0.01					(b)				ANL-4519	
6	620	500	1-3	3.50								(2)(3)	9											ANL-4795	
7	1655	540												T = 3.33	0									ANL-5059	
8	1000	482	1300	158				30	158															ANL-HE-1101	
9	1000	500	2	-2.70				30	-2.70	Yes														ORNL-1605	
10	1000	500	2	-0.52				0.01	-0.52	Yes											(1)	-2.70		ANL-5011	
11	1000	500			500	-0.03		30	-0.03	Yes											(1)	-0.52		ANL-5011	
12	1000	500			500	-0.02		0.01	-0.02	Yes											(1)	-0.03		ANL-5011	
13	1500	500					-0.03	30	-0.03	Yes											(1)	-0.02		ANL-5011	
14	1500	500					-0.04	0.01	-0.04	Yes											(1)	-0.03		ANL-5011	
15																					(1)	-0.04		ANL-5011	
16																									
														T = 4	0.04										As cast
														F = 5											
17														T = 8	0.01										
18														T = 9	-0.14										As cast
19	1655	540												T = 3.3	0.01										As cast
20	1500	500			500	-0.02				Yes														ANL-HE-1101	
21	1500	500			500	-0.02				Yes														ANL-5011	
22	2000	540												T = 3	0.01									ANL-5011	
23	2000	540												T = 3	0.01									ANL-4795	
24	4380	540												F = 1	-0.13									ANL-4795	
														T = 10										ANL-5059	Cpld. to 17-4
25	4380	540												(a)	0.14										
26	4380	540												F = 1	-0.35									ANL-5059	Cpld. to 17-4
														T = 10										ANL-5059	Cpld. to Haynes 25
27	4380	540												(a)	0.28										
28	1000	482			1200	0.11		30	0.11															ANL-5059	
																								ORNL-1605	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODES

(a) Control
(b) 10,000

MATERIAL STELLITE-6

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases: Oxygen (cc/L)	Dissolved Gases: Oxygen Corr.	Dissolved Gases: Hydrogen (cc/L)	Dissolved Gases: Hydrogen Corr.	Degassed Corr.	Flow (fps)	Flow Corr.	Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated: F&T (10^{19} nvt)	Irradiated: Corr.	Welded: Type	Welded: Corr.	Heat Treatment: Type	Heat Treatment: Corr.	Stress (psi)	Surface Finish: Type	Surface Finish: Corr.	Treatment Type	Reference	Remarks
1	339	500	30	0.05				(1)	0.05															ANL-4519	As cast
2	1199	500	30	0.02				(1)	0.02															ANL-4519	As cast
3	1925	500	30	−0.14				(1)	−0.14															ANL-4519	As cast
4	2657	500	30	0				(1)	0															ANL-4519	As cast
5	3374	500	30	1.40				(1)	1.40															ANL-4519	As cast
6	3130	500	30	−0.05				(1)	−0.05															ANL-4519	As cast
7	3845	500	30	0.08				(1)	0.08															ANL-4519	As cast
8	4559	500	30	0.03				(1)	0.03															ANL-4519	As cast
9	5264	500	30	−0.10				(1)	−0.10															ANL-4519	As cast
10	6003	500	30	−0.32				(1)	−0.32															ANL-4519	As cast
11	6760	500	30	0.17				(1)	0.17															ANL-4519	As cast
12	328	500					0.18		0.18															ANL-4519	347 Faced
13	330	500	30	0.08				(1)	0.08							(a)					(1)(d)	−0.08		ANL-4519	347 Faced
																−0.08									
14	664	500	30	−0.04				(1)	−0.04							(a)					(1)(d)	−0.04		ANL-4519	347 Faced
																−0.04									
15	1448	500	30	0				(1)	0							(a)					(1)(d)	0		ANL-4519	347 Faced
																0									
16	330	500	30	−0.07					−0.07							(b)					(1)(d)	−0.07		ANL-4519	347 Faced
																−0.07									
17	664	500	30	−0.54					−0.54							(b)					(1)(d)	−0.54		ANL-4519	347 Faced
																−0.54									
18	1448	500	30	−0.03					−0.03							(b)					(1)(d)	−0.03		ANL-4519	347 Faced
																−0.03									
19	330	500	30	−0.07					−0.07							(c)					(1)(d)	−0.07		ANL-4519	347 Faced
																−0.07									
20	664	500	30	−0.14					−0.14							(c)					(1)(d)	−0.14		ANL-4519	347 Faced
																−0.14									
21	1448	500	30	−0.08					−0.08							(c)					(1)(d)	−0.08		ANL-4519	347 Faced
																−0.08									
22														T = 9	−0.20									RH-3	
23	1000	500	4.5		200	0.06				Yes														WAPD-C-110	
24	1500	500			200	−0.05		30	−0.05	Yes														WAPD-C-115	
25	500	500	0.08	0.01	2	0.01		20	0.01	Yes			10											WAPD-C-122	
26	1900	500			200	0		30	0	Yes														WAPD-C-122	Good

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to axide film

SPECIAL CODE

(a) AC Heliarc
(b) DC Heliarc
(c) Oxyacetylene
(d) Polished

MATERIAL STELLITE-6 (continued)

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen																				
			(cc/L)	Corr.	(cc/L)	Corr.		(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
27	836	500	0.1	−0.07	2	−0.07		10	−0.07				10.5											WAPD-C-125	Blue
28	836	500	0.1	−0.06	2	−0.07		10	−0.07				10.5											WAPD-C-125	Blue
29	3000	500			200	0.01		30	0.01															WAPD-C-135	Good
30	3600	500			200	−0.02		30	−0.02	Yes														WAPD-C-141	Good
31	250	500			200	−0.87		30	−0.87															ANL-5011	
32	250	500			200	−0.04		0.01	−0.04															ANL-5011	
33	260	500			2−3					No			7−8											ANL-4641	
34	310	500			16	−0.28				Yes			7											ANL-4641	
35	290	500			1300	0.02				Yes			7											ANL-4641	
36	4380	540												F = 1	0.01									ANL-5059	Cpld. to USS/W
														T = 10											
37	4380	540												(a)	0.16									ANL-5059	Cpld. to USS/W
38	1000	482	1300	255				30	255															ORNL-1605	
39	1000	482			1200	0.20																		ORNL-1605	
40	168	600					0.06																	See Ref. 122	
41	168	600					0.21																	See Ref. 122	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Control.

MATERIAL STELLITE-12

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen									F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.		(fps)	Corr.																
1	305	600					-0.18	(1)													(a)	-0.18		ANL-4519	Good
2	339	600	30	-0.17				(1)													(a)	-0.17		ANL-4519	
3	339	500	30	-0.17				(1)													(a)			ANL-4519	
4	1199	500	30	0.85				(1)													(a)			ANL-4519	
5	1965	500	30	0.08				(1)													(a)			ANL-4519	
6	2697	500	30	0.03				(1)													(a)			ANL-4519	
7	3438	500	30	0.05				(1)													(a)			ANL-4519	
8	4156	500	30	-0.16				(1)													(a)			ANL-4519	
9	4940	500	30	0.20				(1)													(a)			ANL-4519	
10	5650	500	30	-0.13				(1)													(a)			ANL-4519	
11	6341	500	30	-0.14				(1)													(a)			ANL-4519	
12	7150	500	30	0.14				(1)													(a)			ANL-4519	
13	7863	500	30	0.14				(1)													(a)			ANL-4519	

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film

SPECIAL CODE

(a) Cast

MATERIAL VASCOLOY-RAMET 166

Corrosion Rates in mg/cm^2-mo

No.	Time (hr)	Temp. (°F)	Dissolved Gases				Degassed Corr.	Flow		Dei.	Resist. (megohm-cm)	Add.	pH	Irradiated		Welded		Heat Treatment		Stress (psi)	Surface Finish		Treatment Type	Reference	Remarks
			Oxygen		Hydrogen			(fps)	Corr.					F&T (10^{19} nvt)	Corr.	Type	Corr.	Type	Corr.		Type	Corr.			
			(cc/L)	Corr.	(cc/L)	Corr.																			
1	424	500	30	0.37				(1)	0.37		(1)													ANL-4519	
2	424	500	30	0.23				(1)	0.23		(1)													ANL-4519	
3	1165	500	30	-0.88				(1)	-0.88		(1)													ANL-4519	
4	1883	500	30	-2.60				(1)	-2.60		(1)													ANL-4519	
5	2667	500	30	-0.24				(1)	-0.24		(1)													ANL-4519	
6	3367	500	30	-1.80				(1)	-1.80		(1)													ANL-4519	
7	4071	500	30	-1.20				(1)	-1.20		(1)													ANL-4519	
8	4380	540												F = 1	0.12									ANL-4519	
														T = 10										ANL-5059	
9	4380	540												F = 1	0.10									ANL-5059	Control
														T = 10											

GENERAL KEY

Time – Length of submersion

Flow
1. Autoclave

Dei. – Deionize

Resist. – Resistivity
1. Distilled water

Add. – Additives
1. NaOH
2. LiOH
3. H_3BO_3
4. Passivated

Irradiated
F&T – Fast and thermal neutrons

Welded (Type)
1. As welded
2. Quenched 1900°

Heat Treatment (Type)
1. Annealed
2. Hardened

Surface Finish (Type)
1. Vapor-blasted
2. Machined
3. Electropolished
4. Ground
5. Passivated

Treatment (Type)
1. Malcomized
2. Chrome-plated
3. Scottsonized

Reference – Reference in bibliography

Remarks – Color refers to oxide film