7. ADVANCED PRESSURE VESSEL MATERIALS

(1521)

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The objective of this program is to determine the applicability of high-strength steels and alloys to nuclear reactor pressure vessels and similar critical applications. Materials under investigation include a 12Ni – 5Cr – 3Mo maraging steel and precipitation-hardening stainless steel, PH13-8Mo. The nickel-base alloy, Inconel alloy 718, is also being investigated together with a quenched and tempered alloy steel, HP 9Ni – 4Co – 0.2C.

All alloys studied in this program can be processed to far greater tensile and yield strength levels than the current alloys which are ASME Boiler and Pressure Vessel Code-approved and in current use. If it can be established that these alloys meet strength criteria and other significant requirements for pressure vessel applications, their eventual use may achieve one or more of the following:

1. Greater pressure vessel reliability and safety.
2. Reduced pressure vessel weight and section size.
3. Improved reactor performance resulting from higher permissible pressures and/or temperatures.

The type of materials being studied will necessitate greater unit costs for materials and processing, but it is believed that overall reactor economics may disclose an acceptable cost balance, particularly in view of such intangibles as greater safety or equal safety with less weight.

The experimental approach being followed encompasses two phases. The first phase consists of selecting and procuring candidate materials in the form of approximately 2.54-cm-thick plate, and evaluating pertinent properties, response to heat treatment, weldability, and radiation resistance. The second phase involves procurement of heavier plate (≥ 10 cm thick) to determine size effects on properties, response to heat treatment, and weldability. Ultimately one or more materials are expected to emerge as candidates for high-strength pressure vessels. For the most part all alloys currently under study are well into the first phase. The 12-5-3 maraging steel is entering the second phase.

7.1 EXPERIMENTAL PROGRAM

12Ni – 5Cr – 3Mo MARAGING STEEL

The 12-5-3 maraging steel is a heat-treatable alloy capable of high strength with excellent toughness. Heat treatment consists of solution annealing, air cooling or quenching to form martensite, and aging to effect precipitation strengthening. Because of the low carbon level (0.03C max, Table 7.1) the alloy is relatively soft (approximately R_C 30) and is work-

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TABLE 7.1
DESCRIPTION OF 12Ni – 5Cr – 3Mo MATERIAL

Lot No.	Heat No.	Melting Procedure ^a	Size, cm	Condition	Vendor's Chemical Analysis												ppm		
					wt %														
					C	Mn	P	S	Si	Cr	Ni	Ti	Al	Mo	Fe	O	N	H	
Nominal analysis					0.03 Max	0.10 Max	0.010 Max	0.010 Max	0.12 Max	4.75– 5.25	11.5– 12.5	0.10– 0.35 ^b	0.20– 0.50 ^b	2.75– 3.25	Bal				
1	01378	AM + VCEM	2.7 x 61 x 61	815 ^o C for 1 hr – air cool	0.02 0.015 ^c	0.06 <0.01 ^c	0.006 0.005 ^c	0.006 0.001 ^c	0.06 0.02 ^c	5.00 –	11.90 –	0.13 0.14 ^c	0.37 0.40 ^c	3.08 3.08 ^c	Bal	–	–	–	
2	01434	AM + VCEM	0.32 dia x spool (Filler metal)	–	0.02	0.01	0.005	0.008	0.02	2.75	11.97	0.33	0.09	2.63	Bal	–	–	–	
3	IP0193	AM	2.54 x 35.6 x 57 2.54 x 15.2 x 61	815 ^o C for 1 hr – air cool	0.018	0.06	0.002	0.007	0.10	5.00	12.1	0.23	0.27	3.24	Bal	15	80	–	
4	V91230	IVM	0.155 dia x spool ~10 kg	Cold drawn	0.004	0.1	0.002	0.004	0.02	5.05	12.9	0.43	0.05	2.37	Bal	7	3.5	–	
5	60539	IVM	10.2 x 20.3 x 122 (2 pieces)	815 ^o C for 1 hr/ 2.54-cm thickness – air cool	0.006	0.01	0.005	0.004	0.02	5.08	12.15	0.25	0.24	3.00		20	80	–	
5	60540	IVM	10.2 x 20.3 x 122 (1 piece)	–	0.005	0.01	0.005	0.004	0.01	5.00	12.02	0.26	0.24	3.09		10	50	–	
6	04514	IVM	110 kg 0.155 dia wire ^e	–	0.01	0.05	0.007	0.004	0.08	4.91	12.10	0.24	0.38	3.08		–	–	–	

^aAM – Air melt; VCEM – Vacuum consumable electrode melt; IVM – Induction vacuum melt.

^b0.35 – 0.50% Al and 0.10 – 0.25% Ti are reported to offer the best combination of properties in conjunction with air-melted composition control.

^cGE-NMPO analysis.

^dForged to size.

^eMaterial in ingot form to be processed to wire as indicated for use in welding 10-cm-thick plate specimens.

able as solution annealed; after aging the alloy has a hardness of R_C 40 to 44 and is not easily worked. A standard heat treatment consists of 815°C for 1 hour, air cool, plus 480°C for 3 hours, air cool.

The aging treatment for optimum properties may vary between different heats of material. The alloy can be prepared by air melting techniques, but vacuum melting techniques are preferable. It is reportedly weldable by either TIG or MIG methods and requires no pre- or post-heating. For best properties, heat treatment by aging or solution treatment and aging are required after welding.

Table 7.1 describes the 12-5-3 material procured to date. Lots 1 and 2 were obtained first and most data subsequently reported involve these materials. Lots 3 and 4 were obtained more recently, principally to evaluate the 12-5-3 wire composition compared to the 12-3-3 composition. Lots 5 and 6 will be used to study size effects on properties, response to heat treatment, and weldability. Initial inquiries have been made to procure 20-cm-thick material.

Base Metal Studies

Aging Studies – Table 7.2 and Figure 7.1 show the effect of aging at temperatures of 425°, 450°, 480°, and 510°C for times up to 25 hours on the hardness of the four heats of the 12-5-3 alloy. Specimens were approximately 1.27-cm to 2-cm cubes. Heat No. 01378 developed the lowest hardness for the three higher aging temperatures; heat No. 1P0193 developed the highest hardness under every aging condition. This is probably due to a more favorable Ti/Al ratio and a higher molybdenum level. Heat No. 60539 and 60540, fabricated into 10.2-cm by 20.3-cm forgings, show intermediate to high hardness values except at the lowest aging temperature.

These studies indicate that the generally recommended aging treatment of 480°C for 3 hours results in about the same hardness for all four heats, but longer aging times can be used to increase the hardness from 1.5 to 4 R_C . Increased aging times may be useful when greater strength with somewhat lower toughness is desired.

TABLE 7.2
12Ni – 5Cr – 3Mo AGING STUDIES

Heat No.	Aging Temperature, °C	Aging Time, hr																	
		1	2	3	4	5	6	8	9	10	11	12	14	15	20	21	24	25	
		Rockwell C Hardness																	
01378	425	38		39.5		40				42								42	
	450	39		40			40											42	
	480	38.5		40			41				41.5							41.5	
	510	39		39			39.5				39.5							39.5	
IP0193	425	38		39.5			41.5		42		42		43			43			
	450	39		41			42		42.5		43				43.5		44		
	480	39		41			42		42.5		43				44				
	510	39.5		40			41		42.5		43		44		43.5		44		
60539	425		36		36.5			38										41.5	
	450		37		40.5		41.5		42									43.5	
	480		37.5		40		40.5	41					41.5			42.5		42.5	
	510		39		39.5		40	39.5					40			41		41	
60540	425			36		37		38.5										41.5	
	450		37.5		41		41		42.5									44.5	
	480		37		41		41	41.5					42			43.5		42.5	
	510		39		39		40	40					40			41		41

Fig. 7.1 - 12Ni - 5Cr - 3Mo aging studies

The relatively slow rate of aging to peak hardness values is an excellent feature of this alloy since it indicates no serious aging problem associated with thick sections or complicated structures.

Tensile Properties - Tensile data obtained on specimens from the 12-5-3 plate from heat No. 01378 at 25°, 315°, and 425°C in orientations transverse and parallel to the rolling direction are summarized in Table 7.3 and Figure 7.2. Although earlier tests¹ had indicated a difference in values due to orientation, additional aging has produced essentially equal and higher strength levels in both directions.

Toughness - Charpy V-notch impact tests at 25°, -40°, and -78°C on specimens oriented both transverse and parallel to the rolling direction from heat No. 01378 are shown in Table 7.4 and Figure 7.2. Additional aging has reduced the transverse values somewhat, which has reduced but not eliminated the difference between values for the two rolling directions.

As a further measure of fracture toughness, specimens are being prepared for drop-weight tear testing (DWTT) at the Naval Research Laboratory.

Fatigue Properties - Hourglass specimens are being prepared for preliminary low-cycle fatigue testing. Material from heat 1P0193 is being employed.

Radiation Effects - Tensile blanks and Charpy V-notch specimens of the 12-5-3 alloy and similar specimens of PH13-8Mo and Inconel alloy 718, were irradiated in the MTR at pile-ambient temperature to an approximate fluence of 4 to 5×10^{19} n/cm² ($E_n \geq 1$ Mev). Testing will be conducted at the Naval Research Laboratory.

¹"Fuels and Materials Development Program Progress Report No. 71," GE-NMPO, GEMP-1002, December 29, 1967, p. 109.

TABLE 7.3
TENSILE PROPERTIES OF 12Ni – 5Cr – 3Mo PLATE^a

Specimen Orientation	Specimen No.	Specimen Type ^b	Test Temperature, °C	0.2% Yield Strength		Tensile Strength		Elongation ^c in 4D, %	Reduction of Area, %
				kg/cm ²	psi	kg/cm ²	psi		
Transverse to rolling direction	K1	I	25	11,330	161,200	11,860	168,700	22	72
	K2	I	25	11,450	162,900	11,950	169,900	22	70
	K3	I	315	9,010	128,100	10,030	142,700	16	69
	K4	I	315	9,060	128,900	10,060	143,100	14	69
	K5	I	425	8,100	115,200	9,170	130,500	9	73
	K6	I	425	8,090	114,800	9,140	129,700	18	74
	2E	II	315	8,700	124,200	9,580	139,200	14	66
	3E	II	425	8,100	115,300	9,150	130,000	17	70
	L1 ^d	I	25	12,250	175,700	12,600	180,100	19	70
	L2 ^d	I	25	12,200	175,400	12,600	180,000	19	70
	L3 ^e	I	25	12,650	180,900	13,000	185,400	18	70
	L4 ^e	I	25	12,700	181,400	13,100	186,200	18	69
Parallel to rolling direction	1B	I	25	12,330	175,400	12,570	178,800	22	68
	2B	I	25	12,200	173,900	12,520	178,000	22	67
	3B	I	315	9,630	136,900	10,410	148,100	17	41
	4B	I	315	9,560	136,000	10,440	148,500	16	66
	5B	I	425	8,340	119,500	9,400	133,900	18	70
	6B	I	425	8,020	114,300	9,030	127,900	14	72
	1A	II	25	12,340	175,200	12,600	179,200	17	65
	2A	II	315	9,400	133,700	10,400	148,200	15	65
	3A	II	425	7,950	113,600	9,200	131,100	17	69
	1E ^d	I	25	12,300	176,320	12,600	180,700	18	68
	2E ^d	I	25	12,400	176,570	12,600	180,500	19	67

^aPlate heat treated at 480°C for 3 hours and air cooled before machining to specimen configuration.

^bAll specimens were standard ASTM type: I – 0.636-cm-diameter reduced section.

II – 1.27-cm-diameter reduced section.

^cElongation in four x diameter (4D).

^dSpecimen aged an additional 3 hours at 480°C and air cooled.

^eSpecimen aged an additional 6 hours at 480°C and air cooled.

Thermal Stability – Specimens of the 12-5-3 alloy aged at 480°C for 3 hours were heated for 1000 hours at 315°, 370°, 425°, and 480°C. Exposures up to 100 hours resulted in no change in hardness except at 480°C where a slight increase was noted. After 1000-hour exposures at 315°C and 370°C, hardness increases of 3 to 4 R_C were observed. The specimens heated for 1000 hours at 425°C and 480°C tended to drop in hardness. Properly aged, the alloy can apparently be made stable to at least 315°C.

Weldment Studies

Four weldments of the 12-5-3 alloy were prepared using the 2.54-cm-thick plate from heat 01378. Joint designs were similar to those shown earlier for Inconel alloy 718.² Of these, two were made using the U-joint and two with the double U-joint preparation. The former is utilized in developing weld metal properties and the latter in determining weld joint properties. The manual TIG welding method was used. The filler metal was 0.32-cm-diameter spooled bare wire of 12Ni – 3Cr – 3Mo (heat 01434). Additional details of weldment preparation were given in an earlier report.³

Weld Zone Hardness versus Heat Treatment – The effect of post-weld heat treatment on weld zone hardness was studied on several sections cut from the two U-joint weldments of 12-5-3 plate made using 12-3-3 weld wire.⁴ The first heat treatment consisted of post-

²"Sixth Annual Report – High-Temperature Materials Program, Part A," GE-NMPO, GEMP-475A, March 31, 1967, Fig. 9.1, p. 232.

³"AEC Fuels and Materials Development Program Progress Report No. 67," GE-NMPO, GEMP-67, June 30, 1967, pp. 141–145.

⁴GEMP-67, Fig. 10.1, p. 144.

Fig. 7.2 — Tensile and Charpy V-notch impact properties of 12Ni — 5Cr — 3Mo maraging steel plate and weldments. Data points taken from Tables 7.3 through 7.6.

weld aging at 480°C for 3 hours. Figure 7.3 illustrates the results of a Rockwell C hardness transverse of weldment sections which received this treatment. Weld center hardnesses varied from R_C 30 to 35. Two sections, B and C, were then annealed for 1 hour at 815°C (air cooled) and aged at 450°C for 24 hours. Weld center hardnesses after this treatment rose to R_C 37 to 38. Figure 7.4 illustrates sections from a weldment annealed at 815°C for 1 hour (air cooled) and aged at 480°C for 3 hours. Weld center hardnesses ranged from R_C 32 to 35.

Both base metal and weld metal hardnesses are low after aging at 480°C for 3 hours (Figure 7.4). Re-aging such segments at 450°C for 24 hours or at 480°C for an additional 3 to 6 hours achieved higher centerline weld hardnesses in the range of R_C 36 to 38; base metal hardnesses increased to R_C 40 to 42. This is a further indication that aging practice must be adjusted to effect optimum properties. The disparity in weld metal and parent metal hardness is particularly important because it indicates that this 12-3-3 wire composition will not achieve optimum weld properties.

Tensile Properties — Joint tensile strength data at 25°C and 315°C of weldments heat treated in various ways are summarized in Table 7.5 and Figure 7.2. Aging of weldments at 480°C for 3 hours resulted in strengths lower than anticipated, based on base metal

TABLE 7.4
CHARPY V-NOTCH IMPACT STRENGTH OF 12Ni-5Cr-3Mo PLATE^a

Orientation of Major Specimen Axis ^b	Energy Absorbed					
	25°C		-40°C		-78°C	
	ft-lb	m-kg	ft-lb	m-kg	ft-lb	m-kg
Transverse to rolling direction	104	14.4	71	9.8	59	8.2
	103	14.3	66	9.2	54	7.5
	114	15.8	68	9.4	56	7.8
	83 ^c	11.5				
	95 ^c	14.2				
	90 ^c	12.4				
	84 ^d	11.6				
	78 ^d	11.0				
	92 ^d	12.6				
Parallel to rolling direction	70	9.7	49	6.8	42	5.8
	68	9.4	49	6.8	41	5.7
	72	10.0	50	6.9	39	5.4
	76 ^c	10.5				
	64 ^c	8.9				
	72 ^c	10.0				
	62 ^d	8.6				
	67 ^d	9.3				
	83 ^d	11.5				

^aPlate heat treated at 480°C for 3 hours and air cooled before machining to specimen configuration.

^bAll notches perpendicular to surface plate.

^cSpecimens aged an additional 3 hours at 480°C.

^dSpecimens aged an additional 6 hours at 480°C.

properties. Re-aging at 450°C for 24 hours resulted in marked improvements to levels about equivalent to base metal transverse properties reported earlier for the 3-hour age at 480°C. Post-weld annealing at 815°C for 1 hour plus aging at 480°C for 3 hours resulted in about the same properties noted above for the direct aged joint. Re-aging this weldment at 450°C for 24 hours again resulted in about the same improvement noted above for the direct aged and re-aged weldment. Both treatments with re-aging resulted in joint properties about equivalent to the transverse base metal values. Elongation values for most weld joint specimens were 12 to 15 percent except for one which was 9 percent. These values are lower than those of the base metal.

Toughness – Charpy V-notch specimens of the above weldments of the 12-5-3 plate made using the 12-3-3 weld wire showed the welded, annealed, and aged specimens to have an average absorbed energy value of 11.0 m-kg (80 ft-lb) at 25°C, compared to 8.6 m-kg (62 ft-lb) for welded and aged specimens. The values obtained at -40°C were 8.4 m-kg (61 ft-lb) and 4.7 m-kg (34 ft-lb), respectively. These values were lower than the base metal for the direct aged weld but were midway between the transverse and parallel rolling direction values for base metal when the weld was annealed and aged. Table 7.6 and Figure 7.2 summarize the Charpy V-notch data.

PH13-8Mo

The PH13-8Mo alloy is a martensitic precipitation-hardening stainless steel which has excellent toughness at high-strength levels. It is heat treated by solution annealing, air cooling or quenching, and aging. In the solution-treated condition the alloy has a hardness of approximately R_C 35 maximum; as-aged, depending on aging temperature, its hardness ranges from about R_C 36 to 48. Normally, the material is supplied from the vendor in the solution-treated condition (925°C for 0.5 hour and air cooled or quenched to below 15°C) and is only aged by the user at 510° to 590°C, depending on the properties required.

Fig. 7.3 – Sections of weldments of the 12Ni – 5Cr – 3Mo maraging steel made using 12Ni – 3Cr – 3Mo filler metal. Sections were maraged after welding at 480°C for 3 hours which resulted in the Rockwell C hardness values shown beside the indentations. After maraging, sections B and C were annealed 1 hour at 815°C, air cooled, and aged at 450°C for 24 hours. The hardnesses achieved by this treatment are shown by the numbers beside the X-marks. (Neg. P67-8-33B)

Fig. 7.4 — Sections of weldments of the 12Ni — 5Cr — 3Mo maraging steel made using 12Ni — 3Cr — 3Mo filler metal. After welding, sections were annealed at 815°C, air cooled, and aged at 480°C for 3 hours. Numbers at indentations are Rockwell C hardness values. (Neg. P67-8-33A)

TABLE 7.5
TENSILE PROPERTIES OF 12Ni – 5Cr – 3Mo WELDMENTS

Specimen Type ^a	Specimen No.	Specimen Treatment ^b	Test		0.2% Yield Strength		Tensile Strength ^c		Elongation in 4D, %	Reduction of Area, %
			Temperature, °C		kg/cm ²	psi	kg/cm ²	psi		
I	22E	W+A	25		10,430	148,800	11,100	157,100	15	64
I	22K	W+A	25		10,400	148,600	10,800	154,800	14	67
I	22F	W+A	315		8,300	118,900	9,130	132,300	13	63
I	22L	W+A	315		8,400	119,700	9,080	129,300	13	53
II	22A	W+A	25		10,900	155,300	11,600	161,300	11	61
II	22B	W+A	315		8,450	120,300	9,000	127,200	11	62
I	22G	W+A+R	25		11,280	159,800	11,845	167,900	14	59
I	22H	W+A+R	25		11,200	159,200	11,840	167,700	14	60
I	22I	W+A+R	315		9,060	130,100	10,000	142,400	12	60
I	22J	W+A+R	315		9,300	132,100	10,000	142,700	12	59
I	24A	W+An+A	25		10,500	149,500	11,100	156,500	15	65
I	24B	W+An+A	25		10,800	153,600	11,250	158,600	14	64
I	24C	W+An+A	315		9,030	127,700	9,550	135,100	13	63
I	24D	W+An+A	315		9,100	130,000	9,550	136,800	13	63
I	24E	W+An+A+R	25		11,700	166,300	11,900	169,300	9	33
I	24F	W+An+A+R	315		9,800	139,100	10,250	145,800	12	59

^aAll specimens were standard ASTM type: I – 0.636-cm-diameter reduced section.

II – 1.27-cm-diameter reduced section.

Reduced sections contained weld metal, heat-affected zone, and base metal.

^bHeat Treatments: W – Weld.

A – Aged 3 hours at 480°C and air cooled prior to machining.

R – Re-aged an additional 24 hours at 450°C.

An – Annealed 1 hour at 815°C and air cooled to room temperature.

^cAll specimens fractured in the weld.

TABLE 7.6
CHARPY V-NOTCH^a IMPACT STRENGTH
OF 12Ni – 5Cr – 3Mo WELDMENTS

Condition of Specimen ^b	Energy Absorbed			
	25°C		–40°C	
	ft-lb	m-kg	ft-lb	m-kg
W + A	68	9.4	35	4.8
	58	8.0	30	4.1
	60	8.3	37	5.1
W+An+A	80	11.0	56	7.8
	81	11.1	66	9.1
	78	10.8	61	8.4

^aNotch oriented perpendicular to surface of plate and through weld metal.

^bHeat treatment: W – Welded.

A – Aged 3 hours at 480°C.

An – Annealed 1 hour at 815°C and air cooled to room temperature.

A standard aging temperature for a good combination of strength and toughness is 565°C for 5 hours, air cool. The alloy is best prepared by a combination of vacuum induction melting plus vacuum consumable arc remelting. It is reportedly weldable by techniques used for other precipitation-hardening stainless steels with no pre- or post-heating. For best properties, heat treatment by aging or solution treating and aging are required after welding.

Table 7.7 describes the PH13-8Mo material procured to date. Lots 1 and 3 were obtained first, and the majority of the data reported are for these materials. Lot 2 was

TABLE 7.7
DESCRIPTION OF PH13 — 8Mo MATERIALS

Lot No.	Heat No.	Melting Procedure ^a	Size, cm	As-Received Condition	Chemical Analysis, wt %																						
					C		Mn		P		S		Si		Cr		Ni		Al		Mo		N ₂		Fe		
					Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	Vendor NMPO	
Nominal analysis					0.05	0.10	0.010	0.008	0.10	12.25—	7.50—	0.90—	2.00—	0.010	Bal												
					Max	Max	Max	Max	Max	13.25	8.50	1.35	2.50	Max													
1	VC 5281	IVM + VCEM	1.27 x 30 x 183	925°C—0.5 hr—air cool	0.042	0.024	0.02	<0.01	0.003	0.006	0.004	0.002	0.02	<0.01	12.58	—	8.07	—	1.11	1.25	2.06	2.31	—	—	Bal	Bal	
2	VC 5281	IVM + VCEM	2.54 x 46 x 46	925°C—0.5 hr—air cool	0.042	0.024	0.02	<0.01	0.003	0.006	0.004	0.002	0.02	<0.01	12.58	—	8.07	—	1.11	1.25	2.06	2.31	—	—	Bal	Bal	
3	VC 5178	IVM + VCEM	0.155 dia x spool (Filler metal)	Overaged and cold drawn	0.044	—	—	0.002	0.003	0.016	12.74	8.58	0.46	2.20	—	—	—	—	—	—	—	—	—	Bal			

^aIVM — Induction vacuum melt.

VCEM — Vacuum consumable electrode melt.

obtained to provide additional material for testing and to further study aging response following welding on somewhat heavier plate. The study of plate 10-cm thick or greater has been considered. It is not certain, however, that a post-weld heat treatment can be developed which is practical for large pressure vessels, and the cost involved for experimental quantities in these thicknesses is high. Accordingly a more certain qualification will be made in the 2.54-cm thickness before proceeding to heavier plate.

Base Metal Studies

Aging Studies – Specimens from the 1.27-cm-thick plate (925°C solution-treated condition) were aged in air for various times up to 25 hours at 510°, 540°, 565°, and 590°C. Hardnesses ranging from R_C 46 to 48 were attained within 1 to 2 hours at 510°C and 540°C; after 24 hours the hardnesses dropped slightly to about R_C 45. Hardnesses of the order of R_C 42 to 43 were attained in 1 hour at 565°C and 590°C; these dropped to R_C 40 to 42 in about 4 hours, and to about R_C 36 to 39 after 24 hours. Data are given in Table 7.8 and aging curves are shown in Figure 7.5.

The alloy apparently hardens extremely rapidly to a peak hardness level and then over-ages to a lower hardness at longer times. This is particularly apparent at aging temperatures of 565°C and 590°C which, incidentally, produce the highest toughness levels. Aging temperatures above about 540°C can apparently present significant problems in large complicated structures; high- and low-strength zones might develop during aging, depending on section thickness and/or design configuration.

Tensile Properties – Tensile data obtained on 1.27-cm PH13-8Mo plate were determined at 25°, 315°, and 425°C, and are presented in Table 7.9 and Figure 7.6. The figure shows that PH13-8Mo possesses a tensile strength greater than 11,500 kg/cm² (156,000 psi) up to about 300°C, combined with a yield strength of nearly 11,000 kg/cm². These values are the lower for the two orientations tested, i. e., parallel to the rolling direction. The tensile and yield strengths of the specimens whose principal axis was transverse to the direction of rolling were higher by as much as 15 percent. Tensile elongation was approximately the same in both directions.

Toughness – Charpy V-notch impact tests were made on 1.27-cm-thick PH13-8Mo plate at 25°, -40°, and -78°C. Energy absorption values at 25°C were above 9 m-kg for both orientations; the transverse direction showed values above 10 m-kg. At lower temperatures, however, Charpy V-notch values for the transverse orientation fell off quickly to about 2.7 m-kg at -78°C, and those for the parallel orientation dropped to 4.3 m-kg. Table 7.10 and Figure 7.6 summarize impact data obtained on PH13-8Mo 1.27-cm-thick plate.

To further evaluate the fracture toughness of the PH13-8Mo alloy, specimens for drop-weight tear testing are being prepared of the 2.54-cm plate. Testing will take place at the Naval Research Laboratory.

Fatigue Properties – Hourglass specimens of material from the 2.54-cm-thick plate are being prepared for low-cycle fatigue testing.

Radiation Effects (NRL) – Tensile blanks and Charpy V-notch specimens have been irradiated in the MTR at pile-ambient temperature. The fluence level to which they were exposed is approximately 4 to 5×10^{19} n/cm² ($E_n \geq 1$ Mev). Post-irradiation testing will be conducted at the Naval Research Laboratory.

Thermal Stability – The effects on hardness and microstructure of the aged alloy after longtime heating at various temperatures are being determined. No change in hardness or microstructure was noted after exposure at 315°, 370°, 425°, 480°, and 540°C for 100 hours. Moreover, no significant hardness changes were noted after heating for 1000 hours at 315°, 370°, and 425°C. Heating for 1000 hours at 480°C and 540°C, however, resulted in softening

TABLE 7.8
PH13 – 8Mo AGING STUDIES^a

Specimen No.	Aging Temperature, °C	Aging Time, hr.																
		0	0.25	0.5	1	2	3	4	5	6	7	8	10	11	12	14	16	19
		Rockwell C Hardness																
H-1	510	35				46.5		46		46			46				44.5	
H-2	540	35.5			47	47.5			47			46	46					45.5
H-4	565				43	42.5		42				40	39				37.5	37
H-6	565	35	45	45.5	46		44		44				40					
H-5	590				42	42.5		40			39				37.5	37		36
H-3	590							40										35.5

^aHeat No. VC5281, 1.27-cm-thick plate.

Fig. 7.5 – Aging of PH13 – 8Mo precipitation hardening stainless steel, heat No. VC 5281

TABLE 7.9
TENSILE PROPERTIES OF PH13 – 8Mo PLATE^a

Specimen Orientation	Specimen No. ^b	Test Temperature, °C	0.2% Yield Strength		Tensile Strength		Elongation in 2.54 cm, %	Reduction of Area, %
			kg/cm ²	psi	kg/cm ²	psi		
Parallel to rolling direction	N1	25	13,200	188,900	13,710	195,000	19.4	69.8
	O1	25	13,210	187,900	13,660	194,200	21.2	71.7
	P1	315	11,130	158,300	11,590	164,800	15.8	69.7
	Q1	315	11,070	157,500	11,470	163,100	14.3	69.1
	R1	315	11,065	157,400	11,870	163,800	16.7	69.1
	S1	425	9,740	138,500	10,220	145,300	22.4	74.9
Transverse to rolling direction	Ba	25	14,360	204,200	15,790	224,600	16.8	64.9
	BB	25	14,510	206,300	15,440	219,600	18.7	65.8
	BC	315	12,100	172,100	13,100	186,300	15.0	64.9
	BD	315	10,890	154,900	12,950	184,200	14.2	65.0
	BE	425	10,320	146,800	11,250	160,000	21.1	72.8
	BF	425	10,350	147,200	11,130	158,300	22.0	73.1

^aPortions of the PH13 – 8Mo plate were heat treated at 565°C for 4 hours and air cooled prior to machining to specimen configuration.

^bAll specimens were standard ASTM type with 0.636-cm-diameter reduced section.

Fig. 7.6 — Tensile and Charpy V-notch impact properties of PH13-8Mo precipitation hardening stainless steel plate and weldments

TABLE 7.10

CHARPY V-NOTCH IMPACT STRENGTH OF PH13 — 8Mo PLATE^a

Major Specimen Axis ^b	Energy Absorbed					
	25°C		-40°C		-78°C	
	ft-lb	m-kg	ft-lb	m-kg	ft-lb	m-kg
Transverse to rolling direction	75.5	10.4	21.5	3.0	10.0	1.4
	78.5	10.8	23.5	3.2	24.0	3.3
	80.0	11.0	24.0	3.3	19.5	2.7
Parallel to rolling direction	69.0	9.5	28.5	3.9	31.0	4.3
	69.0	9.5	36.4	5.0	31.0	4.3
	74.0	10.2	36.0	5.0	36.0	4.3

^aPortions of the PH13 — 8Mo plate were heat treated at 565°C for 4 hours and air cooled prior to machining to specimen configuration.

^bAll notches perpendicular to the surface of the plate.

from an original hardness of R_C 43 to R_C 35 to 36. For stable operation of the heat-treated alloy, the maximum use temperature is apparently less than 480°C.

Weldment Studies

Four weldments were prepared from the 1.27-cm-thick plate of PH13-8Mo, using the 0.155-cm-diameter spooled wire of normally matching composition. The manual TIG welding process was employed in conjunction with both single and double bevel weld preparations. Welding procedures were reported previously.⁵

Weld Zone Hardness Versus Heat Treatment – Figure 7.7 illustrates weld zone hardness values of two weldment sections, one after aging only (specimen W11A) and the other after annealing plus aging (specimen W11AA). The weldments shown are for the 1.27-cm-thick plate with a double V-joint weld. The improved weld hardness pattern achieved by annealing and aging after welding is apparent. More pertinent weld data are anticipated from weldments in the 2.54-cm-thick plate.

Tensile Properties – Weld-joint tensile properties of the PH13-8Mo weldments aged after welding were determined at 25°, 315°, and 425°C, and are presented in Table 7.11 and Figure 7.6. Tensile strength is intermediate between the transverse and parallel orientation

Fig. 7.7 – Macroetched cross sections from double-V PH13-8Mo weldments. W11A aged after welding and W11AA annealed and aged after welding. Numbers beside the indentations are Rockwell C hardness values (P67-8-33N)

values of the base metal; yield strength varies from about 93 percent at room temperature to 96 percent at 415°C of the base metal, parallel orientation values. Ductility of the welds is significantly lower and more variable than observed in base metal tests. Effects of other post-weld heat treatments are being studied.

All-weld specimen data in two post-weld heat-treated conditions are also presented in Table 7.11. The properties are generally quite good, although post-weld annealing and aging apparently produce higher yield strength values than aging alone.

Toughness – Charpy V-notch impact tests were completed on specimens machined from weldments aged only after welding. Table 7.12 and Figure 7.6 summarize the absorbed energy values obtained at 25°, -40°, and -78°C. The values decrease approximately linearly from 25°C to -78°C, and are about the same as those reported earlier for base metal transverse specimens at -40°C, but much lower at 25°C and -78°C. Effects of other post-weld heat treatments are being studied.

INCONEL ALLOY 718

Inconel alloy 718 is a precipitation-hardening nickel-base alloy which has a nominal composition of 53Ni, 19Cr, 19Fe, 5Nb, 3Mo, 1Ti, 0.5Al, 0.05C, and 0.004B (wt %). It is strengthened by a coherent Nb-rich gamma-prime precipitate believed to be $Ni_3(Nb, Ti)$

⁵GEMP-67, p. 146.

TABLE 7.11
TENSILE PROPERTIES OF PH13-8Mo WELDMENTS

Specimen Type ^a	Specimen No.	Specimen Treatment ^b	Test Temperature, °C	0.2% Yield Strength		Tensile Strength		Elongation in 2.54 cm, %	Reduction of Area %	Location of Fracture
				kg/cm ²	psi	kg/cm ²	psi			
Joint tensile	C	W + A	25	12,160	172,800	14,120	201,300	14.0	68	Base metal
Joint tensile	E	W + A	25	12,390	176,000	14,280	203,000	8.2	22	Weld
Joint tensile	D	W + A	315	10,410	148,300	12,130	172,100	12.6	52	Weld
Joint tensile	F	W + A	315	10,540	150,000	12,110	172,000	9.2	38	Weld
Joint tensile	G	W + A	425	9,330	133,300	11,120	158,100	10.8	35	Weld
Joint tensile	H	W + A	425	9,400	133,700	11,030	157,400	9.3	34	Weld
All weld tensile	D	W + A	25	11,620	165,000	14,300	203,200	12.9	27	—
All weld tensile	C	W + A	25	11,600	164,600	14,300	203,200	20.8	58	—
All weld tensile	4	W+An+A	25	13,030	186,400	14,520	206,500	7.8	20	—
All weld tensile	3	W+An+A	25	12,500	176,800	14,400	207,400	11.0	21	—

^aAll specimens were standard ASTM type with 0.636-cm diameter reduced section.

^bHeat treatments: W — Welded.

A — Aged 4 hours at 565°C, air cooled to room temperature.

An — Annealed at 925°C for 0.5 hour, air cooled to 15°C.

TABLE 7.12
CHARPY V-NOTCH^a IMPACT STRENGTH
OF PH13-8Mo WELDMENTS

Condition of Specimen ^b	Energy Absorbed					
	25°C		-40°C		-78°C	
	ft-lb	m-kg	ft-lb	m-kg	ft-lb	m-kg
W + A	44	6.1	14	1.94	8	1.08
W + A	46	6.4	26	3.6	7	0.97
W + A	41	5.7	22	3.0	8	1.08

^aNotch oriented perpendicular to surface of plate and through weld metal.

^bHeat treatment: W — Welded.

A — Aged for 4 hours at 565°C, air cooled to room temperature.

Al). The alloy has better strength at higher temperatures than any other compositions being studied, retaining approximately 90 percent of its room-temperature strength above 480°C. This high-temperature strength was the principal reason for selection, since it offered an opportunity for temperature growth in advanced reactor systems. Several heat treatments are employed, depending on the properties required. A typical heat treatment consists of solution treating at 950°C for 1 hour, air cool followed by aging at 715°C for 8 hours, furnace cool to 620°C, hold 12 hours, and air cool. The alloy can be prepared by air melting techniques, but vacuum melting techniques are preferred. For some applications, double vacuum melting is employed. It is reportedly quite weldable by inert arc techniques, its sluggish response to age hardening favors good weldability, and it requires no pre- or post-heating. For best properties, heat treatment by aging or solution treating and aging are required after welding.

Table 7.13 describes the Inconel alloy 718 material procured for test. Preliminary inquiries were made for 10-cm-thick material, but further procurement action has been delayed pending additional qualification of the alloy, particularly with respect to fracture toughness.

Base Metal Studies

Tensile Properties — The tensile properties of the Inconel alloy 718 plate were determined at 25°, 425°, 540°, and 650°C using three different heat treatments. These data are shown in Tables 7.14, 15, and 16 and in Figure 7.8. Heat treatment I resulted in the low-

TABLE 7.13
DESCRIPTION OF INCONEL ALLOY 718 MATERIALS

Heat No.	Melting Procedure ^a	Size, cm	As-Received Condition	Chemical Analysis, wt %																															
				C		Mn		P		S		Si		Cr		Ni		Ti		Al		Mo		Nb + Ta		Co		Cu		B		Fe			
				Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO		Vendor NMPO	
Nominal analysis				0.08		0.45		0.015		0.015		0.45		17.0		50.0		0.65		0.80		2.8		4.75		1.0		0.30		0.006		Bal			
				Max		Max		Max		Max		Max		Min		Min		Min		Max		Min		Min		Max		Max		Max					
														21.0		55.0		1.40				3.3		5.50											
														Max		Max		Max				Max		Max											
02A0ES	IVM	2.5 x 96 x 140	As-hot rolled	0.02	0.007	0.10	—	0.02	0.005	0.007	0.005	0.18	0.10	18.27	18.02	53.28	—	1.01	0.89	0.54	0.59	3.07	3.06	5.10	5.20	0.06	—	0.04	—	0.003	—	18.30	19.16		
4878E	IVM	0.32 dia. x 91 (Filler metal)	Ascold drawn	0.04		0.30		0.011		0.007		0.18		18.39		52.95		0.84		0.44		3.11		4.76		0.05		0.03		0.002		18.95			

^aIVM — Induction vacuum melt.

TABLE 7.14

TENSILE PROPERTIES OF INCONEL ALLOY 718 PLATE AFTER HEAT TREATMENT I^a

Specimen Orientation	Specimen No. ^b	Test Temperature, °C	0.2% Yield Strength		Tensile Strength		Elongation in 4D, %	Reduction of Area, %
			kg/cm ²	psi	kg/cm ²	psi		
Parallel to rolling direction	Y1 ^c	25	10,000	140,200	13,960	197,000	15.9	23
	Y2 ^c	425	9,150	129,900	12,900	183,200	19.9	33
	Y3 ^c	540	8,800	125,200	12,700	180,200	17.4	35
	D	25	9,650	137,000	13,700	193,800	17.8	22
	H	25	9,650	137,000	13,600	192,200	13.3	18
	B	425	8,300	118,000	12,570	178,700	21.6	32
	I	425	8,700	124,000	12,600	179,800	12.9	15
	C	540	8,350	119,000	12,400	176,500	16.3	33
	J	540	8,900	119,900	12,450	177,100	12.9	21
	E	650	8,150	116,000	10,400	148,000	21.0	39
	K	650	8,100	115,800	10,500	149,000	18.9	50
Transverse to rolling direction	C1	25	9,900	140,800	13,300	189,100	13.7	15.3
	C2	25	9,940	141,300	13,270	188,700	11.9	14.8
	C3	425	8,920	126,900	12,370	175,900	17.6	19.1
	C4	425	8,940	127,100	12,360	175,800	19.1	20.3
	B1	540	8,630	122,700	12,300	174,900	20.8	31.6
	B3	540	8,590	122,200	12,310	175,000	20.5	31.6
	C5	650	8,290	117,900	10,570	150,300	16.5	21.6
	C6	650	8,300	118,000	10,630	151,200	23.9	30.7

^aHeat treatment: 950°C for 1 hr, furnace cool 100 min to 715°C, hold 8 hr, furnace cool to 620°C, hold for 12 hr (including furnace cooling time), air cool to room temperature.

^bStandard ASTM type with 0.636-cm-diameter reduced section.

^c1.27-cm-diameter reduced section.

est strength levels. Heat treatment II, which is similar to I except for more rapid cooling from the solutioning temperature, results in the highest strength levels. Heat treatment III, involving a much higher solutioning temperature and a modified aging cycle, resulted in intermediate strength values. In general, heat treatment III, which was selected for improved toughness, resulted in better elongation and reduction of area values than the other two heat treatments. It is clear from heat treatments I and II that the cooling rate from

TABLE 7.15

TENSILE PROPERTIES OF INCONEL ALLOY 718 PLATE AFTER HEAT TREATMENT II^a

Specimen Orientation	Specimen No. ^b	Test Temperature, °C	0.2% Yield Strength		Tensile Strength		Elongation in 4D, %	Reduction of Area, %
			kg/cm ²	psi	kg/cm ²	psi		
Parallel to rolling direction	P1	25	11,600	165,000	14,700	209,500	21	24
	AA	25	12,150	172,400	14,800	211,100	21	33
	Q1	425	10,400	147,900	13,120	186,160	21	35
	R1	425	10,300	145,580	13,150	186,500	15	37
	S1	540	10,090	143,500	12,810	182,270	24	26
	T1	540	10,330	146,680	12,750	181,330	17	34
	U1	650	9,950	141,610	11,830	168,220	14	32
	V1	650	—	c	11,970	170,120	21	40
Transverse to rolling direction	FA	25	12,970	170,000	14,400	204,700	19	23
	FD	25	12,970	170,000	14,350	204,200	18	23
	FB	425	10,760	152,830	12,810	182,210	17	29
	FE	425	10,790	153,300	12,690	180,490	18	29
	FC	540	10,290	146,340	12,490	177,670	14	24
	FF	540	10,630	150,980	12,410	176,440	12	23
	FH	650	c	c	11,290	160,600	14	26
	FG	650	9,310	132,570	11,030	156,980	6	32

^aHeat treatment: 950°C for 1 hr, air cool to room temperature, heat to 715°C, hold 8 hr, furnace cool to 620°C, hold for 12 hr (including furnace cool time), air cool to room temperature.

^bAll specimens were standard ASTM type with 0.636-cm-diameter reduced section.

^cExtensometer slipped.

TABLE 7.16

TENSILE PROPERTIES OF INCONEL ALLOY 718 PLATE AFTER HEAT TREATMENT III^a

Specimen Orientation	Specimen No. ^b	Test Temperature, °C	0.2% Yield Strength		Tensile Strength		Elongation in 4D, %	Reduction of Area, %
			kg/cm ²	psi	kg/cm ²	psi		
Parallel to rolling direction	M	25	10,020	142,490	13,590	193,290	24	31
	N	425	8,830	125,620	12,425	176,950	24	37
	O	540	8,580	122,300	12,180	173,140	23	37
Transverse to rolling direction	A	25	11,300	160,740	13,870	197,300	18	23
	D	25	11,350	161,600	13,930	198,300	20	26
	B	425	—	c	12,510	177,930	23	33
	E	425	10,140	143,990	12,510	177,900	22	33
	C	540	9,780	139,060	12,310	175,000	20	33
	F	540	9,550	135,800	12,270	174,340	22	33

^aHeat treatment: 1070°C for 1 hr, air cool to room temperature, heat to 760°C, hold for 10 hr, furnace cool to 650°C, hold for 10 hr (including furnace cool time), air cool to room temperature.

^bAll specimens were standard ASTM type with 0.636-cm-diameter reduced section.

^cExtensometer slipped.

Fig. 7.8 — Tensile and Charpy V-notch impact properties of Inconel alloy 718 plate and weldments

the annealing temperature has a major effect on tensile properties. This suggests that the quenching procedures employed in the solution annealing of the type of heavier plate potentially useful in nuclear pressure vessel construction must be carefully selected to assure optimum properties.

Toughness – Charpy V-notch impact tests were completed for the parallel and transverse orientations at 25°, -40°, and -78°C for heat treatments I and II. Table 7.17 and Figure 7.8 show these data. No evidence of a transition from ductile-to-brittle fracture was noted and the cooling rate apparently had little effect on the absorbed energy levels, but a distinct toughness anisotropy exists. Charpy V-notch specimens which received heat treatment III will be evaluated. Drop-weight tear test specimens for each of the three heat treatment are being prepared and will be tested at NRL to further define the toughness of this fcc alloy.

Fatigue Properties – Specimens are being prepared for preliminary low-cycle fatigue testing. These specimens are being made from material which has received heat treatment III.

Radiation Effects – Charpy V-notch data have been obtained at NRL on Inconel alloy 718 specimens irradiated to a fluence of 1.15×10^{19} n/cm² ($E_n \geq 1$ Mev). Specimens were irradiated in the Union Carbide Research Reactor in a helium environment at less than 120°C. The specimens received heat treatment I prior to machining for irradiation. Table 7.18 and Figure 7.9 summarize data obtained. The irradiation exposure apparently did not reduce impact resistance, at least when similar test temperatures were employed. Additional control tests will be made at higher temperatures.

A second capsule containing tensile blanks and Charpy V-notch specimens of Inconel alloy 718 had been irradiated in the MTR at pile-ambient temperature to a fluence level of about 4 to 5×10^{19} n/cm² ($E_n \geq 1$ Mev). Post-testing will be conducted at NRL.

Thermal Stability – Specimens of Inconel alloy 718 representing all three heat treatments have been exposed in air at 540°C for 1000 hours. No change in hardness was noted. Another plate which had received heat treatment II was exposed for 1000 hours at 650°C and a small

TABLE 7.17
CHARPY V-NOTCH IMPACT STRENGTH OF INCONEL ALLOY 718 PLATE

Orientation of Major Specimen Axis	Heat Treatment ^a	Energy Absorbed					
		25°C		-40°C		-78°C	
		ft-lb	m-kg	ft-lb	m-kg	ft-lb	m-kg
Parallel to rolling direction	I	20	2.76	20	2.76	20	2.76
		20	2.76	20	2.76	18	2.50
		20	2.76	19	2.64	19	2.64
Parallel to rolling direction	II	20	2.76	18	2.50	17	2.35
		20	2.76	17	2.35	17	2.35
		18	2.50	18	2.50	17	2.35
Transverse to rolling direction	I	11.0	1.52	12	1.66	11.5	1.59
		12.0	1.66	12	1.66	9.0	1.24
		12.0	1.66	12	1.66	11.0	1.52
Transverse to rolling direction	II	10	1.38	9	1.24	—	—
		9	1.24	8	1.08	—	—
		—	—	11	1.52	—	—

^aHeat treatment: I — 950°C for 1 hr, furnace cool 100 min. to 715°C, hold 8 hr, furnace cool to 620°C, hold 12 hr (including furnace cooling time), then air cool to room temperature.

II — 950°C for 1 hr, air cool to room temperature, heat to 715°C, hold 8 hr, furnace cool to 620°C, hold 12 hr (including furnace cool time), then air cool to room temperature.

Fig. 7.9 — Effect of nuclear irradiation ($<122^{\circ}\text{C}$ 1.15×10^{19} n/cm^2 ; $E_n \geq 1$ Mev) on Inconel alloy 718

TABLE 7.18

INCONEL 718 CHARPY V-NOTCH DATA FOR IRRADIATED SPECIMENS^a

Specimen No.	Orientation ^b	Charpy V Properties ^c				Rockwell
		Temperature		Energy		Hardness,
		°F	°C	ft-lb	mg-kg	R _C
T9	T	+80	27	13	1.8	40 ^d
E3	P	+300	150	23	3.2	
T1	T	+500	260	16	2.2	
T15	T	+400	205	15	2.1	
T7	T	+200	93	20	2.8	
G3	P	+200	93	23	3.2	40 ^d
D1	P	+100	38	23	3.2	
J3	P	+300	150	22	3.0	
C3	P	±0	-18	21	2.9	
F3	P	+200	93	22	3.0	
K3	P	+100	38	21	2.9	
I3	P	-160	-107	18	2.5	
K1	P	+400	205	22	3.0	
T5	T	+80	27	12	1.7	
D3	P	±0	-18	21	2.9	
T13	T	+300	150	14	1.9	
E1	P	-160	-107	18	2.5	
H1	P	-160	-107	19	2.6	
G1	P	+500	260	23	3.2	
L1	P	+400	205	23	3.2	
H3	P	+500	260	26	3.6	

^a 1.15×10^{19} n/cm^2 , $E_n \geq 1$ Mev (σ 68 mb Mn^{54} fission).

^b T = Major specimen axis transverse to rolling direction.

P = Major specimen axis parallel to rolling direction.

^c Material given Heat Treatment I prior to radiation exposure.

^d Average of 3 readings.

increase in hardness was noted. Tensile and Charpy V-notch impact specimens are being prepared from each plate.

Weldment Studies

Four weldments of the Inconel 718 alloy were prepared in 2.54-cm-thick plate, using joint designs described previously.⁶ Of these, two were made using the U-joint for all-weld metal specimens, and two were made with the double U-joint preparation for determining joint properties. The manual TIG welding method was employed according to procedures described earlier.⁶

Weld Zone Hardness Versus Heat Treatment – Sections of double U weldments with two different post-weld heat treatments were ground, etched, and surveyed for Rockwell C hardness. Figure 7.10 illustrates two sections from a weldment which, after welding, were aged at 715°C for 8 hours, furnace cooled to 620°C and held for 12 hours including furnace cooling time, and air cooled. Prior to welding the plate was heated at 950°C for 1 hour and air cooled. Weld center hardnesses ranged from R_C 34 to 44; base metal hardnesses ranged from R_C 38 to 46. The reason for the disparity in hardness between the two weld areas is not known but must tentatively be assigned to weld metal heterogeneity. Differences in base metal hardness are probably associated with inadvertent variations in pre-weld heat treatment.

Figure 7.11 presents the results of hardness surveys on two sections of a weldment subjected, following welding, to a solution anneal at 950°C for 1 hour followed by furnace cooling to 715°C, holding 8 hours, furnace cooling to 620°C, holding for 12 hours, and air cooling. Weld center hardnesses range from R_C 35 to 41, with base metal hardnesses of R_C 41 to 43.

Tensile Properties – Data obtained on weld-joint tensile specimens machined from double U weldments are presented in Table 7.19 and Figure 7.8. These specimens possess significantly lower strength and ductility than the base metal similarly treated. The deleterious effect on properties of slow cooling from the solution annealing temperature is again apparent. The W2 series specimens were cut from plate air cooled from 950°C prior to welding; hence they should be compared with base metal specimens given heat treatment II listed in Table 7.15. The effect of post-weld solution annealing and air cooling, and aging on weldment properties will be determined. All-weld specimens in various conditions of heat treatment are being prepared.

Toughness – Table 7.20 and Figure 7.8 contain results of Charpy V-notch tests conducted on specimens machined from weldments. The specimens aged only after welding (solution annealed at 950°C for 1 hour and air cooled prior to welding) possessed approximately the same impact strength as the base metal at 25°C but only half as much at -40°C. Even lower values at -40°C were obtained on specimens from weldments given a solution anneal (furnace cooled) and aged after welding.

HP 9Ni – 4Co – 0.20C

HP 9Ni – 4Co – 0.20C, a heat-treatable steel, has been added to the program and will be evaluated. This alloy can achieve high tensile strengths while retaining excellent toughness. It is recommended for use in the quenched and double-tempered condition. The material is reported to be quite weldable in the quenched and tempered condition, and no post-weld heat treatment is required to achieve virtually 100 percent weld efficiencies.

A plate 2.54 cm thick by 91.4 by 122 cm has been received from heat No. 3932354* and is being machined into test pieces for tensile, impact, low-cycle fatigue, DWTT, and weld

*Composition in wt % of heat 3932354: C – 0.017, Mn – 0.29, P – 0.004, S – 0.007, Si – 0.01, Ni – 9.11, Cr – 0.79, V – 0.09, Co – 4.40, Fe – balance.

⁶GEMP-475A, Fig. 9.1, p. 232.

Fig. 7.10 — Macroetched cross sections from a double-U Inconel alloy 718 weldment aged at 715°C for 8 hours, furnace cooled to 620°C, held for 12 hours, and air cooled to room temperature. Numbers beside the indentations are Rockwell C values. (Neg. P67-8-33L)

Fig. 7.11 — Macroetched cross sections from double-U Inconel alloy 718 weldment annealed (furnace cool) and aged after welding. Numbers beside the indentations are Rockwell C hardness values. (Neg. P67-8-33M)

TABLE 7.19
TENSILE PROPERTIES OF INCONEL ALLOY 718 WELDMENTS

Specimen	Specimen No.	Specimen Treatment ^a	Test Temperature, °C	0.2% Yield Strength		Tensile Strength		Elongation in 4D, %	Reduction of Area, %	Location of Fracture
				kg/cm ²	psi	kg/cm ²	psi			
Joint tensile	W3A	W+An+A	25	9,700	138,300	10,900	155,200	12.7	11	W
	W3A	W+An+A	25	9,300	132,900	10,300	147,000	12.3	13	W
	W3C	W+An+A	425	8,100	115,400	10,300	146,900	7.3	22	W
	W3D	W+An+A	425	8,900	119,800	10,000	143,200	4.9	13	HAZ ^b
	W3E	W+An+A	540	8,300	118,200	10,500	148,700	8.9	34	W
	W3F	W+An+A	540	8,100	115,290	9,200	131,100	4.1	15	HAZ ^b
	W3G	W+An+A	540	8,300	118,000	9,700	137,600	14.0	14	W
	W2E	W + A	25	10,500	149,600	12,500	178,200	6.9	30	W
	W2K	W + A	25	10,600	150,700	12,700	179,800	7.6	28	W
	W2G	W + A	425	9,500	134,700	10,900	154,800	8.5	33	HAZ ^b
	W2L	W + A	425	9,200	130,400	10,100	143,800	4.1	22	W
	W2I	W + A	540	9,200	131,140	10,400	148,300	7.3	31	W
	W2H	W + A	540	8,700	123,700	9,500	135,800	4.5	22	W

^aHeat treatment: W — Welded.

An — Annealed at 950°C for 1 hour, furnace cooled to aging temperature.

A — Aged at 715°C for 8 hours, furnace cooled to 620°C and held 12 hours, including furnace cooling time.

^bHAZ — Heat-affected zone.

TABLE 7.20
CHARPY V—NOTCH IMPACT STRENGTH
OF INCONEL ALLOY 718 WELDMENTS

Notch Location ^a	Specimen Condition ^b	Energy Absorbed			
		25°C		-40°C	
		ft-lb	m-kg	ft-lb	m-kg
HAZ ^c	W + A	21	2.90	10	1.38
Weld	W + A	16	2.11	11	1.52
Weld	W + A	20	2.76	11	1.52
BM ^d	A	20	2.76	17	2.35
BM ^d	A	10	1.38	Parallel to RD	
				9	1.24
				Transverse to RD	
HAC ^c	W+An+A	—	—	10	1.38
HAZ ^c	W+An+A	—	—	8	1.08
HAZ ^c	W+An+A	—	—	8	1.08
Weld	W+An+A	—	—	6	0.83
Weld	W+An+A	—	—	6	0.83
Weld	W+An+A	—	—	6	0.83
BM ^d	An+A	20	2.76	20	2.76
BM ^d	An+A	10	1.38	Parallel to RD	
				9	1.24
				Transverse to RD	

^aAll notches perpendicular to surface of plate.

^bHeat treatment: W — Welded.

A — Aged at 715°C for 8 hours, furnace cooled to 620°C, held 12 hours, including furnace cooling time.

An+A — Annealed at 950°C for 1 hour, furnace cooled to 715°C, held 8 hours, furnace cooled to 620°C, held 12 hours including furnace cooling time.

^cHAZ — Heat-affected zone.

^dBM — Base metal.

specimens. This material was air melted and vacuum consumable electrode remelted and arrived in the heat-treated condition. Nominal heat-treating procedures are as follow ;

Normalize: 900°-930°C - 1 hr/2.54 cm thickness, air cool

Austenitize: 845° ± 10°C - 1 hr/2.54 cm thickness, water or oil quench

Temper: Double temper - each temper consists of 2 hours minimum at 540°C (for 13,360 kg/cm² minimum tensile strength).

The vendor reports the following room-temperature properties for this material:

Tensile strength, kg/cm ²	13,910 (198,000 psi)
Yield strength, kg/cm ²	13,290 (188,600 psi)
Elongation in 5.08 cm, %	17
Reduction of area, %	68.5
Charpy V-notch impact energy (avg), m-kg	9.1 (66 ft-lb)

Welding wire designed to match the base metal properties in the as-welded condition is being procured.

7.2 CONSIDERATION OF PRESSURE VESSEL FAILURE MODES AND RELATED PROPERTIES

Studies have been made to identify special material properties beyond those normally obtained which may eventually be required to properly qualify a potential pressure vessel material. This gives reasonable assurance that no major basic limitation of the concept of using high-yield-strength materials or of using a given advanced pressure vessel material is overlooked.

The first step in these studies is to consider potential failure modes and to identify special material properties or tests required to evaluate a factor of safety for each mode of failure. Six principal modes of failure have been considered:

1. Burst due to over-pressure.
2. Fatigue cracking.
3. Fast fracture including both brittle fracture and low-energy tearing.
4. Buckling collapse due to external pressure.
5. Corrosion, including stress corrosion and corrosion fatigue.
6. Progressive distortion (ratchetting).

Although the foregoing six modes of failure are potentially all significant failure modes, only the first three are considered immediately pertinent to the development of advanced pressure vessel materials. The other three failure modes are being eliminated from further studies of advanced pressure vessel materials for the following reasons.

Buckling collapse is eliminated from further consideration simply because the vast majority of pressure vessels pertinent to this program are vessels subject only to internal pressure. There is a possibility of developing an instability at the knuckle of a poorly designed dished head, but this is considered primarily a design problem unrelated to development of advanced pressure vessel materials.

Corrosion, on the other hand, is definitely a materials problem, but it is assumed that, should corrosion be a problem with these materials, a corrosion-resistant cladding could be applied in a manner similar to that currently used for the conventional low-carbon steels.

Progressive distortion or ratchetting is eliminated from further consideration because it is primarily a design problem. A well designed structure (including adequate analysis) should not be subjected to ratchetting.

The remaining three failure modes require careful consideration in the development of advanced pressure vessel materials, and are treated in some detail in the following paragraphs.

BURST DUE TO OVER-PRESSURE

Investigators have shown⁷ that burst pressure can be expressed in terms of ultimate tensile strength, strain-hardening exponent, and geometry of the vessel. For a thin-walled cylinder, Langer⁷ gives the following equation for the burst pressure:

$$P_b = \sigma_u' F_{cyl} \left(\frac{2t}{d_i} \right) \left(1 - \frac{t}{d_i} \right) \quad (7.1)$$

where

P_b = burst pressure

σ_u' = nominal stress at ultimate load, i. e., nominal engineering ultimate tensile strength

t = vessel wall thickness

d_i = vessel inside diameter

$$F_{cyl} = \left[\frac{0.25}{\epsilon_u + 0.227} \right] \left(\frac{e}{\epsilon_u} \right)^{\epsilon_u}$$

e = base of the natural logarithms

ϵ_u = true strain at ultimate load

Langer states that equation (7.1) should be used for

$$W < 1.4$$

$$\text{where } W = d_o/d_i = \frac{d_i + 2t}{d_i} = 1 + \frac{2t}{d_i}$$

and d_o = vessel outside diameter

when the strain-hardening exponent, n , is defined as the true strain at ultimate load $n = \epsilon_u$ and equation (7.1) then defines the burst pressure in terms of the nominal tensile strength, strain-hardening exponent, and vessel geometric parameters.

For a cylindrical vessel designed to Section III of the ASME Boiler and Pressure Vessel Code with the minimum permissible thickness, the design pressure, P_d , is given by the following:

$$\begin{aligned} P_d &= 2S_m \left(\frac{t}{d_i} \right) \left[\frac{1}{1+t/d_i} \right] \\ &\cong 2S_m \left(\frac{t}{d_i} \right) \left[1 - \frac{t}{d_i} \right] \end{aligned} \quad (7.2)$$

where

S_m = membrane stress allowable.

If one defines the factor of safety, FS , on burst as the ratio of the burst pressure to the design pressure, and if it is further assumed that for the high-strength materials in this program the value of S_m will always be based on the ultimate tensile strength, and using the Section III value of

$$S_m = 1/3 \sigma_u',$$

⁷B. F. Langer, "PVRC Interpretive Report of Pressure Vessel Research, Section I - Design Considerations," Welding Research Council Bulletin, No. 95, April 1964.

the factor of safety on burst due to over-pressure for a thin-walled cylinder becomes simply:

$$FS = 3 F_{cyl} \quad (7.3)$$

The definition of F_{cyl} indicates that it is a function only of the strain-hardening exponent ($n = \epsilon_u$), Langer's tabulated values of F_{cyl} as a function of n together with equation (7.3) were used in preparing Figure 7.12 which shows the relationship between the factor of safety and the strain-hardening exponent.

Gross⁸ gives plots which show the variation of yield strength and strain-hardening exponent with tensile strength for typical pressure vessel steels. Figure 7.13 combines

Fig. 7.12 — Factor of safety of burst of over pressure for a thin-walled cylindrical pressure vessel

Fig. 7.13 — Variation of the strain-hardening exponent with the yield-to-tensile strength ratio for typical pressure vessel steels — based on the data of Gross

⁸J. H. Gross, "PVRC Interpretive Report of Pressure Vessel Research, Section II — Materials Considerations," Welding Research Council Bulletin, No. 101, November 1969.

Fig. 7.14 — Variation of factor of safety with the yield-to-tensile strength ratio — obtained by cross plotting information contained in Figures 7.12 and 7.13

these plots of Gross to obtain a plot of the variation of the strain-hardening exponent with the yield-to-tensile strength ratio for the typical pressure vessel steels. The information contained in Figures 7.12 and 7.13 was combined to obtain the plot of factor of safety versus the yield-to-tensile strength ratio shown in Figure 7.14. This plot indicates that the factor of safety on burst due to over-pressure tends to increase with increasing yield-to-tensile strength ratio.

The foregoing discussion demonstrates the need for somewhat more detailed tensile data and evaluation than are normally obtained from routine tensile tests in order to evaluate the factor of safety on burst due to over-pressure. In addition to the normal data, the true strain at the ultimate (maximum) load is required. The true strain at the ultimate load is needed to define the strain-hardening exponent which, in turn, can be used to obtain a calculated factor of safety on burst. Strain-hardening exponents obtained for candidate pressure vessel materials can be compared with the data of Gross presented in Figure 7.13 to assess the behavior of these materials compared to current typical pressure vessel materials.

FATIGUE CRACKING

Coffin,⁹ Coffin and Tavernelli,¹⁰ and Manson¹¹ have shown that low-cycle (or strain) fatigue data can be related to the tensile properties of a material. Manson has presented several different techniques for doing this, but his method of Universal slopes which has been correlated with fatigue data on numerous materials was selected for these studies due to its simplicity of application. Manson gives the following equation for relating the fatigue strain range with the tensile properties:

$$\Delta \epsilon = 3.5 \frac{\sigma_u'}{E} N_f^{-0.12} + \left(\frac{D}{N_f} \right)^{0.6} \quad (7.4)$$

⁹L. F. Coffin, Jr., "A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal," Trans. ASME, Vol. 76, 1954, pp. 931-950.

¹⁰L. F. Coffin, Jr., and J. F. Tavernelli, "Experimental Support for a Generalized Equation Predicting Low-Cycle Fatigue," Trans. ASME, Vol. 84, Series D, 1962, pp. 533-591.

¹¹S. S. Manson, "Fatigue: A Complex Subject — Some Simple Approximations," Exp. Mech., Vol. 5, No. 7, 1965, pp. 2-35.

where

$\Delta\epsilon$ = total strain range, elastic plus plastic
 E = modulus of elasticity
 σ_u = nominal stress at the ultimate (max) load
 N_f = number of cycles to failure
 D = ductility = $[1/(1-RA)]$
 RA = reduction in area expressed as a fraction

Manson does not propose that this equation be used in lieu of actual fatigue data. Since it has correlated well with fatigue data for a wide range of materials, however, it is considered to give a good indication of the potential fatigue performance of materials. Accordingly, Manson's equation (7.4) has been used to give a preliminary indication of the potential fatigue performance of the candidate advanced pressure vessel materials.

Since these advanced pressure vessel materials are specifically intended for nuclear service, the Manson equation was used to compare potential fatigue properties of these materials with design fatigue strength curves for the currently approved materials presented in Section III of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels. To make this comparison, the Code philosophy as delineated in the supplementary criteria¹² issued with the first edition of Section III was used to apply corrections for the effect of mean stress and factors of safety on stress and cycles.

Code criteria in essence assume that the materials behave in an elastic – perfectly plastic manner and that, due to residual stresses of unknown magnitude in the as-fabricated vessel, one must assume that the maximum possible mean stress exists at any point in the vessel. The Code criteria also assume a linear rule for correcting for the effect of mean stress.

Figure 7.15 helps to illustrate the manner in which the correction for mean stress has been made. After shakedown,* all possible stress states lie either within the triangular region A-O-B along line A-B, or on the alternating stress axis above point A. Line C-D from the point on the alternating stress axis represents the stress, S_N , required to produce failure in N cycles at zero mean stress to the ultimate tensile strength on the mean stress axis. This line represents the limiting combinations of mean and alternating stress required to produce failure in N cycles according to the linear rule.

However, since line A-B represents the limits of the possible stress states, point E corresponds to the highest possible mean stress point corresponding to N cycles. The corresponding alternating stress value, S_N is the alternating stress amplitude corrected for the maximum possible effect of mean stress. Applying this procedure for a number of different values of N gives the fatigue curve corrected for the maximum effect of mean stress. The next step in obtaining the calculated fatigue design curve is to apply the Code factors of safety of 2 on stress and 20 on cycles to the fatigue curve corrected for the maximum effect of mean stress. The calculated design fatigue strength curves obtained in this manner are compared with the applicable Section III design fatigue strength curves in Figures 7.16 and 7.17.

For many materials the Peterson Cubic Rule¹³ is a better representation of the fatigue behavior under combined mean and alternating stress; hence the foregoing comparison was repeated using this rule, and results are shown in Figures 7.18 and 7.19.

*Shakedown refers to an elastic cyclic condition after a few cycles which is assumed to be assured by the Code's $3S_m$ limit on the primary plus secondary stresses.

¹²"Criteria of Section III of the ASME Boiler and Pressure Vessel Code for Nuclear Vessels," ASME, New York, N.Y., 1964.

¹³R. E. Peterson, "Brittle Fracture and Fatigue in Machinery," Fatigue and Fracture of Metals, Wiley, New York, N.Y., 1952, pp. 79-102.

Fig. 7.15 – Modified Goodman diagram showing the application of the linear rule to obtain the correction for the maximum effect of mean stress

Fig. 7.16 – Comparison of calculated design fatigue curves for PH13-8Mo and 12Ni-5Cr-3Mo (using the Linear Rule to correct for the maximum effect of mean stress) with design fatigue curve for carbon and alloy steels from Section III of ASME Boiler and Pressure Vessel Code for Nuclear Vessels

Another item which should be considered in evaluating the maximum effect of mean stress correction is the fact that, in general, high yield strength materials tend to exhibit a high degree of cyclic strain softening, a decrease in the stress range with cycles during strain cycling tests. This amounts to a decrease in the effective yield strength with cycles, eventually stabilizing at some asymptotic value after many cycles. This asymptotic value is commonly referred to as the dynamic yield strength. It has been suggested¹⁴ that it may be more realistic to base the mean stress correction on the dynamic yield strength rather than

¹⁴Dr. W. E. Cooper, private communication.

Fig. 7.17 – Comparison of calculated design fatigue curve for Inconel 718 (using the Linear Rule to correct for the maximum effect of mean stress) with design fatigue curve for 18-8 stainless steels and nickel-chrome-iron alloy from Section III of ASME Boiler and Pressure Vessel Code for Nuclear Vessels

Fig. 7.18 – Comparison of calculated design fatigue curves for PH13-8Mo and 12Ni-5Cr-3Mo (using the Peterson Cubic Rule to correct for the maximum effect of mean stress) with design fatigue curve for carbon and alloy steels from Section III of ASME Boiler and Pressure Vessel Code for Nuclear Vessels

Fig. 7.19 – Comparison of calculated design fatigue curve for Inconel 718 (using the Peterson Cubic Rule to correct for the maximum effect of mean stress) with design fatigue curve for 18-8 stainless steels and nickel-chrome-iron alloy from Section III of ASME Boiler and Pressure Vessel Code for Nuclear Vessels

the static yield strength for these high yield strength materials. Manson¹⁵ shows data for a 4340 steel in which the asymptotic value of the stress range is only about two-thirds its initial value. To examine the potential significance of this factor, assumed values of dynamic yield strength, σ_{dy} , of 8790 and 10,540 kg/cm² were used to obtain calculated design fatigue strength curves for the 12Ni – 5Cr – 3Mo material, and these are compared with the calculated curve based on the static yield strength, σ_{sy} , and with the corresponding Section III design fatigue strength curve in Figure 7.20 using the linear rule and in Figure 7.21 using the Peterson Cubic Rule. These figures demonstrate that the use of dynamic yield strength and the Peterson Cubic Rule can greatly influence assessment of the fatigue behavior of these high-strength materials.

The preceding discussion of fatigue properties is only an indicator, at best, of the potential fatigue properties of the candidate pressure vessel materials, but it does serve to identify significant facets of the fatigue aspects which will be considered in evaluating the candidate materials.

In summary, the foregoing analysis indicates:

1. Up to about 400 cycles, the 12Ni – 5Cr – 3Mo and PH13-8Mo materials appear to be potentially somewhat better than the conventional materials regardless of the type of mean stress correction used, but this remains to be demonstrated through actual fatigue test data. (Many reactor pressure vessels are currently designed on the basis of fewer than 500 specified operating cycles.)
2. The Inconel alloy 718 appears to have a somewhat reduced fatigue strength over the full cyclic range compared to the Section III curve for the 18-8 stainless steels and Ni-Cr-Fe alloy. This remains to be demonstrated through actual fatigue tests.

¹⁵Manson, op. cit.

Fig. 7.20 — Comparison of calculated design fatigue curves for 12Ni — 5Cr — 3Mo corrected (Linear Rule) for mean stress using assumed values for the dynamic yield strength, σ_{dy} , with the uncorrected curve and with the curve corrected using the static yield strength, σ_{sy}

Fig. 7.21 — Comparison of calculated design fatigue curves for 12Ni — 5Cr — 3Mo corrected (Peterson Cubic Rule) for mean stress using assumed values for the dynamic yield strength, σ_{dy} , with the uncorrected curve and with the curve corrected using the static yield strength, σ_{sy}

3. The use of the Peterson Cubic Rule indicates significant potential gains in design fatigue life. The validity of the cubic rule should be investigated experimentally if such gains need to be exploited.
4. Potentially even more significant than the use of the cubic rule are the gains indicated through the use of the dynamic yield strength in lieu of the static yield strength in making mean stress corrections. These results identify the need for experimental investigations exploring use of the dynamic yield strength in lieu of the static yield strength in making the mean stress corrections. They demonstrate specifically the need to establish the actual dynamic yield strength of these materials in the presently planned fatigue tests to determine whether it would be advantageous to use dynamic data in making the mean stress correction.

FAST FRACTURE BY EITHER BRITTLE FRACTURE OR LOW-ENERGY TEARING

As used herein the term fast fracture refers to either brittle fracture or low-energy tearing. These types of failure are characterized by high-velocity crack propagation with little prior plastic deformation. These types of failure have been studied extensively in recent years, but no single approach has achieved wide acceptance for the full spectrum of significant strength levels. The two approaches most widely accepted are the NRL Fracture Analysis Diagram Procedure¹⁶ and the fracture mechanics approach which is the outgrowth of Griffith's failure theory for brittle materials and its subsequent modifications for metallic materials by Orowan¹⁷ and Irwin.¹⁸

Brittle Fracture

NRL Fractural Analysis Diagram Procedures – These procedures are generally accepted as providing a usable procedure for the lower-strength steels with yield strengths below about 3500 kg/cm². Pellini and Puzak have used the fracture analysis diagram procedures to correlate numerous service failures,¹⁶ including some examples for higher-strength materials. This procedure applies only to materials having a "well defined transition temperature," according to Pellini and Puzak; which is apparently not true of Inconel 718 material.¹⁹ Since this procedure has not been specifically validated for materials of the strength levels involved in this program, considerable experimental data will be needed if this approach is to be employed in fracture-safe evaluation of these advanced pressure vessel materials. To establish a fracture analysis diagram for these materials one needs (1) crack initiation data to define the crack initiation curves, (2) crack arrest data to define the crack arrest (CAT) curve, (3) Charpy V-notch or drop-weight test data to define the nil-ductility transition temperature (NDT), (4) explosion tear test¹⁶ data to define the fracture transition plastic (FTP) point, and (5) correlation with service failures of model pressure vessels to establish validity of the procedure in this strength range.

Fracture Mechanics Approach – This approach is currently limited to the linear fracture mechanics range in which stress levels are in the elastic range everywhere except very locally at the crack tip. This limits current usefulness to very high strength materials (yield strengths 14,000 kg/cm²) and to materials operating below their nil-ductility transition temperature (NDT). Since the materials of interest in this program approach the 14,000 kg/cm² yield strength level, it appears appropriate to consider determination of

¹⁶W. S. Pellini and P. P. Puzak, "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering of Steel Structures," NRL Report 5920, March 1963.

¹⁷E. Orowan, "Fundamentals of Brittle Behavior in Metals," *Fatigue and Fracture of Metals*, J. Wiley and Sons, New York, N.Y., 1952.

¹⁸G. R. Irwin, "Fracture Mechanics in Structural Mechanics," *Proceedings of the First Symposium on Naval Structural Mechanics*, Pergamon Press, New York, N.Y., 1960.

¹⁹GEMP-1002, p. 115.

plane-strain fracture toughness (K_{IC}) values for these materials. Of the many different test specimens currently in use for the determination of K_{IC} values, it has been suggested²⁰ that the wedge-opening loading (WOL) specimen developed by Westinghouse is most applicable for use with the heavy sections appropriate for pressure vessels.

Low-Energy Tearing – The term low-energy tearing has been used by Pellini and Puzak to describe "fracture propagation not involving a cleavage mode but resulting from a very low energy absorption in tearing." Neither the fracture mechanics approach nor the NRL fracture analysis diagram procedures have been proved applicable for analysis of the low-energy tearing problem. Pellini and Puzak²¹ indicate modifications to the fracture analysis diagram which they apparently feel would make the same type of procedure applicable to the low-energy tear case. This remains to be demonstrated and much more work is required before this procedure or the specific tests required to define the procedure can be explicitly identified. Pellini and Puzak point out that the higher-strength materials may be particularly susceptible to low-energy tearing of the welds or the heat-affected zone; they recommend using their explosion bulge test of welded sections to obtain at least a relative picture of the weld and heat-affected zone low-energy tearing problem.

7.3 GENERAL DISCUSSION

All alloys for which data have been obtained have relatively high yield-to-tensile strength ratios which would cause their Design Stress Intensity Values (S_m) to be based on the one-third tensile strength criterion of the Code. Table 7.21 is a compilation of tentative values for three alloys studied in this program, based upon the tests made to date. Modified heat

TABLE 7.21
ESTIMATED DESIGN STRESS INTENSITY VALUES, S_m ,
FOR ADVANCED PRESSURE VESSEL MATERIALS

Grade	Maximum Allowable Stress ^a for Maximum Metal Temperature, psi				
	38°C	315°C	371°C	427°C	538°C
12Ni – 5Cr – 3Mo	59,000	47,800	—	41,000	—
PH13 – 8Mo	65,000	54,000	—	48,000	—
Inconel alloy 718	63,300	—	—	59,000	56,600
SA212B ^b	23,300	18,700	18,300	—	—
SA302B ^b	26,700	26,700	26,700	—	—
SA533B, ^b Class I	26,700	26,700	26,700	—	—

^aThe maximum allowable stress values for the materials based on the lowest of the following:

1/3 of the specified minimum tensile strength at room temperature.

1/3 of the tensile strength at temperature.

2/3 of the specified minimum yield strength at room temperature.

^bActual values listed in Section III of ASME Boiler and Pressure Vessel Code.

treatments and multiheat data would alter these values somewhat. Included in the table are corresponding Code-approved values for three materials of current use in pressure vessels. Of significance is the potential strength margin possessed by the advanced materials, although this is only one of many aspects which must be considered before any materials can be proved suitable for advanced pressure vessels. In the following paragraphs, an attempt has been made to assess the relative potential of these alloys, based on results to date.

²⁰Dr. W. E. Cooper, private communication.

²¹W. S. Pellini and P. P. Puzak, "Practical Considerations in Applying Laboratory Fracture Test Criteria to the Fracture-Safe Design of Pressure Vessels," NRL Report 6030, November 1963.

12Ni - 5Cr - 3Mo

Properties determined thus far for base metal and welded joints have involved one plate composition (heat No. 01378) and one filler metal composition, 12Ni - 3Cr - 3Mo (heat No. 01434). Both base metal and weldments, when given the recommended aging treatment of 480°C for 3 hours, showed room-temperature properties which were lower than expected. Re-aging of the base metal and weldments for longer times, however, resulted in improved hardness and strength. A major advantage of the alloy is its favorable aging characteristics (slow rise to peak hardness) in the temperature range which produces a favorable balance in strength and toughness.

Weld efficiencies have exceeded 90 percent and the possibility exists that improvements can be made with modified aging procedures. The 12Ni - 3Cr - 3Mo filler metal on hand is apparently not optimum from a weld efficiency standpoint, however, and current efforts center on a matching 12Ni - 5Cr - 3Mo filler metal. The new 2.54-cm plate (heat No. 1PO193) and weld filler wire (heat No. V91230) are expected to develop higher properties under the same heat treatments with better joint efficiencies. Welding characteristics of heavier sections remain to be determined.

It was expected from the outset that this alloy could achieve satisfactory weld properties by aging only after welding. The attractiveness of 12Ni - 5Cr - 3Mo, as well as the other two age-hardening alloys, PH13-8Mo and Inconel alloy 718, would be much reduced if a complete heat-treating cycle after welding is required. It appears that a suitable aging treatment can be devised which will make it unnecessary to solution-treat prior to aging after welding the 12Ni - 5Cr - 3Mo alloy, although this is not clearly established.

Table 7.22 and Figure 7.22 compare some properties of this alloy with those of PH13-8Mo and Inconel alloy 718. The 12-5-3 (heat 01378) shows the lowest tensile strength, is intermediate in yield strength, shows little or no orientation effects in tensile tests but some in impact tests, and has the best overall Charpy V-notch energy absorption values.

If the alloy responds favorably relative to the foregoing considerations, achieves the low cycle fatigue life estimated for it, and continues to show the radiation resistance found in early tests at NRL,²² it must be considered a primary candidate for advanced pressure vessels.

In any case, continued consideration of this alloy is planned with emphasis on determining DWTT, low-cycle fatigue behavior, radiation effects, weldability, and weld properties in heavy sections.

PH13-8Mo

Studies of PH13-8Mo have involved one heat (heat No. VC5281) of 1.27-cm-thick plate and one heat of wire filler metal (heat No. 5178). The alloy showed the highest room-temperature tensile and yield strengths, but also the highest degree of anisotropy. Its Charpy V-notch impact energy absorption level fell somewhat more rapidly with temperature than the 12-5-3 alloy.

PH13-8Mo developed the highest weld strength and had the best joint efficiency (98%), based on an average plate strength of the two orientations tested. It is not yet clear, however, whether the alloy will develop satisfactory properties after welding by aging alone. Weldments planned for the 2.54-cm-thick plate will be used to further evaluate this question. Aging studies on parent metal indicate that for aging temperatures which produce adequate toughness (e.g., 565°C), the alloy ages quite rapidly to a very high level and then

²²L. E. Steele, J. R. Hawthorne, R. A. Gray, "Neutron Irradiation Embrittlement of Several Higher Strength Steels," NRL-6419, September 7, 1966.

TABLE 7.22

COMPARISON OF ROOM-TEMPERATURE PROPERTIES OF THREE ALLOYS IN PLATE AND WELD JOINT^a

Heat Treatment ^b	Orientation to Rolling Direction ^c	Variation in Tensile Strength, %	Strength, kg/cm ²		Plates		Welded Joint				Joint Efficiency, ^d %
			Tensile	Yield	Elongation in 4D, %	CVN Energy, m-kg	Strength, kg/cm ²		Elongation in 4D, %	CVN Energy, m-kg	
							Tensile	Yield			
12Ni – 5Cr – 3Mo (2.54 cm)											
A	T	5	11,900	11,400	22	14.7	11,000	10,400	14	8.5 – 11.0	92
	P		12,550	12,250	22	9.7	11,000	10,400	14	8.5 – 11.0	92
B	T	0	12,600	12,200	19	12.7	—	—	—	—	—
	P		12,600	12,200	19	10.0	—	—	—	—	—
C	—	—	—	—	—	—	11,840	11,250	14	—	93 ^e
PH13 – 8Mo (1.27 cm)											
D	T	12	15,500	14,400	18	10.7	14,200	12,250	11	6.1	98
	P		13,700	13,200	20	9.7	14,200	12,250	11	6.1	98
Inconel 718 (2.54 cm)											
E	T	0	13,300	9,900	13	1.6	10,600	9,500	12	1.7 est.	80
	P		13,500	9,650	15	2.8	10,600	9,500	12	1.7 est.	80
F	T	2	14,350	12,970	18	1.3	12,600	10,550	7	2.8	87 ^f
	P		14,700	11,900	21	2.7	12,600	10,550	7	2.8	87 ^f
G	T	2	13,900	11,300	19	—	—	—	—	—	—
	P		13,590	10,000	24	—	—	—	—	—	—

^aAverage properties.^bHeat treatment A – Age at 480°C – 3 hr – air cool, weld direct aged.

B – A + 480°C – 3 hr – air cool.

C – A + 450°C – 24 hr – air cool.

D – Age at 565°C – 4 hr – air cool.

E – Heat Treatment I, see Table 7.14 for details.

F – Heat Treatment II, see Table 7.15 for details.

G – Heat Treatment III, see Table 7.16 for details.

^cT = Transverse, P = Parallel.^dJoint efficiency = tensile strength of joint/tensile strength of base metal x 100.^eTreatments differ, but other studies showed hardness to be about the same. Value is included as example of what can be expected.^fWeld double-aged directly after welding per heat treatment II.

Fig. 7.22 — Comparison of tensile and impact properties of 12Ni – 5Cr – 3Mo, PH13 – 8Mo, and Inconel 718 alloys at various temperatures

overages to a significant degree within about a 20-hour period. This type of aging behavior is not favorable for heavy, complex shapes.

The estimated low-cycle fatigue behavior and indicated radiation resistance of PH13-8Mo²³ appear to favor its consideration as an advanced pressure vessel material.

Continued evaluation of this alloy is planned for the immediate future, with emphasis on further delineating aging behavior, weldability, weld properties, DWTT, preliminary low-cycle fatigue characteristics, and completing radiation effects studies currently in process.

INCONEL ALLOY 718

Investigation of Inconel alloy 718 has involved one composition of plate and one lot of filler metal. Figure 7.22 and Table 7.22 show a comparison of certain properties of Inconel alloy 718 with the PH13-8Mo and 12Ni – 5Cr – 3Mo alloys. Tensile properties of this alloy

²³Unpublished data, NRL.

are only slightly lower than those of PH13-8Mo at room temperature but, as expected, they eventually exceed that alloy as test temperature increases. The low toughness values for both parent metal and welds place the potential of this alloy in some question, however. An alternate heat treatment (III) expected to improve toughness is being investigated. Toughness values do not change significantly with temperature nor are they apparently worsened by radiation to approximately 10^{19} n/cm² ($E_n \geq 1$ Mev). Drop-weight tear tests will be conducted at NRL for additional information on the toughness of this fcc alloy.

Weld joint properties of Inconel alloy 718 show welding efficiencies of 80 percent with heat treatment I and 87 percent with heat treatment II. No testing has been done on weldments given heat treatment III. Compared to the parent metal, weld joint properties of Inconel alloy 718 show lower tensile ductility and reduced toughness.

No new work is contemplated on this alloy in the immediate future, although efforts will be made to complete studies already initiated.

7.4 SUMMARY AND CONCLUSIONS

The following data have been obtained on approximately 2.54-cm-thick plate of 12Ni - 5Cr - 3Mo, PH13-8Mo, and Inconel alloy 718, relative to the potential of these candidate high-strength materials for advanced pressure vessels.

12Ni - 5Cr - 3Mo

The 12Ni - 5Cr - 3Mo alloy possesses aging characteristics which appear to be suited to the uniform aging of heavy sections. Its tensile properties and toughness are most promising. Low-cycle fatigue data and effects of irradiation on toughness remain to be determined. The alloy gives evidence of adequate structural stability at temperatures up to at least 315°C. The weldability of the 12-5-3 composition with 12-3-3 filler metal is good but the resulting weld efficiency should be even better if a filler metal composition (12-5-3) matching the base metal is employed. Further data are necessary to indicate whether post-weld aging alone will produce adequate properties.

The 12-5-3 alloy continues to be regarded as a promising candidate for advanced pressure vessels, and will be evaluated in thicknesses ≥ 10 cm.

PH13-8Mo

The aging characteristics of PH13-8Mo, at least for aging temperatures which produce high toughness levels, may not be suited to the uniform aging of heavy sections. Excellent tensile properties and good toughness can be developed in the alloy. Low-cycle fatigue data and effects of irradiation on toughness remain to be determined. PH13-8Mo appears acceptably stable structurally upon longtime heating at temperatures to 425°C. The alloy has good weldability and weld strength with filler metal of matching composition; weld ductility and toughness are only fair. It is not yet clear whether aging alone will be an acceptable post-weld heat treatment.

Further qualification of this alloy will be made on a 2.54-cm-thick plate, before heavy section studies are considered.

INCONEL ALLOY 718

Excellent strength properties characterize Inconel alloy 718, particularly at higher temperatures. It is much superior to the 12-5-3 alloy or PH13-8Mo in this respect. Its toughness is quite low, based on Charpy V-notch tests, under two conditions of heat treatment; a third heat treatment is being evaluated for toughness. Initial radiation effects indicate no reduction in toughness levels. Low-cycle fatigue data remain to be determined. The alloy apparently possesses good structural stability at temperatures to at least 540°C. In-

conel alloy 718 developed sound welds with filler metal of matching composition, although weld strength and toughness were significantly lower than those of the parent metal.

No new work will be initiated on this alloy; studies presently underway will be completed.

A heat-treatable steel, HP 9Ni - 4Co - 0.20C, has been added to the program.

Consideration has been given to the types of failure which need to be prevented in pressure vessel applications, and special material properties which are related, e.g., strain-hardening coefficient, dynamic yield strength, and plane strain fracture toughness. It is estimated that the 12-5-3 and PH13-8Mo alloys, at least, possess satisfactory low-cycle fatigue behavior, particularly if dynamic yield strength and the Peterson Cubic relationship can be employed in applying mean stress corrections.

7.5 PLANS AND RECOMMENDATIONS

Prepare additional weldments of 2.54-cm-thick plate of the 12-5-3 alloy using filler metal of matching composition.

Initiate preparation for welding of 10-cm-thick plate of 12-5-3 alloy.

Complete initial property determinations on the 10-cm-thick plate of 12-5-3 alloy.

Continue heat-treating studies on 12-5-3 and PH13-8Mo alloys.

Prepare weldments of 2.54-cm-thick plate of PH13-8Mo.

Continue study of heat treatment influence on toughness of Inconel alloy 718.

Complete initial determination of irradiation effects on toughness of 12-5-3 and PH13-8Mo.

Complete preparation of low-cycle fatigue specimens of 12-5-3, PH13-8Mo, and Inconel alloy 718.

Complete preparation of DWTT specimens of 12-5-3, PH13-8Mo, and Inconel alloy 718.