

Metallic Material Limits for API Equipment Used in High Temperature Applications

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Introduction

The First Edition of this document was based on an API-funded project that was conducted by a task group charged by the Association of Well Head Equipment Manufacturers (AWHEM). The task group examined mechanical properties of metallic materials used for API 6A and API 17D wellhead equipment for service above 250 °F. A total of 11 different alloys meeting API 6A, PSL 3 conditions were supplied “in condition” by a variety of suppliers. Materials in this test program included alloys common to the oil and gas industry. The alloys tested included low-alloy steels, martensitic, precipitation-hardened, and duplex stainless steels, and nickel alloys. Yield strength reduction ratios at temperatures of 300 °F, 350 °F, 400 °F, and 450 °F are reported. As a result of testing, yield strength reduction ratios at 300 °F to 450 °F ranged from 92 % to 87 % for the low-alloy steels, 92 % to 88 % for the martensitic stainless steels, 81 % to 73 % for super duplex, 99 % to 89 % for the precipitation-hardened stainless steel, and 94 % to 89 % for the nickel alloys. The reported results represent an average over the different heats for each type of material. These results are intended to expand the data shown in API 6A for design and rating of equipment for use at elevated temperatures. The First Edition covered Phases I-III.

The Second Edition of this document incorporated the results of testing performed after the accuracy of the derating factors for the precipitation-hardened stainless steel as published in the First Edition and in API 6A, 19th Edition, Annex G was questioned. An API-funded project was conducted by a task group operating under the direction of API Subcommittee 21 and this work is described as Phase IV.

The Third Edition incorporates the results of an API-funded project initiated in 2014. This work is described as Phase V and was established through laboratory testing:

- tensile yield properties, tensile modulus at room, elevated temperature in both longitudinal and transverse directions;
- compression yield properties, compression modulus at room, elevated temperature in both longitudinal and transverse directions.

UNS N07718 was selected as the first alloy to be tested to demonstrate the feasibility of obtaining the desired material properties. Due to personnel changes over time and laboratory testing issues, the project took longer than anticipated, and only UNS N07718 was tested. The results of the testing have been used to update the recommended yield strength reduction ratios for UNS N07718 in Table 6, add recommended compression yield strength reduction ratios for UNS N07718 in Table 8, add recommended chord modulus values for UNS N07718 from tension testing in Table 9, and add recommended chord modulus for UNS N07718 from compression testing in Table 10. Analysis of test data indicated UNS N07718 had little anisotropy between longitudinal and transverse directions for tensile yield. Similarly, the anisotropy in the compression yield strength, while slightly higher than tensile yield strength anisotropy, was still quite low. Also, the compression yield strength at a given temperature in either direction was higher than corresponding tensile yield strength consistently.

Metallic Material Limits for API Equipment Used in High Temperature Applications

1 Scope

This document covers testing performed to develop recommended yield strength reduction ratios and elevated temperature properties for several steels, stainless steels, and nickel alloys used in oil and gas drilling and production equipment.

2 Normative References

There are no normative references in this document.

3 Abbreviations

For the purpose of this document, the following abbreviated terms apply.

AWHEM	Association of Well Head Equipment Manufacturers
ER	equivalent round
RT	room temperature
YS	yield strength

4 Testing Criteria

Testing was performed in five phases, presented herein in chronological order as Phase I, Phase II, Phase III, Phase IV, and Phase V. Initially, all testing was to be completed in two phases, but testing anomalies in Phase II prompted re-testing of some alloys in Phase III and later in Phase IV. Phase V was a separate test program intended to develop both tensile and compression yield data on one alloy.

For Phases I-III, alloy candidates were recommended by AWHEM membership for analysis and confirmed by API's approval of New Work Item No. 2003-100786 in June 2002. Several material suppliers and several AWHEM member companies donated material for testing. Metallurgists on the task group screened material certificates to ensure a "normal" chemistry without enhancements for the material candidates listed in Table 1, Table 2, and Table 3.

Table 1—List of Alloys Included in Phase I Testing

Material	Yield Strength Class	Bar Size
AISI 4130	75K	5 in. ER
AISI 8630M	75K	5 in. ER
2 ¹ / ₄ Cr 1 Mo	75K	5 in. ER
AISI 4140	75K	5 in. ER
AISI 410 SS	75K	5 in. ER
F6NM	75K	5 in. ER

Table 2—List of Alloys Included in Phase II Testing

Material	Yield Strength Class	Material Size
25 Cr Super Duplex ^a	80K	2.4 in. to 5.5 in. OD
ASTM A453 Gr 660	105K	0.75 in. to 1.5 in. OD
UNS N07718 (per API Spec 6A718)	120K	1.25 in. to 8.5 in. OD x 5.5 in.
UNS N07725/UNS N07716	120K	0.63 in. to 6.5 in. OD data, 9 in. OD test
UNS N09925	110K	1 in. to 6.5 in. OD
^a Pitting resistance equivalence number, PREN >40.		

Table 3—List of Alloys Included in Phase III Testing

Material	Yield Strength Class	Material Size
UNS N07725/UNS N07716	120K	1.25 in. to 6.0 in. OD
UNS N09925	110K	1.0 in. to 8.7 in. OD

For Phase IV, another API New Work Item approved in 2014 covered a new round of testing of austenitic precipitation-hardened stainless steel ASTM A453 Grade 660 Class D (see Table 4). As described in the introduction, the accuracy of the derating factors for the precipitation-hardened stainless steel as published in the First Edition and in API 6A, 19th Edition, Annex G was questioned since the derating factors showed an increase in the yield strength with increasing temperature. For Phase IV, three heats of material, each from a different mill were tested.

For Phase V, an API SC21 work item approved in 2014 covered a new round of testing of UNS N07718 per API 6ACRA or API 6A718 UNS N07718–120 (see Table 5). Three heats of material, each from a different mill were tested.

A summary of the yield strength derating factors from testing of the 11 alloys is provided in Table 6 and compares favorably with the available data from literature, as provided in Table 7.

NOTE See Annex L for alloy chemistries from the material certificates for each of the supplied alloy candidates.

Table 4—List of Alloys Included in Phase IV Testing

Material	Yield Strength Class	Material Size
ASTM A453 Gr 660 CI D	105K	1 in. OD

Table 5—List of Alloys Included in Phase V Testing

Material	Yield Strength Class	Material Size
UNS N07718 (API 6ACRA/API 6A718 UNSN 07718–120)	120K	8 in. OD

Table 6—Recommended Tensile Yield Strength Reduction Ratios in Percent by Temperature

Material ^a	Temperature °F (°C)					
	300 (149)	350 (177)	400 (204)	450 (232)	500 (260)	550 (288)
AISI 4130 Low-Alloy Steel	91	90	89 ^c	88	—	—
AISI 8630M Low-Alloy Steel	92	90	89 ^c	87	—	—
2 ¹ / ₄ Cr 1 Mo Low-Alloy Steel	92	91	90 ^c	89	—	—
AISI 4140 Low-Alloy Steel	92	90	89 ^c	88	—	—
AISI 410 Martensitic Stainless Steel	91	90	89 ^c	88	—	—
F6NM Martensitic Stainless Steel	92	91	89 ^c	88	—	—
25 Cr Super Duplex	81	78	76 ^c	73	—	—
ASTM A453 Gr 660 Precipitation-Hardened Austenitic Stainless Steel ^b	97	96	95	94	—	—
UNS N07718 (per API Spec 6A718/API 6ACRA)	95	94	93	92	90	89
UNS N07725/UNS N07716	93	92	90	89	—	—
UNS N09925	92	92	91	90	—	—

^a See the annexes for strength level of materials tested.

^b Phase IV data used to replace the Phase II recommended reduction ratios in the Second Edition.

^c Value calculated through interpolation of test results at other temperatures.

Table 7—Tensile Yield Strength Reduction Factors in Percent by Temperature (from Literature)

Material	Temperature °F (°C)				Reference
	300 (149)	350 (177)	400 (204)	450 (232)	
25 Cr (various UNS)	80	78	76	—	ASME BPVC Part D, Table Y-1
ASTM A453 Grade 660 Class D	—	—	98	—	Carpenter Technology ^a
UNS N07718	96	95	95	—	MIL Handbook 5 ^{b, c}
UNS N07725/ UNS N07716	93	92	92	92	Special Metals Corporation ^d
UNS N09925	93	92	90	90	Special Metals Corporation ^d
Carbon and Low-Alloy Steels	—	—	85	—	API 6A, Annex G
Martensitic Stainless Steels	—	—	85	—	API 6A, Annex G
Austenitic and Duplex Stainless Steels	—	—	80	—	API 6A, Annex G
Corrosion-Resistant Alloys	—	—	95	—	API 6A, Annex G

^a Carpenter Technology Corporation, 1735 Market Street, 15th Floor, Philadelphia, PA 19103.

^b Available at <https://assist.dla.mil>.

^c Not known if these data were for the aerospace grade of UNS N07718 or the API grade of UNS N07718.

^d Special Metals Corporation, 3200 Riverside Drive, Huntington, West Virginia, 25705.

Table 8—Recommended Compression Yield Strength Reduction Ratios for UNS N07718 (API 6A718/ API 6ACRA) in Percent by Temperature

Temperature °F (°C)	300 (149)	350 (177)	400 (204)	450 (232)	500 (260)	550 (288)
% Retained Compression Yield	96	95 ^a	95	94 ^a	93	92
NOTE See the annexes for strength level of materials tested for UNS N07718 (API 6A718/API 6ACRA).						
^a Value calculated through interpolation of test results at other temperatures.						

Table 9—Recommended Chord Modulus (30–90 ksi) for UNS N07718 (API 6A718/API 6ACRA) from Tensile Testing

Temperature °F (°C)	75 (24)	300 (149)	400 (204)	500 (232)	550 (260)
Chord Modulus, 10 ⁶ psi	30.7	28.2	27.9	27.5	27.1
NOTE See the annexes for strength level of materials tested.					

Table 10—Recommended Chord Modulus (30–90 ksi) for UNS N07718 (API 6A718/API 6ACRA) from Compression Testing

Temperature, °F (°C)	75 (24)	300 (149)	400 (204)	500 (232)	550 (260)
Chord Modulus, 10 ⁶ psi	29.6	30.1	29.7	29.3	28.7
NOTE See the annexes for strength level of materials tested for UNS N07718 (API 6A718/API 6ACRA).					

5 Procedure

5.1 Phase I, Phase II, and Phase III Procedure

In Phase I and Phase II testing, three material test laboratories were selected to conduct elevated-temperature tests in accordance with ASTM E21 using 0.505 in. diameter test specimens. Of the three participating laboratories, the one with the best performance was selected to conduct all testing in Phase III. Phase I tensile specimens were removed from the mid-radius position. In Phase II and III, tensile specimens were removed from the $\frac{1}{4}T$ position where possible. Mechanical tests were then performed at room temperature (RT), 300 °F, 350 °F, and 450 °F to permit bracketing of results. The task group analyzed the resulting yield strength (YS) data from all the laboratories for each heat of material. Finally, each supplier's data are reported confidentially to that supplier only in exchange for the donation of material.

The tensile properties at elevated temperature used conventional tensile testing equipment modified slightly to accommodate a radiant heating chamber. For precise control of temperature, the chamber was well insulated, which also minimized specimen exposure to undesirable surface contamination.

The heating chamber was monitored using two thermocouples to maintain precise temperature control. A single thermocouple was used to control chamber atmosphere temperature while the second thermocouple was attached to the test specimen. Testing was initiated once the specimen and chamber atmosphere temperatures both reached equilibrium. Predetermined strain rates were maintained through break.

Tensile strength determination was made by use of an attached Class B-2 extensometer. The extensometer was modified to accommodate an extended reach into the heating chamber to fully engage the test piece through break while shielding the instrument from extreme temperatures.

Full size round test specimens were used. Measurements to determine percent elongation and percent reduction of area within the gauge length were conducted on broken specimens after cooling sufficiently to facilitate handling.

All test procedures and calibrations were in full compliance with ASTM E21 without exception. No special equipment or processes were used in conducting hot tensile testing and there were no deviations to standard testing practices.

5.2 Phase IV Procedure

Prior to the start of Phase IV elevated-temperature tensile testing, a study of the effects of low-temperature aging was conducted. The purpose was to determine if low-temperature aging could have occurred during the Phase II testing and resulted in an increase in yield strength with increasing test temperature. This aging study was performed by a mill that melts and processes ASTM A453 Grade 660 into various mill product forms. Bars from a single heat of ASTM A453 Grade 660 were heat treated using the two different solution-annealing temperatures specified in ASTM A453 for Grade 660 Class D, and precipitation hardened using the single aging cycle from ASTM A453 for Grade 660 Class D. After solution annealing and precipitation hardening, the bars were subjected to additional thermal processing for 16 hours at the test temperatures used in the elevated-temperature tensile test program. Tensile specimens were then removed from the bars and tested at room temperature.

Next, the elevated-temperature tensile test program was performed. Three heats of ASTM A453 Grade 660 Class D material from three different manufacturers were tested in accordance with ASTM E8 and ASTM E21, at two independent test laboratories.

Another aging study was performed to investigate the behavior of the three specific heats used in this elevated-temperature tensile test program. Bars from each heat were aged at 400 °F for one hour to simulate the time the tensile test specimens spent at temperature during the elevated-temperature testing. Tensile specimens were then removed from the bars and tested at room temperature at one laboratory using triplicate samples.

5.3 Phase V Procedure

Blanks for tensile and compression testing were removed from provided bars. Figure 1 shows the schematic used to get tensile and compression specimens for transverse testing. The blanks were sectioned via EDM (Electrical Discharge Machining) from near surface as that was deemed the area of prime interest early in the process during discussions. It is to be noted that testing of raw material as per API 6ACRA UNS N07718-120 specification is done at mid-radius location for bar stock. The blanks were oriented to ensure all testing would be performed on samples from the same relative location within the bar cross section. Full-size standard tensile specimens (0.5 in. diameter and 2.0 in. gauge length) were machined from these blanks per ASTM E8-16a and standard compression specimens per ASTM E9-09. Machining of all specimens was performed by the same facility to ensure uniformity of the machined surface and remove variability otherwise present from multiple machining sources. The machined specimens were provided to the testing facilities. Each facility performed a room temperature tensile test in both longitudinal and transverse orientations, as well as elevated temperature tests per ASTM E21-09 and ASTM E209-89a (2000) for tension and compression respectively in both orientations. In addition to this, chord modulus between 30 ksi and 90 ksi for each test was also evaluated. Sample ID was maintained to ensure traceability to the original bars.

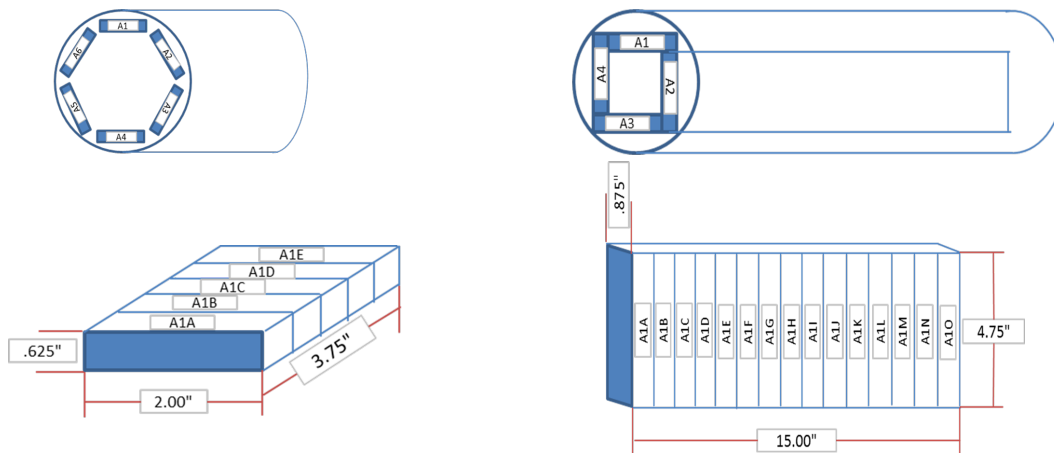


Figure 1—Machining of Blanks for Transverse Tensile (Right) and Transverse Compression (Left)

6 Results

6.1 Phase I Results

The detailed results for the alloys tested in Phase I are presented in Annex A through Annex F.

Each material type was analyzed by comparing yield strength readings at RT, 300 °F, 350 °F, and 450 °F for each heat and laboratory individually, using a pivot table. In this manner, differences due to either material behavior or laboratory abnormalities or a combination thereof could be easily detected. Since the data set was too small to afford any statistical analysis, the results were averaged.

Room temperature yield strength test results from three of the five heats of AISI 4130 were below 75 ksi. One heat was only 2 % below the required room temperature properties. However, two of those three heats were 12 % and 17 % below the minimum requirement. Material certification reports were reviewed by metallurgists on the task group and reasons for the low properties were not obvious. Averaging data from all the heats produced higher yield derating factors than seemed appropriate [92 % at 350 °F compared with current values in API 6A, for carbon and low-alloy steels of 85 % (see Bibliography)]. Consequently, results from two lowest property heats were ignored in the average, resulting in a yield derating of 90 % at 350 °F. This discrepancy from reported room temperature yield properties was not found on any of the other five alloys tested. The conclusion from this discovery is that low hardenability alloys used for heavy section equipment must have proper design qualification. Thus, averaging only three heats of 4130 produced an improved correlation to the other low-alloy steel's yield reduction ratio than averaging all five heats (see Annex A).

One data point for 2 $\frac{1}{4}$ Cr 1 Mo at 450 °F appeared bad, so it was excluded from the average. In all other cases, all data points for all five heats of the material were used. The variation of results for heats within a material showed ~15 % over each temperature range, except for 410 that ran ~20 %. The variation between laboratories was ~10 % for most materials, with one laboratory measuring on the low side in a majority of cases. A sample plot of average yield strength reduction ratio (derating factor) for 8630M is shown in Figure 2. Thus, the derating factor at 400 °F was interpolated as 88.5 %.

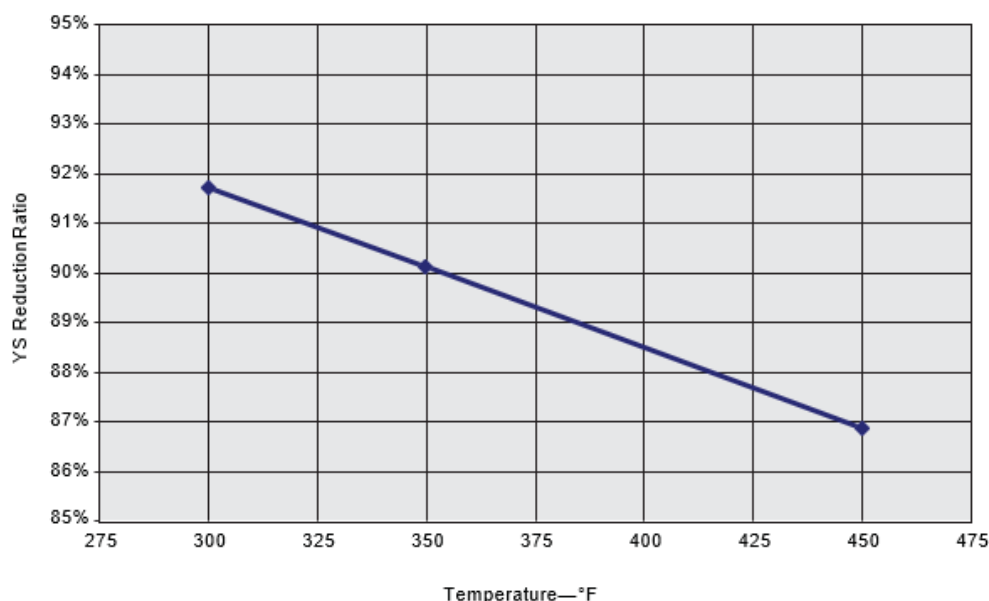


Figure 2—AISI 8630M Strength Reduction with Temperature

6.2 Phase II Results

The detailed results for the alloys tested in Phase II, with the exception of UNS N07725/UNS N07716 and UNS N09925, are presented in Annex G through Annex K.

As a result of limited material availability, material size for testing was variable and in one case the task group had to purchase a limited amount of one heat. One supplier furnished their own test data for several heats in two material types. Test temperatures were slightly different, and results did not correlate exactly with actual test data from our material testing. The greatest data correlation problem was with UNS N07725/UNS N07716. Each material type was analyzed by comparing yield strength readings at RT, 300 °F, 350 °F, and 450 °F for each heat and laboratory individually, using a pivot table. In this manner, differences due to either material behavior or laboratory abnormalities or a combination thereof could be detected. Since the data set was too small to afford much statistical analysis, the results were averaged.

In a few cases, inconsistent data (11 points) were rejected to prevent distortion of results. In each of those cases, the rationale used was to drive the results in a conservative direction. Inconsistent data points were examined with the laboratories. At one laboratory, some strange data points were caused by the extensometer extensions slipping or by movement of the test specimen. Examination of stress/strain curves verified the problem. These data were rejected and re-tested as Phase III.

6.3 Phase III Results

The detailed results for the alloys tested in Phase III are presented in Annex J and Annex K.

Seven heats of UNS N07725/UNS N07716 and eight heats of UNS N09925 were tested. To maintain consistency in the data analysis methodology of Phase I and Phase II testing, the yield strength reduction factors were averaged. A linear relationship between temperature and reduction factor was assumed, given the narrow temperature range in the study. Typically, for high-strength nickel alloys the temperature range that is of interest spans a much larger range. Each material type was analyzed by comparing yield strength readings at RT, 300 °F, 350 °F, and 450 °F for each heat. Since the data set was too small to afford much statistical analysis, the results were averaged. The raw data along with the stress/strain curves were examined to cull any data that would appear unusual. No anomalies in the data were observed that allowed the use of the entire data set to define the reduction factors.

6.4 Phase IV Results

The detailed results for the re-testing performed on ASTM A453 Grade 660 are presented in Annex H, along with the earlier results for this alloy.

The results of the initial aging study as provided in Table H.2 and Table H.3 demonstrated that exposure to the elevated-temperature test program temperatures for 16 hours did not result in any increase in either the room temperature yield strength or tensile strength of the bars. This 16-hour aging was significantly longer than the duration of the elevated temperature tensile test.

The elevated-temperature tensile testing was performed next. The results of the elevated-temperature tensile testing are provided in Table H.4. The data set was analyzed by comparing yield strength readings at room temperature, 300 °F, 350 °F, 400 °F and 450 °F for each heat.

The analysis of the yield strength data from the three heats indicated that the heat designated as Heat A in Table H.4 demonstrated a significant increase in yield strength at 350 °F and 400 °F. Although Heat B and Heat C also demonstrated some nonlinear behavior, it was not as pronounced as with Heat A.

The results of the second aging study as provided in Table H.5 demonstrated that exposure to the elevated-temperature test program temperatures for one hour did not result in any increase in either the room temperature yield strength or tensile strength of the specific heats of ASTM A453 Grade 660 Class D material used in this study.

Derating factors were determined using linear regression analysis, with factors based on all three heats and factors based on only Heats B and C. These calculated derating factors are shown in Table H.6, along with the derating factors that originally appeared in API 6A, Table G.4.

The API Subcommittee 21 task group coordinating this test program decided to recommend derating factors based on only the data from Heat B and Heat C, as shown in Table H.7. The task group considered the nonlinear aspect of the data and agreed to use only the data from Heat B and Heat C to provide a conservative approach for design purposes.

6.5 Phase V Results

6.5.1 General

The detailed results for the Phase V testing performed on UNS N07718 are presented in Annex I, along with the earlier results for this alloy.

6.5.2 Yield Strength

Yield strengths measured from the tensile and compression tests in both longitudinal and transverse directions were analyzed to assess anisotropy. Figure I.2, Figure I.3, and Figure I.4 show the plots of yield strength versus temperature for tensile and compression in both directions. The plots show very little anisotropy in the tensile yield strength measurements with testing in both longitudinal and transverse directions showing quite similar values at room temperature and elevated temperatures. Anisotropy in the compression yield strength while bit higher than tensile yield strength was still quite low on average for each heat. Additionally, compression yield strength was higher than tensile yield strength for all the three heats at all temperatures consistently. With low anisotropy, the test data for a given heat in both longitudinal and transverse condition was combined for analysis of retained yield strength for tensile yield and compression yield.

Figure I.5 and Figure I.6 show percentage retained tensile yield and percentage compression yield strengths respectively for each individual heat tested as a function of temperature. The data indicates that the three heats had very similar retained tensile yield but there was more variation among the heats in retained compression yield strength.

Using the data for the three heats in tensile testing in both longitudinal and transverse directions, the combined derated tensile yield values and compression yield values are in Table 1.4 along with original derate tensile yield values from Phase II. The derated tensile yield values from Phase V were higher than from Phase II. The two tensile yield data sets were reconciled statistically to produce a new derating value set while for compression statistical analysis was done using data set from Phase V. As part of statistical analysis, it was ensured that the retained yield strength decreased with temperature as expected for UNS N07718 is the temperature range of interest based on material behavior even though some individual tests might have shown higher retained yield at higher temperature. Table 1.5 provides recommended tensile, compression yield derate values up to 550 °F.

6.5.3 Chord Modulus

As part of performing tensile and compression testing, chord modulus between 30 ksi and 90 ksi was measured in most cases. The chord modulus measured at a given temperature in either direction was quite similar. Table 1.6 shows the average chord modulus at each temperature for all the three heats from tensile testing while Table 1.7 shows the average chord modulus at each temperature for all the three heats from compression testing.

7 Conclusions

Material selection for high pressure-high temperature (HPHT) equipment and validation for actual properties are important. For example, AISI 4130 properties must be validated in the section of interest. This material lacks the hardenability of other materials tested. Bar stock appeared to produce lower properties than did forged material, but hardenability was the real issue. Three heats out of five of 4130 fell below the minimum yield strength even though the material certification report showed the yield strength above the minimum.

Elevated-temperature tensile testing can result in significant scatter, even when performed in accordance with ASTM standards using reputable independent laboratories. When performing elevated-temperature testing, careful analysis of the test data is required to see if it is acceptable for use in developing yield strength reduction ratios.

UNS N07718 per API 6ACRA UNS N07718-120 did not show anisotropy in yield strength between longitudinal and transverse directions in either tensile or compression testing. Compression yield strength of this grade was shown to be higher than tensile yield strength at both room and elevated temperature.

As noted earlier, a summary of the yield strength derating factors from testing of the 11 alloys is shown in Table 6, while detailed results for each material are shown in the individual annexes

For comparison, available data from published literature compared favorably as shown in Table 7.

Table 8 provides recommended compression yield derating factors for UNS N07718 per API 6ACRA UNS N07718-120, while Table 9 and Table 10 provide chord modulus for this grade in tension and compression respectively.

8 Recommendations

The factors presented herein should be used as the basis for estimating the nominal reduction of yield strength with temperature for the alloys presented. As a cautionary note, the data presented herein does not include a statistical analysis such as a prediction interval to establish a confidence level for defining a lower bound. A full statistical analysis for a more robust prediction tool would require additional data points for one or more of the alloys tested to benchmark the total number of data points required for a valid statistical analysis.

Annex A (informative)

AISI 4130 Test Results

Annex A contains the results of the testing of AISI 4130 low alloy steel performed in Phase I.

Table A.1—AISI 4130 Test Results

Heat Code	Cylinder	Barstock or Forging	Test Agency	Test Temp. (°F)	Vendor Reported RT Yield (psi)	Tensile (psi)	Yield 0.2% (psi)	YS Avg. of Valid Heats at Temp. (psi)	YS Avg. of All Heats at Temp. (psi)	YS Avg. of Heats at Temp. (psi)	Test Temp. (°F)	YS Reduction Ratio (%)
1	A	B	A	75	83,000	101,000	74,300	78,589	72,840	Valid Heats		
1	B	B	B	75	83,000	103,100	74,900	—	—	78,589	75	100.00
1	C	B	C	75	83,000	98,300	71,400	—	—	71,611	300	91.12
2	A	F	A	75	79,600	102,800	82,100	—	—	70,566	350	89.78
2	B	F	B	75	79,600	104,600	81,700	—	—	69,367	450	88.27
2	C	F	C	75	79,600	100,200	78,700	—	—	—	—	—
3	A	B	A	75	76,000	95,100	67,500	—	—	All Heats		
3	B	B	B	75	76,000	96,600	66,900	Questionable results based on pivot table		72,840	75	100.00
3	C	B	C	75	76,000	92,400	64,300			67,313	300	92.41
4	A	F	A	75	80,500	101,700	81,000	—	—	67,300	350	92.39
4	B	F	B	75	80,500	104,000	81,700	—	—	66,767	450	91.66
4	C	F	C	75	80,500	101,900	81,500	—	—	—	—	—
5	A	B	A	75	87,159	94,500	62,900	—	—	—	—	—
5	B	B	B	75	87,159	96,700	63,000	Questionable results based on pivot table		—	—	—
5	C	B	C	75	87,159	92,400	60,700			—	—	—
1	A	B	A	300	—	91,100	66,800	71,611	67,313	—	—	—
1	B	B	B	300	—	91,000	64,000	—	—	—	—	—
1	C	B	C	300	—	90,700	65,000	—	—	—	—	—
2	A	F	A	300	—	94,400	74,700	—	—	—	—	—
2	B	F	B	300	—	96,100	75,700	—	—	—	—	—
2	C	F	C	300	—	94,500	73,300	—	—	—	—	—
3	A	B	A	300	—	87,100	61,100	—	—	—	—	—
3	B	B	B	300	—	87,500	65,000	Questionable results based on pivot table		—	—	—
3	C	B	C	300	—	86,200	61,400			—	—	—
4	A	F	A	300	—	94,600	75,100	—	—	—	—	—
4	B	F	B	300	—	95,600	75,900	—	—	—	—	—
4	C	F	C	300	—	95,000	74,000	—	—	—	—	—
5	A	B	A	300	—	86,700	58,900	—	—	—	—	—

Table A.1—AISI 4130 Test Results (Continued)

Heat Code	Cylinder	Barstock or Forging	Test Agency	Test Temp. (°F)	Vendor Reported RT Yield (psi)	Tensile (psi)	Yield 0.2% (psi)	YS Avg. of Valid Heats at Temp. (psi)	YS Avg. of All Heats at Temp. (psi)	YS Avg. of Heats at Temp. (psi)	Test Temp. (°F)	YS Reduction Ratio (%)
5	B	B	B	300	—	87,200	60,500	Questionable results based on pivot table			—	—
5	C	B	C	300	—	87,100	58,300				—	—
1	A	B	A	350	—	90,600	65,000	70,566	67,300	—	—	—
1	B	B	B	350	—	92,700	66,500	—	—	—	—	—
1	C	B	C	350	—	91,200	65,100	—	—	—	—	—
2	A	F	A	350	—	94,400	73,000	—	—	—	—	—
2	B	F	B	350	—	95,100	74,300	—	—	—	—	—
2	C	F	C	350	—	94,600	72,700	—	—	—	—	—
3	A	B	A	350	—	85,900	62,000	—	—	—	—	—
3	B	B	B	350	—	87,300	62,000	Questionable results based on pivot table			—	—
3	C	B	C	350	—	85,700	63,300				—	—
4	A	F	A	350	—	93,500	72,200	—	—	—	—	—
4	B	F	B	350	—	95,100	73,300	—	—	—	—	—
4	C	F	C	350	—	95,500	72,900	—	—	—	—	—
5	A	B	A	350	—	85,800	61,000	—	—	—	—	—
5	B	B	B	350	—	87,300	63,900	Questionable results based on pivot table			—	—
5	C	B	C	350	—	85,300	62,300				—	—
1	A	B	A	450	—	92,300	63,700	69,367	66,767	—	—	—
1	B	B	B	450	—	91,300	64,900	—	—	—	—	—
1	C	B	C	450	—	91,300	65,000	—	—	—	—	—
2	A	F	A	450	—	95,700	72,000	—	—	—	—	—
2	B	F	B	450	—	94,400	72,900	—	—	—	—	—
2	C	F	C	450	—	94,200	72,000	—	—	—	—	—
3	A	B	A	450	—	87,000	63,000	—	—	—	—	—
3	B	B	B	450	—	87,100	63,100	Questionable results based on pivot table			—	—
3	C	B	C	450	—	87,600	65,500				—	—
4	A	F	A	450	—	93,600	69,800	—	—	—	—	—

Table A.1—AISI 4130 Test Results (Continued)

Heat Code	Cylinder	Barstock or Forging	Test Agency	Test Temp. (°F)	Vendor Reported RT Yield (psi)	Tensile (psi)	Yield 0.2% (psi)	YS Avg. of Valid Heats at Temp. (psi)	YS Avg. of All Heats at Temp. (psi)	YS Avg. of Heats at Temp. (psi)	Test Temp. (°F)	YS Reduction Ratio (%)
4	B	F	B	450	—	94,300	72,600	—	—	—	—	—
4	C	F	C	450	—	95,400	71,400	—	—	—	—	—
5	A	B	A	450	—	86,900	60,800	—	—	—	—	—
5	B	B	B	450	—	87,500	63,200	Questionable results based on pivot table			—	—
5	C	B	C	450	—	86,800	61,600				—	—

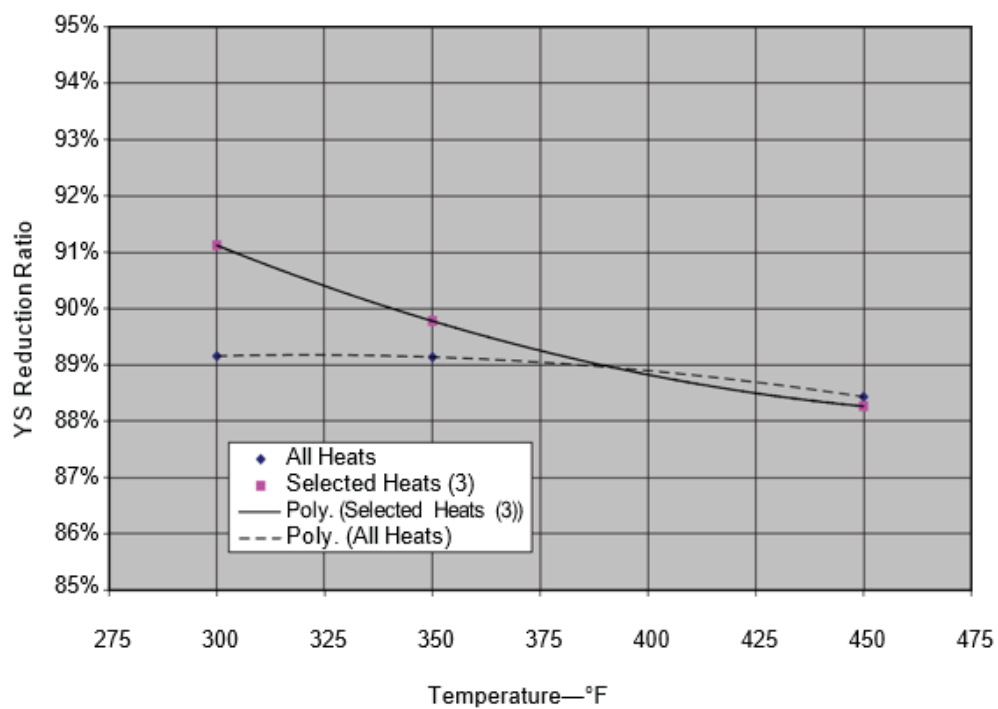


Figure A.1—Plot of 4130 Test Results

Annex B (informative)

AISI 8630M Test Results

Annex B contains the results of the testing of AISI 8630 Mod low alloy steel performed in Phase I.

Table B.1—AISI 8630M Test Results

Heat Code	Cylinder	Barstock or Forging	Test	Test Temp. (°F)	Vendor	Tensile (psi)	Yield 0.2% (psi)	YS Avg. of Valid Heats at Temp. (psi)	YS Reduction Ratio (%)
1	A	B	A	75	90,203	109,400	85,400	85,933	100.0
1	B	B	B	75	90,203	110,900	89,200	—	—
1	C	B	C	75	90,203	103,300	77,200	—	—
2	A	F	A	75	82,600	102,100	83,900	—	—
2	B	F	B	75	82,600	103,400	87,900	—	—
2	C	F	C	75	82,600	97,300	79,700	—	—
3	A	F	A	75	90,000	109,700	91,200	—	—
3	B	F	B	75	90,000	108,500	86,400	—	—
3	C	F	C	75	90,000	102,400	82,700	—	—
4	A	B	A	75	89,300	109,900	89,100	—	—
4	B	B	B	75	89,300	110,400	87,300	—	—
4	C	B	C	75	89,300	105,300	84,900	—	—
5	A	F	A	75	98,300	112,800	91,200	—	—
5	B	F	B	75	98,300	113,700	90,900	—	—
5	C	F	C	75	98,300	103,600	82,000	—	—
1	A	B	A	300	—	100,000	73,600	78,807	91.7
1	B	B	B	300	—	101,500	76,200	—	—
1	C	B	C	300	—	95,700	76,400	—	—
2	A	F	A	300	—	92,800	75,100	—	—
2	B	F	B	300	—	94,400	79,800	—	—
2	C	F	C	300	—	90,400	73,100	—	—
3	A	F	A	300	—	100,600	82,500	—	—
3	B	F	B	300	—	100,900	82,100	—	—
3	C	F	C	300	—	96,500	78,200	—	—
4	A	B	A	300	—	101,400	80,800	—	—
4	B	B	B	300	—	102,900	82,200	—	—
4	C	B	C	300	—	99,400	78,900	—	—
5	A	F	A	300	—	105,100	84,000	—	—
5	B	F	B	300	—	104,900	83,600	—	—
5	C	F	C	300	—	97,700	75,600	—	—
1	A	B	A	350	—	99,300	76,500	77,433	90.1
1	B	B	B	350	—	100,500	78,600	—	—
1	C	B	C	350	—	96,300	77,200	—	—
2	A	F	A	350	—	91,900	73,200	—	—
2	B	F	B	350	—	93,500	76,900	—	—

Table B.1—AISI 8630M Test Results (Continued)

Heat Code	Cylinder	Barstock or Forging	Test	Test Temp. (°F)	Vendor	Tensile (psi)	Yield 0.2% (psi)	YS Avg. of Valid Heats at Temp. (psi)	YS Reduction Ratio (%)
2	C	F	C	350	—	89,100	70,000	—	—
3	A	F	A	350	—	98,900	80,300	—	—
3	B	F	B	350	—	99,800	80,700	—	—
3	C	F	C	350	—	97,200	75,200	—	—
4	A	B	A	350	—	99,900	78,900	—	—
4	B	B	B	350	—	101,000	80,500	—	—
4	C	B	C	350	—	94,800	73,300	—	—
5	A	F	A	350	—	104,600	83,200	—	—
5	B	F	B	350	—	103,000	81,500	—	—
5	C	F	C	350	—	98,500	75,500	—	—
1	A	B	A	450	—	99,900	75,200	74,633	86.9
1	B	B	B	450	—	100,000	79,200	—	—
1	C	B	C	450	—	99,000	74,200	—	—
2	A	F	A	450	—	93,200	71,400	—	—
2	B	F	B	450	—	92,200	72,500	—	—
2	C	F	C	450	—	93,700	69,200	—	—
3	A	F	A	450	—	98,200	75,400	—	—
3	B	F	B	450	—	99,100	77,300	—	—
3	C	F	C	450	—	97,200	71,900	—	—
4	A	B	A	450	—	97,000	73,900	—	—
4	B	B	B	450	—	99,500	76,700	—	—
4	C	B	C	450	—	96,700	72,600	—	—
5	A	F	A	450	—	105,100	80,400	—	—
5	B	F	B	450	—	102,800	78,400	—	—
5	C	F	C	450	—	97,500	71,200	—	—

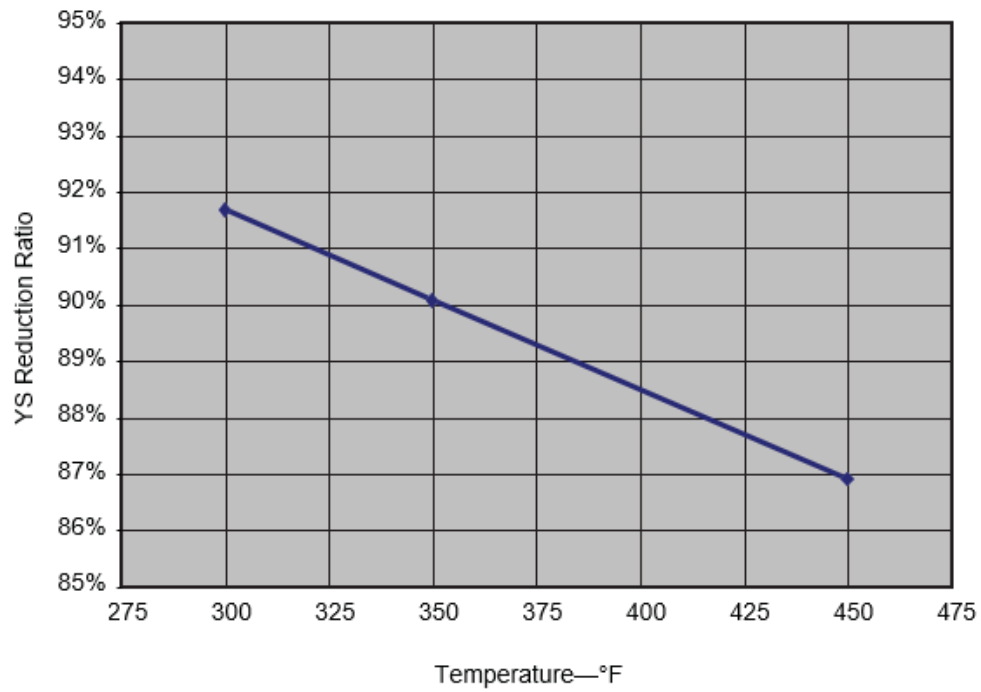


Figure B.1—Plot of 8630M Test Results

Annex C

(informative)

2¹/₄ Cr 1 Mo Test Results

Annex C contains the results of the testing of 2¹/₄ Cr 1 Mo low alloy steel performed in Phase I.

Table C.1—2¹/₄ Cr 1 Mo Test Results

Heat Code	Cylinder	Barstock or Forging	Test Agency	Test Temp.	Vendor Reported RT Yield (psi)	Tensile (psi)	Yield 0.2% (psi)	YS Avg. of Valid Heats at Temp. (psi)	YS Reduction Ratio (%)
1	A	F	A	75	87,000	106,600	89,900	84,993	100
1	B	F	B	75	87,000	107,700	87,700	—	—
1	C	F	C	75	87,000	104,700	86,000	—	—
2	A	F	A	75	85,500	101,400	88,000	—	—
2	B	F	B	75	85,500	102,800	87,400	—	—
2	C	F	C	75	85,500	101,600	80,500	—	—
3	A	F	A	75	79,500	98,000	83,400	—	—
3	B	F	B	75	79,500	100,100	82,900	—	—
3	C	F	C	75	79,500	98,400	80,900	—	—
4	A	F	A	75	82,400	96,100	79,900	—	—
4	B	F	B	75	82,400	102,900	84,300	—	—
4	C	F	C	75	82,400	95,000	73,400	—	—
5	A	F	A	75	89,900	106,500	90,500	—	—
5	B	F	B	75	89,900	108,000	90,500	—	—
5	C	F	C	75	89,900	106,600	89,600	—	—
1	A	F	A	300	—	97,200	82,500	78,607	92.5
1	B	F	B	300	—	97,300	81,100	—	—
1	C	F	C	300	—	95,600	80,000	—	—
2	A	F	A	300	—	92,900	80,400	—	—
2	B	F	B	300	—	93,800	80,000	—	—
2	C	F	C	300	—	92,200	78,800	—	—
3	A	F	A	300	—	88,700	75,800	—	—
3	B	F	B	300	—	90,000	73,300	—	—
3	C	F	C	300	—	89,500	75,000	—	—
4	A	F	A	300	—	87,600	71,500	—	—
4	B	F	B	300	—	94,800	79,900	—	—
4	C	F	C	300	—	90,500	73,100	—	—
5	A	F	A	300	—	97,700	83,200	—	—

Table C.1—2¹/₄ Cr 1 Mo Test Results (Continued)

Heat Code	Cylinder	Barstock or Forging	Test Agency	Test Temp.	Vendor Reported RT Yield (psi)	Tensile (psi)	Yield 0.2% (psi)	YS Avg. of Valid Heats at Temp. (psi)	YS Reduction Ratio (%)
5	B	F	B	300	—	96,300	83,100	—	—
5	C	F	C	300	—	95,800	81,400	—	—
1	A	F	A	350	—	95,100	80,000	76,960	90.5
1	B	F	B	350	—	96,900	80,900	—	—
1	C	F	C	350	—	94,600	78,900	—	—
2	A	F	A	350	—	97,800	79,600	—	—
2	B	F	B	350	—	92,500	79,800	—	—
2	C	F	C	350	—	91,200	77,400	—	—
3	A	F	A	350	—	87,900	74,600	—	—
3	B	F	B	350	—	90,600	76,400	—	—
3	C	F	C	350	—	86,500	72,000	—	—
4	A	F	A	350	—	90,000	73,600	—	—
4	B	F	B	350	—	85,400	67,300	—	—
4	C	F	C	350	—	88,200	69,600	—	—
5	A	F	A	350	—	94,400	80,800	—	—
5	B	F	B	350	—	97,200	82,900	—	—
5	C	F	C	350	—	95,300	80,600	—	—
1	A	F	A	450	—	95,100	79,000	75,400	88.7
1	B	F	B	450	—	95,600	79,600	—	—
1	C	F	C	450	—	93,200	76,700	—	—
2	A	F	A	450	—	90,300	76,100	—	—
2	B	F	B	450	—	89,800	74,800	—	—
2	C	F	C	450	—	90,200	74,800	—	—
3	A	F	A	450	—	86,100	71,800	—	—
3	B	F	B	450	—	88,200	74,200	—	—
3	C	F	C	450	—	85,500	71,000	—	—
4	A	F	A	450	—	87,200	71,000	—	—

Table C.1—2¹/₄ Cr 1 Mo Test Results (Continued)

Heat Code	Cylinder	Barstock or Forging	Test Agency	Test Temp.	Vendor Reported RT Yield (psi)	Tensile (psi)	Yield 0.2% (psi)	YS Avg. of Valid Heats at Temp. (psi)	YS Reduction Ratio (%)
4	B	F	B	450	—	88,200	69,600	—	—
4	C	F	C	450	—	77,000	51,200	Bad data point?	—
5	A	F	A	450	—	92,300	78,900	—	—
5	B	F	B	450	—	94,300	79,800	—	—
5	C	F	C	450	—	92,900	78,300	—	—

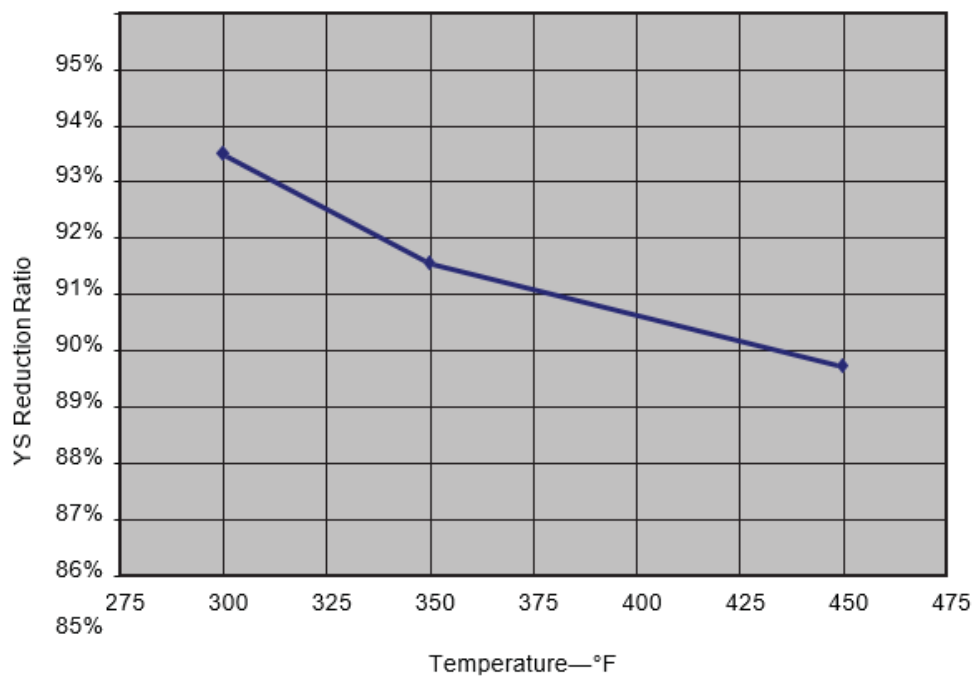


Figure C.1—Plot of 2 $\frac{1}{4}$ Cr 1 Mo Test Results