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Welding Research Council, Inc.

Bulletin

Guidelines for the Approval of New Materials in WRC Bulletin 541, API Std 530, and API 579-1/ASME FFS-1

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FOREWORD

API Std 530 Calculation of Heater-tube Thickness in Petroleum Refineries specifies the requirements and gives recommendations for the procedures and design criteria used for calculating the required wall thickness of new tubes and associated component fittings for fired heaters for the petroleum, petrochemical, and natural gas industries. A key element in the design procedures are material strength parameters and physical properties. The required strength parameters include yield and tensile strength as a function of temperature and the time-dependent properties (i.e., creep regime) include the creep rupture strength. The need for new materials for fired heater tubes is being driven by higher pressures and temperatures to increase production yields, and the need for enhanced creep strength and increased corrosion resistance to extend unit operation. This Bulletin defines the requirements to add new materials to API Standard 530. As API Std 530 references material properties and high temperature data from WRC Bulletin 541, this Bulletin also serves to provide guidelines for the incorporation of new materials into WRC Bulletin 541. These requirements include mechanical and physical property testing requirements, along with compositional, metallurgical, and welding requirements as well as justification for these requirements. Temperature intervals and the minimum number of heats for testing are specified for both time-independent and time-dependent mechanical properties, as well as for physical properties. Similarly, data requirements for the testing of welds consisting of new base materials are defined. The final section of this Bulletin describes additional data requirements for inclusion of materials (and welded joints) into API 579-1/ASME FFS-1 Part 10, on top of the basic requirements for inclusion of the material into API Std 530.

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ABSTRACT

Requirements and recommendations to calculate the required wall thickness of new fired heater tubes in the refining industry are provided in API Standard 530, *Calculation of Heater-Tube Thickness in Petroleum Refineries* (API Std 530). The rules of API Std 530 are sometimes used to determine the required thickness of heater tubes in other process industries. API Std 530 references material requirements and data from WRC Bulletin 541. Improving technologies and processes in these industries have led to the development of new grades of materials. Considerable research aimed at the development and testing of new or upgraded steels and alloys has been conducted leading to application of these materials in the industry. This Bulletin defines the requirements to add new materials to API Standard 530. Guidelines for the inclusion of new materials include mechanical and physical testing requirements, along with compositional, metallurgical, and welding requirements as well as justification for these requirements. Temperature intervals and minimum number of heats for testing are specified for both time-independent and time-dependent mechanical properties, as well as for physical properties. Similarly, data requirements for the testing of welds consisting of new base materials are defined. The final section of this Bulletin describes additional data requirements for inclusion of materials (and welded joints) into API 579-1/ASME FFS-1 Part 10, on top of the basic requirements for inclusion of the material into API Std 530.

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1 INTRODUCTION

1.1 Overview

This Bulletin identifies the essential mechanical and physical properties data required to add new materials to API Std 530 *Calculation of Heater-Tube Thickness in Petroleum Refineries* (API Std 530). This Bulletin is a modification of the data requirements outlined in the ASME Boiler and Pressure Vessel Code Section II, Part D, Mandatory Appendix 5 Guidelines on the Approval of New Materials Under the ASME Boiler and Pressure Vessel Code. This Bulletin also incorporates the historical data requirements used by the Materials Property Council (MPC) for development of material properties for inclusion into WRC Bulletin 541 and API Std 530. The properties shall be obtained from tests of materials conforming to recognized applicable national and international standards (see Table 1). Technical literature provided by the suppliers of materials, such as tables of calculated rupture stresses or stresses for specified creep rates are not acceptable alternatives to these requirements.

Where a new material is offered for inclusion, the requester shall identify the following:

a) Potential applications,

b) The temperature range of potential application, and

c) All product forms, size ranges, and specifications or specification requirements for the material for which approval is desired.

Additionally, the requester shall furnish information describing service experience in the temperature range requested, when available.

The final section of this Bulletin pertains to additional data requirements if the material submitted for inclusion into API Std 530 is also being added to Part 10 of API 579-1/ASME FFS-1.

1.2 Process for Incorporation of New Materials

Although deviations to the following process may be made, the general process to add a new material to Std 530 is listed below. This process may begin once the new material has been recognized, with relevant specification requirements defined, by an applicable national or international standards entity (e.g., ASTM).

1) Material Supplier, Equipment Fabricator or Operator, or other requestor submits a material data package meeting the requirements of this Bulletin to WRC for review and analysis. The material data package may be submitted to another organization designated by WRC to perform the review and analysis.

2) A WRC Bulletin will be developed and published documenting the data package submitted as well as the analysis and resulting material properties. WRC may either obtain additional data, as necessary to achieve the requested maximum use temperature desired by the requestor for the new material or may determine the maximum use temperature and any appropriate margins to be applied, based on available data. The authors of this WRC Bulletin will typically perform the lot-centering data analysis

as described in WRC Bulletin 564. If the material is being added into Part 10 of API 579-1/ASME FFS-1, this Bulletin will also contain the appropriate analysis (See Section 10).

3) WRC Bulletin 541 will be updated, either as a new edition or as an addendum to the most current edition, referencing the Bulletin developed in (2) above, and incorporating the necessary properties of the new material.

4) WRC will release the updated WRC Bulletin 541 to the API Committee on Refining Equipment, Subcommittee on Heat Transfer Equipment, API Std 530 Working Group, for evaluation.

5) The API Std 530 Working Group will ballot the proposed addition of the new material to members of the API Std 530 committee, in addition to performing any additional analysis using the properties referenced from WRC Bulletin 541. Additional analysis may include the tabulation of allowable stresses for inclusion into API Std 530.

If the material is being added into Part 10 of API 579-1/ASME FFS-1, WRC will share the material properties for both Larson-Miller and MPC Omega method calculations with the API 579 committee.

1.3 Definitions and Terms

Maximum Use Temperature – Based on the available data submitted by the requestor and according to the requirements of this Bulletin, this is the highest design temperature for which a material may be utilized for construction, as set by WRC.

Requestor – The company, organization or entity submitting data pertaining to the new material to WRC. Requestors may be equipment end users, owners, or operators, fabricators, designers, engineering firms, manufacturers, suppliers, or third parties.

Material Specification (also, **Reference Specification**) – A standardized document defining the requirements for a material, developed, and maintained by a national or international standards entity (e.g., ASTM). The material specification will typically list the composition, manufacturing, refining practices, forming operations, heat treatment, inspection, repair, testing, marking, and other requirements.

New Material – A material not currently listed in WRC 541 or API Std 530, which the requestor is seeking to incorporate into these documents. In general, new materials must be a unique grade within a reference specification. Specifications typically include requirements for multiple grades (e.g., ASTM A213 contains dozens of unique grades), while the same grade will typically appear in other specifications for additional product forms. The high temperature properties developed by WRC and incorporated into WRC 541 and API Std 530 will generally only apply to one grade. However, these properties may apply across multiple specifications where the grade appears, as applicable to WRC 541 and API Std 530.

Existing Material – A material which is currently listed in WRC 541 or API Std 530.

Lot – For cast product forms, a single production pour from a master heat. For wrought product forms, a quantity of metal made by melting followed by working or by working and heat treatment as a unique batch. In practice, although different lots may come from the same heat and may be made into different product forms, for the purposes of this Bulletin, each unique lot submitted to satisfy material data requirements shall come from a separate heat.

Heat – A quantity of metal with one chemical composition, produced by a recognized production process from a single primary melt of the metal. Remelted ingot material is not recognized as a separate heat unless it is produced from a melt having a different chemical composition than the other heats.

2 TEST METHODS

Test methods, units, and significant digits for material property requirements for use in this Bulletin are given in Table 1. Alternatively, equivalent national or international test standards may be used. The test methods used shall be indicated in the data package. The data offered should be for test specimen material that is fully described in terms of its complete production history and composition. Additional detail is provided in the following sections; however, the data shall be generally obtained using material from lots which are representative of the possible ranges of key variables allowed by the material specification. Key variables which are likely to affect the high-temperature behavior, include composition, thickness, mechanical working, heat treatment, and others. If, in the course of analyzing the submitted data, WRC determines that the lots contained within the submitted data do not adequately represent the range of specification key variables, WRC may seek additional data from the requestor, or may impose additional limits on the use of the new material such that the properties regressed from the submitted data accurately predict in-service behavior of future commercial heats used in heater coil construction.

3 CHEMICAL COMPOSITION

The requester shall recommend to WRC whether the chemical composition specified in the reference specification applies or whether restrictions to this composition shall be imposed for the intended application. When coverage by a recognized national or international standardization body has been requested but not yet obtained, the requester shall indicate the detailed chemical composition in the inquiry. The requester shall explain the reasons for the chemistry and chemistry limits, and their relationship to the metallurgical structure (e.g., influence on precipitates and their morphology, grain size, and phases), heat treatment effect (e.g., strengthening mechanisms and their stability), and mechanical properties. Elements that significantly influence strength, ductility, toughness, weldability, oxidation resistance and other behavior under service conditions should be identified.

After review of the submitted data, WRC reserves the right to modify the permitted compositional ranges for key elements so that they more accurately reflect the range of the elements of the submitted test heats.

4 METALLURGICAL STRUCTURE AND HEAT TREATMENT

When applicable for the proposed material, the Requester shall indicate the intended metallurgical structure(s) to be achieved in order to comply with the mechanical properties requirements and, where applicable, fully describe the heat treatment (including temperatures, hold times, and cooling rates) to be applied to achieve this (or these) structure(s), the mechanical properties, and the expected behavior under service conditions.

An explanation for the proposed heat treatment temperature ranges shall be furnished. When such concepts apply, metallurgical transformation curves and information on the transformation points and conditions for appearance of the major phases in the microstructure (e.g., continuous cooling transformation diagram or time–temperature precipitation plots) should be submitted for WRC's consideration. These transformation curves should be used to identify specific heat treatments or heat treatment ranges to be avoided, such as those which may degrade the material by causing a loss in corrosion resistance (e.g., sensitization of austenitic stainless steels) or leading to the formation of detrimental secondary or intermetallic phases (e.g., sigma phase, gamma prime). The properties described herein should be considered applicable only to the materials normally supplied and meeting the governing referenced specification for product form and size, processing, composition, heat treatment times and temperatures, grain size, and final microstructure.

5 MECHANICAL PROPERTIES

5.1 Requirements for Material Heats and Lots

5.1.1 General Requirements

For all mechanical properties, data shall be provided over the required range of test temperatures from at least six (6) lots of material meeting all the requirements of the applicable specifications. Data submitted on six (6) lots of one wrought product form for which coverage is requested may be applicable for all other wrought product forms with the same chemistry ranges.

Where cast product forms are to be covered, even if its nominal composition is the same or very similar to that of an approved wrought material, it shall be treated as a separate material and data from at least six (6) lots for one of the cast product forms shall be submitted.

For all product forms addressed in this Bulletin, the lots required shall each come from different heats of material as defined in Section 1.3, unless the requestor provides sufficient justification as to why multiple lots from the same heat should be considered.

The requirements for minimum number of lots based on material characteristics and the type of data (rupture, creep rate, etc.) is summarized in Table 2.

5.1.2 Age Hardened, Strain Hardened, and Creep-Strength Enhanced Ferritic Alloys

Where the alloy derives its strength, toughness, or stress rupture behavior in part from strain hardening and/or precise heat treatment beyond what is considered a typical heat treatment, the number of lots of material for which data are to be provided shall be increased to at least eight (8) to assure that a fully representative population for each grade has been included in the data. An example of a potential high temperature tube material that is intended to be used in the thermally age-hardened condition would be Alloy 740H. Examples of potential high temperature tube materials that could be proposed for intended used in the strain-hardened or cold-drawn/cold-worked (including cold-drawn/cold-worked and stress relieved) condition could be Alloy 800, (UNS N08800), Alloy 600 (N06600), or even possibly Alloy 400 (N04400) or variants of these materials. Such materials requested for use in these conditions (as opposed to the more normal solution annealed conditions of these alloys used in high temperature applications) would require a minimum of eight (8) lots.

Conversely, “typical” heat treatment would include normalizing and tempering or quenching and tempering for ferritic low alloy steels (not including creep strength enhanced ferritics), or solution annealing and quenching, for austenitic stainless steels and most nickel alloys. These heat treatment regimens do not require additional heats beyond the minimum six (6).

For Creep Strength Enhanced Ferritic materials (similar to Grade 91, including Grades 92, 115, 911, etc., the normalizing and tempering heat treatment is considered precise, given the need for this heat treatment to achieve the proper fine dispersion of metal carbonitrides to impart creep strength. Furthermore, the potential for a miscarriage of the specified heat treatment regimen can result in a dramatically lower creep strength than intended. Therefore, the minimum number of heats for creep strength enhanced ferritic materials shall be eight (8). The heat treatment variables represented in these heats should span the full range allowed in the reference specification.

In general, materials which require a specific strain hardening and/or heat treatment regimen may exhibit greater scatter between lots. This variability may arise when the acceptable ranges for key variables of strain hardening and/or heat treatment regimens, as defined in the reference specification for the material grade, are wide and include combinations which may not result in the ideal final properties. Alternatively, this variability may arise from the inherent variation encountered in manufacturing processes, such as the variation in temperature at different locations within a heat treatment furnace, sometimes even along a single tube.

5.1.3 Alloys Exhibiting Thickness-Dependency of Material Properties

For materials for which the mechanical properties may be reasonably expected to be thickness-dependent, data from two (2) additional lots of material at the maximum thickness for which coverage is requested shall be submitted. If a maximum thickness is not given, information shall be provided by the requestor to support the suitability of the thickness used for the tested samples.

Thickness dependency in this regard does not include the expected variation in properties between the surface and the mid-thickness in air hardened low alloy steels that are used in the normalized and tempered or quenched and tempered condition, including creep strength enhanced ferritics.

In fired heater tubes for refinery service, which generally have a wall thickness below 1 inch, it is considered unlikely that materials (even new proposed materials) will exhibit significant variation from surface to mid-thickness. Sampling materials at the mid-thickness location will serve to capture the minor effects of any variation for tube materials. For example, thick sections of some low alloy steels have lower allowable stresses provided in ASME Section II-D, partially resulting from variation in the cooling rate at the mid-thickness compared to that at the surfaces. The cooling rate at the mid-thickness is lower during normalizing/air cooling, resulting in less effective transformation to martensite and lower tensile and creep strength at mid-thickness. Again, this effect will rarely be realized for thicknesses applicable to fired heater tubes, and the additional two (2) lots are not required when the variation of properties with thickness is due simply to slight differences in cooling rates during typical heat treatments.

5.1.4 Use of Datasets with Fewer than the Specified Minimum Number of Lots

WRC, or the authors performing the data analysis for the new material on behalf of WRC, will utilize the methods described in Section 9 of this Bulletin. Especially for time-dependent property determination, the number of lots provided by the requestor and ranges of key variables (heat treatment, composition, grain size, etc.) represented among these lots will influence the amount of scatter within and between the lots. When fewer than the minimum required number of lots are available in the provided data package, this may be resolved by imposing some additional safety margin, of design factor. This margin/factor could be simply a fraction by which the calculated stress to produce rupture in the designated design life is multiplied. Such a margin/factor can be applied over the entire temperature range or a part of the intended range of use temperatures.

A trade-off exists between the number of lots provided, the relative scatter within and between the lots, and the variation of the key variables between lots relative to the variation in these variables allowed by the specification. A requestor may submit data for only the minimum number of lots required. However, if these lots exhibit more scatter within and between themselves, the resulting lot-centered minimum properties (which reflect a confidence level tied to the variation/scatter in data, as described in WRC Bulletin 564) may be lower and therefore detract from the advantage of using the new material. Alternatively, if the lots do not adequately represent the full range of key variables allowed by the reference specification, then use of the resulting properties may be accompanied by additional restrictions above and beyond the base specification requirements. This may impose additional costs to material procurement and similarly detract from the advantage of using the new material.

5.2 Requirements for Time-Independent Mechanical Properties

The ultimate tensile strength, 0.2% offset yield strength, % reduction of area at failure, and % elongation shall be furnished for the minimum number of lots as determined in Section 5.1. If additional lots are required beyond the minimum six (6), as noted above, to characterize the effects of composition, thickness and heat treatment, the requester shall document the basis used for selecting the number of lots of material.

For steels (including carbon steel, low alloy steels, and austenitic stainless steels), nickel alloys, cobalt alloys, and aluminum alloys, the ultimate tensile strength, 0.2% offset yield strength, and % elongation shall be provided for each lot, at room temperature and 100°F intervals, beginning at 200°F to 100°F above the maximum intended use temperature, unless the maximum intended use temperature does not exceed 100°F. However, if the change in yield and/or tensile strength over an interval tested exceeds 20%, the interval shall be reduced appropriately. It is not required that % reduction of area at failure be supplied for every data point if this information is not readily available; it is desirable to have more yield and tensile test results without necessarily having ductility for each specimen, as opposed to having fewer yield and tensile results with complete ductility results available. In addition, when specified in the material specification, hardness values shall be provided at room temperature and shall be determined as specified in the material specification.

Other types of alloys than those listed above will rarely be sought for use in creep-limited designs in petroleum refining heaters. When requested for incorporation into API Std 530 however, maximum temperature intervals for these other alloy types shall be defined by WRC considering the suggestion of the requestor.

5.3 Requirements for Time-Dependent Mechanical Properties

For each lot of material required, as defined in Section 5.1, time-dependent data shall be provided, starting at temperatures approximately 50°F below the temperature where time-dependent properties may govern and extending at least 50°F above the maximum intended use temperature. The minimum number of lots is as defined in Section 5.1. From the lots used for time-dependent properties, at least five (5) must overlap with the lots used for time-independent properties. Time-dependent data requirements are as follows:

a) The minimum temperature for which time-dependent properties are to be determined shall be no greater than the intersection temperature of the time-independent and time-dependent design property curves. For the purposes of API Std 530, this is the intersection between the time-independent “elastic” allowable stress curve (which is a fraction of yield strength at temperature), and the time-dependent “rupture” allowable stress curve for 100,000 hours, based on the minimum rupture properties.

b) For at least four (4) of the required minimum number of lots as defined in Section 5.1, the maximum temperature intervals in the time-dependent data provided shall not exceed the values specified below:

Alloy Type:	US Customary	Metric
1) Ordinary ferritic steels:	75°F	42°C
2) Creep strength enhanced ferritic steels:	50°F	28°C
3) Austenitic steels:	100°F	55°C
4) Solid solution Nickel-base alloys:	100°F	55°C
5) PH Nickel base alloys:	75°F	42°C
6) Cast austenitic alloys:	100°F	55°C

For the remaining lots, the temperature intervals in the time-dependent data provided shall not exceed 100°F (55°C).

c) In addition to the above general requirements, material-specific behavior should be considered. The interval between successive test temperatures shall be chosen such that it permits an accurate estimation of the slope of the parametric stress-rupture curve and the optimization of the Larson-Miller Parameter constant for the specific material being evaluated. In addition, for certain types of steels or alloys, it may be necessary to choose different temperature intervals to adequately reflect the evolution of the properties with time at temperature.

d) Tests of shorter duration than 500 hours are not desired for long-term stress rupture prediction. Longer times and additional test data are beneficial. Either the intervals between test temperatures or the test stress range at a given temperature should be chosen such that the stress for the longest time to rupture at each test temperature shall give at least 1000 hours duration at the next higher temperature as confirmed by the test data.

For example, for an ordinary ferritic steel material, if test data at 1000°F contains test stresses ranging from 5.0-8.0 ksi, and presumably the longest rupture time is associated with the 5.0 ksi test stress, then the rupture time at 5.0 ksi at the next test temperature (1075°F based on the intervals above) must be at least 1000 hours. If the rupture time at 5.0 ksi and 1075°F in this example is not at least 1,000 hours, then either the temperature interval must be lowered (effected by adding test data at some intermediate temperature between 1000°F and 1075°F) or additional tests at both 1000°F and 1075°F must be performed at a stress below 5.0 ksi, in order to obtain a rupture time of at least 1000 hours at 1075°F and the new test stress.

e) Alternative test plans that deviate from the prior descriptions but achieve the overall objective may be considered. This may apply to solid solution alloys for which the stability of strength-controlling microstructures is certain.

f) In addition, for certain types of steels or alloys, it may be necessary to choose different temperature intervals to adequately reflect the evolution of the properties. In such cases, the interval between successive test temperatures shall be chosen such that rupture lives do not differ by more than a factor of ten (10) at any given stress for two adjacent temperatures.

g) At each stress-rupture test temperature required, specimen rupture times from at least three (3) of the lots shall exceed 10,000 hours.

h) Minimum creep rate, as well as time and strain to reach the minimum creep rate shall be provided. The temperature range, and maximum temperature interval between successive minimum creep rate data test temperatures shall be determined in the same manner as described above in Section 5.3 (a) through (e).

   1) The minimum number of lots for minimum creep rate data shall be half of the minimum lots determined in Section 5.1 for rupture data, but no less than four (4). The minimum creep rate data shall come from the same lots as the rupture data for at least the minimum number of lots (additional creep rate data can be submitted for separate lots provided this requisite overlap between the rupture and minimum creep rate lots is met).

   2) Additionally, the stresses for minimum creep rate data shall be selected such that the range of minimum creep rates at any single temperature covers approximately one (1) order of magnitude (factor of 10). For each lot, at least one specimen at each test temperature shall have a minimum creep rate less than 3 x 10^{-4} %/hour.

i) For both rupture and minimum creep rate data, considering all lots, there shall be at least ten (10) tests conducted at each test temperature for which creep rates and/or rupture data are required.

j) For each specimen tested the results of the creep/rupture testing shall include the following: stress, temperature, rupture time and/or minimum creep rate (%/hour), time and strain (%) until the minimum creep rate was measured (if creep rate is supplied), elongation and reduction of area at failure (applicable only to tests resulting in rupture). Where metallurgical transformation can impact the material performance or where detrimental metallurgical changes are expected (sensitization, intermetallic phase precipitation), photomicrographs of tested specimens (the longest rupture time at each required temperature) shall be provided, with commentary describing the transformation.

For new materials, and particularly for those whose creep-rupture properties are affected by heat treatment or deformation processes or a combination of these, it is important to know the structural stability characteristics and the degree of retention of properties with long-term exposure at temperature. Where particular temperature ranges of service exposure or fabrication heat treatment, cooling rates, and combination of mechanical working and thermal treatments cause significant changes in the microstructure on which the creep-rupture properties depend, these shall be brought to the attention of WRC.

6 PHYSICAL PROPERTIES

Using samples from at one or more lots of material meeting the requirements of the material specification, the requester shall furnish to WRC adequate data necessary to establish values for the:

- Modulus of Elasticity,
- Mean Coefficient of Thermal Expansion,
- Coefficients of Thermal Conductivity,
- Coefficients of Thermal Diffusivity,
- Poisson's Ratio, and
- Density.

For elastic modulus, thermal expansion, thermal conductivity, and thermal diffusivity, data shall be provided over the range of temperatures for which the material is to be used and shall represent the range of compositions, mechanical properties and/or heat treatments expected. Data shall be collected at temperature intervals not greater than 200°F (111°C).

If significantly different trends or properties are obtained due to differences in composition or processing of the materials, such effects shall be reported.

If the specimen physical properties are altered by time at temperature, sufficient time shall be provided during the test or during a pre-conditioning period for the physical property to stabilize with time at temperature. The results of the tests of all the lots will be combined and used to describe the above noted characteristics of the alloy. In the event that the test results display scatter deemed to be due to material variability the cause of such scatter must be identified, and appropriate action taken to provide additional data to explain the variation or notice given in the material report. The average property at each temperature shall be reported.

As opposed to executing physical property testing on the material, the requestor may substitute existing well-documented physical properties from materials with a similar chemical composition and structure to the new material. In such cases, the requestor shall provide WRC with tabulated values of physical properties of the reference material and shall provide a justification for the substitution.

7 OXIDATION RATES

Oxidation rates shall be determined using samples from one or more lots of material lots of material meeting the requirements of the material specification. The method used to determine the oxidation rate shall be as identified in Table 1 typically, although alternative test methods achieving comparable quality results to the listed standards will be considered if the corresponding procedure is provided by the requester. As opposed to executing oxidation rate testing on the material, the requestor may substitute existing well-documented oxidation rate data from materials with a similar chemical composition to the new material. In such cases, the requestor shall provide WRC with justification for the substitution as well as with tabulated values of oxidation rates of the reference material in 100°F intervals, ranging from the temperature at thick an oxidation rate of 0.001 inches per year is exceeded, up to 100°F above the maximum intended use temperature. This data may be in the form of a curve of oxidation rate versus temperature, or as tabulated values of penetration depth versus temperature.

Data shall be provided over the range of temperatures for which the material is to be used and shall represent the range of compositions, mechanical properties and/or heat treatments expected. Data shall be provided at temperature intervals not greater than 100°F.

Sufficient time shall be provided during the test to establish an oxidation rate. The results of the tests of all the lots will be combined and used to describe the above noted characteristics of the alloy. In the event that the test results display scatter deemed to be due to material variability, the cause of such scatter must be identified, and appropriate action taken to provide additional data to explain the variation or notice given in the material report. The average property data will be obtained and reported using up to a fourth order polynomial. The average property at each temperature shall be reported.

If significantly different trends or properties may be obtained due to differences in composition or processing of the materials, then such effects shall be reported.

WRC will generally utilize any oxidation data that can be supplied with respect to exposure schedule (continuous/isothermal or cyclic) as well as environments. In oxidation testing, the most common environments include air as well as typical "fired heater atmosphere" simulated environments, consisting of N_2, O_2, water vapor and CO_2. Oxidation data in air is useful if to "correct" the Larson-Miller fits for oxidation of longer-duration test data. To accomplish this, the change in thickness during each test is calculated, and the test duration is sub-incremented based on a threshold change in stress. The life equation used to optimize the Larson-Miller constants and coefficients, then, requires the sum of the fraction of time for each sub-increment, divided by the calculated rupture time at the stress of that sub-increment, to equal 1.0 (Robinson's Rule). Due to the uncertainty in predicted oxidation rates, however, WRC will rarely provide the Larson-Miller properties, adjusted in this manner for oxidation effects, for inclusion in API Std 530. Oxidation data in the simulated fired heater atmosphere environment is useful if we want to predict external wall loss in actual fired heater applications.

8 DATA REQUIREMENTS FOR WELDMENTS AND WELDABILITY

8.1 Introduction

Three types of welding information are required: data on general weldability, data on time-independent strength and toughness, and data on time-dependent strength.

API Std 530 design procedures and allowable stress curves (elastic or rupture) are not applicable to tubes with a longitudinal seam weld; API Std 560 allows only for seamless tubes. Although butt-welded joints in fired heater coils, properly welded, are not typically expected to be life-limiting, when novel materials are considered for inclusion into API Std 530, some test data is required to demonstrate that the long-term elevated temperature properties of welded joints is at least equal to or, preferably, superior to that of base materials. Weldability considerations given to new materials being incorporated into API Std 530 should therefore focus not only on the general weldability of the material, but also long-term elevated temperature mechanical properties of the welded joints. Typically fired heater coils are constructed using weld procedure specifications (WPS) that have been qualified to ASME Section IX and will therefore meet general strength, fusion, and ductility requirements at room temperature. The additional high-temperature data requirements in the following Sections 8.3 and 8.4 are intended to demonstrate adequacy of butt-welded joints for high temperature service. The extent of data required depends on whether welding consumable specifications exist that are suitable for the base material, as follows:

1) When there is one or more AWS, ASME, or equivalent consumable specifications/classifications suitable for use with the new base material, data for the consumable/process combinations shall be provided to demonstrate that welded joints between representative base material lots made with this (these) consumables have both good weldability as well as both time-independent and time-dependent strengths equal to or greater than those of the base metal over the range of expected service temperatures. The requestor shall identify to WRC the suitable consumables for each welding process that can be used in heater coil fabrication, in addition to supplying the data as required in Sections 8.3 and 8.4.

2) When there is no such suitable consumable having an AWS, ASME, or equivalent specification and classification from an international standards entity, or when it is necessary or desirable to use a new, perhaps nominally matching, welding consumable, the supplier shall provide the additional data noted in Sections 8.3 and 8.4 to demonstrate the high temperature strength of the welded joints, as well as the chemistry ranges for each element specified for the consumable to be used. If the chemistry ranges vary for the consumables to be used for different processes, then the chemistry ranges of the consumables appropriate for each process shall be provided.

If butt-welded joints (made to a Section IX-qualified WPS) between components of the new material are expected to behave similarly to those of an existing material or are otherwise reasonably expected to be superior to base material in the temperature range of use, the requestor can claim exemption from the cross-weld testing requirements in Sections 8.3 and 8.4. This request for exemption shall be accompanied by sufficient written technical justification demonstrating why butt welds of the new material are expected to behave similarly to those of the existing material.

8.2 Data on General Weldability

Because the concept of weldability is so broad, there are a wide variety of test techniques that can be used to assess or quantify weldability. These tests can address issues associated with the process and/or welding procedures, cracking during welding or post-weld processing, required post-weld processing, and other welded fabrication steps needed to obtain the intended service performance of the welded joint. Weldability test techniques can be broadly grouped into four major categories: mechanical, non-destructive, service performance, and specialty. Weldability data for mechanical tests shall be provided to WRC by the requester at a minimum.

For general mechanical weldability tests (e.g., tensile, bending ductility, impact toughness, etc.) of weld metal and surrounding heat-affected zone (HAZ), sufficient experience and test data should be submitted to demonstrate the ability to produce a sound weldment. The requestor shall indicate general welding requirements including suitable filler metal selection (AWS, ASME, or equivalent consumable specification, if one exists), preheat, post-weld heat treatment, and other requirements that can be used to develop a WPS in accordance with Section IX. If the requestor believes that inspection requirements above those of ASME Section IX are needed for the new material, then these additional weld inspection requirements shall be specified. For example, macroscopic cross sections of cast austenitic or nickel-based alloy weldments are required to examine for fissuring. Information on deposited metal, such as effects from post-weld processing, susceptibility to air hardening, effects of joining processes, expected notch toughness values, and the amount of experience in use of the consumable shall be provided to WRC.

8.3 Welded Joint Time-Independent Strength and Toughness

Elevated temperature tensile test data shall be submitted for cross-weld joint samples welded using one of the typical welding processes for the material. The intent of this data requirement is to demonstrate adequate service performance of welded joints in the new material. Temperature intervals for cross-weld elevated temperature tensile tests, and the temperature range for test data shall be the same as that required in 5.2 for base material.

1) When an existing AWS, ASME, or equivalent consumable is recommended by the requestor for use with the new base material, cross-weld data at the above required temperatures is required for welds joining base materials from one (1) lot of base material using two (2) lots of this consumable (2 total combinations).

2) When a non-AWS, ASME, or equivalent consumable is recommended by the requestor for use with the new base material, cross-weld data at the above required temperatures is required for welds joining base materials from two (2) lots of material using three (3) lots of consumables for each process intended to be used with the new base material (6 total combinations).

In both cases above, when multiple welding process/consumable combinations exist for a joint in the new base material, and variation in the welding process/consumable is expected to produce significantly different high temperature time-independent strength behavior, data shall be provided from each multiple welding process/consumable combinations. Additionally, the base material lot(s) used for cross-weld joints in each case shall be one of the lots use in determination of base metal properties in Section 5.

At each temperature, the yield and tensile strength of the welded joint shall equal or exceed the value of the base metal average trend curve, as defined in Section 9.2 below. For testing at room temperature, this aligns with Section IX QW-153 requirements for weld procedure qualification record (PQR) acceptance criteria. Revisions or modifications to the recommended welding procedures should be provided by the requestor to promote sufficient high temperature weld strength meeting this requirement. The data shall indicate the failure location (base metal, weld metal, or heat-affected zone). Consideration should be given to the toughness of welded joints in the new material. Welding consumables and processes should be selected such that welded joints fabricated to WPS's qualified per Section IX will display adequate impact toughness for the application. However, data regarding material toughness is not explicitly required for incorporation of a material into API Std 530.

8.4 Welded Joint Time-Dependent Strength

8.4.1 Overview

For many materials (new materials as well as existing materials) welded joints will have lower creep strength (sometimes markedly lower) than base metal. In certain classes of materials, this behavior is generally expected and acceptable. Typically, new materials considered for API Std 530 already have an associated ASME code case, and since many fired heater tube materials are also used for boiler tube materials, this is often a Section I code case. The Section I code case will usually include requirements to be applied for longitudinally welded joints of the new material, per Section I, PG-26 weld strength reduction factor guidance.

8.4.2 Use of Weld Strength Reduction Factor

Upon review of the supplied welded joint data, if it is demonstrated that butt-welded joints have a time-dependent strength equal to or superior to that of the base material, no further analysis is needed. If the data demonstrate that the welds are (as often expected) inferior to base metal properties, then WRC will determine if the data supplied for welded joints is at least bounded by the minimum weld strength reduction factor (*w*) for the appropriate material group in Section I, PG-26. For materials without a *w* listed in the code case (such as Section VIII code cases), or for materials that do not fit into the categories of Table PG-26, a *w* of 0.5 will be assumed.

The *w* of 0.5 is rationalized by the fact that the welds in an API Std 530 heater design will be circumferential and therefore subject to half hoop direction pressure stress. If the supplied welded joint creep results are bounded with a *w* of 0.5 applied to the minimum properties, they are not expected to limit the life of the heater coil, provided system loads (span and contents weight, expansions, etc.) are not excessive. If this is true, then no additional margin is needed for API Std 530 construction. If the weld data are not bounded by this reduction factor, then WRC will have to determine on a case-by-case basis what additional margin on the creep rupture design factor needs to be applied.

8.4.3 Welded Joint Time-Dependent Strength Data Requirements

Rupture data shall be submitted for cross-weld joint samples welded using each of the typical welding processes for the material. Temperature intervals for cross-weld rupture tests and the temperature range for test data shall be the same as that required in Section 5.2 for base material.

1) When an existing AWS, ASME, or equivalent consumable is recommended by the requestor for use with the new base material, cross-weld data at the above required temperatures is required for welds joining base materials from one (1) lot of base material using two (2) lots of this consumable (2 total combinations). Test stresses shall be selected to produce rupture times of approximately 1000 hours (not less than 500 hours).

2) When a non-AWS, ASME, or equivalent consumable is recommended by the requestor for use with the new base material, cross-weld data at the above required temperatures is required for welds joining base materials from two (2) lots of material using three (3) lots of consumables for each process intended to be used with the new base material (6 total combinations). For each lot and at each temperature, a minimum of two (2) stresses shall be selected to produce rupture times of approximately 1000 hours (not less than 500 hours) and greater than 5,000 hours.

In both cases above, when multiple welding process/consumable combinations exist for joints in the new base material, and variation in the welding process/consumable is expected to produce significantly different high temperature time-dependent strength behavior, data shall be provided from multiple welding process/consumable combinations. Additionally, at least one (1) of the base material lots used for cross-weld joints in each case shall also be included in the data used for determination of base metal properties in Section 5.

The data shall indicate the test temperature; stress rupture time; specimen size and configuration, including weld location; and failure location (base metal, weld metal, or heat-affected zone), for each test condition. Minimum Creep Rate data is not required for welded joints.

If the requestor suspects that high temperature exposure of the welded joint could lead to significant alteration of the material properties, including embrittlement (degradation of material toughness) or loss of strength with prolonged service, this shall be brought to the attention of WRC. If the material's general weldability or high temperature time-dependent or time-independent strength is derived from a specific phase balance, age-hardening operation, or similar manufacturing/fabrication step, it shall be assumed that the high temperature exposure of the welded joint could lead to significant alteration of the material properties. For such materials, additional data demonstrating satisfactory mechanical properties after prolonged exposure in the temperature range at which material property changes are experienced will be required. The type of data, lot and temperature requirements will be determined by WRC with input from the requestor.

9 DATA ANALYSIS METHODS

9.1 Data Analysis Performance

WRC will utilize the following data analysis methods to produce material property curves, using the data package submitted by the requestor for the new material.

9.2 Time-Independent Properties

The analysis for time-independent data represents an approximation to the lot-centering analysis used for time-dependent data. The yield and tensile strengths at all temperatures above room temperature within a given lot are normalized to the room temperature yield or tensile strength measured for that lot. One polynomial function for all lots is obtained by regression analysis of this normalized data as a function of temperature. The resulting polynomials obtained for the yield and tensile strength ratios are known as trend curves. The value of yield strength and tensile strength at temperature is determined by multiplying the minimum specified values at room temperature times the trend curve ratio evaluated at a specific temperature.

9.3 Time-Dependent Strength Parameters

The data analysis methods for determining the rupture strength and optimized Larson-Miller parameter are provided in WRC 564 *The MPC Lot-Centered Analysis Method for Determining High Temperature Strength Parameter*.

The rupture life obtained from creep tests conducted at elevated temperatures in air are affected by oxidation. These effects were more pronounced for small specimens, at low stresses, high temperatures, and long durations. In these tests significant metal loss may occur that significantly change the rupture strength. The MPC lot-centered parametric analysis in WRC 564 has been extended to include the effects of oxidation of the sample.

9.4 Physical Properties

The Modulus of Elasticity, Mean Coefficient of Thermal Expansion, Coefficients of Thermal Conductivity, and Coefficients of Thermal Diffusivity as a function of temperature are determined by fitting up to a fourth order polynomial to the average value reported for each temperature. Density and Poisson’s ratio will simply be reported in WRC’s analysis, without explicit regard to temperature dependence of either property.

9.5 Oxidation Rates

The oxidation rate as a function of temperature is determined by fitting up to a fourth order polynomial to the average value reported for each temperature. If no data are provided by the supplier, oxidation rates may be omitted from the Bulletin developed for the new material.

10 MATERIAL DATA FOR API 579-1/ASME FFS-1, PART 10, ANNEX 10B

10.1 Supplemental Requirements

This Bulletin has primarily focused on the requirements for material additions to WRC 541 and API Std 530. In many cases, it will be advantageous for a material to be added to Part 10, Annex 10B of API 579-1/ASME FFS-1 (API 579) while it is added to WRC 541 and API Std 530. Minimal additional data is needed for this purpose.

Part 10 of API 579 provides properties and equations for use of either the Larson-Miller of MPC Omega creep models in a Fitness-For-Service evaluation of material operating in the creep regime. Threshold temperatures for the lower end of the creep regime are provided in API 579. The Larson-Miller properties utilized in API 579 should match the properties in the current edition of API Std 530 and WRC Bulletin 541. Notably, the stress calculation used in the API 579 Larson-Miller evaluation differs from the stress calculation shown in API Std 530, and differs from the MPC Omega multiaxial stress calculation.

The MPC Omega method properties utilized in API 579, wherever possible, should be based on consideration of rupture time, creep strain rate (minimum creep rate or initial strain rate), as well as the acceleration of creep rate due to strain accumulation (i.e., the Omega Parameter). Multiple approaches exist to obtain the MPC Omega properties, depending on the available creep strain versus time data (i.e., full creep test curves) that can be provided by the requestor. At a minimum, creep strain versus time data shall be provided for half of the required number of lots identified in Section 5. For each of these lots, full creep curves, showing some portion of tertiary creep (strain rate acceleration with time) shall be supplied at temperatures over the following range:

- Minimum temperature for creep strain versus time data – equal to or less than the minimum temperature for which time depended material properties govern design
- Maximum temperature for creep strain versus time data – no less than the maximum intended use temperature plus 50°F.

Over this temperature range, the interval between test temperatures shall be no greater than 100°F. At each required temperature thus identified, two creep curves shall be provided, one with a rupture time longer than 1000 hours and one with a rupture time longer than 5000 hours.

For most materials, 3 lots of creep strain versus time data will be required, with 4 to 6 test temperatures required and at least 2 stresses at each temperature, totaling around 24-36 total creep curves.

10.2 Accounting for Weld Behavior

Unlike API Std 530, the procedures in API 579 can be used to evaluate longitudinally welded structures. Generally, in a Level 1 or 2 assessment using the MPC Omega methodology, a creep strain rate adjustment factor, Δ_{Ω}^{SR} of -0.5 is used.

To provide guidance for use in an API 579 Part 10 assessment of a welded joint of the new material, both Larson-Miller and Omega methodologies need to be considered. For Larson-Miller, the analysis described in 8.4 of this Bulletin shall be used, taking advantage of existing ASME weld strength reduction factors for consistency wherever possible. A shift of the minimum Larson-Miller constant obtained for base material can be made, using an appropriate weld strength reduction factor to bound all the weld data available, and a weld joint Larson-Miller constant can be obtained. For the MPC Omega method, the standard Δ_{Ω}^{SR} of -0.5 can be combined with an appropriate Δ_{Ω}^{CD} of greater than or equal to 0.0, such that the resulting properties bound all the weld joint data points.

Creep strain versus time data are required to validate the use of the MPC Omega method base material properties of the new alloy for welded joints. Specifically, these data shall be provided at the required temperatures noted for base metal creep strain versus time data, for weldments joining one (1) of the base metal heats and using one (1) lot of consumable. Two test stresses at each temperature for these lots are required.

As in the case of Larson-Miller rupture time property development in Sections 8.3 and 8.4 for welds, the intent is not to develop unique properties for welds, but rather simply to validate the modifications applied to base metal properties to reflect weld behavior.

11 ACKNOWLEDGEMENTS

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12 REFERENCES

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[3] API/ASME, 2016. API 579-1/ASME FFS-1 *Fitness-For-Service*, The American Petroleum Institute, Washington DC.

[4] D.A. Osage, D.A., Janelle, J.L, Bednarz, J., Kowalski, P., Mekker, J.G., Orosz, K.T., Sutton, N.G., WRC Bulletin 503, *Compendium of Temperature-Dependent Physical Properties for Pressure Vessels, Piping and Tankage Materials*, Welding Research Council, Inc., Shaker Heights, OH.

[5] E. Gassama, J.D. Cochran, C.H. Panzarella and D.A. Osage, WRC Bulletin 564, *The MPC Lot-Centered Analysis Method for Determining High Temperature Strength Parameters*, Welding Research Council, Inc., Shaker Heights, OH.

13 TABLES

Table 1 –Test Method Standards and Units for Reporting Material Properties

ASTM Designation	Title	Property	US Customary Units	SI Units	Significant Digits
A370	Standard Test Methods and Definitions for Mechanical Testing of Steel Products	Tensile strength and yield strength	ksi	---	3
A1058	Standard Test Methods for Mechanical Testing of Steel Products – Metric	Tensile strength and yield strength	---	MPa	3
C177	Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus	Thermal conductivity	Btu/hr-ft-°F	---	3
		Thermal diffusivity	ft^2/hr	m^2/sec	3
E8	Standard Test Methods for Tension Testing of Metallic Materials	Tensile strength and yield strength	ksi	MPa	3
		Density	lb/in^3	kg/m^3	3
E21	Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials	Tensile strength and yield strength	ksi	MPa	3
E132	Standard Test Method for Poisson's Ratio at Room Temperature	Poisson's Ratio	---	---	2
E139	Standard Test Methods for Conducting Creep, Creep - Rupture, and Stress - Rupture Tests of Metallic Materials	Rupture Time	hr	hr	5

Table 1 –Test Method Standards and Units for Reporting Material Properties

<table>
<tr><th>ASTM Designation</th><th>Title</th><th>Property</th><th>US Customary Units</th><th>SI Units</th><th>Significant Digits</th></tr>
<tr><td>E228</td><td>Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push-Rod Dilatometer</td><td>Mean linear coefficient</td><td>in/in/ºF</td><td>mm/mm/ºC</td><td>3</td></tr>
<tr><td>E831</td><td>Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis</td><td>Mean linear coefficient</td><td>in/in/ºF</td><td>mm/mm/ºC</td><td>3</td></tr>
<tr><td>E1875</td><td>Standard Test Method for Dynamic Young’s Modulus, Shear Modulus, and Poisson's Ratio by Sonic Resonance</td><td>Modulus of elasticity</td><td>psi</td><td>MPa</td><td>3</td></tr>
<tr><td rowspan="3">ASTM G54 (withdrawn)

ISO 21608

JIS Z 2281</td><td rowspan="3">Standard Practice for Simple Static Oxidation Testing (G54),

Test method for isothermal-exposure oxidation testing under high-temperature corrosion conditions for metallic materials, (21608)

Test method for continuous oxidation test at elevated temperatures for metallic materials (Z2281)</td><td>Oxidation Rate (calculated, depth of attack/time)</td><td>in/year</td><td>mm/year</td><td>3</td></tr>
<tr><td>Mass Change per Unit Area</td><td>lb_m/ft^2</td><td>g/m^2</td><td>4</td></tr>
<tr><td>Total Depth of attack</td><td>in</td><td>mm</td><td>4</td></tr>
</table>

Table 2 – Summary of Lot Requirements for Each Property

Material Property	**Characteristics of "New" Material**		
	All materials not fitting the categories listed to the right	**Strain hardened or cold worked (and not subsequently annealed) materials, thermally age-hardened materials, creep strength enhanced ferritics**	**Material with thickness-dependent mechanical or rupture behavior (beyond that occurring due to variation in cooling rates from surface to mid-thickness)**
Yield and Tensile (Including Elongation and Reduction of Area)	6	8	+2 to number at left
Rupture	6 (5 of which should be the same as those used for yield and tensile)	8 (5 of which should be the same as those used for yield and tensile)	+2 to number at left
Creep Rate (MCR)	4	4	+1 to number at left
Creep strain versus time - base metal (only for materials being added to API 579)	3	3	No additional Data Required
Weldment Yield and Tensile Data (When AWS/ASME filler Specification exists)	1 lot of base metal with 2 lots of consumables (2 combinations)		
Weldment Yield and Tensile Data (Non-AWS/ASME filler)	2 lots of base metal with 3 lots of consumables (6 combinations)		
Weldment Rupture Data (When AWS/ASME filler Specification exists)	1 lot of base metal with 2 lots of consumables (2 combinations)		
Weldment Rupture Data (Non-AWS/ASME filler)	2 lots of base metal with 3 lots of consumables (6 combinations)		
Creep strain versus time - welded joints (only for materials being added to API 579)	1 lot of base metal with 1 lot of consumables (1 combination)		

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