U.S. Program on Advanced Ultrasupercritical Power Plant Materials – The Economy of Using Advanced Alloys

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Abstract

The United States Department of Energy (U.S. DOE) Office of Fossil Energy and the Ohio Coal Development Office (OCDO) have been the primary supporters of a U.S. effort to develop the materials technology necessary to build and operate an advanced-ultrasupercritical (A-USC) steam boiler and turbine with steam temperatures up to 760°C (1400°F). The program is divided into two consortia representing the U.S. boiler and steam turbine manufacturers (Alstom, Babcock & Wilcox, Foster Wheeler, Riley Power, and GE Energy); additional support to both consortia is provided by national laboratories (Oak Ridge National Laboratory and the National Energy Technology Laboratory). The entire effort is managed by the Energy Industries of Ohio with the Electrical Power Research Institute (EPRI serving as the program technical lead. Over the last decade, the program has conducted extensive laboratory testing, shop fabrication studies, field corrosion tests, and design studies. Based on the successful development and deployment of materials as part of this program, the Coal Utilization Research Council (CURC) and EPRI roadmap has identified the need for further development of A-USC technology as the cornerstone of a host of fossil energy systems and CO_2 reduction strategies. This paper will present some of the key consortium successes and ongoing materials research in light of the next steps being developed to realize A-USC technology in the U.S. The importance of materials selection and the use of advanced alloys to improve the economy of A-USC steam cycles (world-wide) will be highlighted with specific examples comparing plant piping system designs for different materials.

Introduction

In 2001, the U.S. Department of Energy in conjunction with the Ohio Coal Development Office (OCDO) and cost share from all the major U.S. boiler and turbine original equipment manufacturers (Alstom, B&W, Foster Wheel, Riley Power, GE), the Energy Industries of Ohio (EIO), and the Electric Power Research Institute (EPRI) with support from Oak Ridge National Laboratory (ORNL) and managed through the National Energy Technology Laboratory (NETL) began an ambitious pre-competitive research and development project that would lead to higher efficiency coal-fired power plants with reduced CO_2 emissions [1,2]. Achieving major increases in coal-fired power plant efficiency requires an increase in steam conditions (temperature and pressure) and therefore demands the utilization of new materials and technologies to implement these new materials. Hence, the R&D program's goal was to develop the materials technology necessary to achieve Advanced Ultrasupercritical steam (A-USC) power plant steam conditions up to temperatures and pressures of 760°C (1400°F) and 35 MPa (5000

psi), respectively which can reduce all emissions, including CO_2, by 20% or greater compared to today's U.S. fleet [3]. Since that time, the A-USC steam boiler and turbine consortia have conducted extensive research which shows that materials and fabrication technologies now exist to construct such a system.

Achievements

The consortium first defined the conditions required for the materials to operate at A-USC conditions up to 760°C. Based on these preliminary design studies, nickel-based alloys were selected for detailed evaluation because only these alloys had the requisite strength required to operate at A-USC conditions. Current USC boilers operate at temperature of approximately 600°C which is the limit of the most advanced creep-strength enhanced ferritic (CSEF) steels, but for temperatures above 700°C, nickel-based alloys are clearly required. Figure 1 shows the temperature required to produce creep-rupture in 100,000 hours for various alloys at 100MPa. Using this criterion, these temperature limits can be observed from the plot. Although strength is an important consideration, a number of other critical material properties, must be considered for materials operating at A-USC conditions.

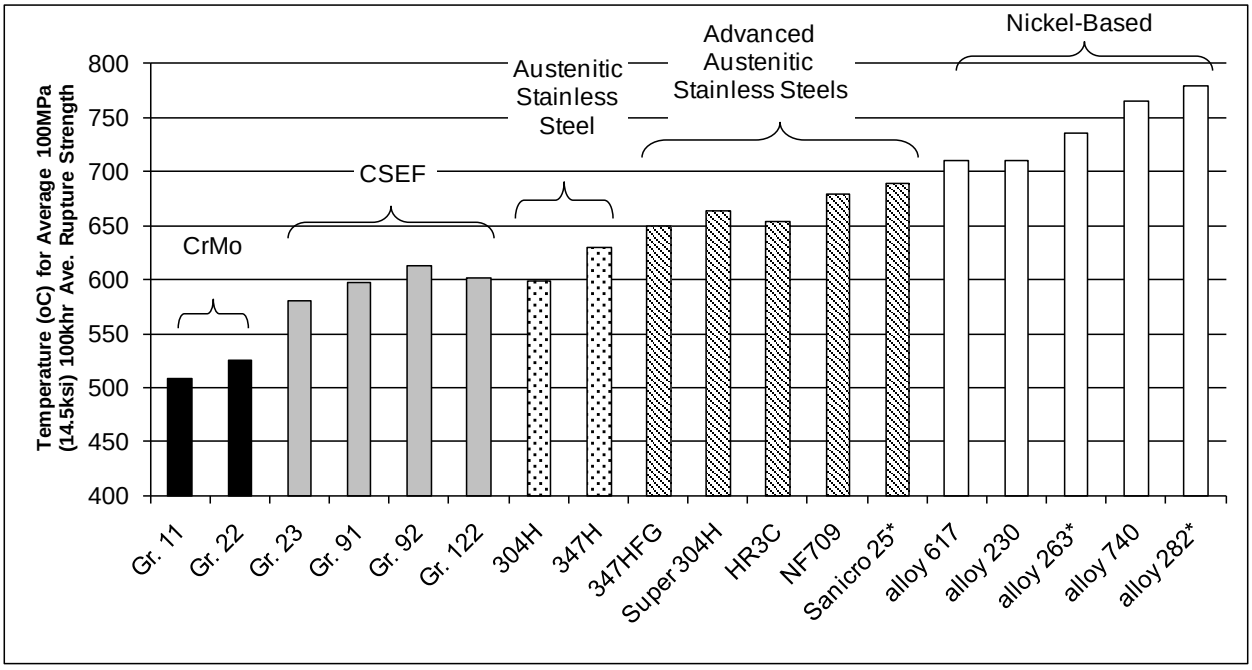

*Figure 1. Temperature capability (based on high-temperature creep strength) for various alloys. Nickel-based alloys are the only materials with the requisite high-temperature strength for A-USC plant components operating at 700°C (1300°F) or higher. * denotes alloys which are not approved for use in the U.S. per the ASME Boiler and Pressure Vessel Code.*

To understand the applicability of nickel-based alloys for boiler and turbine conditions, extensive studies were conducted and covered the following: long-term strength, fireside corrosion resistance, and steam oxidation resistance, boiler fabrication processes, forging and casting for steam turbine applications, weldability, weld performance, and weld repair. Most of these studies are complete and a detailed list of accomplishments can be found in reference [4]. Critical findings/successes included:

- Alloy Inconel 740/740H was found to have the necessary long-term creep strength, corrosion resistance, and weldability to operate up to 760°C. Based on the consortium's data and research, the alloy was approved for use by ASME in 2011 and has been designated Code Case 2702.
- Fireside corrosion studies, including laboratory tests, air cooled probes in three boilers, and steam loop tests in two boilers show nickel-based alloys, weld overlays, and coatings exists which can be utilized to mitigate fireside corrosion for a wide array of coals at A-USC conditions including higher sulfur coals indigenous to the U.S.
- Fabrication studies were completed successfully for all alloys and included the production of demonstration articles for welding, bending, machining, forging, etc. large boiler components
- Casting research identified key alloys, including a new alloy – Haynes 282 – for large turbine and valve components.
- Assessment of steam turbine alloys showed a number of alloys with appropriate properties for steam turbine design with Haynes 282 appearing the most attractive for the steam turbine rotors.

Currently, the consortium continues research on:

- An additional field corrosion loop operating in a boiler with 760°C (1400°F) steam
- Scale-up of castings and forgings for steam turbine components
- Simulated weld repair activities for nickel-based boiler components

Economy of Using Advanced Alloys and Importance of Alloy Selection

Background on Alloy Selection

A-USC materials research programs in Europe have identified and extensively tested an optimized composition of alloy 617, referred to as CCA617 or 617B, as the key alloy to enable A-USC conditions of approximately 700°C [5]. Alloy 617 is approved for use in the ASME B&PV code and the CCA variant was studied by the US Consortium. However, the current material of choice for the A-USC consortium designs is Inconel® alloy 740H which was approved as code case 2702. As shown in Figure 2, the allowable stress of 740H is far greater than alloy 617 which makes it attractive not only for 760°C steam but 700°C as well. A higher strength alloy requires thinner walls which will reduce material usage, reduce structural supports, and reduce the amount of required welding. Another advantage of using 740H is its reduced flow-stress at forming/forging temperatures compared to alloy 617 (and alloys 230, 263, and 282) [6]. A material with a lower flow stress is easier to form/forge/extrude. With regard to the pipe extrusion process, which is one of the preferred methods for making heavy wall boiler piping; 740H has more possible pipe sizes than alloy 617. An additional benefit of a lower flow stress is the ability to extrude longer pipe lengths; both the cross-sectional area and length have been verified with full-scale pipe extrusions for 740H, CCA617 and 263. Figure 3 is a chart showing the sizes possible for 617 compared to 740H which shows this trend [7].

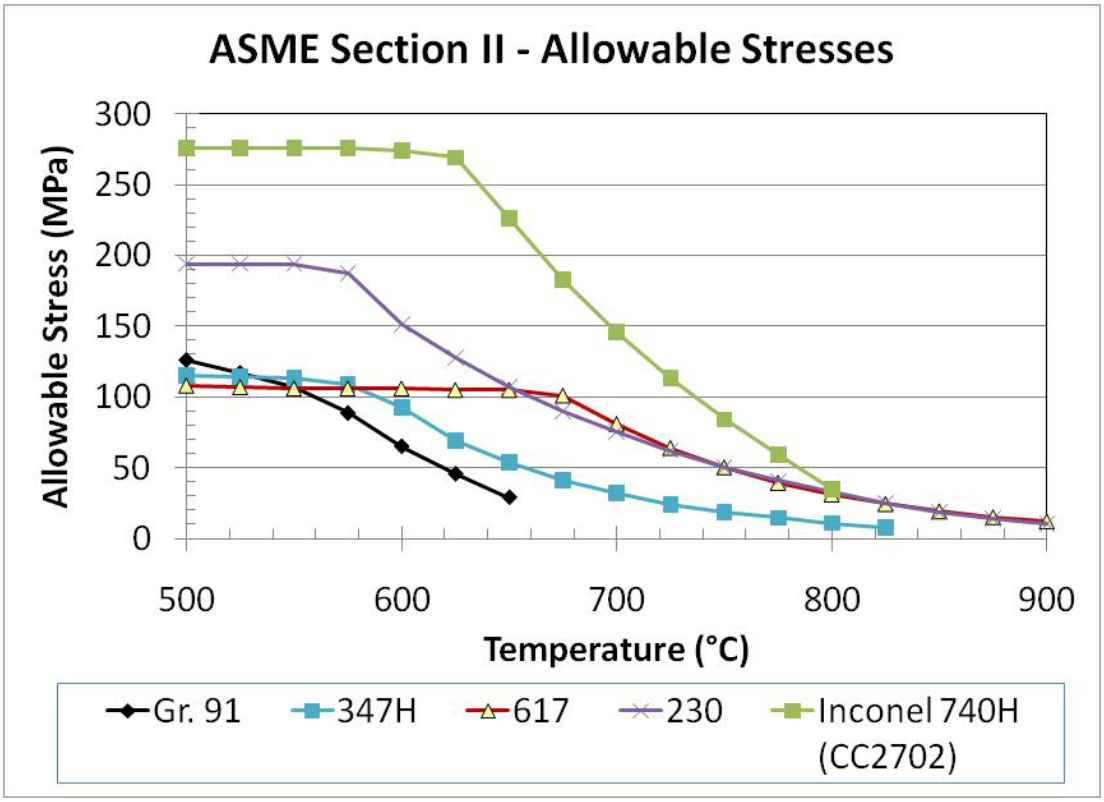

Figure 2. ASME B&PV Code Section II maximum allowable stress as a function of temperature. 740H has greater strength than other code approved nickel-based alloys 617 and 230. Stainless steel 347H and ferritic steel Grade 91 (both used in today's USC plants) are shown for comparison.

Minimum Wall Thickness	8-in (203mm) I.D.	11-in (279mm) I.D.	14-in (355mm) I.D.	17-in (431mm) I.D.	20-in (508mm) I.D.	23-in (584mm) I.D.	26-in (660mm) I.D.	29-in (736mm) I.D.
1.0-in (25.4mm)	40 - 40ft (12.1m)	40 - 40ft (12.1m)	33 - 36ft (10m)	35 - 38ft (10.6m)	27 - 27ft (8.2m)	19 - 34ft (5.7m)	26ft (7.9m)	25ft (7.8m)
1.5-in (38.1mm)	40 - 40ft (12.1m)	32 - 34ft (9.7m)	23 - 34ft (7m)	26 - 26ft (7.9m)	19 - 22ft (5.7m)	19 - 25ft (5.7m)	25ft (8.8m)	18ft (5.4m)
2.0-in (50.8mm)	36 - 36ft (10.9m)	23 - 35ft (7m)	22 - 26ft (6.7m)	19 - 19ft (5.7m)	17 - 23ft (5.1m)	16 - 18ft (4.8m)	18ft (5.4m)	18ft (5.4m)
2.5-in (63.4mm)	27 - 35ft (8.2m)	18 - 28ft (5.4m)	22 - 22ft (6.7m)	19 - 24ft (6m)	17 - 19ft (5.1m)	19ft (5.7m)	18ft (5.4m)	14ft (4.2m)
3.0-in (76.1mm)	26 - 30ft (7.9m)	23 - 36ft (7m)	18 - 25ft (5.4m)	15 - 19ft (4.5m)	18ft (5.4m)	16ft (4.8m)		
3.5-in (88.8mm)	30 - 30ft (9.1m)	20 - 20ft (6.1m)	18 - 21ft (5.4m)	16ft (4.8m)	16ft (4.8m)			
4.0-in (101.5mm)	23ft (7m)	23ft (7m)	18ft (5.4m)	18ft (5.4m)	14ft (4.2m)			
4.5-in (114.2mm)								
Possible Alloy Nimonic 263, 617CCA or Inconel 740H Sizes					Other Possible Inconel 740H Sizes			

Figure 3. Possible pipe sizes for CCA617/263 compared to 740H [7]. The red numbers represent the maximum length for extruded pipe made from CCA617 or Nimonic 263. The green and the white numbers represent the maximum length for extruded pipe made from 740H. 740H has a larger forging window and can be made into larger sizes or longer pipe lengths due to its lower flow stress.

Calculations for an A-USC Piping System

To demonstrate the economy of using a higher strength alloy for an A-USC steam system, the data in Figures 2 and 3 for 617 and 740H were utilized to estimate the possible configurations for a nickel-based piping system. The reference plant was based on a past EPRI study of a single reheat 685 /705°C 750MW A-USC power plant [9]. In that study, the plant had 2 main steam (MS) and 2 hot reheat (HRH) pipes with an inner diameter (ID) of 250mm and 467mm, respectively. Through design optimization, the length of each of these piping runs was 128m from the boiler outlet to the turbine. Utilizing these ID dimensions and assuming equivalent volumetric steam flow, the wall thicknesses were calculated for two single reheat steam conditions: 704/704°C (1300/1300°F) and 732/760°C (1350/1400°F) with the first being close to proposed 700°C A-USC plants in Europe and the latter being designs suggested by the U.S. DOE A-USC consortium. The use of a single pipe, compared to two pipes, was also evaluated. Table 1 shows the results of these calculations and Figure 4 shows the estimated piping lengths for these sizes.

Inspection of Table 1 shows a two MS-two HRH piping system for alloy 617. A single piping system was considered, but the wall thickness at 704°C exceeded 100mm for the MS dimension which is generally

the limit for ease of fabrication (machining, welding, erection). Additionally, at 704°C the pipe size for the HRH was beyond the practical dimensions for pipe extrusion (see Figure 3) thus, alternate and more expensive fabrication methods would have to be utilized. For 740H, both a two pipe (dual pipe) and single pipe system were evaluated. The data show the 740H piping system is approximately 50% the weight of the 617 piping system regardless of configuration at the same steam temperature. In fact, the 740H piping system at 732/760°C has less mass than the 617 piping system at 704/704°C. Figure 4 shows that the thinner pipe sizes at the 704/704°C condition for alloy 740H allows for longer pipe runs compared to alloy 617. The exact ratio depends on pipe diameter with the MS having a greater advantaged compared to the HRH. The single 740H pipe is nearly equivalent in length to the 617 two-pipe system. Thus, two 617 extrusions would be required for every 740H extrusion in this 704/704°C configuration.

Table 1. Calculated Size and Weight for MS and HRH Piping Systems in This Study

Component and Material Design (number of pipes)		Temp. °C (°F)		Minimum Total Piping Length Required	MS Dimensions (mm)		HRH Dimensions (mm)		Total Mass of MS+HRH
MS	HRH	MS	HRH	meters	ID	Wall Thick.	ID	Wall Thick.	kg
617 (2)	617 (2)	704 (1300)	704 (1300)	256	248.92	71.12	467.4	22.9	227,420
740 (2)	740 (2)	704 (1300)	704 (1300)	256	248.92	35.56	467.4	12.7	108,548
740 (1)	740 (1)	704 (1300)	704 (1300)	128	353.06	50.8	660.4	17.8	109,045
617 (2)	617 (2)	732 (1350)	760 (1400)	256	248.92	96.52	467.4	40.6	361,453
740 (2)	740 (2)	732 (1350)	760 (1400)	256	248.92	48.26	467.4	25.4	179,819
740 (1)	740 (1)	732 (1350)	760 (1400)	128	353.06	68.58	660.4	35.6	179,647

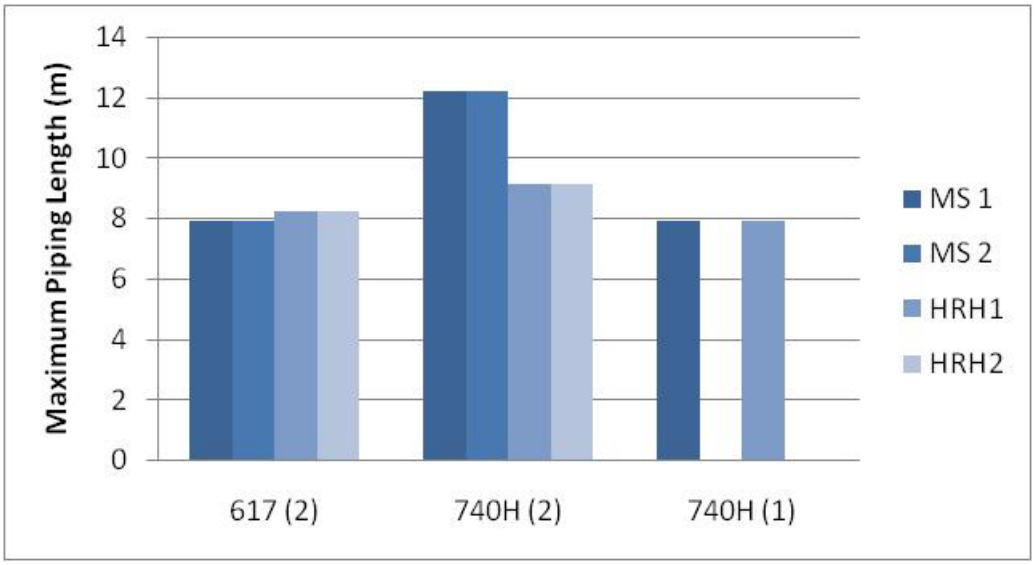

Figure 4. Estimated maximum piping lengths for various piping configurations at the 704/704°C condition. The use of 740H allows for longer piping runs at equivalent ID dimensions or similar lengths to alloy 617 with larger pipe IDs.

Piping Cost Estimates

Nickel-based alloy prices are much greater (ten times or more) than typical chromium-molybdenum steels used in today's USC boilers. To estimate the cost of the piping system, the delivered cost of a finished nickel-based pipe was evaluated from $55-110 USD/kg ($25-50 USD/lb) which represents average to very high costs for nickel-based materials. Due to market fluctuations in Ni, Mo, Co, and other major alloying elements as well as similar processing for both 617 and 740H, the two alloys can be considered to be roughly equivalent. Figure 5 shows the results for both steam conditions. The piping system costs, at $55USD/kg ($25USD/lb), were on the order of 5 to 16 million USD. This is similar to other estimates for a nickel-based MS and HRH piping system [8]. Thus, the results show than 740H could save, in delivered material cost alone, 6M USD or more compared to alloy 617.

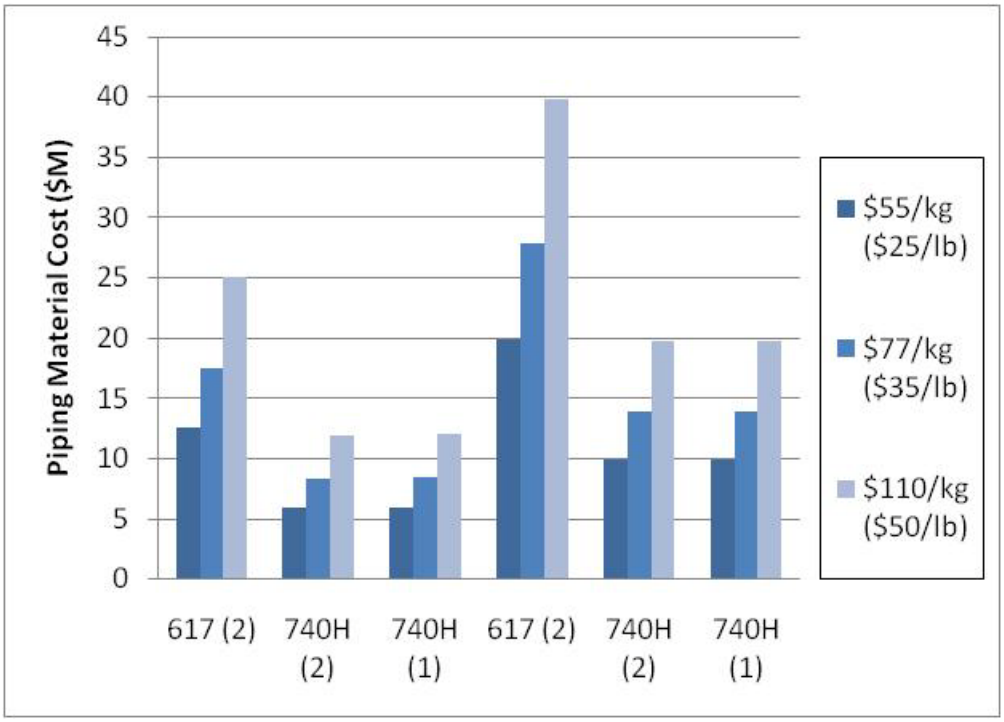

Figure 5 Estimated delivered piping (material) costs for the piping system configurations in this study. 740H can save over 50% ($6M USD or greater) compared to 617.

Additional Costs and Considerations

In addition to raw material cost considerations, a major advantage to the use of longer-runs of pipe or a single piping system compared to a dual piping system is a lower number of welds. This is clearly shown in Figure 6 where moving from a dual 617 system to a dual 740H system eliminates a large number of welds and the number of welds is almost cut in half by moving to a single 740H piping system. Assuming the use of a narrow groove welding technology, which has historic precedence in stainless steel USC piping systems [9], the welding time and volume of weld metal for the various systems were calculated. The results in Table 2 show the 617 system has over twice the amount of weld metal (and hence weld metal cost) and double the welding time compared to both alternative 740H systems.

On the basis of volume of weld metal, there appears to be a slight advantage to a dual 740H system over a single 740H system, but there are other considerations beyond the volume of weld metal. First, less welds lead to decreased construction costs from weld inspection (time to inspect, equipment set-up, paperwork) and post-weld heat-treatment (which is required for both alloys). Second, since welds are the 'weakest link' in most piping systems, high-temperature life assessment activities require ongoing periodic inspection of welds and weldments. Less weldments simplify and reduce ongoing maintenance costs with plant life management. A single piping system also has the advantage of fewer hangers and less insulation which reduces construction costs and ongoing maintenance costs. Conversely, larger and heavier pipes (617 system) are more costly due to additional hangers and structural support required.

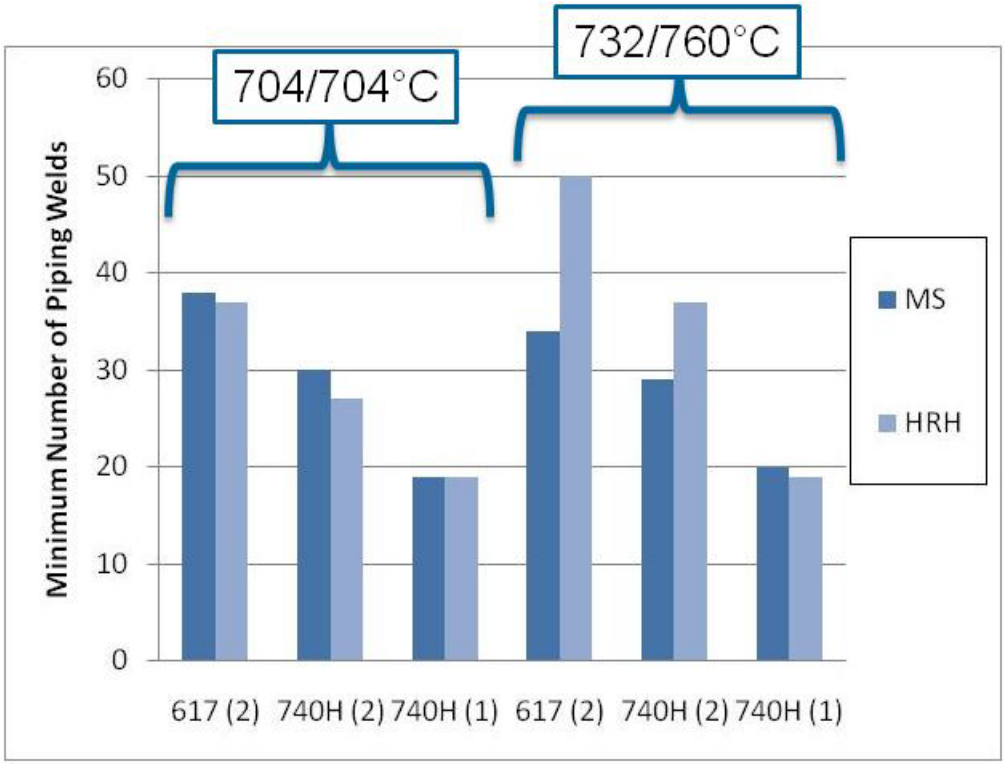

Figure 6. Number of minimum required heavy-section welds for various configurations and steam systems.

Table 2. Estimated weld metal cost and welding time required for various piping system configurations.

Configuration	Temp.	Total Welds		Estimated Weld Metal Cost	Estimated Welding Time
	(°C)	MS	HRH	USD	hrs
617 (2)	704/704	38	37	$37,360	598
740H (2)		30	27	$12,185	195
740H (1)		19	19	$17,715	283
617 (2)	732/760	34	50	$66,494	1,064
740H (2)		29	37	$24,869	398
740H (1)		20	19	$32,595	522

Summary

The U.S. DOE/OCDO A-USC steam boiler and turbine consortium have developed much of the materials technology to deploy an A-USC power plant with steam conditions up to 760°C. Some work on turbine materials is ongoing, and the turbine materials technology is estimated to be ready in 3 to 5 years. While the U.S. program has studied alloys with strength, fabrication, and corrosion resistance up to

760°C, the alloys have direct applicability to lower A-USC temperatures. This paper presents one example of how higher-strength and temperature capable alloys used at lower temperatures will improve the overall economy of an A-USC steam cycle. The specific finding comparing alloy 617 to 740H for a prototypical A-USC main steam and hot reheat piping system showed that by using 740H in lieu of 617, the number of pipes required would decrease, the length of each individual extruded pipe section would increase, the number of welds for the piping system would decrease, and the amount of welding (both filler material and welding time) would decrease. The combined effect of these results demonstrates that the utilization of 740H over 617 will result in a significant cost savings with regard to both construction and life management of an AUSC piping system.

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