ELECTRIC POWER RESEARCH INSTITUTE

Inclusion of Clad Thickness in the Calculated Strength of ASME Section I Boiler Tubes

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Technical Update, December 2005

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

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CITATIONS

This document was prepared by

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Chattanooga, TN 37416-3152

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B.W. Roberts

This document describes research sponsored by the Electric Power Research Institute (EPRI) .

This publication is a corporate document that should be cited in the literature in the following manner:

Inclusion of Clad Thickness in the Calculated Strength of ASME Section I Boiler Tubes. EPRI, Palo Alto, CA : 2005, 1010510.

ABSTRACT

Utilities frequently use weld overlays for corrosion and erosion protection of waterwalls and superheat/reheat tubing. Under the current rules of the ASME Code, none of the thickness of the overlay may be considered when performing the strength calculations for minimum tube wall thickness. This results in added cost to the boiler manufacturer and utility. It also adds substantial weight to the boiler and hinders heat transfer which in the case of waterwalls can lead to premature thermal fatigue damage. Tangent tube fireboxes are further hindered by this requirement because there is frequently not enough physical room to accommodate the added thickness. This project is aimed at changing the rules in the Code to at least allow the thickness to be considered as if it were no stronger than the base metal. This means that if the weld overlay is stronger than the base metal, the added thickness could be considered to be the same strength as the base metal.

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1
INTRODUCTION

It has become common practice to provide protection to tubes used in waste conversion, pulp and paper, and fossil boilers by applying corrosion resistant surface cladding. The substrate tubes are typically carbon steel or low alloy steel tubes [0.5Cr-0.5Mo (T2), 1Cr-0.5Mo (T12), 1.25Cr-0.5Mo-Si (T11) and 2.25Cr-1Mo (T22)] and the corrosion resistant clad is typically an austenitic stainless steel (304, 304L,and 309), a duplex stainless steel (312), or a nickel-based alloy (622, 625, or 825). The methods for applying the cladding include co-extrusion, arc welding, or laser welding. The service experience has been generally good with the exception of substantial cracking in 304L cladding used in pulp and paper (black liquor) boilers. While there is not universal agreement, this cracking has been classified as stress-corrosion cracking in which the role of the aggressive environment, differential thermal expansion, and high residual stresses collectively play a dominant role.

In waste conversion and coal-fired utility boilers a range of clad alloys have been applied to superheater tubes to improve resistance to fireside wastage. In the waterwalls of mostly supercritical utility boilers, cladding has included diffusion chromizing, arc welded 309 and 312, and arc and laser welded 622 and 625. The service experience in superheater tubes and waterwall tubes has been generally good with life extended three to ten times that of an unprotected (bare) tube. In all the aforementioned applications a metallurgical bond is achieved between the substrate tube and the cladding, which is in contrast to protective coatings that are essentially mechanically bonded.

The equation for calculating the minimum required wall thickness in an ASME Section I boiler is in paragraph PG-27.2.1 and gives no credit for the strength of the clad. The apparent basis is not a fundamental objection to the concept. Rather, it appears that those providing protection by cladding have accepted the “status quo” and have never requested that a change be made to formally account for the strength of the clad for sizing the tube.

Thus, this project is aimed toward developing a sound engineering basis to give credit for the cladding strength in the thickness calculation of ASME Section I boiler tubes and to achieve appropriate Code revision.

2
APPROACH

The design basis for pressure parts in Section I is to restrict the average membrane stress of the first principal stress to a level that will preclude: (a) gross distortion in short term loading at temperatures below the creep range, (b) substantial distortion at long times in the creep range, and (c) bursting at any temperature. In the case of a pressurized tube, the first principal stress is the hoop stress.

The safeguard against gross distortion in short term loading is to limit the average hoop stress to two-thirds of the yield strength at temperature. In cases of highly ductile alloys where some modest distortion is permissible, nine-tenths of the yield strength at temperature is permitted. The safeguard against substantial distortion at long time in the creep range is to limit the allowable stress to one which will produce a secondary creep rate of 1%/100,000 hours for an average material. There are two safeguards against bursting. First, the design stress at temperature is limited to 0.314 times the expected tensile strength at temperature (1.1/3.5); the factor was formerly 0.275 (1.1/4.0). Second, at temperatures in the creep range, the design stress is limited to the lower of either: (a) the aforementioned creep rate, (b) 0.67 of the average stress to cause rupture in 100,000 hours. or (c) 0.80 of the minimum stress to cause rupture in 100,000 hours.

For a clad tube, the stresses arising from differential thermal expansion are classified as secondary stresses. Section I has no explicit rules to account for such secondary stresses, which by definition are displacement controlled, or for fatigue due to cyclic stresses, whether of thermal or mechanical origin. By providing generous design margins on the average primary membrane stress, an adequate margin generally exists to accommodate secondary stresses and cyclic stresses as validated by the usual long component life. There are occasional exceptions in which the boiler designer has to go "beyond the rules of Section I" to assure long service lives.

For this project, a so-called "strength of materials" approach has been used to develop the basis to include the cladding strength in the tube sizing formula. In this approach, the average hoop stress can be established from simple equilibrium, which is the fundamentally the basis for the Section I tube-sizing formula, without resorting to more complex formulations or use of finite element methods.

But recognizing that there will be some concern over differential thermal expansion and associated cyclic fatigue, simple estimates of the cyclic secondary stresses will be made to facilitate a fatigue analysis for the substrate and the clad.

3
SCOPE OF WORK

Potential revisions to the tube sizing formula in PG-27.2.1 will be developed and a series of numerical exercises will be performed to judge the impact these will have for a bare tube under current rules and a clad tube under the proposed rules. Based on the outcome from these trials, a revision to the sizing equation to include the cladding strength will be developed and balloted through the appropriate ASME Code Committees.

The numerical exercises will be performed using the following parameters:

Clad thickness - A typical cladding thickness of 0.070 in will be used

Configuration - Only the 360 degree clad tube will be considered. A later extension of the work may consider one-sided cladding configurations.

Tube OD – From 1.00 in to 2.50 in OD, in increments of 0.25 in (six tube ODs)

Pressures – 2000, 2400, 2800, 3200, 3600, and 4200 psig to span a typical spectrum that includes subcritical and supercritical boilers

Mean wall temperatures – 700F (simulate subcritical water walls), 900F (simulate supercritical water walls), and 1050F (simulate superheater tubes)

Heat Fluxes – To simulate through wall OD to ID temperature differentials of 0 (isothermal), 50, and 100°F in a bare tube; the associated heat flux will be calculated. The axisymmetric heat conduction formula will be used to establish the temperature profile through the tubes.

Tube Materials – SA-210-A1 Carbon Steel, SA-213-T11 (1.25Cr-0.5Mo-Si), and SA-213-T22 (2.25Cr-1Mo)

Cladding Materials – 309 austenitic stainless steel and, 622, 625, and 825 nickel based alloy.

Allowable Stresses – From Section II, Part D Tables 1A and 1B. For weld claddings, the equivalent wrought product allowable stresses will be used.

4
RESULTS

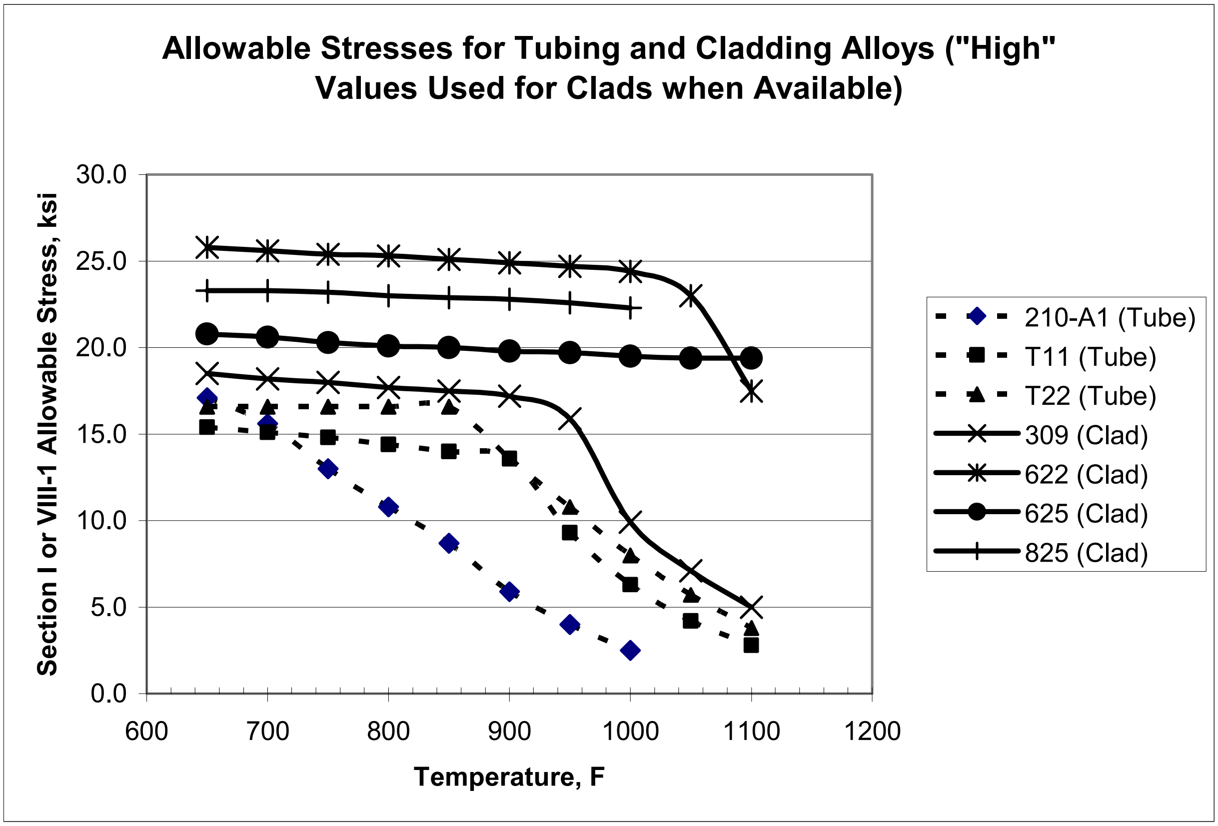
Progress reports have been made to three ASME B&PV Code Section I Subgroups (Design, Fabrication and Examination, and Materials) during their meetings in December 2004, August 2005, and December 2005. Feedback provided by these discussions has been integrated into the project. The intent is to provide a formal recommendation for Code change to these groups at their meetings in February 2006.

4.1 Relative Strengths of Tubes and Clads

Some of the feedback from the ASME B&PV Code meetings in San Francisco, CA in December 2004 indicated that Part UCL in Section VIII, Division 1 (VIII-1) provided rules which permitted the clad strength to be included in the "component sizing" calculation. The VIII-1 rules are based on the relative strength of the clad material (c), using wrought properties from Section II, Part D, to the base material (b). The strength is judged by the allowable stresses in either Table 1A (ferrous) or Table 1B (nonferrous) of Section II, Part D. So long as the clad strength equals or exceeds the base metal strength, the VIII-1 rules permit the clad thickness to be included as equivalent to the base metal; i.e., a one-for-one replacement. If the clad strength is less than the base metal, the "clad strength thickness" is adjusted downward from the "actual thickness" by the ratio of clad strength to base metal strength, still giving credit for the clad contribution.

The following table shows the Section I allowable stresses, followed by a figure showing the information graphically.

	Code Allowable Stress for Wrought Product, ksi, at Temperature, F										
Tube or Clad	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**	**1150**
210-A1 (Tube)	17.1	***15.6***	***13.0***	***10.8***	***8.7***	***5.9***	***4.0***	***2.5***			
T11 (Tube)	15.4	15.1	14.8	14.4	14.0	13.6	***9.3***	***6.3***	***4.2***	***2.8***	
T22 (Tube)	16.6	16.6	16.6	16.6	16.6	***13.6***	***10.8***	***8.0***	***5.7***	***3.8***	
309 (Clad)	18.5	18.2	18.0	17.7	17.5	***17.2***	***15.9***	***9.9***	***7.1***	***5.0***	***3.6***
622 (Clad)	25.8	25.6	25.4	25.3	25.1	24.9	24.7	24.4	23.0	***17.5***	***12.7***
625 (Clad)	20.8	20.6	20.3	20.1	20.0	19.8	19.7	19.5	19.4	19.4	19.3
825 (Clad)	23.3	23.3	23.2	23.0	22.9	22.8	22.6	22.3			



The traditional Section I tube sizing formula was chosen and "thick wall" sizes (thickness > 0.5 inside radius) were excluded. These concepts are expressed mathematically as:

$$teff = tb + tc' = tb + (Sc/Sb)tc$$

$$tc' = (Sc/Sb)tc$$

$tb + tc' = \{[PD/(2Sb+P)] + 0.005D\}$, note that the right hand side is the Section I tube sizing formula

$$tb = \{[PD/(2Sb+P)] + 0.005D\} - (Sc/Sb)tc$$

where:

tb= Minimum base metal thickness of the clad tube, in.

tc = Physical clad thickness, in.

tc' = Effective clad thickness for strength purposes = (Sc/Sb)tc

teff =Total effective thickness of the clad tube, in.

D = Outside Diameter of the "composite/clad tube," in.

t = tb+tc = Total wall thickness of clad tube, in.

P = Internal pressure, psig

Sc = Allowable stress of clad based on wrought product, psi

Sb = Allowable stress of the base metal, psi

This equation is subject to the following constraints"

$t < D/2$ (excludes thick walled tubes from the exercise)

If $(Sc/Sb) \geq 1$, the ratio is set equal to 1 in the calculation

If $(Sc/Sb) < 1$, the actual ratio is used in the calculation

Based on analysis to be presented later, Sb is evaluated at the midwall temperature for the bare tube of Diameter D and total thickness of (tb + tc) whereas Sc is evaluated at the mid-clad temperature.

In the following three tables, one for each tube material, the clad strength is evaluated at the same temperature as the tube and at a 50°F higher temperature. It can be seen that the ratio of (Sc/Sb) is less than unity only for the 309 clad on a T22 tube, with the clad temperature exceeding the tube mean wall temperature by 50°F over the tube temperature of 950F to 1100F. Even in this instance, the lowest ratio is 0.877 which means a 0.070 in. clad effectively adds 0.061 in. for strength purposes. This analysis indicates that there will be substantial benefit in all instances by including the clad thickness in the tube sizing calculation.

SA-210 A1	Allowable Stress Ratio: Clad/Tube at Temperature (F)							
	650	**700**	**750**	**800**	**850**	**900**	**950**	**1000**
309 Clad ΔT=0°F	1.082	1.167	1.385	1.639	2.011	2.915	3.975	3.960
309 Clad ΔT=50°F	1.064	1.154	1.362	1.620	1.977	2.695	2.475	2.840
622 Clad ΔT=0°F	1.509	1.641	1.954	2.343	2.885	4.220	6.175	9.760
622 Clad ΔT=50°F	1.497	1.628	1.946	2.324	2.862	4.186	6.100	9.200
625 Clad ΔT=0°F	1.216	1.321	1.562	1.861	2.299	3.356	4.925	7.800
625 Clad ΔT=50°F	1.205	1.301	1.546	1.852	2.276	3.339	4.875	7.760
825 Clad ΔT=0°F	1.363	1.494	1.785	2.130	2.632	3.864	5.650	8.920
825 Clad ΔT=50°F	1.363	1.487	1.769	2.120	2.621	3.831	5.575	

SA-213 T11	Allowable Stress Ratio: Clad/Tube at Temperature (F)									
	650	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**
309 Clad ΔT=0°F	1.201	1.205	1.216	1.229	1.250	1.265	1.710	1.571	1.690	1.786
309 Clad ΔT=50°F	1.182	1.192	1.196	1.215	1.229	1.169	1.065	1.127	1.190	1.286
622 Clad ΔT=0°F	1.675	1.695	1.716	1.757	1.793	1.831	2.656	3.873	5.476	6.250
622 Clad ΔT=50°F	1.662	1.682	1.709	1.743	1.779	1.816	2.624	3.651	4.167	4.536
625 Clad ΔT=0°F	1.351	1.364	1.372	1.396	1.429	1.456	2.118	3.095	4.619	6.929
625 Clad ΔT=50°F	1.338	1.344	1.358	1.389	1.414	1.449	2.097	3.079	4.619	6.893
825 Clad ΔT=0°F	1.513	1.543	1.568	1.597	1.636	1.676	2.430	3.540		
825 Clad ΔT=50°F	1.513	1.536	1.554	1.590	1.629	1.662	2.398			

SA-213 T22	Allowable Stress Ratio: Clad/Tube at Temperature (F)									
	650	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**
309 Clad ΔT=0°F	1.114	1.096	1.084	1.066	1.054	1.265	1.472	1.238	1.246	1.316
309 Clad ΔT=50°F	1.096	1.084	1.066	1.054	1.036	1.169	**0.917**	**0.888**	**0.877**	**0.947**
622 Clad ΔT=0°F	1.554	1.542	1.530	1.524	1.512	1.831	2.287	3.050	4.035	4.605
622 Clad ΔT=50°F	1.542	1.530	1.524	1.512	1.500	1.816	2.259	2.875	3.070	3.342
625 Clad ΔT=0°F	1.253	1.241	1.223	1.211	1.205	1.456	1.824	2.438	3.404	5.105
625 Clad ΔT=50°F	1.241	1.223	1.211	1.205	1.193	1.449	1.806	2.425	3.404	5.079
825 Clad ΔT=0°F	1.404	1.404	1.398	1.386	1.380	1.676	2.093	2.788		
825 Clad ΔT=50°F	1.404	1.398	1.386	1.380	1.373	1.662	2.065			

4.2 Cladding "Opportunity Matrices"

For the exercises presented next, the weld clad was assumed to always be 0.070 in. thick and the ratio of (Sc/Sb) ≥1, meaning (Sc/Sb) was set to 1. Two scenarios were performed to identify cladding opportunities with and without water backing; i.e., tubes that could not be cooled during welding (without water backing) and tubes that could be cooled by flowing water through the tube during welding (water backing).

Without water backing, the tube thickness before cladding must be 0.140 in. minimum to avoid “burn-through.”

With water backing, the tube thickness before cladding must be 0.100 in. minimum to avoid “burn-through.”

A consequence of these assumptions is that the total tube wall thickness must be 0.210 in. minimum for the tube to be a candidate for weld cladding without water backing and 0.170 in. minimum with water backing.

4.2.1 Cladding Opportunity Matrices without Water Backing

The next series of three tables (one for each tube material) shows the tubes which meet the cladding criteria without water backing. The left “diagonal” tubes (original colored yellow) are too thin, the right “diagonal” tubes (original colored light blue) are too thick for the usual Section I formula, and the tubes in the middle (original background white) are “just right” to be eligible for cladding. It can be seen that the cladding opportunities increase with larger OD and higher pressure.

		MWT for SA-210-A1							
		Mean Wall Temperatures, F							
		650	700	750	800	850	900	950	1000
Sall, ksi		17.1	15.6	13.0	10.8	8.7	5.9	4.0	2.5
Tube OD, in	Pressure, psig								
1.00	2000	0.0602	0.0652	0.0764	0.0897	0.1081	0.1499	0.2050	Thk. Wall
1.00	2400	0.0706	0.0764	0.0895	0.1050	0.1262	0.1740	0.2358	Thk. Wall
1.00	2800	0.0807	0.0874	0.1022	0.1198	0.1436	0.1968	Thk. Wall	Thk. Wall
1.00	3200	0.0906	0.0980	0.1146	0.1340	0.1603	0.2183	Thk. Wall	Thk. Wall
1.00	3600	0.1002	0.1084	0.1266	0.1479	0.1764	0.2388	Thk. Wall	Thk. Wall
1.00	4200	0.1144	0.1236	0.1441	0.1678	0.1994	Thk. Wall	Thk. Wall	Thk. Wall
1.25	2000	0.0753	0.0816	0.0955	0.1122	0.1351	0.1874	0.2563	Thk. Wall
1.25	2400	0.0882	0.0955	0.1119	0.1313	0.1578	0.2175	0.2947	Thk. Wall
1.25	2800	0.1008	0.1092	0.1278	0.1497	0.1795	0.2460	Thk. Wall	Thk. Wall
1.25	3200	0.1132	0.1225	0.1432	0.1675	0.2004	0.2729	Thk. Wall	Thk. Wall
1.25	3600	0.1253	0.1356	0.1583	0.1848	0.2205	0.2985	Thk. Wall	Thk. Wall
1.25	4200	0.1430	0.1546	0.1801	0.2097	0.2493	Thk. Wall	Thk. Wall	Thk. Wall
1.50	2000	0.0904	0.0979	0.1146	0.1346	0.1621	0.2249	0.3075	Thk. Wall
1.50	2400	0.1059	0.1146	0.1343	0.1575	0.1893	0.2610	0.3537	Thk. Wall
1.50	2800	0.1210	0.1310	0.1533	0.1796	0.2154	0.2952	Thk. Wall	Thk. Wall
1.50	3200	0.1358	0.1470	0.1719	0.2010	0.2405	0.3275	Thk. Wall	Thk. Wall
1.50	3600	0.1504	0.1627	0.1899	0.2218	0.2646	0.3581	Thk. Wall	Thk. Wall
1.50	4200	0.1716	0.1855	0.2161	0.2517	0.2992	Thk. Wall	Thk. Wall	Thk. Wall
1.75	2000	0.1054	0.1142	0.1338	0.1571	0.1892	0.2624	0.3588	Thk. Wall
1.75	2400	0.1235	0.1338	0.1566	0.1838	0.2209	0.3045	0.4126	Thk. Wall
1.75	2800	0.1412	0.1529	0.1789	0.2096	0.2513	0.3444	Thk. Wall	Thk. Wall
1.75	3200	0.1585	0.1715	0.2005	0.2346	0.2806	0.3821	Thk. Wall	Thk. Wall
1.75	3600	0.1754	0.1898	0.2216	0.2588	0.3088	0.4178	Thk. Wall	Thk. Wall
1.75	4200	0.2002	0.2164	0.2521	0.2936	0.3490	Thk. Wall	Thk. Wall	Thk. Wall
2.00	2000	0.1205	0.1305	0.1529	0.1795	0.2162	0.2999	0.4100	Thk. Wall
2.00	2400	0.1411	0.1529	0.1790	0.2100	0.2524	0.3480	0.4715	Thk. Wall
2.00	2800	0.1614	0.1747	0.2044	0.2395	0.2872	0.3936	Thk. Wall	Thk. Wall
2.00	3200	0.1811	0.1960	0.2292	0.2681	0.3207	0.4367	Thk. Wall	Thk. Wall
2.00	3600	0.2005	0.2169	0.2532	0.2957	0.3529	0.4775	Thk. Wall	Thk. Wall
2.00	4200	0.2288	0.2473	0.2881	0.3356	0.3989	Thk. Wall	Thk. Wall	Thk. Wall
2.25	2000	0.1356	0.1468	0.1720	0.2019	0.2432	0.3373	0.4613	Thk. Wall
2.25	2400	0.1588	0.1720	0.2014	0.2363	0.2840	0.3915	0.5305	Thk. Wall
2.25	2800	0.1815	0.1965	0.2300	0.2694	0.3231	0.4428	Thk. Wall	Thk. Wall
2.25	3200	0.2038	0.2206	0.2578	0.3016	0.3608	0.4913	Thk. Wall	Thk. Wall
2.25	3600	0.2255	0.2440	0.2849	0.3327	0.3970	0.5372	Thk. Wall	Thk. Wall
2.25	4200	0.2573	0.2782	0.3242	0.3775	0.4488	Thk. Wall	Thk. Wall	Thk. Wall
2.50	2000	0.1506	0.1631	0.1911	0.2244	0.2702	0.3748	0.5125	Thk. Wall
2.50	2400	0.1764	0.1911	0.2238	0.2625	0.3155	0.4350	0.5894	Thk. Wall
2.50	2800	0.2017	0.2184	0.2556	0.2994	0.3590	0.4920	Thk. Wall	Thk. Wall
2.50	3200	0.2264	0.2451	0.2865	0.3351	0.4008	0.5458	Thk. Wall	Thk. Wall
2.50	3600	0.2506	0.2711	0.3166	0.3696	0.4411	0.5969	Thk. Wall	Thk. Wall
2.50	4200	0.2859	0.3091	0.3602	0.4195	0.4986	Thk. Wall	Thk. Wall	Thk. Wall

		MWT for SA-213-T11									
		Mean Wall Temperatures, F									
		650	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**
Sall, ksi		15.4	15.1	14.8	14.4	14.0	13.6	***9.3***	***6.3***	***4.2***	***2.8***
Tube OD, in	**Pressure, psig**										
1.00	2000	0.0660	0.0671	0.0683	0.0699	0.0717	0.0735	0.1021	0.1420	0.1973	Thk. Wall
1.00	2400	0.0773	0.0786	0.0800	0.0819	0.0839	0.0861	0.1193	0.1650	0.2272	Thk. Wall
1.00	2800	0.0883	0.0898	0.0914	0.0936	0.0959	0.0983	0.1358	0.1868	Thk. Wall	Thk. Wall
1.00	3200	0.0991	0.1008	0.1026	0.1050	0.1076	0.1103	0.1518	0.2075	Thk. Wall	Thk. Wall
1.00	3600	0.1097	0.1115	0.1134	0.1161	0.1189	0.1219	0.1672	0.2272	Thk. Wall	Thk. Wall
1.00	4200	0.1250	0.1271	0.1293	0.1323	0.1354	0.1388	0.1892	Thk. Wall	Thk. Wall	Thk. Wall
1.25	2000	0.0825	0.0839	0.0854	0.0874	0.0896	0.0919	0.1276	0.1775	0.2466	Thk. Wall
1.25	2400	0.0966	0.0983	0.1000	0.1024	0.1049	0.1076	0.1491	0.2063	0.2840	Thk. Wall
1.25	2800	0.1104	0.1123	0.1143	0.1170	0.1199	0.1229	0.1698	0.2335	Thk. Wall	Thk. Wall
1.25	3200	0.1239	0.1260	0.1282	0.1313	0.1345	0.1378	0.1897	0.2594	Thk. Wall	Thk. Wall
1.25	3600	0.1371	0.1394	0.1418	0.1451	0.1487	0.1524	0.2090	0.2840	Thk. Wall	Thk. Wall
1.25	4200	0.1563	0.1589	0.1616	0.1653	0.1693	0.1734	0.2365	Thk. Wall	Thk. Wall	Thk. Wall
1.50	2000	0.0990	0.1007	0.1024	0.1049	0.1075	0.1102	0.1531	0.2130	0.2960	Thk. Wall
1.50	2400	0.1159	0.1179	0.1200	0.1229	0.1259	0.1291	0.1789	0.2475	0.3408	Thk. Wall
1.50	2800	0.1325	0.1348	0.1371	0.1404	0.1439	0.1475	0.2038	0.2802	Thk. Wall	Thk. Wall
1.50	3200	0.1487	0.1512	0.1538	0.1575	0.1613	0.1654	0.2277	0.3113	Thk. Wall	Thk. Wall
1.50	3600	0.1645	0.1673	0.1702	0.1742	0.1784	0.1828	0.2507	0.3408	Thk. Wall	Thk. Wall
1.50	4200	0.1875	0.1906	0.1939	0.1984	0.2032	0.2081	0.2838	Thk. Wall	Thk. Wall	Thk. Wall
1.75	2000	0.1155	0.1174	0.1195	0.1224	0.1254	0.1286	0.1787	0.2485	0.3453	Thk. Wall
1.75	2400	0.1353	0.1376	0.1400	0.1434	0.1469	0.1506	0.2088	0.2888	0.3976	Thk. Wall
1.75	2800	0.1546	0.1572	0.1600	0.1638	0.1678	0.1721	0.2377	0.3269	Thk. Wall	Thk. Wall
1.75	3200	0.1735	0.1764	0.1795	0.1838	0.1882	0.1930	0.2656	0.3632	Thk. Wall	Thk. Wall
1.75	3600	0.1919	0.1951	0.1985	0.2032	0.2081	0.2133	0.2925	0.3976	Thk. Wall	Thk. Wall
1.75	4200	0.2188	0.2224	0.2262	0.2315	0.2370	0.2428	0.3311	Thk. Wall	Thk. Wall	Thk. Wall
2.00	2000	0.1320	0.1342	0.1366	0.1399	0.1433	0.1470	0.2042	0.2840	0.3946	Thk. Wall
2.00	2400	0.1546	0.1572	0.1600	0.1638	0.1679	0.1722	0.2386	0.3300	0.4544	Thk. Wall
2.00	2800	0.1767	0.1797	0.1828	0.1872	0.1918	0.1967	0.2717	0.3736	Thk. Wall	Thk. Wall
2.00	3200	0.1982	0.2016	0.2051	0.2100	0.2151	0.2205	0.3036	0.4151	Thk. Wall	Thk. Wall
2.00	3600	0.2193	0.2230	0.2269	0.2322	0.2378	0.2438	0.3343	0.4544	Thk. Wall	Thk. Wall
2.00	4200	0.2500	0.2542	0.2585	0.2645	0.2709	0.2775	0.3784	Thk. Wall	Thk. Wall	Thk. Wall
2.25	2000	0.1484	0.1510	0.1537	0.1574	0.1613	0.1654	0.2297	0.3195	0.4439	Thk. Wall
2.25	2400	0.1739	0.1769	0.1800	0.1843	0.1889	0.1937	0.2684	0.3713	0.5113	Thk. Wall
2.25	2800	0.1988	0.2022	0.2057	0.2106	0.2158	0.2213	0.3056	0.4203	Thk. Wall	Thk. Wall
2.25	3200	0.2230	0.2268	0.2308	0.2363	0.2420	0.2481	0.3415	0.4669	Thk. Wall	Thk. Wall
2.25	3600	0.2467	0.2509	0.2552	0.2613	0.2676	0.2742	0.3761	0.5113	Thk. Wall	Thk. Wall
2.25	4200	0.2813	0.2860	0.2908	0.2976	0.3047	0.3122	0.4257	Thk. Wall	Thk. Wall	Thk. Wall
2.50	2000	0.1649	0.1678	0.1707	0.1748	0.1792	0.1837	0.2552	0.3550	0.4933	Thk. Wall
2.50	2400	0.1932	0.1965	0.2000	0.2048	0.2099	0.2152	0.2982	0.4125	0.5681	Thk. Wall
2.50	2800	0.2208	0.2246	0.2285	0.2340	0.2398	0.2458	0.3396	0.4670	Thk. Wall	Thk. Wall
2.50	3200	0.2478	0.2520	0.2564	0.2625	0.2689	0.2757	0.3795	0.5188	Thk. Wall	Thk. Wall
2.50	3600	0.2741	0.2788	0.2836	0.2903	0.2973	0.3047	0.4179	0.5681	Thk. Wall	Thk. Wall
2.50	4200	0.3125	0.3177	0.3232	0.3307	0.3386	0.3469	0.4730	Thk. Wall	Thk. Wall	Thk. Wall

		MWT for SA-213-T22									
		Mean Wall Temperatures, F									
		650	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**
Sall, ksi		16.6	16.6	16.6	16.6	16.6	***13.6***	***10.8***	***8.0***	***5.7***	***3.8***
Tube OD, in	**Pressure, psig**										
1.00	2000	0.0618	0.0618	0.0618	0.0618	0.0618	0.0735	0.0897	0.1161	0.1543	0.2133
1.00	2400	0.0724	0.0724	0.0724	0.0724	0.0724	0.0861	0.1050	0.1354	0.1789	0.2450
1.00	2800	0.0828	0.0828	0.0828	0.0828	0.0828	0.0983	0.1198	0.1539	0.2022	Thk. Wall
1.00	3200	0.0929	0.0929	0.0929	0.0929	0.0929	0.1103	0.1340	0.1717	0.2242	Thk. Wall
1.00	3600	0.1028	0.1028	0.1028	0.1028	0.1028	0.1219	0.1479	0.1887	0.2450	Thk. Wall
1.00	4200	0.1173	0.1173	0.1173	0.1173	0.1173	0.1388	0.1678	0.2129	Thk. Wall	Thk. Wall
1.25	2000	0.0773	0.0773	0.0773	0.0773	0.0773	0.0919	0.1122	0.1451	0.1928	0.2667
1.25	2400	0.0905	0.0905	0.0905	0.0905	0.0905	0.1076	0.1313	0.1693	0.2236	0.3063
1.25	2800	0.1035	0.1035	0.1035	0.1035	0.1035	0.1229	0.1497	0.1924	0.2527	Thk. Wall
1.25	3200	0.1161	0.1161	0.1161	0.1161	0.1161	0.1378	0.1675	0.2146	0.2802	Thk. Wall
1.25	3600	0.1285	0.1285	0.1285	0.1285	0.1285	0.1524	0.1848	0.2358	0.3063	Thk. Wall
1.25	4200	0.1466	0.1466	0.1466	0.1466	0.1466	0.1734	0.2097	0.2662	Thk. Wall	Thk. Wall
1.50	2000	0.0927	0.0927	0.0927	0.0927	0.0927	0.1102	0.1346	0.1742	0.2314	0.3200
1.50	2400	0.1086	0.1086	0.1086	0.1086	0.1086	0.1291	0.1575	0.2032	0.2684	0.3675
1.50	2800	0.1242	0.1242	0.1242	0.1242	0.1242	0.1475	0.1796	0.2309	0.3033	Thk. Wall
1.50	3200	0.1394	0.1394	0.1394	0.1394	0.1394	0.1654	0.2010	0.2575	0.3363	Thk. Wall
1.50	3600	0.1542	0.1542	0.1542	0.1542	0.1542	0.1828	0.2218	0.2830	0.3675	Thk. Wall
1.50	4200	0.1759	0.1759	0.1759	0.1759	0.1759	0.2081	0.2517	0.3194	Thk. Wall	Thk. Wall
1.75	2000	0.1082	0.1082	0.1082	0.1082	0.1082	0.1286	0.1571	0.2032	0.2699	0.3733
1.75	2400	0.1267	0.1267	0.1267	0.1267	0.1267	0.1506	0.1838	0.2370	0.3131	0.4288
1.75	2800	0.1449	0.1449	0.1449	0.1449	0.1449	0.1721	0.2096	0.2694	0.3538	Thk. Wall
1.75	3200	0.1626	0.1626	0.1626	0.1626	0.1626	0.1930	0.2346	0.3004	0.3923	Thk. Wall
1.75	3600	0.1799	0.1799	0.1799	0.1799	0.1799	0.2133	0.2588	0.3302	0.4288	Thk. Wall
1.75	4200	0.2053	0.2053	0.2053	0.2053	0.2053	0.2428	0.2936	0.3726	Thk. Wall	Thk. Wall
2.00	2000	0.1236	0.1236	0.1236	0.1236	0.1236	0.1470	0.1795	0.2322	0.3085	0.4267
2.00	2400	0.1448	0.1448	0.1448	0.1448	0.1448	0.1722	0.2100	0.2709	0.3578	0.4900
2.00	2800	0.1656	0.1656	0.1656	0.1656	0.1656	0.1967	0.2395	0.3079	0.4044	Thk. Wall
2.00	3200	0.1858	0.1858	0.1858	0.1858	0.1858	0.2205	0.2681	0.3433	0.4484	Thk. Wall
2.00	3600	0.2057	0.2057	0.2057	0.2057	0.2057	0.2438	0.2957	0.3773	0.4900	Thk. Wall
2.00	4200	0.2346	0.2346	0.2346	0.2346	0.2346	0.2775	0.3356	0.4258	Thk. Wall	Thk. Wall
2.25	2000	0.1391	0.1391	0.1391	0.1391	0.1391	0.1654	0.2019	0.2613	0.3471	0.4800
2.25	2400	0.1629	0.1629	0.1629	0.1629	0.1629	0.1937	0.2363	0.3047	0.4026	0.5513
2.25	2800	0.1863	0.1863	0.1863	0.1863	0.1863	0.2213	0.2694	0.3464	0.4549	Thk. Wall
2.25	3200	0.2091	0.2091	0.2091	0.2091	0.2091	0.2481	0.3016	0.3863	0.5044	Thk. Wall
2.25	3600	0.2314	0.2314	0.2314	0.2314	0.2314	0.2742	0.3327	0.4245	0.5513	Thk. Wall
2.25	4200	0.2639	0.2639	0.2639	0.2639	0.2639	0.3122	0.3775	0.4791	Thk. Wall	Thk. Wall
2.50	2000	0.1545	0.1545	0.1545	0.1545	0.1545	0.1837	0.2244	0.2903	0.3856	0.5333
2.50	2400	0.1810	0.1810	0.1810	0.1810	0.1810	0.2152	0.2625	0.3386	0.4473	0.6125
2.50	2800	0.2069	0.2069	0.2069	0.2069	0.2069	0.2458	0.2994	0.3848	0.5055	Thk. Wall
2.50	3200	0.2323	0.2323	0.2323	0.2323	0.2323	0.2757	0.3351	0.4292	0.5604	Thk. Wall
2.50	3600	0.2571	0.2571	0.2571	0.2571	0.2571	0.3047	0.3696	0.4717	0.6125	Thk. Wall
2.50	4200	0.2932	0.2932	0.2932	0.2932	0.2932	0.3469	0.4195	0.5323	Thk. Wall	Thk. Wall

4.2.2 Cladding Opportunity Matrices with Water Backing

The next series of three tables (one for each tube material) shows the tubes which meet the cladding criteria with water backing. The left "diagonal" tubes (original colored yellow) are too thin, the right "diagonal" tubes (original colored light blue) are too thick for the usual Section I formula, and the tubes in the middle (original background white) are "just right" to be eligible for cladding. It can be seen that the cladding opportunities increase with larger OD and higher pressure. Additionally, water backing offers more cladding opportunities than exist without water backing by permitting thinner original tubes (0.170 in. versus 0.210 in. thickness).

		MWT for SA-210-A1							
		Mean Wall Temperatures, F							
		650	**700**	**750**	**800**	**850**	**900**	**950**	**1000**
Sall, ksi		17.1	***15.6***	***13.0***	***10.8***	***8.7***	***5.9***	***4.0***	***2.5***
Tube OD, in	**Pressure, psig**								
1.00	2000	0.0602	0.0652	0.0764	0.0897	0.1081	0.1499	0.2050	Thk. Wall
1.00	2400	0.0706	0.0764	0.0895	0.1050	0.1262	0.1740	0.2358	Thk. Wall
1.00	2800	0.0807	0.0874	0.1022	0.1198	0.1436	0.1968	Thk. Wall	Thk. Wall
1.00	3200	0.0906	0.0980	0.1146	0.1340	0.1603	0.2183	Thk. Wall	Thk. Wall
1.00	3600	0.1002	0.1084	0.1266	0.1479	0.1764	0.2388	Thk. Wall	Thk. Wall
1.00	4200	0.1144	0.1236	0.1441	0.1678	0.1994	Thk. Wall	Thk. Wall	Thk. Wall
1.25	2000	0.0753	0.0816	0.0955	0.1122	0.1351	0.1874	0.2563	Thk. Wall
1.25	2400	0.0882	0.0955	0.1119	0.1313	0.1578	0.2175	0.2947	Thk. Wall
1.25	2800	0.1008	0.1092	0.1278	0.1497	0.1795	0.2460	Thk. Wall	Thk. Wall
1.25	3200	0.1132	0.1225	0.1432	0.1675	0.2004	0.2729	Thk. Wall	Thk. Wall
1.25	3600	0.1253	0.1356	0.1583	0.1848	0.2205	0.2985	Thk. Wall	Thk. Wall
1.25	4200	0.1430	0.1546	0.1801	0.2097	0.2493	Thk. Wall	Thk. Wall	Thk. Wall
1.50	2000	0.0904	0.0979	0.1146	0.1346	0.1621	0.2249	0.3075	Thk. Wall
1.50	2400	0.1059	0.1146	0.1343	0.1575	0.1893	0.2610	0.3537	Thk. Wall
1.50	2800	0.1210	0.1310	0.1533	0.1796	0.2154	0.2952	Thk. Wall	Thk. Wall
1.50	3200	0.1358	0.1470	0.1719	0.2010	0.2405	0.3275	Thk. Wall	Thk. Wall
1.50	3600	0.1504	0.1627	0.1899	0.2218	0.2646	0.3581	Thk. Wall	Thk. Wall
1.50	4200	0.1716	0.1855	0.2161	0.2517	0.2992	Thk. Wall	Thk. Wall	Thk. Wall
1.75	2000	0.1054	0.1142	0.1338	0.1571	0.1892	0.2624	0.3588	Thk. Wall
1.75	2400	0.1235	0.1338	0.1566	0.1838	0.2209	0.3045	0.4126	Thk. Wall
1.75	2800	0.1412	0.1529	0.1789	0.2096	0.2513	0.3444	Thk. Wall	Thk. Wall
1.75	3200	0.1585	0.1715	0.2005	0.2346	0.2806	0.3821	Thk. Wall	Thk. Wall
1.75	3600	0.1754	0.1898	0.2216	0.2588	0.3088	0.4178	Thk. Wall	Thk. Wall
1.75	4200	0.2002	0.2164	0.2521	0.2936	0.3490	Thk. Wall	Thk. Wall	Thk. Wall
2.00	2000	0.1205	0.1305	0.1529	0.1795	0.2162	0.2999	0.4100	Thk. Wall
2.00	2400	0.1411	0.1529	0.1790	0.2100	0.2524	0.3480	0.4715	Thk. Wall
2.00	2800	0.1614	0.1747	0.2044	0.2395	0.2872	0.3936	Thk. Wall	Thk. Wall
2.00	3200	0.1811	0.1960	0.2292	0.2681	0.3207	0.4367	Thk. Wall	Thk. Wall
2.00	3600	0.2005	0.2169	0.2532	0.2957	0.3529	0.4775	Thk. Wall	Thk. Wall
2.00	4200	0.2288	0.2473	0.2881	0.3356	0.3989	Thk. Wall	Thk. Wall	Thk. Wall
2.25	2000	0.1356	0.1468	0.1720	0.2019	0.2432	0.3373	0.4613	Thk. Wall
2.25	2400	0.1588	0.1720	0.2014	0.2363	0.2840	0.3915	0.5305	Thk. Wall
2.25	2800	0.1815	0.1965	0.2300	0.2694	0.3231	0.4428	Thk. Wall	Thk. Wall
2.25	3200	0.2038	0.2206	0.2578	0.3016	0.3608	0.4913	Thk. Wall	Thk. Wall
2.25	3600	0.2255	0.2440	0.2849	0.3327	0.3970	0.5372	Thk. Wall	Thk. Wall
2.25	4200	0.2573	0.2782	0.3242	0.3775	0.4488	Thk. Wall	Thk. Wall	Thk. Wall
2.50	2000	0.1506	0.1631	0.1911	0.2244	0.2702	0.3748	0.5125	Thk. Wall
2.50	2400	0.1764	0.1911	0.2238	0.2625	0.3155	0.4350	0.5894	Thk. Wall
2.50	2800	0.2017	0.2184	0.2556	0.2994	0.3590	0.4920	Thk. Wall	Thk. Wall
2.50	3200	0.2264	0.2451	0.2865	0.3351	0.4008	0.5458	Thk. Wall	Thk. Wall
2.50	3600	0.2506	0.2711	0.3166	0.3696	0.4411	0.5969	Thk. Wall	Thk. Wall
2.50	4200	0.2859	0.3091	0.3602	0.4195	0.4986	Thk. Wall	Thk. Wall	Thk. Wall

		MWT for SA-213-T11									
		Mean Wall Temperatures, F									
		650	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**
Sall, ksi		15.4	15.1	14.8	14.4	14.0	13.6	***9.3***	***6.3***	***4.2***	***2.8***
Tube OD, in	**Pressure, psig**										
1.00	2000	0.0660	0.0671	0.0683	0.0699	0.0717	0.0735	0.1021	0.1420	0.1973	Thk. Wall
1.00	2400	0.0773	0.0786	0.0800	0.0819	0.0839	0.0861	0.1193	0.1650	0.2272	Thk. Wall
1.00	2800	0.0883	0.0898	0.0914	0.0936	0.0959	0.0983	0.1358	0.1868	Thk. Wall	Thk. Wall
1.00	3200	0.0991	0.1008	0.1026	0.1050	0.1076	0.1103	0.1518	0.2075	Thk. Wall	Thk. Wall
1.00	3600	0.1097	0.1115	0.1134	0.1161	0.1189	0.1219	0.1672	0.2272	Thk. Wall	Thk. Wall
1.00	4200	0.1250	0.1271	0.1293	0.1323	0.1354	0.1388	0.1892	Thk. Wall	Thk. Wall	Thk. Wall
1.25	2000	0.0825	0.0839	0.0854	0.0874	0.0896	0.0919	0.1276	0.1775	0.2466	Thk. Wall
1.25	2400	0.0966	0.0983	0.1000	0.1024	0.1049	0.1076	0.1491	0.2063	0.2840	Thk. Wall
1.25	2800	0.1104	0.1123	0.1143	0.1170	0.1199	0.1229	0.1698	0.2335	Thk. Wall	Thk. Wall
1.25	3200	0.1239	0.1260	0.1282	0.1313	0.1345	0.1378	0.1897	0.2594	Thk. Wall	Thk. Wall
1.25	3600	0.1371	0.1394	0.1418	0.1451	0.1487	0.1524	0.2090	0.2840	Thk. Wall	Thk. Wall
1.25	4200	0.1563	0.1589	0.1616	0.1653	0.1693	0.1734	0.2365	Thk. Wall	Thk. Wall	Thk. Wall
1.50	2000	0.0990	0.1007	0.1024	0.1049	0.1075	0.1102	0.1531	0.2130	0.2960	Thk. Wall
1.50	2400	0.1159	0.1179	0.1200	0.1229	0.1259	0.1291	0.1789	0.2475	0.3408	Thk. Wall
1.50	2800	0.1325	0.1348	0.1371	0.1404	0.1439	0.1475	0.2038	0.2802	Thk. Wall	Thk. Wall
1.50	3200	0.1487	0.1512	0.1538	0.1575	0.1613	0.1654	0.2277	0.3113	Thk. Wall	Thk. Wall
1.50	3600	0.1645	0.1673	0.1702	0.1742	0.1784	0.1828	0.2507	0.3408	Thk. Wall	Thk. Wall
1.50	4200	0.1875	0.1906	0.1939	0.1984	0.2032	0.2081	0.2838	Thk. Wall	Thk. Wall	Thk. Wall
1.75	2000	0.1155	0.1174	0.1195	0.1224	0.1254	0.1286	0.1787	0.2485	0.3453	Thk. Wall
1.75	2400	0.1353	0.1376	0.1400	0.1434	0.1469	0.1506	0.2088	0.2888	0.3976	Thk. Wall
1.75	2800	0.1546	0.1572	0.1600	0.1638	0.1678	0.1721	0.2377	0.3269	Thk. Wall	Thk. Wall
1.75	3200	0.1735	0.1764	0.1795	0.1838	0.1882	0.1930	0.2656	0.3632	Thk. Wall	Thk. Wall
1.75	3600	0.1919	0.1951	0.1985	0.2032	0.2081	0.2133	0.2925	0.3976	Thk. Wall	Thk. Wall
1.75	4200	0.2188	0.2224	0.2262	0.2315	0.2370	0.2428	0.3311	Thk. Wall	Thk. Wall	Thk. Wall
2.00	2000	0.1320	0.1342	0.1366	0.1399	0.1433	0.1470	0.2042	0.2840	0.3946	Thk. Wall
2.00	2400	0.1546	0.1572	0.1600	0.1638	0.1679	0.1722	0.2386	0.3300	0.4544	Thk. Wall
2.00	2800	0.1767	0.1797	0.1828	0.1872	0.1918	0.1967	0.2717	0.3736	Thk. Wall	Thk. Wall
2.00	3200	0.1982	0.2016	0.2051	0.2100	0.2151	0.2205	0.3036	0.4151	Thk. Wall	Thk. Wall
2.00	3600	0.2193	0.2230	0.2269	0.2322	0.2378	0.2438	0.3343	0.4544	Thk. Wall	Thk. Wall
2.00	4200	0.2500	0.2542	0.2585	0.2645	0.2709	0.2775	0.3784	Thk. Wall	Thk. Wall	Thk. Wall
2.25	2000	0.1484	0.1510	0.1537	0.1574	0.1613	0.1654	0.2297	0.3195	0.4439	Thk. Wall
2.25	2400	0.1739	0.1769	0.1800	0.1843	0.1889	0.1937	0.2684	0.3713	0.5113	Thk. Wall
2.25	2800	0.1988	0.2022	0.2057	0.2106	0.2158	0.2213	0.3056	0.4203	Thk. Wall	Thk. Wall
2.25	3200	0.2230	0.2268	0.2308	0.2363	0.2420	0.2481	0.3415	0.4669	Thk. Wall	Thk. Wall
2.25	3600	0.2467	0.2509	0.2552	0.2613	0.2676	0.2742	0.3761	0.5113	Thk. Wall	Thk. Wall
2.25	4200	0.2813	0.2860	0.2908	0.2976	0.3047	0.3122	0.4257	Thk. Wall	Thk. Wall	Thk. Wall
2.50	2000	0.1649	0.1678	0.1707	0.1748	0.1792	0.1837	0.2552	0.3550	0.4933	Thk. Wall
2.50	2400	0.1932	0.1965	0.2000	0.2048	0.2099	0.2152	0.2982	0.4125	0.5681	Thk. Wall
2.50	2800	0.2208	0.2246	0.2285	0.2340	0.2398	0.2458	0.3396	0.4670	Thk. Wall	Thk. Wall
2.50	3200	0.2478	0.2520	0.2564	0.2625	0.2689	0.2757	0.3795	0.5188	Thk. Wall	Thk. Wall
2.50	3600	0.2741	0.2788	0.2836	0.2903	0.2973	0.3047	0.4179	0.5681	Thk. Wall	Thk. Wall
2.50	4200	0.3125	0.3177	0.3232	0.3307	0.3386	0.3469	0.4730	Thk. Wall	Thk. Wall	Thk. Wall

		MWT for SA-213-T22									
		Mean Wall Temperatures, F									
		650	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**
Sall, ksi		16.6	16.6	16.6	16.6	16.6	***13.6***	***10.8***	***8.0***	***5.7***	***3.8***
Tube OD, in	**Pressure, psig**										
1.00	2000	0.0618	0.0618	0.0618	0.0618	0.0618	0.0735	0.0897	0.1161	0.1543	0.2133
1.00	2400	0.0724	0.0724	0.0724	0.0724	0.0724	0.0861	0.1050	0.1354	0.1789	0.2450
1.00	2800	0.0828	0.0828	0.0828	0.0828	0.0828	0.0983	0.1198	0.1539	0.2022	Thk. Wall
1.00	3200	0.0929	0.0929	0.0929	0.0929	0.0929	0.1103	0.1340	0.1717	0.2242	Thk. Wall
1.00	3600	0.1028	0.1028	0.1028	0.1028	0.1028	0.1219	0.1479	0.1887	0.2450	Thk. Wall
1.00	4200	0.1173	0.1173	0.1173	0.1173	0.1173	0.1388	0.1678	0.2129	Thk. Wall	Thk. Wall
1.25	2000	0.0773	0.0773	0.0773	0.0773	0.0773	0.0919	0.1122	0.1451	0.1928	0.2667
1.25	2400	0.0905	0.0905	0.0905	0.0905	0.0905	0.1076	0.1313	0.1693	0.2236	0.3063
1.25	2800	0.1035	0.1035	0.1035	0.1035	0.1035	0.1229	0.1497	0.1924	0.2527	Thk. Wall
1.25	3200	0.1161	0.1161	0.1161	0.1161	0.1161	0.1378	0.1675	0.2146	0.2802	Thk. Wall
1.25	3600	0.1285	0.1285	0.1285	0.1285	0.1285	0.1524	0.1848	0.2358	0.3063	Thk. Wall
1.25	4200	0.1466	0.1466	0.1466	0.1466	0.1466	0.1734	0.2097	0.2662	Thk. Wall	Thk. Wall
1.50	2000	0.0927	0.0927	0.0927	0.0927	0.0927	0.1102	0.1346	0.1742	0.2314	0.3200
1.50	2400	0.1086	0.1086	0.1086	0.1086	0.1086	0.1291	0.1575	0.2032	0.2684	0.3675
1.50	2800	0.1242	0.1242	0.1242	0.1242	0.1242	0.1475	0.1796	0.2309	0.3033	Thk. Wall
1.50	3200	0.1394	0.1394	0.1394	0.1394	0.1394	0.1654	0.2010	0.2575	0.3363	Thk. Wall
1.50	3600	0.1542	0.1542	0.1542	0.1542	0.1542	0.1828	0.2218	0.2830	0.3675	Thk. Wall
1.50	4200	0.1759	0.1759	0.1759	0.1759	0.1759	0.2081	0.2517	0.3194	Thk. Wall	Thk. Wall
1.75	2000	0.1082	0.1082	0.1082	0.1082	0.1082	0.1286	0.1571	0.2032	0.2699	0.3733
1.75	2400	0.1267	0.1267	0.1267	0.1267	0.1267	0.1506	0.1838	0.2370	0.3131	0.4288
1.75	2800	0.1449	0.1449	0.1449	0.1449	0.1449	0.1721	0.2096	0.2694	0.3538	Thk. Wall
1.75	3200	0.1626	0.1626	0.1626	0.1626	0.1626	0.1930	0.2346	0.3004	0.3923	Thk. Wall
1.75	3600	0.1799	0.1799	0.1799	0.1799	0.1799	0.2133	0.2588	0.3302	0.4288	Thk. Wall
1.75	4200	0.2053	0.2053	0.2053	0.2053	0.2053	0.2428	0.2936	0.3726	Thk. Wall	Thk. Wall
2.00	2000	0.1236	0.1236	0.1236	0.1236	0.1236	0.1470	0.1795	0.2322	0.3085	0.4267
2.00	2400	0.1448	0.1448	0.1448	0.1448	0.1448	0.1722	0.2100	0.2709	0.3578	0.4900
2.00	2800	0.1656	0.1656	0.1656	0.1656	0.1656	0.1967	0.2395	0.3079	0.4044	Thk. Wall
2.00	3200	0.1858	0.1858	0.1858	0.1858	0.1858	0.2205	0.2681	0.3433	0.4484	Thk. Wall
2.00	3600	0.2057	0.2057	0.2057	0.2057	0.2057	0.2438	0.2957	0.3773	0.4900	Thk. Wall
2.00	4200	0.2346	0.2346	0.2346	0.2346	0.2346	0.2775	0.3356	0.4258	Thk. Wall	Thk. Wall
2.25	2000	0.1391	0.1391	0.1391	0.1391	0.1391	0.1654	0.2019	0.2613	0.3471	0.4800
2.25	2400	0.1629	0.1629	0.1629	0.1629	0.1629	0.1937	0.2363	0.3047	0.4026	0.5513
2.25	2800	0.1863	0.1863	0.1863	0.1863	0.1863	0.2213	0.2694	0.3464	0.4549	Thk. Wall
2.25	3200	0.2091	0.2091	0.2091	0.2091	0.2091	0.2481	0.3016	0.3863	0.5044	Thk. Wall
2.25	3600	0.2314	0.2314	0.2314	0.2314	0.2314	0.2742	0.3327	0.4245	0.5513	Thk. Wall
2.25	4200	0.2639	0.2639	0.2639	0.2639	0.2639	0.3122	0.3775	0.4791	Thk. Wall	Thk. Wall
2.50	2000	0.1545	0.1545	0.1545	0.1545	0.1545	0.1837	0.2244	0.2903	0.3856	0.5333
2.50	2400	0.1810	0.1810	0.1810	0.1810	0.1810	0.2152	0.2625	0.3386	0.4473	0.6125
2.50	2800	0.2069	0.2069	0.2069	0.2069	0.2069	0.2458	0.2994	0.3848	0.5055	Thk. Wall
2.50	3200	0.2323	0.2323	0.2323	0.2323	0.2323	0.2757	0.3351	0.4292	0.5604	Thk. Wall
2.50	3600	0.2571	0.2571	0.2571	0.2571	0.2571	0.3047	0.3696	0.4717	0.6125	Thk. Wall
2.50	4200	0.2932	0.2932	0.2932	0.2932	0.2932	0.3469	0.4195	0.5323	Thk. Wall	Thk. Wall

4.3 Thermal Analysis

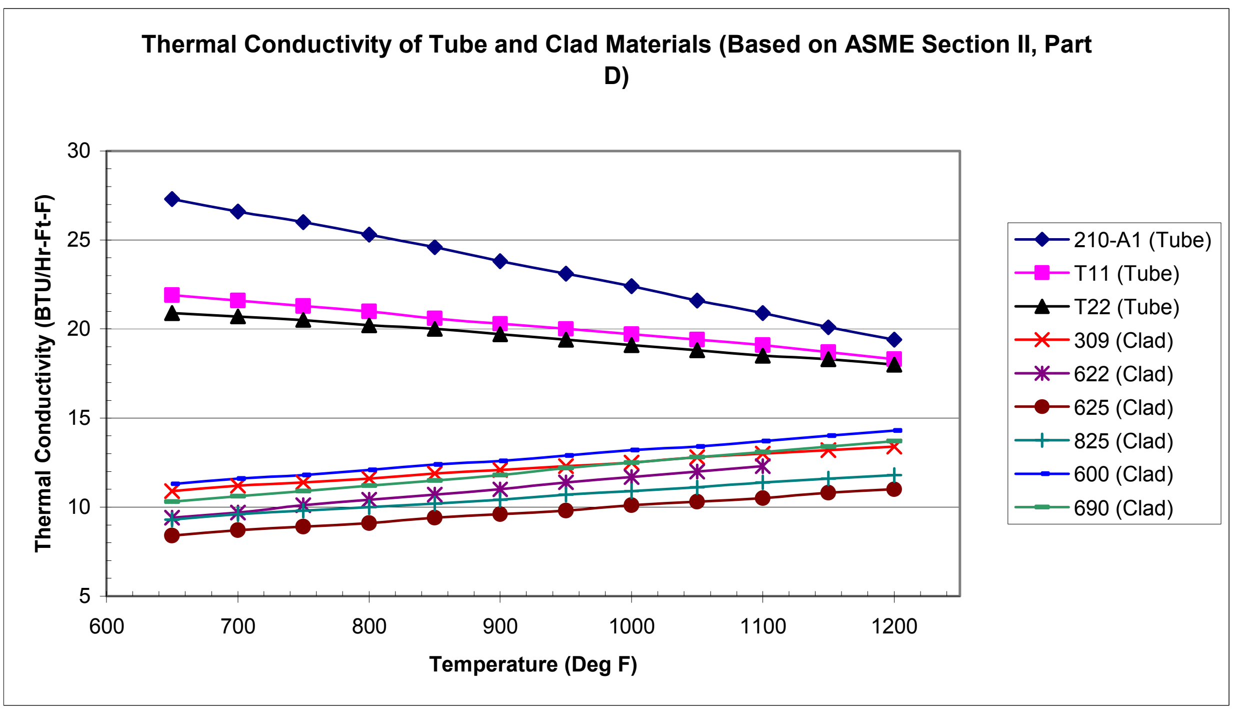
The methodology initially considered the cases where the base metal was ≥0.100 in. thick and the clad was 0.070 in. thick with analysis first performed for SA-210 A1 carbon steel tubing; this is the scenario with water backing. The methodology was as follows:

Computed heat flux (BTU/Hr-Ft^2) for bare tubes from the “opportunity matrix” for a through-wall ΔT of 50°F and 100°F. Heat flux was based on OD area.

Applied this heat flux to clad tube and computed interface temperature and surface OD temperature (Note interface temperature is same as that for bare tube at same heat flux)

4.3.1 Thermal Conductivities

The thermal conductivities are based on the compilation in the ASME B&PV Code Section II, Part D, Subpart 2, Table TCD (Nominal Coefficients of Thermal Conductivity (TC) and Thermal Diffusivity (TD)). The US Customary units for TC are BTU/Hr-Ft-°F. The figure below shows the results.



4.3.2 Thermal Flux for Bare Tubes and Fixed OD-to-ID Temperature Differential

The fundamental heat conduction equation is:

$$T - T1 = (q/A)(r3/k13) \ln (r/r1)$$

Where:

T = Temperature at arbitrary radius, r, F
T1 = Temperature at ID which is taken as the "1" location in this nomenclature, F

q = Heat transfer rate, BTU/Hr

A = Area; arbitrary for a cylinder and taken as the OD surface, Ft^2

(q/A) = Heat flux, BTU/Hr-Ft^2

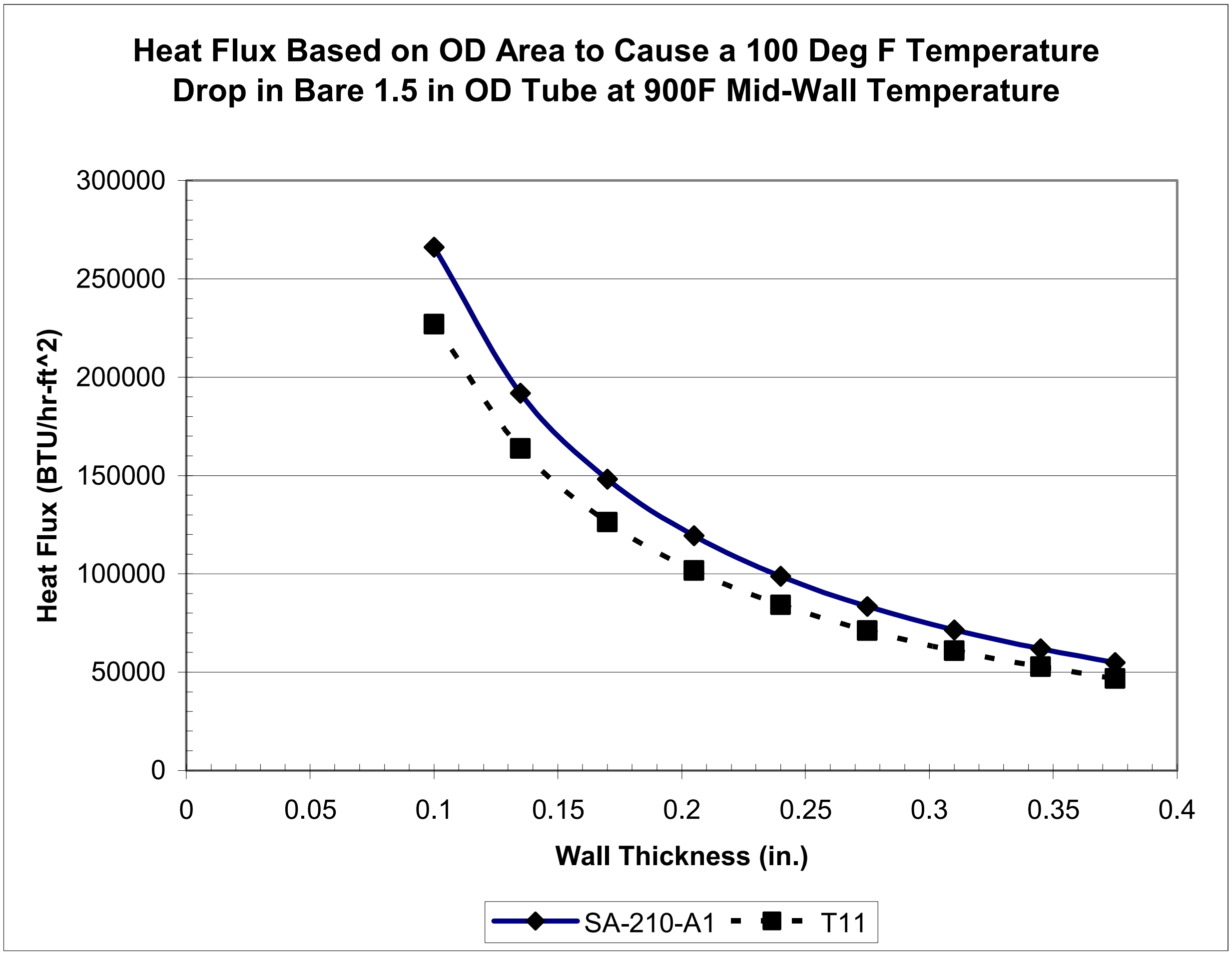
r = Arbitrary radius, Ft

r1 = Inside radius, Ft
r3 = Outside radius, Ft
k13 = Conductivity of the base material between the ID (1) and the OD (3), BTU/Hr-Ft-°F

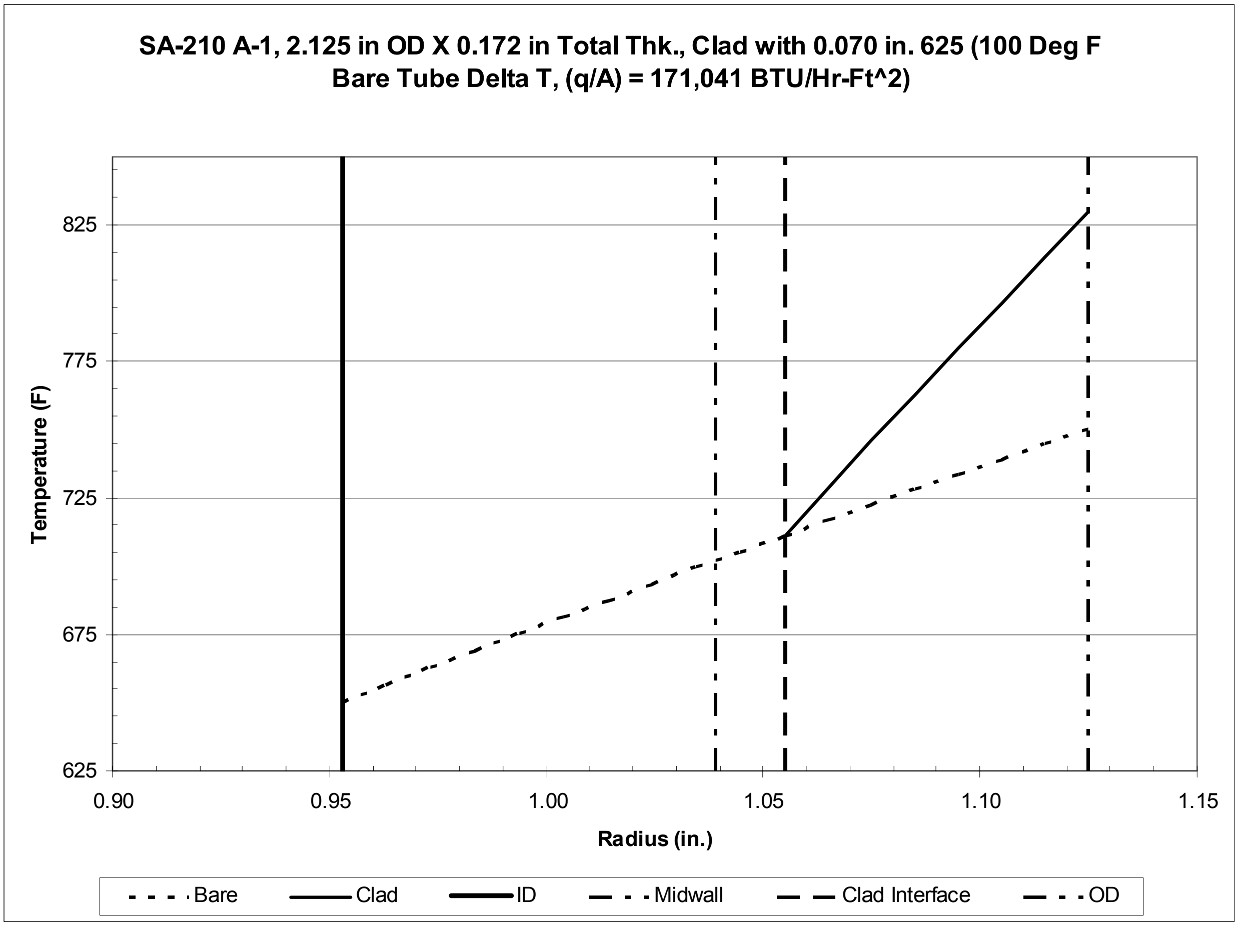
Considering the case where the OD and the ID temperature are fixed, the heat flux can be expressed as:

$$(q/A) = [2k13(T3 - T1)]/[D3 \ln (D3/D1)]$$

where D3 and D1 are the OD and ID, respectively, and T3 is the OD temperature. The following figure shows the heat flux for a 1.5 in. OD carbon steel and a T11 tube with a 900F midwall temperature ((T1+T3)/2) and a 100°F throughwall temperature drop.



While the temperature distribution is logarithmic, for thin walls it approaches linearity as illustrated in the following figure.



4.3.3 Clad Tube

For a fixed OD and ID temperature, the temperature, T2, at the interface between the base metal and the clad is:

$$T2 = \{T1 + T3[k23 \ln(D2/D1)/k12 \ln(D3/D2)]\} / \{1 + [k23 \ln(D2/D1)/k12 \ln(D3/D2)]\}$$

Where:

k12 = Thermal conductivity of tube base metal, BTU/Hr-Ft-°F

k23 = Thermal conductivity of clad, BTU/Hr-Ft-°F

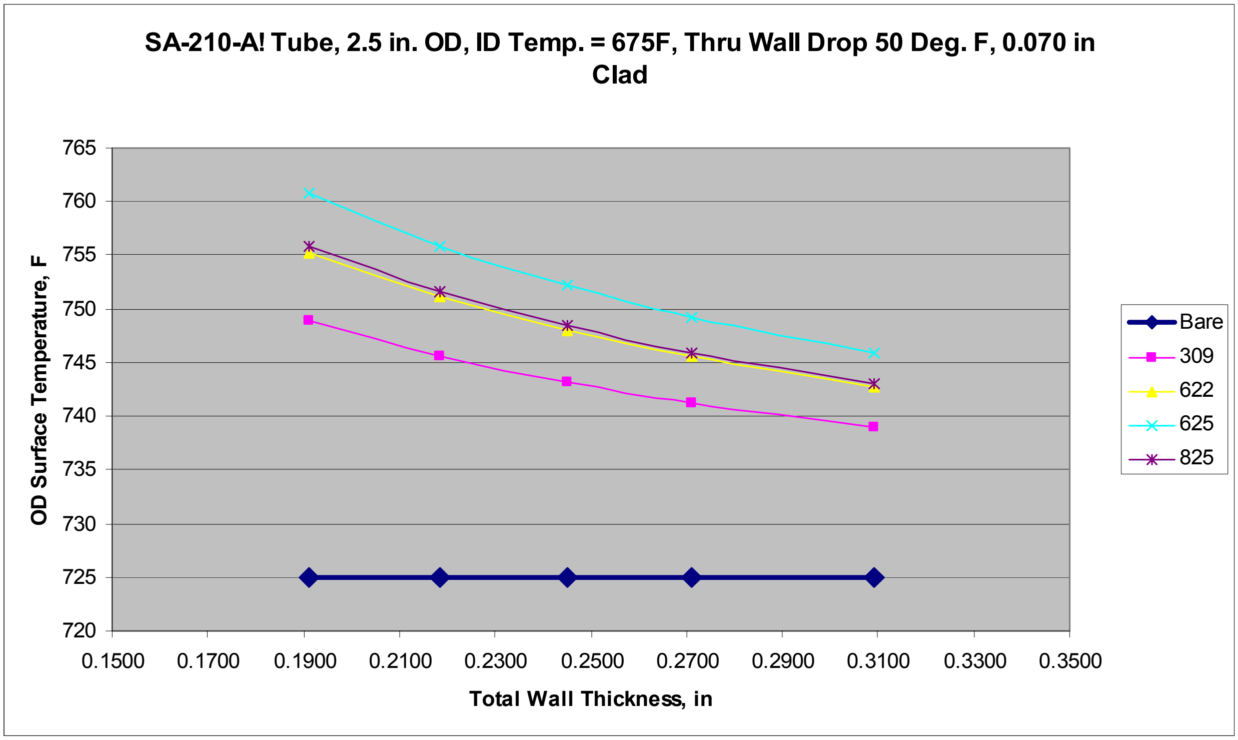
It follows that the heat flux for the bare tube is imposed on the clad tube using the following equation.

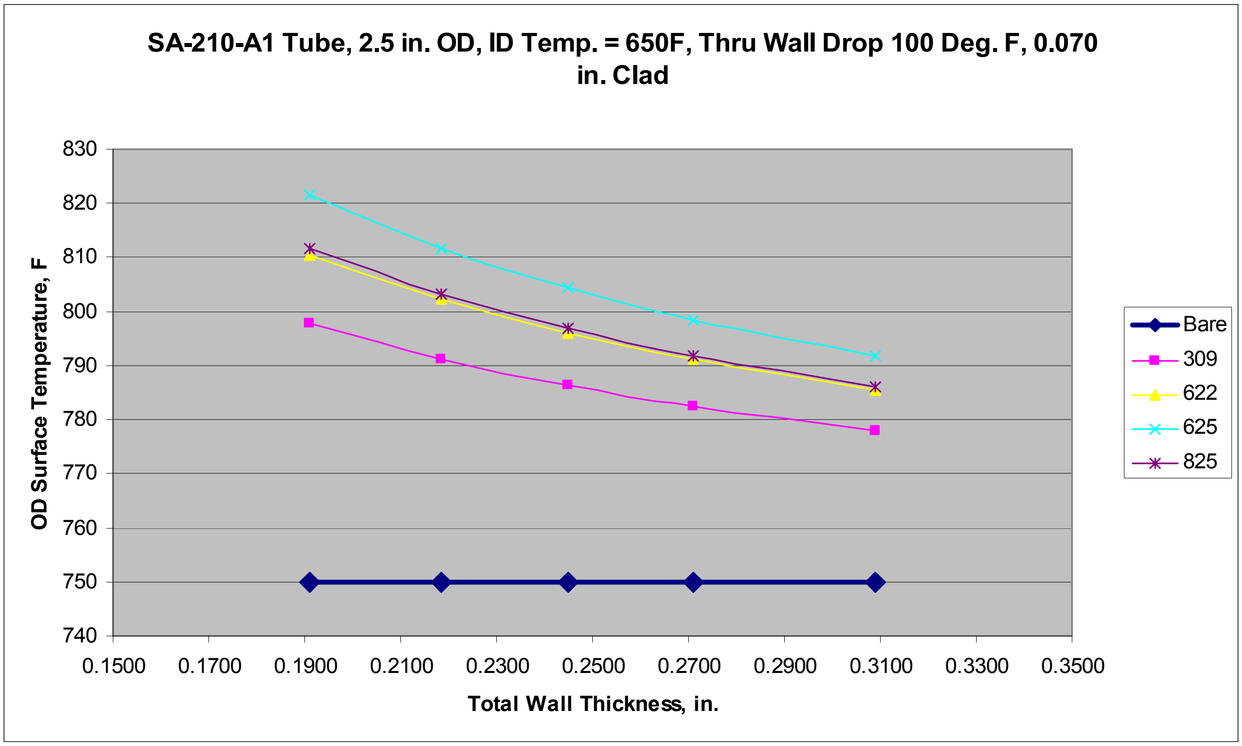
$$(q/A) = [2k12\ (T2-T1)/D3\ \ln(D2/D1)]$$

The interface temperature, T2, is the same for the bare and clad tube since the heat flux is taken as constant. Knowing the interface temperature and heat flux, the OD temperature of the clad can be calculated by solving for T3 in the following equation:

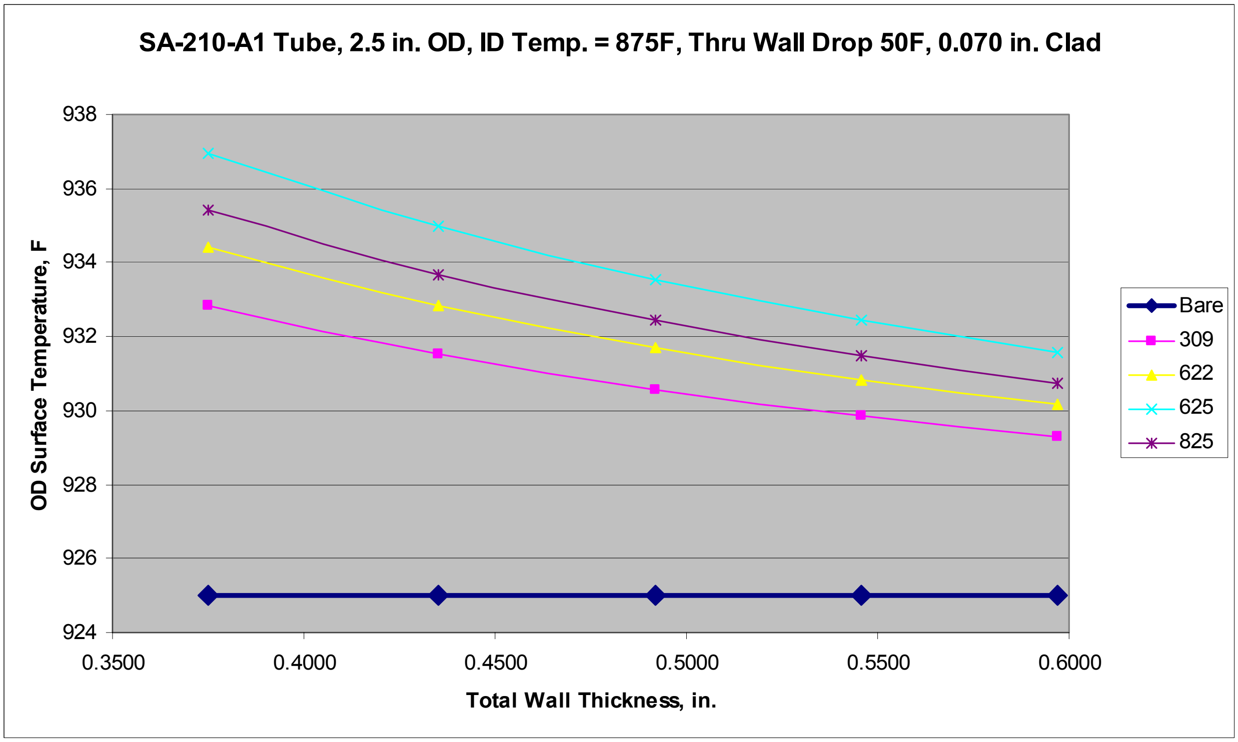
$$(q/A) = [2k23\ (T3-T2)/D3\ \ln(D3/D2)]$$

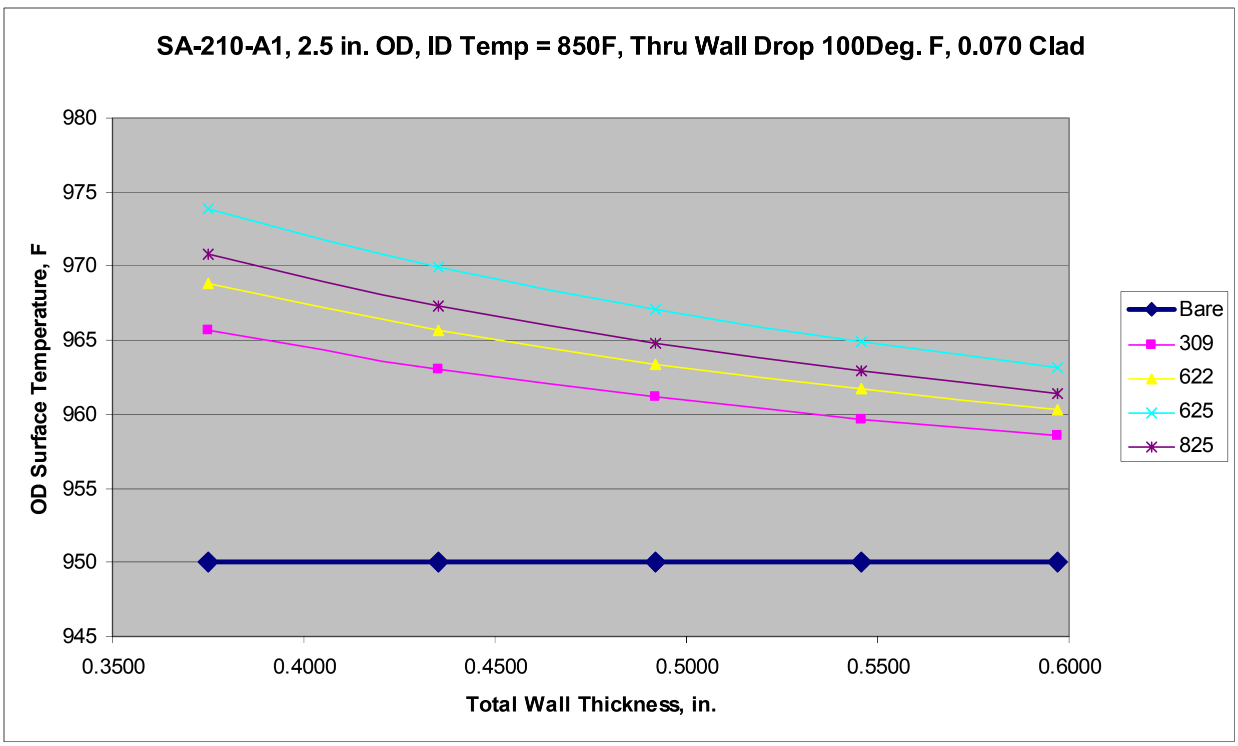
The next six figures show example cases in which the midwall temperature is 700F or 900F and the ΔT is either 50°F or 100°F for two tube ODs.

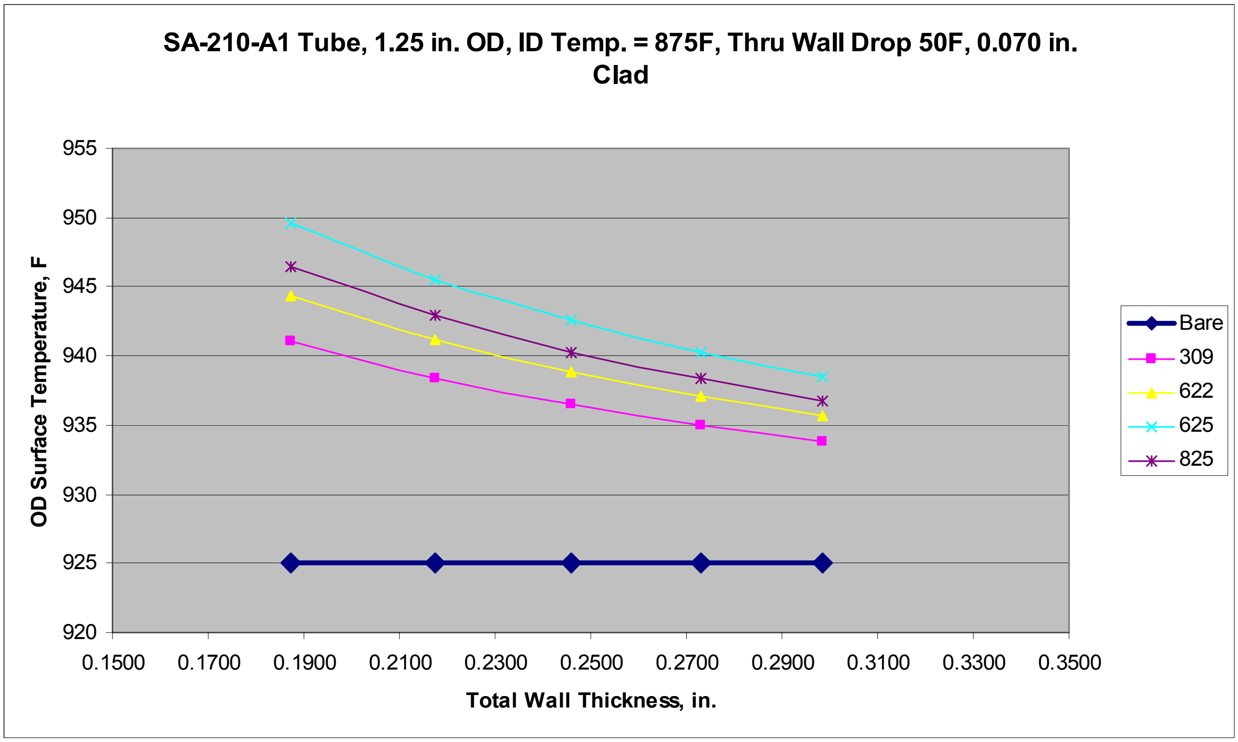


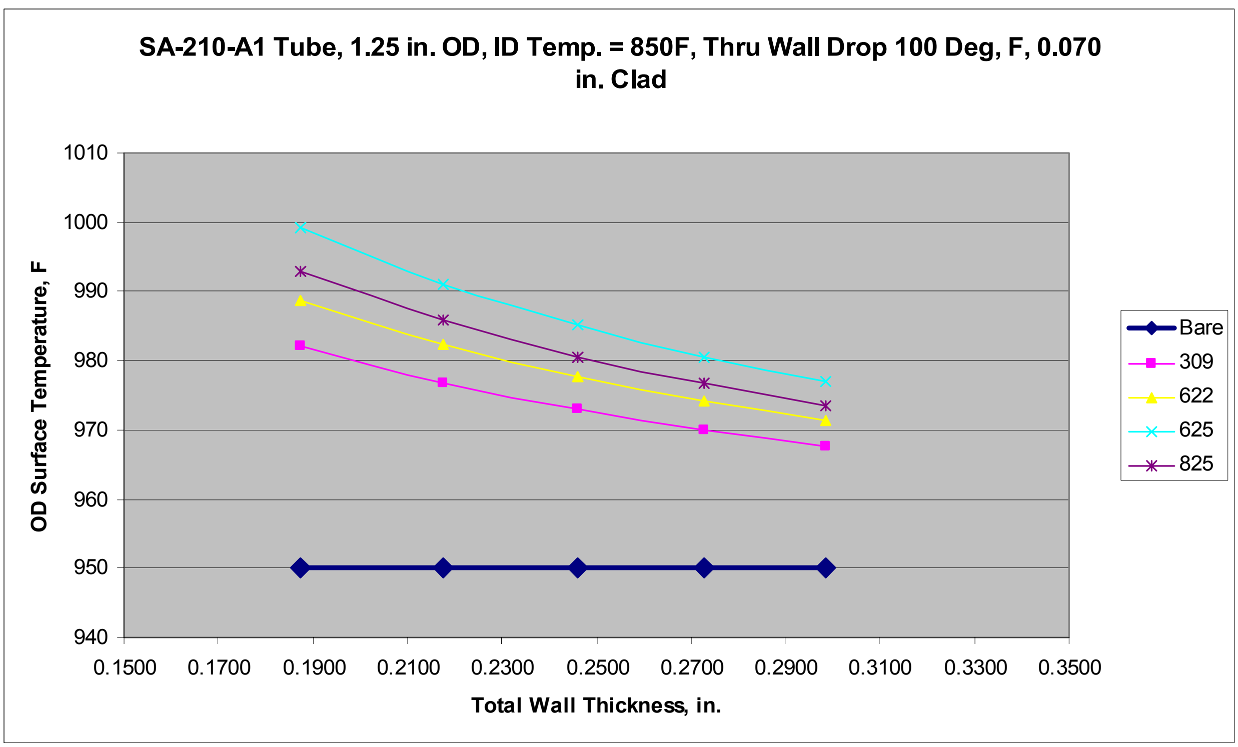


SA-210-A1 Tube, 2.5 in. OD, ID Temp. = 650F, Thru Wall Drop 100 Deg. F, 0.070 in. Clad
OD Surface Temperature, F
Total Wall Thickness, in.
830
820
810
800
790
780
770
760
750
740
0.1500
0.1700
0.1900
0.2100
0.2300
0.2500
0.2700
0.2900
0.3100
0.3300
0.3500
Bare
309
622
625
825


SA-210-A1 Tube, 2.5 in. OD, ID Temp. = 875F, Thru Wall Drop 50F, 0.070 in. Clad
OD Surface Temperature, F
938
936
934
932
930
928
926
924
0.3500
0.4000
0.4500
0.5000
0.5500
0.6000
Total Wall Thickness, in.
Bare
309
622
625
825


SA-210-A1, 2.5 in. OD, ID Temp = 850F, Thru Wall Drop 100Deg. F, 0.070 Clad
OD Surface Temperature, F
980
975
970
965
960
955
950
945
0.3500
0.4000
0.4500
0.5000
0.5500
0.6000
Total Wall Thickness, in.
Bare
309
622
625
825


SA-210-A1 Tube, 1.25 in. OD, ID Temp. = 875F, Thru Wall Drop 50F, 0.070 in. Clad
OD Surface Temperature, F
955
950
945
940
935
930
925
920
0.1500
0.1700
0.1900
0.2100
0.2300
0.2500
0.2700
0.2900
0.3100
0.3300
0.3500
Total Wall Thickness, in.
Bare
309
622
625
825


SA-210-A1 Tube, 1.25 in. OD, ID Temp. = 850F, Thru Wall Drop 100 Deg, F, 0.070 in. Clad
OD Surface Temperature, F
1010
1000
990
980
970
960
950
940
0.1500
0.1700
0.1900
0.2100
0.2300
0.2500
0.2700
0.2900
0.3100
0.3300
0.3500
Total Wall Thickness, in.
Bare
309
622
625
825

The initial cases used SA-210 A1 because the highest clad temperatures occur with the most conductive base metal relative to the clad. The following table shows the two cases from the SA-210 A1 opportunity matrix which produced the maximum through-clad ΔT. In both cases the total wall thickness was near the lower limit of 0.170 in.; i.e., the thinnest clad tubes possible. Note that without the clad the temperature drop through the first 0.070 in. of base metal was 38.73 and 35.26°F for the 2.25 in. OD and 1.00 in OD tube, respectively. Because it has the lowest thermal conductivity, the greatest through-clad ΔT occurs with Alloy 625. The ΔT through the clad minus the ΔT that would occur through the outer 0.070 in. is shown in the next-to-last column and the "Extra ΔT per Mil of Clad" is shown in the last column. Note that the highest extra ΔT for the 2.25 in. OD tube is 1.14°F per Mil and for the 1.00 in. OD tube 0.75°F per Mil. Thus, it appears a good thumb rule for conservatively estimating the OD temperature increase which results from cladding is about 1°F per Mil of clad thickness.

Maximum Clad Temperature for Tmw = 700F Cases and Thru-Wall ΔT=100°F						
Clad	**OD**	**t**	**Flux, BTU/Hr-Ft^2**	**Clad ΔT (T3-T2), °F**	**Clad less BM, °F**	**Extra ΔT per Mil of Clad**
210-A1	2.25	0.1720	171,041	38.73		
309	2.25	0.1720	171,041	91.98	53.25	0.76
622	2.25	0.1720	171,041	106.20	67.47	0.96
625	2.25	0.1720	171,041	118.41	79.68	**1.14**
825	2.25	0.1720	171,041	107.31	68.58	0.98
Maximum Clad Temperature for Tmw = 900F Cases and Thru-Wall ΔT=100°F						
Clad	**OD**	**t**	**Flux, BTU/Hr-Ft^2**	**Clad ΔT (T3-T2), °F**	**Clad less BM, °F**	**Extra ΔT per Mil of Clad**
210 A-1	1.00	0.1740	133,535	35.26		
309	1.00	0.1740	133,535	69.35	34.09	0.49
622	1.00	0.1740	133,535	76.29	41.03	0.59
625	1.00	0.1740	133,535	87.41	52.15	**0.75**
825	1.00	0.1740	133,535	80.69	45.43	0.65

4.3.4 Conclusions from Thermal Analysis

The thermal conductivity is highest for ferritic steels.

Thermal conductivity of ferritic steels decreases with temperature whereas the austenitics and nickel-based alloys increase. As a consequence, the clad OD surface temperature increase above midwall temperature diminishes with increasing temperature.

Through-wall ΔT is directly proportional to heat flux

At fixed through-wall ΔT and diameter, thin tubes have higher heat flux than thick tubes.

5

OVERALL CONCLUSIONS FROM STRENGTH AND THERMAL ANALYSIS

The Section VIII, Div. 1 clad rule is appropriate for use in clad boiler tubes for Section I with a recommended limit of clad thickness to total tube thickness of
≤ 0.50.

Tube base metal sizing should be based on midwall temperature of bare tube with same total thickness as clad tube.

For nickel-based alloys, the analyses performed indicate that clad will substitute on a 1:1 basis for carbon and low alloy steel.

For austenitic clads, there may be instances in which the equivalent clad thickness for strength has to be reduced by the ratio of $(S_c/S_b)t_c$ where t_c is the actual clad thickness.

Clad temperature for strength to be based on temperature at mid-clad thickness

Base metal temperature for strength to be based on bare tube (conservative).

6 REMAINING WORK

Add new rules to ASME Section I, Paragraph PG-27 to implement the Section VIII, Div. 1, Part UCL rules and achieve passage from ASME Section I and Standards Committee.

As a formality, complete the thermal analysis for T11 and T22 (SA-210 A-1 represents a "worse case" because it has the highest thermal conductivity).

Perform a simplified fatigue analysis to include a stress-concentration factor for fusion-line ripple.

Prepare a "white paper" summarizing results to facilitate Code passage.

Pursue similar changes in the NBIC Code and address the issue of whether restoration of BM by matching composition before cladding is necessary. This step will probably require some finite element analysis.

Explore tube sizing options for one-sided clad, such as occurs in field overlay of waterwalls, for the possibility of different wall thicknesses on the clad fireside versus the unclad casing side.

Completion of a final report detailing all analysis and results of work to incorporate into Code sections.

A
APPENDIX OF CLADDING RULES FROM UCL OF SECTION VIII, DIV. 1

SA-265, Nickel and Nickel–Base Alloy Clad Steel Plate.

In addition to the above, weld metal overlay cladding may be used as defined in this Part.

(b) Base material with corrosion resistant integral or weld metal overlay cladding used in constructions in which the design calculations are based on the base material thickness, exclusive of the thickness of the cladding material, may consist of any base material satisfying the requirements of UCL-10 and any metallic corrosion resistant integral or weld metal overlay cladding material of weldable quality that in the judgment of the user is suitable for the intended service.

(c) Base material with corrosion resistant integral cladding in which any part of the cladding is included in the design calculations, as permitted in UCL-23(c), shall show a minimum shear strength of 20,000 psi (140 MPa) when tested in the manner described in the clad plate specification. One shear test shall be made on each such clad plate as rolled, and the results shall be reported on the certified material test report.

When the composite thickness of the clad material is $^3/_4$ in. (19 mm) or less, and/or when the cladding metal thickness is nominally 0.075 in. (1.9 mm) or less, the "Bond Strength" test, as described in SA-263, SA-264, or SA-265, may be used in lieu of the bond "Shear Strength" test to fulfill the criteria for acceptable minimum shear strength, except that the bend test specimen shall be $1^1/_2$ in. (38 mm) wide by not more than $^3/_4$ in. (19 mm) in thickness and shall be bent, at room temperature, through an angle of 180 deg to the bend diameter provided for in the material specifications applicable to the backing metal. The results of the "Bond Strength" test shall be reported on the certified material test report.

(d) A shear or bond strength test is not required for weld metal overlay cladding.

(e) When any part of the cladding thickness is specified as an allowance for corrosion, such added thickness shall be removed before mill tension tests are made. When corrosion of the cladding is not expected, no part of the cladding need be removed before testing, even though excess thickness seems to have been provided or is available as corrosion allowance.

UCL-12 LINING

Material used for applied corrosion resistant lining may be any metallic material of weldable quality that in the judgment of the user is suitable for the intended purpose.

DESIGN

UCL-20 GENERAL

(a) The rules in the following paragraphs apply specifically to pressure vessels and vessel parts constructed of base material with corrosion resistant integral or weld metal overlay cladding and those having applied corrosion resistant linings and shall be used in conjunction with the general requirements for *Design* in Subsection A, and with the specific requirements for *Design* in Subsection B that pertain to the method of fabrication used.

(b) Minimum Thickness of Shells and Heads. The minimum thickness specified in UG-16(b) shall be the total thickness for clad material with corrosion resistant integral or weld metal overlay cladding and the base-material thickness for applied-lining construction.

UCL-23 MAXIMUM ALLOWABLE STRESS VALUES

(a) Applied Corrosion Resistant Linings. The thickness of material used for applied lining shall not be included in the computation for the required thickness of any lined vessel. The maximum allowable stress value shall be that given for the base material in Table UCS-23, or UNF-23.

(b) Integrally Clad Material Without Credit for Full Cladding Thickness. Except as permitted in (c) below, design calculations shall be based on the total thickness of the clad material less the specified nominal minimum thickness of cladding. A reasonable excess thickness either of the actual cladding or of the same thickness of corrosion resistant weld metal may be included in the design calculations as an equal thickness of base material. The maximum allowable stress value shall be that given for the base material referenced in Table UCS-23, UF-6, or UHT-23 and listed in Table 1A of Section II, Part D.

(c) Base Material with Corrosion Resistant Integral or Weld Metal Overlay Cladding With Credit for Cladding Thickness. When the base material with corrosion resistant integral cladding conforms to one of the specifications listed in UCL-11(a), or consists of an acceptable base material with corrosion resistant weld metal overlay and the joints are completed by depositing corrosion resisting weld metal over the weld in the base material to restore the cladding, the design calculations may be based on a thickness equal to the nominal thickness of the base material plus S_c/S_b times the nominal thickness of the cladding after any allowance provided for corrosion has been deducted, where

S_c = maximum allowable stress value for the integral cladding at the design temperature, or for corrosion resistant weld metal overlay cladding, that of the wrought material whose chemistry most closely approximates that of the cladding, at the design temperature

S_b = maximum allowable stress value for the base material at the design temperature

Where S_c is greater than S_b, the multiplier S_c/S_b shall be taken equal to unity. The maximum allowable stress value shall be that given for the base material referenced in Table UCS-23, UF-6, or UHT-23 and listed in Table 1A of Section II, Part D. Vessels in which the cladding is included in the computation of required thickness shall not be constructed for internal pressure under the provisions of Table UW-12, column (c).

The thickness of the corrosion resistant weld metal overlay cladding deposited by manual processes shall be verified by electrical or mechanical means. One examination shall be made for every head, shell course, or any other pressure retaining component for each welding process used. The location of examinations shall be chosen by the Inspector except that, when the Inspector has been duly notified in advance and cannot be present or otherwise make the selection, the fabricator may exercise his own judgment in selecting the locations.

UCL-24 MAXIMUM ALLOWABLE WORKING TEMPERATURE

(a) When the design calculations are based on the thickness of base material exclusive of lining or cladding thickness, the maximum service metal temperature of the vessel shall be that allowed for the base material.

(b) When the design calculations are based on the full thickness of base material with corrosion resistant integral or weld metal overlay cladding as permitted in UCL-23(c), the maximum service metal temperature shall be the lower of the values allowed for the base material referenced in Table UCS-23, UF-6, or UHT-23 and listed in Table 1A of Section II, Part D, or refer to UCL-23(c) for corrosion resistant weld metal overlay cladding and the cladding material referenced in Table UHA-23 or UNF-23.

(c) The use of corrosion resistant integral or weld metal overlay cladding or lining material of chromium-alloy stainless steel with a chromium content of over 14% is not recommended for service metal temperatures above 800°F (425°C).

UCL-25 CORROSION OF CLADDING OR LINING MATERIAL

(a) When corrosion or erosion of the cladding or lining material is expected, the cladding or lining thickness shall be increased by an amount that in the judgment of the user will provide the desired service life.

(b) *Telltale Holes.* The requirements of UG-25(e) and UG-46(b) shall apply when telltale holes are used in clad or lined vessels, except that such holes may extend to the cladding or lining.

UCL-26 THICKNESS OF SHELLS AND HEADS UNDER EXTERNAL PRESSURE

The thickness of shells or heads under external pressure shall satisfy the requirements of the Part of Subsection C applicable to the base material. The cladding may be included in the design calculations for clad material to the extent provided in UCL-23(b) and (c).

UCL-27 LOW TEMPERATURE OPERATIONS

The base materials used in the construction of vessels shall satisfy the requirements of UCS-66, UCS-67, UCS-68, Part UF, or UHT-5.

FABRICATION

UCL-30 GENERAL

The rules in the following paragraphs apply specifically to pressure vessels and vessel parts constructed of base material with corrosion resistant integral or weld metal overlay cladding and those having applied corrosion resistant linings, and shall be used in conjunction with the general requirements for *Fabrication* in Subsection A, and with the specific requirements for *Fabrication* in Subsection B that pertain to the method of fabrication used.

UCL-31 JOINTS IN INTEGRAL OR WELD METAL OVERLAY CLADDING AND APPLIED LININGS

(a) The types of joints and welding procedure used shall be such as to minimize the formation of brittle weld composition by the mixture of metals of corrosion resistant alloy and the base material.

(b) When a shell, head, or other pressure part is welded to form a corner joint, as in Fig. UW-13.2, the weld shall be made between the base materials either by removing the clad material prior to welding the joint or by using weld procedures that will assure the base materials are

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