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**EVALUATION OF THE FABRICABILITY OF
ADVANCED IRON ALUMINIDE-CLAD AUSTENITIC
STAINLESS STEEL TUBING**

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EXECUTIVE SUMMARY

Researchers at Babcock & Wilcox Alliance Research Center have investigated methods to produce bimetallic tubing consisting of iron aluminide-clad austenitic stainless steel for practical use in fossil fueled energy equipment. In the course of this work, the compatibility of iron aluminide with four candidate austenitic stainless steel substrates was first evaluated using diffusion couples. Based on these results, a combination of iron aluminide and 304 stainless steel was selected for further development. Two composite billets of this combination were then prepared and extruded in separate trials at 2200°F and 2000°F. Both extrusions yielded 2-inch O.D. clad tubes, each approximately 18 feet long. Results of the evaluation show that the tube extruded at 2000°F had a sound, integrally bonded clad layer throughout its entire length. However, the tube extruded at 2200°F exhibited regions of disbonding between the clad layer and the substrate. In supplement to this work, an assessment of the technical and economic merits of iron aluminide-clad austenitic stainless steel components in power generation systems was conducted by B&W Fossil Power Division. Future activities should include an investigation of lower extrusion processing temperatures to optimize the fabrication of high quality iron-aluminide clad tubing.

Key Words: Tubing, Iron Aluminide, Cladding, Austenitic Stainless Steel, Fabrication, Composite, Interface Bond, Assessment

Research sponsored by the U.S. Department of Energy, Fossil Energy AR&TD Materials Program, DOE/FE AA 15 10 10 0, Work Breakdown Structure Element B&W-4.

1.0 INTRODUCTION

Results of development work at ORNL and other laboratories have shown that iron aluminide intermetallics exhibit excellent oxidation and sulfidation resistance, as well as good resistance to abrasive wear and erosion¹. Although iron aluminides initially displayed low room temperature ductilities, advanced compositions of these materials could be heated and easily formed into useful shapes by carefully controlling the thermomechanical processing parameters. The successes in fabricating iron aluminide shapes also suggested the potential application of these materials as protective claddings, particularly for components used at high temperatures in corrosive environments²⁻⁵.

In an earlier research program funded by ORNL under the Fossil Energy Materials Program, the Babcock & Wilcox Company had conducted research to investigate cladding of advanced austenitic structural materials with high chromium alloys (671 and 690) to potentially enhance resistance to coal ash corrosion⁶. As a logical extension of this work, a research and development program was initiated with the support of ORNL to evaluate the fabricability of iron aluminide-clad austenitic stainless steel tubing. Clad superheater and reheater tubing could eventually serve to extend the capabilities of fossil fueled energy generation systems to operate at higher temperatures.

The objectives of this program have been to develop and to demonstrate a method to produce iron aluminide-clad austenitic stainless steel tubing. To meet those objectives, the compatibility of Fe₃Al with four different austenitic stainless steels (304, 310, 316 LSS, and m800H) was first evaluated at elevated temperature using diffusion couples. An experimental processing sequence was then devised and tested in two separate fabrication trials.

2.0 EVALUATION OF COMPATIBILITY

Prior to establishing a preferred process for fabricating clad tubing, the compatibility of Fe_3Al with the selected austenitic stainless steel substrates first had to be assessed. This was accomplished by producing small specimens of each Fe_3Al /substrate combination under conditions of time, temperature, and shear deformation simulating those anticipated for full scale clad tube fabrication. Metallographic samples were subsequently prepared to enable examination of the Fe_3Al /substrate interfaces and surrounding microstructures within the clad specimens.

The chemical compositions of the iron aluminide and the austenitic stainless steels used in this evaluation are shown in Table 1. The iron aluminide was procured as -100 mesh powder from ORNL through an approved vendor. The m800H and the modified 316 lean stainless steel were retrieved from remaining inventory produced under a previous ORNL program; and the standard 304 and standard 310 stainless steels were obtained from a commercial vendor.

Table 1. Chemical compositions of iron aluminide powder and austenitic stainless steel substrates (wt %)

<i>Alloy</i>	<i>Cr</i>	<i>Ni</i>	<i>Fe</i>	<i>Al</i>
<i>Fe_3Al (FAS)</i>	<i>2.11</i>	<i>-</i>	<i>bal</i>	<i>14.8</i>
<i>304SS</i>	<i>18.0 - 20.0</i>	<i>8.0 - 11.0</i>	<i>bal</i>	<i>-</i>
<i>310SS</i>	<i>24.0 - 26.0</i>	<i>19.0 - 22.0</i>	<i>bal</i>	<i>-</i>
<i>LSS</i>	<i>13.0 - 15.0</i>	<i>15.0 - 17.0</i>	<i>bal</i>	<i>-</i>
<i>m800H</i>	<i>19.0 - 21.0</i>	<i>29.0 - 31.0</i>	<i>bal</i>	<i>-</i>

2.1 Experimental Procedure

The specimens were prepared by hot forging a stacked series (alternate layers) of substrate coupons and -100 mesh iron aluminide powder at 1050°C (1922°F) in an m800H cylindrical die assembly, Figure 1. This apparatus was designed to consolidate the Fe_3Al powder and to simulate iron aluminide/substrate interface conditions which would be created during the full scale forward extrusion of a canned, Fe_3Al powder-encased austenitic stainless steel billet. To remove residual water vapor and adsorbed gasses within the powder/substrate stack, the die assembly was heated to 300°C (572°F) in a vacuum furnace and alternately evacuated (to 10^{-6} Torr) and backfilled with dry nitrogen for two complete cycles. After bakeout, the clearances between the rams and the cylindrical die were immediately weld sealed; then, the thermocoupled assembly was put into a furnace preheated to 1050°C (1922°F). Thermal equilibrium was attained after 15 minutes, whereupon the assembly was removed from the furnace, immediately positioned on a platen and hot forged with a 4550Kgf (5 ton) steam driven forging hammer. During the six successive strikes of the forging hammer, the temperature of the die assembly did not fall below 910°C (1679°). After forging, the die assembly was allowed to cool to ambient temperature.

Figure 1. *Die Assembly for clad specimen fabrication. The Fe_3Al powder was placed between the 310SS, 304SS, m800H, and modified 316 (LSS) specimens.*

2.2 Microstructural Evaluation

The die assembly was sectioned through the diameter along the axial length, and one exposed face was ground, polished and etched (with chromic acid) for microstructural examination. Each of the four Fe₃Al/substrate interfaces were studied and compared to one another using optical microscopy at various magnifications up to 1000X. The 500X photomicrographs displayed in Figure 2 show that, although full density was not attained in the iron aluminide layers, consolidation was sufficient to establish the desired metallurgical bond between the iron aluminide and the austenitic stainless steel substrates.

Figure 2. Comparison of microstructures showing diffusion zones at interfaces for Fe₃Al-clad substrates, including a) modified 316 (LSS), b) modified 800H, c) standard 310, and d) standard 304.

The principal features of interest in the photomicrographs of Figure 2 are the well defined diffusion zones which extend from the interface into the stainless steel substrate for all four material combinations. Within the boundaries of these distinct layers, having widths ranging from about 13 μm (0.0005") to about 22 μm (0.0009"), are precipitates which have been analytically determined to be nickel aluminides.

Results showed that the $\text{Fe}_3\text{Al}/304$ austenitic stainless steel combination offered the highest potential for success based on the comparative characteristics of the diffusion layers (including total width, sub-layer widths, precipitation particle content, and cracking) which formed at the interfaces. Selection of this combination, established through joint assessment between ORNL and B&W, was based on the relatively low content of embrittling nickel aluminides in the diffusion layer and on the absence of microcracking.

3.0 CLAD TUBE FABRICATION

The processing sequence for producing clad tubing was established, in part, on the basis of earlier work conducted at ORNL and at B&W⁷⁻¹⁰. The principal components of the processing sequence which incorporate commercial metalworking procedures and equipment is as follows:

- * Procurement of Materials (Fe_3Al Powder, 304SS)
- * Hot Isostatic Pressing to Form Two Composite Billets
- * Composite Billet Machining & Preparation
- * Ultrasonic Inspection of Composite Billets
- * Hot Forward Extrusion to Form Two Clad Tubes
- * Evaluation of Fe_3Al -Clad 304SS Tubes

3.1 Procurement of Materials

To produce the composite billets needed for clad tube fabrication, 200 pounds of FAS Fe_3Al powder (-100 mesh) were procured from an ORNL approved commercial vendor, Appendix A. Annealed 304 stainless steel round stock was purchased from another vendor, Appendix B. The chemical compositions of the FAS iron aluminide powder and the 304 austenitic stainless steel are given in Table 2.

Table 2. Chemical compositions of iron aluminide powder and Type 304 austenitic stainless steel substrate (wt.%).

<i>Alloy</i>	<i>Cr</i>	<i>Ni</i>	<i>Fe</i>	<i>Al</i>
<i>Fe_3Al (FAS)</i>	<i>2.2</i>	<i>-</i>	<i>bal</i>	<i>15.0</i>
<i>304SS</i>	<i>18.50</i>	<i>8.22</i>	<i>bal</i>	<i>-</i>

3.2 Hot Isostatic Pressing of Composite Billets

HIP processing was incorporated into the fabrication sequence to simultaneously effect full powder consolidation and to ensure complete encasement and bonding of the Fe_3Al to the machined 304SS hollow cores. The Fe_3Al powder/304SS assemblies were weld sealed in carbon steel jackets, evacuated, degassed, and HIP'ed at 2065°F/14.5 ksi (with argon gas) for 4 hours, Appendix C.

3.3 Machining and Preparation of Composite Billets

The HIP'ed assemblies were initially rough-machined to remove the carbon steel enclosures. Each of the 6-inch diameter billets was further machined to properly size the central core, configure the proper nose geometry, and dress the Fe_3Al exterior surfaces in preparation for hot forward extrusion, Appendix D.

3.4 Ultrasonic Inspection of Composite Billets

The machined composite billets were ultrasonically inspected to confirm the integrity of the bond between the Fe_3Al encasement and the 304SS substrate. Results of the inspection confirmed integral bonding throughout the lengths of both billets.

3.5 Hot Forward Extrusion of Clad Tubing

Extrusion process parameters were selected by B&W based on information obtained from the technical literature, recommendations by ORNL, and practical production experience of the extrusion press operator. During the first extrusion trial, the billet was induction heated to 2200°F, lubricated with powdered silica, and extruded on a 4500 ton hydraulic press, producing an 18-foot long clad tube. In the next trial, the second billet was extruded at a lower temperature of 2000°F, again successfully producing an 18-foot long clad tube.

Both tubes were "natural" air cooled (rather than water quenched) to minimize the generation of stresses which could cause tube distortion or clad layer cracking. After air cooling to room temperature, the two iron aluminide-clad 304SS tubes were carefully packaged, boxed and shipped for subsequent evaluation.

4.0 EVALUATION AND RESULTS

4.1 Visual Inspection

Both extruded Fe₃Al-clad 304SS tubes were visually inspected to assess their overall condition. The tubes were circular, without eccentricity, with a predominantly uniform wall thickness. Measurements of straightness showed a slight, nonuniform bow which skewed randomly from about 1/8" - 1/4" per linear foot. Exterior surfaces were moderately smooth and were still coated with remnants of the silica lubricant used during hot extrusion. There were no observable surface defects or other anomalies on either of the tubes.

4.2 Ultrasonic Inspection

The clad tubes were ultrasonically inspected at one-foot intervals along their length. At each inspection interval, measurements were taken at four radial positions (0°, 90°, 180°, and 270°). Constant (sound) velocity was assumed through both the cladding and substrate materials. Results showed that the tube extruded at 2000°F had no indication of disbonding between the cladding and substrate. However, the tube extruded at 2200°F exhibited regions of peripheral disbonding along its 18-foot length, Appendix E.

4.3 Metallographic Examination

Cross-sectional specimens were taken from the nose, center, and tail regions of each extruded tube for microstructural examination. Dimensional measurements were also taken on the specimens to confirm circularity, determine average outside and inside diameters, establish typical wall thickness, and assess nominal clad layer thickness. The photomacrograph of the nose and tail specimens, Figure 3, shows that both tubes were circular with predominantly uniform wall thicknesses. However, the clad layer thicknesses in the region of the nose for both tubes showed noticeable variations, particularly for the tube extruded at 2200°F (Figure 3a).

Figure 3. *Photomacrograph (0.75X) showing cross-sections from (a) the nose and (b) the tail of the clad tube extruded at 2200°F and from (c) the nose and (d) the tail of the clad tube extruded at 2000°F.*

The microstructures of the cladding/substrate interfaces were next examined to characterize bonding. Etching of the metallic specimens was conducted in accordance with the procedure given in Appendix F. Figure 4 displays a photomicrograph showing the integral metallurgical bond (with associated diffusion layers) that are typical for the nose, center, and tail regions of the tube extruded at 2000°F. In contrast, Figure 5 displays a photomicrograph showing the cracking and disbonding typically observed throughout the tube extruded at 2200°F.

Figure 4. *Photomicrograph (100X) showing the microstructure and diffusion layers associated with the cladding/substrate interface.*

Figure 5. *Photomicrograph (100X) showing the microstructure, diffusion layers, and cracking associated with the cladding/substrate interface.*

4.4 Composition Profiling

Composition (step) profiles for chromium, nickel, and aluminum were determined across the diffusion layers using electron probe microanalysis. Figure 6 illustrates the variation in concentrations for selected elements, in relation to the $\text{Fe}_3\text{Al}/304\text{SS}$ interface, resulting from interdiffusion. Location "A" denotes the center of the dark diffusion zone within the 304SS substrate; location "B" denotes the center of the light diffusion zone within the iron aluminide cladding.

Figure 6. *Composition profiles for chromium, nickel, and aluminum with respect to the iron aluminide-304 SS interface.*

5.0 TECHNICAL AND ECONOMIC ASSESSMENT

The technical and economic merits of Fe₃Al-clad austenitic stainless steels were examined by the Babcock & Wilcox Fossil Power Division (FPD) and assessed with respect to potential power boiler applications. The assessment was based on the understanding that the developed clad tubing would have the necessary properties and characteristics to allow its use at about 1100°F to 1300°F for extended service. A summary of the FPD observations are given below.

- * To be commercially feasible, Fe₃Al-clad austenitic stainless steel tubing must be formable, capable of small bend radii. Superheater and reheater sections currently have bend radii as small as two tube diameters. Bends with R/D ratios of 3 or 4 are common. If such bends cannot be made cold (room temperature), then the feasibility of hot bending, as well as the resultant effects on clad tube properties, must be determined.
- * The cost of clad tubing, due to a more complex production sequence, will be greater than that of monolithic alloy tubing. Accordingly, the gains in extended life and performance provided by the clad tubing will have to justify the greater initial cost.
- * For consideration as superheater and reheater applications, Fe₃Al-clad tubing must be evaluated for resistance to coal ash and oil ash corrosion, as well as for resistance to other types of corrosion and erosive degradation.
- * Practical use of Fe₃Al-clad tubes will require effective methods for fusion welding and for protecting all welds (during service) which are required for assembly, attachment, and installation.
- * Since commercial use of Fe₃Al-clad austenitic stainless steel tubes will always be sensitive to cost, they will first be utilized only in the hottest parts of superheaters. These initial applications will provide a relatively small market compared to the less expensive alloy tubing.
- * Potential applications for fully developed Fe₃Al-clad tubing include superheaters for syngas coolers, conventional utility boilers, and advanced boiler systems where creep and coal ash corrosion are especially problematic.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Separate fabrication trials were conducted in this program to produce two Fe₃Al-clad 304 austenitic stainless steel tubes. These unique bimetallic tubes were initially characterized through visual and ultrasonic inspections. They were subsequently evaluated through microstructural examination and electron probe microanalysis. Both of the 2-inch OD tubes were approximately 18 feet long with a typical wall thickness of 0.375-inch, including a nominal clad layer thickness of 0.1-inch. The tube that was extruded at 2000°F had an integral, metallurgically bonded clad layer throughout its entire length. The tube extruded at 2200°F exhibited multiple regions of clad layer/substrate interface cracking and disbonding.

The results of this work demonstrate that Fe₃Al-clad 304 austenitic stainless steel tubing can be successfully fabricated using the devised processing sequence. The results also indicate the importance of proper temperature selection and control during processing to produce good quality bimetallic tubing. Additional work is recommended to investigate potential benefits of lower extrusion temperatures and to optimize other associated processing parameters. It is also recommended that development trials be conducted to adapt the processing sequence to successfully fabricate Fe₃Al-clad tubing using other austenitic stainless steel substrates.

Submitted By:

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Attach.

7.0 ACKNOWLEDGMENTS

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8.0 REFERENCES

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Appendix A

Certification For Iron Aluminide Powder

Specialty Metal Products Division
Eighty Four, PA 15330
(412) 225-8400

ATOMIZED METAL POWDERS

PROCESS/QUALITY CONTROL DATA SHEET

CUSTOMER: Babcock & Wilcox	PRODUCT: FAX (-100) LOT #: 095392	DATE: 09/16/92 PO #: 03454TB QUANTITY: 200 lbs.
----------------------------	--------------------------------------	---

CHEMICAL COMPOSITION (Weight %)

C :	Ni :	Cr: 2.2	Fe: BAL	Mo:	Si :
Mn:	Co:	Cu:	W :	S :	Cb:
B : 0.01	O :	P :	Al : 15.0	:	:

POWDER PHYSICAL PROPERTIES (Size Distribution)

S STANDARD ESH SIZE	PERCENT
+60	Trace
+100	7.0
+140	19.7
+200	19.7
+270	17.0
+325	6.4
-325	30.2

APPARENT DENSITY: 3.78 g/cc

FLOW: No Flow

OTHER:

COMPACTING PROPERTIES

Compact Pres (tsi)	Green Dens (g/cc)	Green Str (psi)	Sinter Dens (g/cc)	Trans Break Str (psi)	Dim Change (% die size)	Other

LUBRICANT:
SINTERING CONDITIONS:

NOTES AND OTHER DATA:

Specialty Metal Products Division
ROUTE 519, P.O. BOX 427, EIGHTY FOUR, PENNSYLVANIA 15330

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Appendix B

Certification For 304 Stainless Steel Base Metal

BALTIMORE
SPECIALTY STEELS
CORPORATION

A SUBSIDIARY OF ARMCO INC.

CERTIFICATION

DATE
JUL 17 1992

PAGE NO.

1 of 2

5534	CUST. NO. 712416	BILL TO	1504	274	SHIP TO
JOSEPH T. RYERSON - CENTRAL ATTN: ACCOUNTS PAYABLE P O BOX 8000A CHICAGO IL 60680		JOSEPH T RYERSON & SON INC CENTER WAREHOUSE 16TH & ROCKWELL STS CHICAGO IL 60680			
PRODUCT NUMBER	TEST LOT ID	SALES ORDER NO.	PURCHASE ORDER NO.		
8442-10572	526033-D4056A01	20247	1A36406		

HIP LOT ID: 526033-X0603A01

MET LOT NO.: D4056A

FIN BAR STNLS TYPE 304 HFT ANN

RYERSON 7125-R DTD 1/26/90 *
 ISI 304 UNS S30400 * AMS 5639F EX CF OK * ASME SA182 B9ED F304 ANAL &
 ANNLD MECH PROP CPBLTY ONLY * ASME SA193 B9ED GR B8 CL1 ANAL & MECH PROPS
 NLY EX BHN 255 MAX OK * ASME SA194 B9ED THRU A89 ADD GR B ANAL ONLY *
 ASME SA320 B9ED GR B8 CL1 ANAL & MECH PROPS ONLY EX BHN 255 MAX OK * ASME
 A479 B9ED THRU A90 TYPE 304 COND A * ASME SA404 B9ED THRU A90 ADD * ASP
 04 REV 3 DTD 3/30/87 EX PARA 5.4 AIM 1 HT PER SIZE * ASTM A193-90 GR B8
 CL1 ANAL & MECH PROPS ONLY EX BHN 255 MAX OK * ASTM A193-90 GR B8 ANAL
 NLY * ASTM A276-90a TYPE 304 COND A * ASTM A314-90 TYPE 304 * ASTM
 320-90 GR B8 CL1 ANAL & MECH PROPS ONLY EX BHN 255 MAX OK * ASTM A479-90
 COND A TYPE 304 * ASTM A404-90 * CAMOUT FITTINGS I-300A REV 10, DTD
 7/11/89 GR F304 EX PER ASME SA182 ANAL & ANNLD MECH PROP CPBLTY ONLY, EX
 F CONDS OK * DUPONT SW300M DTD 1/82 * MIL-G-9858A DTD 4/9/59 EX PARA
 .6 WVD OK * MIL-S-7720 AMEND 1 COND A ANAL ONLY, EX CU .75 MAX OK *
 IL-S-0620 INT AMEND 2 DTD 12/23/80 ANAL ONLY * QQ-S-763D COND A EX AMEND
 DTD 2/4/83 WVD * QQ-S-763E AMEND 1 DTD 5/15/90 CL 304 COND A EX HT TRT
 IL-M-6870 WVD *

HE: SIZE: SHAPE: LENGTH: WEIGHT:
 0 5.25000"RD 14' 0" TO 16' 0" MIN/MAX 5,663#

PE ANAL: PRODUCT ANALYSIS

HEAT NO: 526033

C: 0.073 MN: 0.800 P: 0.028 S: 0.024 SI: 0.540 CR: 10.50
 NI: 0.22 MO: 0.360 CU: 0.300 CO: 0.150 N: 0.061

PE ANAL: REGULAR

HEAT NO: 526033

C: 0.075 MN: 0.760 P: 0.027 S: 0.029 SI: 0.570 CR: 10.29
 NI: 0.21 MO: 0.360 CU: 0.200 CO: 0.040 W: 0.050 CO: 0.120
 AL: 0.020 N: 0.065 TI: 0.020 V: 0.060

SHIP TEST: ANNEAL

HTL: 12-920369

B HRDNS: 170.

B HRDNG (P/F): OK

TEMP: 1950.

HOURS: 0.

MINS: 30.

QUENCH: WATER

OFFSET X: 0.20

UTS KSI: 86.7

.2X YLD STR KSI: 41.6

% EL 2" OR EQ: 64.0

X RED OF AREA: 74.24

PHYSICAL:

GB AVG: 3.

GB (P/F): OK

MACRO (P/F): OK

CORROSION:

CARB/OX (P/F): OK/OK

Material was Electric furnace melted, AOD refined.

**BALTIMORE
SPECIALTY STEELS
CORPORATION**

A SUBSIDIARY OF ARMCO INC.

CERTIFICATION

DATE

JUL 17 1992

PAGE NO.

2 of 2

3534	CUST. NO. 712416	BILL TO	1504	274	SHIP TO
JOSEPH T. RYERSON - CENTRAL ATTN: ACCOUNTS PAYABLE PO BOX 8000A CHICAGO IL 60680			JOSEPH T RYERSON & SON INC REPAIR WAREHOUSE 1471 & ROCKWELL STS CHICAGO IL 60660		
PRODUCT NUMBER	TEST LOT ID	SALES ORDER NO.	PURCHASE ORDER NO.		
0442-10572	526033-D4056A01	20247	1A36400		

Free from continuous carbide network.

Testing area mid-radius gage width .505"/2" gage length max.

Heat treated at TIME, TEMP and QUENCH indicated above.

Intergranular corrosion test OK. Per ASTM A262-E.

Macro etch test satisfactory.

Mech props reported are from finished bar stock stated within cert.

Ingot/Bar reduction ratio >4:1

Melted and manufactured in the U.S.A.

No welding or weld repair performed on this material.

BSSC certifies conformance to NRC 10CFR PT 21, and 10CFR PT 50 APP E.

This material was manufactured and tested in accordance with the noted specifications, and is in conformance with these specification requirements.

BSSC certifies that this material is manufactured free from mercury, radium, alpha source and low melting metal or alloy contamination.

This material was produced in accordance with the Quality Assurance program, Quality Assurance Manual, Issue 4 Rev 2 dtd 1/22/90.

All testing procedures were conducted in accordance with the latest ASTM standards or applicable specifications.

The recording of false, fictitious or fraudulent statements or entries in this document may be punished as a felony under federal statutes including Federal Law, Title 18, Chapter 47. This certified test report has been delivered to a consignee of material purchased from BSSC. To avoid the possibility of its misuse on the redelivery of this report to a third party it must be recertified by and under the name of such consignee.

The chemical analyses and physical or mechanical test report are correct as contained in the records of the Corporation.

E. FAMULARO, CERTIFICATION CLERK

Post-It™ brand fax transmittal memo 7671		# of pages	2
To	WALTER MOHN	From	CLINTON NICKEL
Co	BABCOCK + WILCOX	Co	CRUCIBLE COMPACTION
Dept.		Phone #	412/923-2670
Fax #	216-829-7831	Fax #	412/788-4240

Appendix C

Diagram Of Hot Isostatic Pressing Of Composite Billets

HIP Consolidation

2065F/14.5 ksi (argon)/4 hrs

Appendix D

Diagram Of Machined Composite Billet

Hybrid Billet

Appendix E

Certification Of Test For Ultrasonic Inspection Of Extruded Composite Tubing

CERTIFICATE OF TEST

Job Order No.: 10020 A
CCMD Report No. 2468

Customer
BABCOCK & WILCOX CO.

Purchase Order No.
03455TB

P.O. Date
4-AUG-1992

Cust. Part No. | Cust. Dwg. No./ Rev. | Specification No. | Master Blend No.
N/A | N/A | B&W TO SPECIFY HIP P | 095392

Item No. | Pieces | Weight | Product Description
1 | 2 | | 304 Stainless Steel Tubing OD Clad with Fe-Al.

Chemical Analysis of Fe-Al Lot 094392
(Weight Percent)

Al	Cr	B	Fe
15.0	2.2	0.01	Bal

HIP Parameters: 2060 $\pm$ 20°F @ 14500 $\pm$ 500 psi. for 4 Hr.

HIP and machined dimensions.

S/N	Length	OD	ID	Nose Chamfer	Nose radius
123748	18.860"	5.890"	1.375"/1.384"	40° 1.5" lg.	1"
123749	18.863"	5.890"	1.381"/1.384"	40° 1.500"	ok
				40° 1.440"	ok

Aproximate HIP and machined clad thickness measured by UT.

Serial Number 123748					Serial Number 123749				
loc.	0°	90°	180°	270°	loc.	0°	90°	180°	270°
2"	.396	.402	.396	.400	2"	.396	.395	.395	.400
4"	.395	.402	.406	.403	4"	.406	.407	.394	.397
6"	.400	.402	.406	.399	6"	.395	.394	.396	.397
8"	.416	.396	.402	.399	8"	.406	.414	.396	.396
10"	.400	.397	.396	.400	10"	.397	.406	.395	.393
12"	.415	.396	.403	.400	12"	.396	.395	.393	.396
14"	.416	.397	.396	.401	14"	.393	.407	.397	.404
16"	.400	.395	.401	.400	16"	.403	.395	.400	.393

Extrusion Parameters: Extruded by ALTECH, Watervliet, NY, 10-20-92.
S/N 123748 was induction heated to 1850°F then 2150°F, pierced to aprox. 1.75" ID., induction heated to 2200°F and extruded over a 1.320" - 1.325" mandrel to a nominal 2" OD. S/N 123749 was induction heated to 1850°F then 2150°F, pierced to aprox. 1.75" ID., induction heated to 2000°F and extruded over a 1.320" - 1.325" mandrel to a nominal 2" OD.

S/N 123748 was noted to be disbonded along the entire length.

S/N 123749 showed no indication of disbond along the entire length.

worn to and Subscribed Before Me

this 3rd Day of November 1992

Judith K. Turek

Certified By:

M.F. Marconis

Date: 11/3/92

Title: QC Foreman

Notarial Seal
Judith K. Turek, Notary Public
North Fayette Twp., Allegheny County
My Commission Expires Nov. 6, 1993

CERTIFICATE OF TEST CONTINUED

UT Dimensional Evaluation: Constant velocity through both materials assumed.

Serial Number 123749.

loc. ft.	0°	90°	180°	270°	
3	---	.112	.127	.121	Clad thickness (in).
	.322	.312	.335	---	Overall wall thickness (in).
4	.120	.113	.128	.148	
	.318	.306	.333	.370	
5	.123	.112	.133	.157	
	.317	.308	.336	.362	
6	.118	.112	.124	.150	
	.316	.315	.332	.357	
7	.116	.112	.123	.148	
	.317	.322	.340	.352	
8	.112	.112	.113	.145	
	.314	.326	.335	.346	
9	.111	.112	.116	.130	
	.316	.326	.331	.346	
10	.111	.111	.115	.131	
	.317	.329	.331	.340	
11	.110	.111	.112	.126	
	.319	.328	.334	.340	
12	.110	.114	.112	.122	
	.320	.331	.337	.336	
13	.113	.118	.114	.122	
	.322	.333	.333	.334	
14	.112	.116	.116	.120	
	.325	.333	.332	.333	
15	.114	.116	.116	.124	
	.326	.332	.329	.335	
16	.116	.113	.116	.124	
	.330	.333	.334	.339	
17	.116	.112	.116	.130	
	.331	.337	.333	.346	
18	.116	---	.118	.129	
	.332	.335	.333	.340	
19	.121	---	.118	.127	
	.333	.334	.330	.336	
20	.118	.110	.116	.112	
	.340	.332	.332	.353	

UT dimensional not performed on S/N 123748, disbond noted.

See attached sketch showing post extrusion cutting.

CUTUP SKETCH FOR HIP + EXTRUDED PART SN 123749
 2" OD NOM. X 0.35" WALL NOM. WITH NOM. 0.080" FE3AL CLAD
 ON OD OF TYPE 304 STAINLESS STEEL TUBE
 $A_1 = 10"$, $A_2 = 14"$, $A_3 = 6\frac{1}{4}"$, $A_4 = 5\frac{3}{4}"$, $B = 205\frac{3}{8}"$, $C = \frac{1}{2}"$, $D = 8\frac{1}{2}"$, $E = 5"$

NOTES: SN 123749 WAS CROPPED AT EXTRUSION TO YIELD PIECES
 A, B, C, D, E. PIECES A2, A3, A4 WERE CROPPED FROM NOSE END
 OF TUBE TO REACH THE POINT WHERE CLADDING BEGINS
 TO BE UNIFORM ON OD. NO DISBOND CONDITION WAS
 FOUND FOR THIS TUBE. SAMPLE "D" KEPT BY CCMD FOR
 QUALITY CONTROL SAMPLE.

JO # 10020

Crucible
Compaction Metals

A Division of Crucible Materials Corporation
 R.D. #1, McKee & Robb Hill Rd., Oakdale, PA 15071

DRAWN BY C. NICKEL DATE 11/03/92

CHK. APPD. SCALE NONE

CUTUP SKETCH SN 123749

DWG. NO. 100CSA4140 REV. 0

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REV.	DATE	DESCRIPTION	BY	APP.

CUTUP SKETCH FOR HIP + EXTRUDED PART SN 123748
 2" OD NOM. X 0.35" WALL NOM. WITH NOM. 0.080 FE3AL CLAD
 ON OD OF TYPE 304 STAINLESS STEEL TUBE
 $A = 7\frac{1}{4}"$, $B = 235\frac{3}{4}"$, $C = \frac{1}{2}"$, $D = 7\frac{1}{2}"$, $E = 5"$

NOTES: SN 123748 WAS CROPPED AT EXTRUSION TO YIELD PIECES
 A, B, C, D, E. NO FURTHER CROPPING WAS PERFORMED BECAUSE
 ENTIRE LENGTH "B" HAD A DISBONDED CONDITION.
 SAMPLE "D" KEPT BY CCMD FOR QUALITY CONTROL SAMPLE.

JO # 10020

Crucible
Compaction Metals

A Division of Crucible Materials Corporation
 R.D. #1, McKee & Robb Hill Rd., Oakdale, PA 15071

DRAWN BY C. NICKEL	DATE 11/03/92	REV.
CKD.	APPD.	SCALE NONE
CUTUP SKETCH SN 123748		
DWG. NO. 100CSA4139		0

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a McDermott company

Research and Development Division

1562 Beeson Street
Alliance, OH 44601
(216) 821-9110

December 1, 1992

Dr. R. W. Swindeman
Martin Marietta Energy Systems, Inc.
Oak Ridge National Laboratory
Bldg. 4500 South, M56155
Bethel Valley Road
Oak Ridge, TN 37831-6155

Ref.: "Evaluation of the Fabricability of Advanced Iron Aluminide-Clad Austenitic
Stainless Steel Tubing"
MMES: 72X-SB775-C
B&W: CRD 1207

Dear Bob:

I am sending to you by express mail a five-foot length of iron aluminide-clad 304 stainless steel tubing that was successfully produced under the referenced contract. This material, which was extruded at 2000°F, has a 2-inch O.D. with a nominal 3/8-inch wall that includes a nominal 1/10-inch thick Fe₃Al clad layer. The five-foot section is representative of the entire eighteen foot clad tube from which it was taken. The remaining material, in addition to another eighteen-foot clad tube (extruded at 2200°F), is currently being evaluated in accordance with the program workscope. I'll continue to keep you informed as our work progresses.

Sincerely,

THE BABCOCK & WILCOX COMPANY
Research and Development Division

W. R. Mohn
Metallurgy & Manufacturing
Technology Section

bp

cc: NCCole - ORNL
RAGleixner - ARC
RWHaggard - CRD
DFLaCount - ARC
MJTopolski - ARC

Babcock & Wilcox

a McDermott company

Research and Development Division

1562 Beeson Street
Alliance, OH 44601
(216) 821-9110

March 3, 1993

Dr. R.W. Swindeman
Martin Marietta Energy Systems, Inc.
Oak Ridge National Laboratory
Bldg. 4500 South, M56155
Bethel Valley Road
Oak Ridge, TN 37831-6155

Ref: MMES: 72X-SB775-C
B&W: CRD 1207

Dear Bob:

In accordance with your request, I am sending you by express mail three pieces of advanced austenitic stainless steel tubing produced under the referenced contract. These include a 5-foot length of iron aluminide-clad 304 stainless steel tubing and two 6-foot lengths of m800H stainless steel tubing (Heat No. V988-1). Please contact me if I may provide further assistance.

Sincerely,

THE BABCOCK & WILCOX COMPANY
Research and Development Division

Walter R. Mohn
Metallurgy & Manufacturing Technology

cc: NCCole - ORNL
RAGleixner - ARC
RWHaggard - CRD
DFLaCount - ARC
MJTopolski - ARC

Appendix F

Procedure For Etching Of Iron Aluminide Clad 304 Stainless Steel

ETCH PROCEDURE

- **Prepare Solution: 50 g NaOH + 100 ml Water.**
- **Immerse 5 minutes in NaOH Solution @ 160F.**
- **Immerse in Chromic Etchant and apply 6 Volts DC Potential for 30 seconds, Then Check Microscopically; As required, Apply for an additional 10 Seconds (or More).**

Appendix G
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