OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ORNL/LTR-2011/413

Reactor Pressure Vessel Task of Light Water Reactor Sustainability Program: Milestone Report on Materials and Machining of Specimens for the ATR-2 Experiment

January 2011

Prepared by

R.K. Nanstad, Oak Ridge National Laboratory
and
G. R. Odette, University of California, Santa Barbara

UT-BATTELLE

ORNL-27 (4-00)

This page intentionally left blank

ORNL/TM-2011/413

Light Water Reactor Sustainability

Reactor Pressure Vessel Task of Light Water Reactor Sustainability Program: Milestone Report on Materials and Machining of Specimens for the ATR-2 Experiment

R.K. Nanstad
Materials Science and Technology Division
Oak Ridge National Laboratory
and
G. R. Odette
Department of Mechanical Engineering
University of California, Santa Barbara

Date Published: January 2011

Prepared under the direction of the
U.S. Department of Energy
Office of Nuclear Energy
Light Water Reactor Sustainability
Materials Aging and Degradation Pathway

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

This page intentionally left blank

CONTENTS

Page

This page intentionally left blank

LIST OF FIGURES

Figure **Page**

This page intentionally left blank

LIST OF TABLES

Table **Page**

This page intentionally left blank

ACKNOWLEDGMENTS

This research was sponsored by the U.S. Department of Energy, Office of Nuclear Energy, for the Light Water Reactor Sustainability Research and Development effort. The authors extend their appreciation to Dr. Jeremy Busby for programmatic support.

This page intentionally left blank

1. INTRODUCTION

The reactor pressure vessel (RPV) in a light-water reactor (LWR) represents the first line of defense against a release of radiation in case of an accident. Thus, regulations, which govern the operation of commercial nuclear power plants, require conservative margins of fracture toughness, both during normal operation and under accident scenarios. In the unirradiated condition, the RPV has sufficient fracture toughness such that failure is implausible under any postulated condition, including pressurized thermal shock (PTS) in pressurized water reactors (PWR). In the irradiated condition, however, the fracture toughness of the RPV may be severely degraded, with the degree of toughness loss dependent on the radiation sensitivity of the materials. As stated in previous progress reports, the available embrittlement predictive models, e.g. [1], and our present understanding of radiation damage are not fully quantitative, and do not treat all potentially significant variables and issues, particularly considering extension of operation to 80y.

The major issues regarding irradiation effects are discussed in [2, 3] and have also been discussed in previous progress and milestone reports. As noted previously, of the many significant issues discussed, the issue considered to have the most impact on the current regulatory process is that associated with effects of neutron irradiation on RPV steels at high fluence, for long irradiation times, and as affected by neutron flux. It is clear that embrittlement of RPV steels is a critical issue that may limit LWR plant life extension. The primary objective of the LWRSP RPV task is to develop robust predictions of transition temperature shifts (TTS) at high fluence (ϕt) to at least 10^{20} n/cm^2 (>1 MeV) pertinent to plant operation of some pressurized water reactors (PWR) for 80 full power years. New and existing databases will be combined to support developing physically based models of TTS for high fluence-low flux ($\phi < 10^{11}$/n/cm^2-s) conditions, beyond the existing surveillance database, to neutron fluences of at least 1×10^{20} n/cm^2 (>1 MeV).

This report provides the status for the Milestone L-11OR040202 Level M3 #M2L11OR04020203: "Complete all hardness and metallography of materials and machining of specimens for the ATR-2 experiment." This milestone is associated with procurement of materials, preparation of specimens, mechanical properties testing, and analysis of the irradiation capsule for the irradiation experiment in the Advanced Test Reactor (ATR-2).

2. PREPARATION OF MATERIALS FOR THE ATR-2 EXPERIMENT

To obtain high fluence data in a reasonable time (e.g., ~ one year), test reactor experiments must be performed in such a way to enable development of a mechanistic understanding of the effects of flux [2, 3]. As described previously, one such experiment is currently under preparation and will be performed as part of a Nuclear Energy University Program (NEUP) grant to the University of California, Santa Barbara (UCSB) in cooperation with ORNL within the LWRSP. The experiment (designated ATR-2) will be performed at the National Scientific User Facility at the Advanced Test Reactor, managed by the Idaho National Laboratory (INL).

A description of the ATR-2 experiment was provided in a previous progress report and will be summarized here. A so-called "Small I" location just inside the reflector of the ATR has been made available. This position will provide space for an irradiation capsule of about 20 mm diameter and 1.2 m long, and will be sufficient to allow for inclusion of more than 2000 small specimens (seven different geometries), including tensile, microhardness, fracture toughness, and specimens for microstructural examination (e.g., small-angle neutron scattering, atom probe, etc. The capsule will incorporate a thermal neutron shield and active temperature control with three regions irradiated at 270, 290 and 310°C. The specimens will be irradiated at a flux of about

$1{\times}10^{12}$ n/cm^2 (>1 MeV) to a fluence of $1{\times}10^{20}$ n/cm^2 and tested. The objective is to obtain a high f1uence, intermediate flux database to couple to a large body of existing data for a large set of common alloys (≥ 100) irradiated over a wide range of flux and fluence. Figure 2.1 shows the flux/fluence range for the ATR-2 experiment (red circles). The results from the experiment will allow for direct comparisons with two existing test reactor databases (IVAR and REVE).

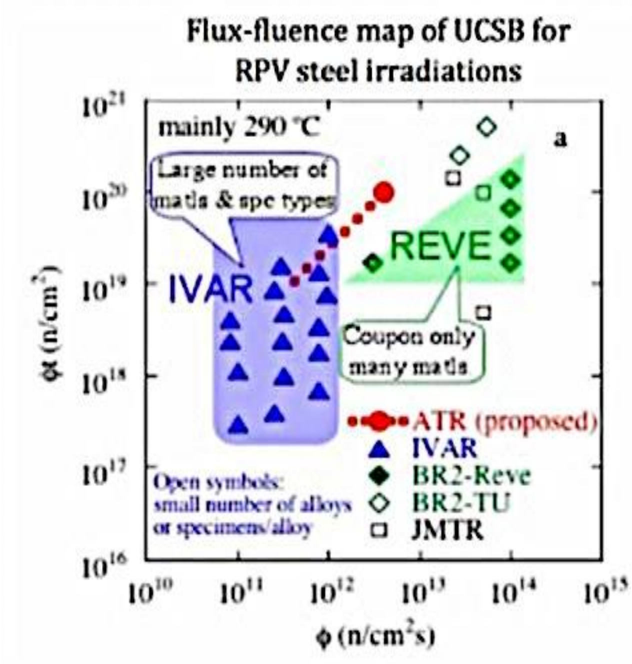

Figure 2.1. Schematic depiction of the flux/fluence range for the ATR-2 experiment, showing overlap of existing data from the IVAR and REVE databases.

Thus, a variety of relatively small specimens of many different RPV steels will be incorporated, including many materials that have been irradiated and tested in previous test reactor programs at different flux levels. Some of the materials are HSST Plate 02, HSSI Weld 73W, Midland Beltline Weld (WF-70), and other alloys from the UCSB IVAR project, etc. Moreover, Rolls-Royce, Ltd. has designed a matrix of 50 forged plates of steels with different chemical compositions encompassing the ranges of elemental compositions within the specification for A508 class 3 steel and beyond. These alloys will include variations in C, Cu, Ni, P, Mn, and Cr to provide results for a wide range of composition variations and synergisms. As reported previously, all 50 plates were fabricated and delivered to ORNL, where hardness testing and optical metallography were performed to enable more informed judgment regarding which materials to include in the experiment.

Figure 2.2 shows a schematic view of the hardness test locations for one of the plates (the values shown are Rockwell B hardness). Sections are removed from two sides of each plate and lightly ground to obtain an adequately smooth surface for hardness testing.

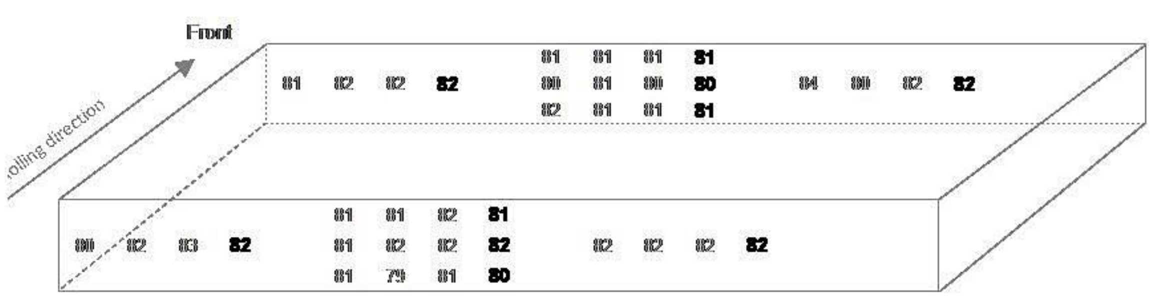

Figure 2.2. Schematic diagram showing hardness indentation locations for one of the Rolls-Royce plates. All 50 plates were tested with the same process.

As shown in Fig.2.2, 15 indentations were performed on the front side and 15 on the back side of each plate. The numbers in bold font are the average hardness values of the three measurements to the left in each case. All the results are combined to give an overall average hardness from which the ultimate tensile strength is estimated by equations representing the correlations given in the ASM Handbook. Tables of the hardness results for all 50 alloys are provided in Attachment 1. Note that the estimated UTS values range from 50.3 to 130.6 ksi (346-900 MPa). In addition to hardness testing, optical metallography of all 50 alloys was performed to document the microstructures. Two examples, alloy numbers 7 and 13 are shown in Attachment 2. The ultimate tensile strength estimated from hardness for Alloy 7 is 86.0 ksi (592 MPa) is typical for RPV steels, while that for Alloy 13, 130.1 ksi (896 MPa) is higher than the specifications for RPV base metals and is one of the alloys that will be re-heat treated to decrease the hardness.

Following hardness testing and optical metallography, all 50 alloys were submitted for electro-discharge machining to fabricate multiple thin plates, "wafers," of about 0.021 in. (0.53 mm) thickness to enable final preparation of discs from each plate of 0.5 mm thickness. Figure 2.3 shows the drawing used for machining of wafers from each plate. Wafers from all 50 alloys have been shipped to UCSB for final preparation and punching of discs for inclusion in the ATR-2 irradiation capsule.

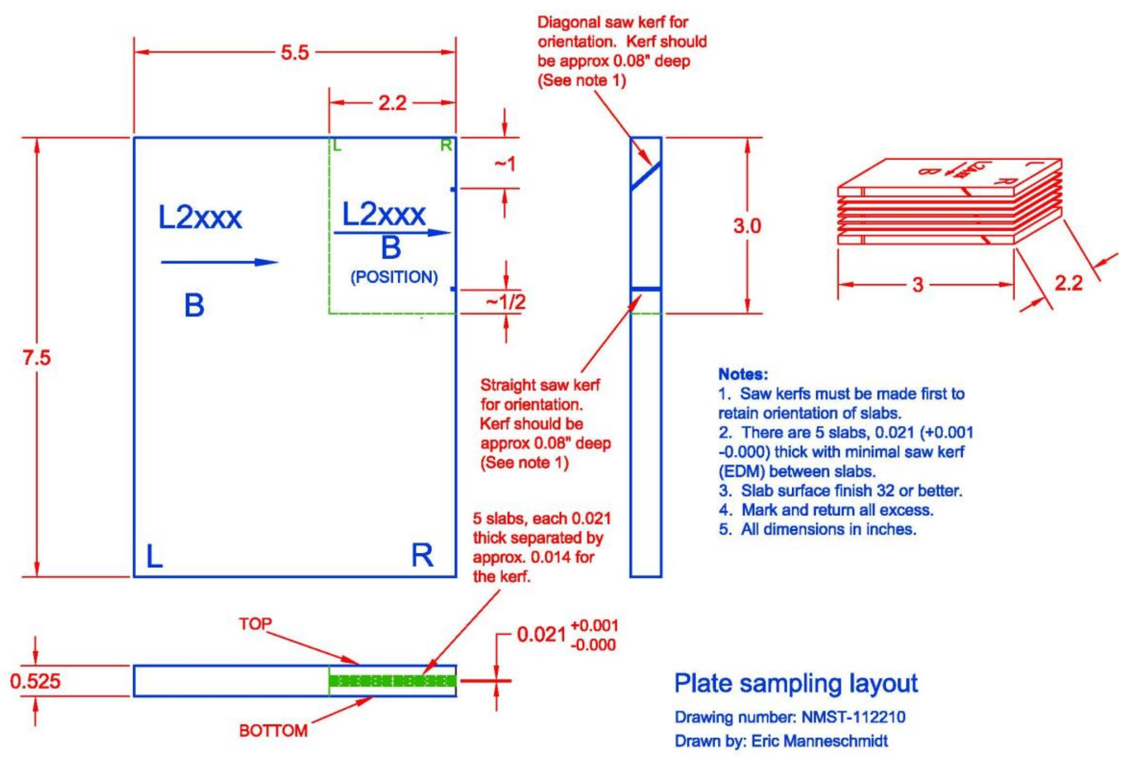

Figure 2.3. Drawing for machining of "wafers" from each of 50 Rolls-Royce supplied plates.

Additionally, surveillance materials from various operating nuclear reactors will be included to enable a direct comparison of results from a test reactor at high flux and a power reactor at low flux. In collaboration with the nuclear power industry and Mr. William Server of ATI-Consulting, archival materials have been procured from various sources within the nuclear industry. Mr. Server contacted all the appropriate utilities to request material and, in one instance, visited the storage facility at Westinghouse in Pittsburgh to locate specific archive materials.

Table 2.1 shows the specific RPV surveillance materials that were previously identified as those that would provide results of particular interest. For the materials in Table 1, contacts have been made with the relevant nuclear utilities to obtain archival material for each case and the right hand column provides the status as of October 2010 in each case. These materials have been selected based not only on their chemical composition but also on their inclusion in capsules intended for relatively high fluence to allow for comparisons of results from surveillance conditions and the test reactor conditions in the ATR-2 experiment.

Table 2.1. RPV surveillance materials being pursued for inclusion in the ATR-2 experiment.

Plant/Capsule	Fluence (E19)	Base Metal Heat	Cu	Ni	Weld	Flux/Heat	Cu	Ni	Comments
Farley1-Z	8.47	SA-533B-1	0.14	0.55	Linde	0091 (33A277)	0.14	0.19	Test reactor data exist for this weld wire heat (low Cu weld MTR program - Hawthorne et al.); archive Farley-1 material **has been located at Westinghouse**; other weldments from this same weld wire heat are **potentially** available ffrom Maine Yankee and Calvert Cliffs-1 archives at another Westinghouse/CE storage location if ever needed; non-irradiated Master Curve data exist for this weld wire heat; **formal approval from utility has been received, and material has been cut and will be shipped to ORNL from Westinghouse**
Farley1-V	7.14								
Farley1-W	4.75								
Farley1-X	3.06								
Farley2-Y	6.79	SA-533B-1 (C7466-1)	0.2	0.6	SMAW	(BOLA)	0.03	0.9	Test reactor data may exist for the weld metal from low Cu weld program (TBD); archive Farley-2 plate and weld metal material has been found (one 1/2-T CT for weld metal and twelve 1/2-T CTs for base metal); also other archive was located at Westinghouse, but will require further work to determine usability; **formal approval from utility has been received and some 1/2-T CT specimens have been shipped to ORNL from Westinghouse**
Farley2-Z	4.92								
Farley2-X	2.98								
Farley2-V	13.6 (2019)								
VC Summer-Z	6.54	SA-533B-1	0.1	0.51	Linde	124 (4P4784)	0.05	0.91	Key comparison of Linde 124 weld with SMAW weld from Farley-2; archive Summer weld metal located (six 1/2-T CTs); also other archive was located at Westinghouse, but will require further work to dertermine usability; **formal approval from utility has been received and material 1/2-T CT specimens have been shipped to ORNL from Westinghouse**
VC Summer-W	4.63								
VC Summer-Y	4.63 (2016)								
Kewaunee-T	5.62	SA-508-2 (122X208VA1 or 123X167VA1)	0.06	0.75	Linde	1092 (1P3571)	0.22	0.72	Same weld wire heats between Kewaunee and MY; fracture toughness data exist from Capsules T and S; **archive material for Kewaunee weld and forging have been located at Westinghouse ; utility approval has been received; pieces of materials will be shipped to ORNL from Westinghouse**
Kewaunee-S	3.67								
Kewaunee-N	9.2 (2022)								
MY-A35	6.11	SA-533B-1	0.1	0.53			0.36	0.78	Test reactor data exist for this weldment; also fracture toughness data exist from Capsule A-35; archive material has been located at Westinghouse (untested CVN specimen(s); utility approval has been received; **specimens have been shipped to ORNL from Westinghouse**

BV2-X	5.6	SA-533B-1 (B9004-2)	0.05	0.56	Linde	0091	0.08	0.07	Low copper plate to be compared with Farley-2 higher copper plate; archive material has been located at Westinghouse, **utility approval has been received, and a piece is is being cut and will be shipped to ORNL from Westinghouse**
BV2-W	3.63								
BV2-Y (2014)	6.0								
Robinson2-X	4.49	SA-302	0.12	N/A	Linde	124	0.34	0.66	Backup
Robinson2-T	3.87								
Robinson2-U (2011)	3.87								
Prairie Is1-R	4.48	SA-508-3	0.06	0.72	SMIT	89	0.13	0.09	Backup
Prairie Is1-S	4.02								
Prairie Is1-S (2011)	5.16								
Prairie Is2-R	4.38	SA-508-3	0.09	0.7	SMIT	89	0.08	0.07	Backup
Prairie Is2-P	4.17								
Prairie Is2-P (2014)	5.2								
Palisades-A240	4.01	SA-302B Mod.	0.25	0.53	Linde	1092	0.23	1.2	Need to get untested Capsule A60 to ORNL; **ORNL is pursuing rental of shiping container from Westinghouse;** older tested specimens probably have been discarded; heat code needs confirmation
Palisades - A60	>10								
Palisades-W80 (2019)	3.06								
Palisades - SA240	2.38	NA					0.307	1.045	Different weld wire heat; fracture toughness data exist
Palisades - SA60	1.5								
Diablo Canyon1 - V	1.37	SA-533B-1	0.08	0.46	Linde	1092	0.21	0.98	Original surveillance program, possibly another capsule will be tested in 2010/2011
Diablo Canyon Supplemental Capsules B, C, & D	TBD	NA				1092			Same weld heat as above, but slightly different chemistry
						80			WW7
						80			W8A/B
						0091			W9A/B
						124			72WP; still researching if capsule with DC-1 will be tested in 2010 or 2011, non-irradiated archive available form ORNL
Turkey Point 4	3.0 and higher with future capsules	NA			Linde	80 (71249)	0.29	0.6	Irradiated data from several sources including B&WOG and Point Beach 1**; material being shipped from Florida Power and Light to ORNL to be cut from archive block**

NOTES:

Blue indicates primary materials of interest

Yellow indicates capsules of interest

Capsules with dates after the fluence are planned values assuming the coordinated PWR surveillance program

Two outcomes of that activity were the shipping of pieces of some materials to ORNL by Dr. Brian Burgos of Westinghouse and Mr. Scott Boggs of Florida Power and Light (Turkey Point Unit 4 weld). They are shown in Table 2.2 below. All of these surveillance materials have been machined into “wafers” and shipped to UCSB for punching of discs.

Table 2.2. List of archival surveillance materials supplied by Westinghouse and Florida Power and Light.

Plant	Material	Heat Number	Specimen Provided
Farley Unit 2	SMAW	BOLA	One (1) 1/2T-CT **“CW25”**
Farley Unit 2	SA533B-1	C7466-1	Two (2) 1/2T-CT **“CT29”** and **“CL28”**[(a)]
V.C. Summer	Linde 124 Weld	4P4784	One (1) 1/2T-CT **“CW26”**
Kewaunee	Linde 1092 Weld	1P3571	0.5” x 3” x 1.5” slice of weldment (weld marked)
Maine Yankee	Linde 1092 Weld	1P3571	Two (2) untested tensile “**4KL”** and **“3J2”** Two (2) broken Charpy halves from specimen **“372”**
Farley Unit 1	Weld	33A277	
Beaver Valley Unit 2	Plate	B9004-1	
Kewaunee	Forging, SA 508-2	B6307-1	
Turkey Point Unit 4	Linde 80 Weld, SA-1094	Weld wire heat #71249 and Linde 80 flux lot 8457.	Piece 3.375x4.25x8.625 in.

Notes:

(a) “CT” refers to transverse orientation and “CL” refers to longitudinal orientation.

REFERENCES

1. **EASON, E. D., ODETTE, G. R., NANSTAD, R. K., and T. YAMAMOTO**, “A Physically Based Correlation of Irradiation-Induced Transition Temperature Shifts for RPV Steels,” **ORNL/TM-2006/530**, Oak Ridge National Laboratory, February 2007.

2. **NANSTAD, R.K. and ODETTE, G.R**., “Reactor Pressure Vessel Issues for the Light-Water Reactor Sustainability Program,” ***Proceedings of Env. Deg. Conf***., *2009.*

3. **ODETTE, G. R. and NANSTAD, R. K.,** “Predictive Reactor Pressure Vessel Steel Irradiation Embrittlement Models: Issues and Opportunities,” ***J. Metals***, 61, 7, July 2009.

Attachment 1

Table A1.1. Hardness Results for Rolls-Royce Alloys

Rockwell hardness values for cross-rolled plate

Rolls Royce PO number 5200017827

				Averages							Data points															
Steel No.	Heat No.	Scale		1/4 W	1/2 W	3/4 W	1/4 T	1/2 T	3/4 T	Overall Avg	1/4 width			center			3/4 width			1/4 T			3/4 T			Estimated UTS, ksi
1	L2385	HRB	Front	81.67	80.33	82.00	80.83	80.33	81.17	81.1	81.0	82.0	82.0	80.0	81.0	80.0	84.0	80.0	82.0	81.0	81.0	80.5	81.5	81.0	81.0	
			Rear	81.50	81.67	81.83	81.33	81.67	80.33	81.4	80.0	82.0	82.5	81.0	82.0	82.0	82.0	81.5	82.0	81.0	81.0	82.0	81.0	79.0	81.0	
			Average	81.58	81.00	81.92	81.08	81.00	80.75	**81.2**	80.5	82.0	82.3	80.5	81.5	81.0	83.0	80.8	82.0	81.0	81.0	81.3	81.3	80.0	81.0	**73.5**
2	L2402	HRB	Front	73.7	72.7	72.3	71.4	72.7	72.8	72.6	73.5	73.5	74.0	72.0	73.0	73.2	70.9	73.0	73.0	71.5	71.2	71.5	71.8	73.5	73.0	
8/13/10			Rear	71.3	71.8	71.1	71.2	71.8	71.9	71.5	70.4	71.6	71.8	71.5	71.7	72.2	69.1	71.8	72.3	70.9	71.0	71.8	71.3	72.0	72.5	
			Average	72.5	72.3	71.7	71.3	72.3	72.4	**72.1**	72.0	72.6	72.9	71.8	72.4	72.7	70.0	72.4	72.7	71.2	71.1	71.7	71.6	72.8	72.8	**62.9**
3	L2403	HRB	Front	56.6	57.6	57.4	57.1	57.6	60.7	57.8	56.1	56.5	57.2	57.9	58.0	56.9	57.1	57.1	57.9	56.8	57.6	57.0	60.3	59.8	61.9	
8/16/10			Rear	61.7	60.6	59.6	58.0	60.6	62.2	60.5	61.5	62.1	61.4	60.2	60.7	61.0	59.4	59.6	59.8	57.9	58.1	58.1	61.8	62.6	62.1	
			Average	59.1	59.1	58.5	57.6	59.1	61.4	**59.1**	58.8	59.3	59.3	59.1	59.4	59.0	58.3	58.4	58.9	57.4	57.9	57.6	61.1	61.2	62.0	**50.3**
4	L2404	HRB	Front	84.2	84.8	83.5	83.9	84.8	84.4	84.3	83.9	84.2	84.6	84.5	85.0	85.0	83.1	83.5	84.0	83.1	84.4	84.2	84.0	84.7	84.5	
8/13/10			Rear	83.1	83.6	83.2	83.8	83.6	84.3	83.6	81.0	84.0	84.2	83.2	83.9	83.8	82.5	83.2	84.0	83.2	84.0	84.2	84.0	84.5	84.5	
			Average	83.7	84.2	83.4	83.9	84.2	84.4	**84.0**	82.5	84.1	84.4	83.9	84.5	84.4	82.8	83.4	84.0	83.2	84.2	84.2	84.0	84.6	84.5	**77.4**
5	L2405	HRB	Front	79.5	79.7	79.1	78.9	79.7	78.8	79.3	79.2	79.8	79.4	79.2	80.0	80.0	78.9	79.1	79.2	78.7	79.2	78.8	78.6	79.5	78.2	
8/16/10			Rear	78.4	78.5	78.8	77.2	78.5	78.2	78.3	78.3	78.9	78.1	78.0	78.8	78.6	79.0	79.2	78.1	77.0	77.2	77.4	79.5	78.1	77.0	
			Average	79.0	79.1	78.9	78.1	79.1	78.5	**78.8**	78.8	79.4	78.8	78.6	79.4	79.3	79.0	79.2	78.7	77.9	78.2	78.1	79.1	78.8	77.6	**70.3**
6	L2406	HRB	Front	84.8	84.6	82.8	83.7	84.6	84.0	84.1	85.0	84.8	84.6	84.5	85.1	84.2	82.1	83.0	83.2	83.2	83.8	84.0	84.0	84.5	83.5	
8/16/10			Rear	85.6	84.8	85.2	85.0	84.8	85.3	85.1	85.8	85.4	85.6	83.1	85.4	85.8	84.6	85.0	85.9	85.0	85.2	84.8	85.2	85.1	85.6	
			Average	85.2	84.7	84.0	84.3	84.7	84.7	**84.6**	85.4	85.1	85.1	83.8	85.3	85.0	83.4	84.0	84.6	84.1	84.5	84.4	84.6	84.8	84.6	**78.4**
7	L2407	HRB	Front	89.0	88.9	88.9	88.4	88.9	89.1	88.9	88.2	89.2	89.6	89.0	88.9	88.8	88.8	89.0	89.0	88.0	88.6	88.6	89.0	88.7	89.6	
8/16/10			Rear	89.0	89.1	89.3	89.1	89.1	89.1	89.1	88.7	90.0	88.4	89.0	89.1	89.2	88.2	90.2	89.5	88.2	89.0	90.0	89.1	89.1	89.0	
			Average	89.0	89.0	89.1	88.7	89.0	89.1	**89.0**	88.5	89.6	89.0	89.0	89.0	89.0	88.5	89.6	89.3	88.1	88.8	89.3	89.1	88.9	89.3	**86.0**
8	L2410	HRB	Front	81.2	81.8	81.2	80.8	81.8	81.1	81.3	80.3	82.2	81.2	82.5	81.9	81.1	80.2	81.5	81.9	80.5	80.8	81.0	81.0	81.1	81.1	
8/18/10			Rear	81.2	81.6	81.6	80.9	81.6	81.3	81.4	80.2	81.9	81.4	81.5	81.8	81.4	81.9	81.9	81.0	81.0	81.0	80.8	81.8	81.2	81.0	
			Average	81.2	81.7	81.4	80.9	81.7	81.2	**81.3**	80.3	82.1	81.3	82.0	81.9	81.3	81.1	81.7	81.5	80.8	80.9	80.9	81.4	81.2	81.1	**73.6**
9	L2414	HRB	Front	85.2	85.4	85.5	84.4	84.7	84.2	84.9	83.6	85.8	86.3	84.0	86.1	83.0	85.0	84.5	85.1	85.4	86.5	86.5	84.0	85.0	84.9	
8/18/10			Rear	84.0	84.3	85.0	85.7	85.0	84.9	84.8	84.0	84.1	83.9	85.0	86.0	86.1	83.0	85.5	85.0	85.4	85.5	85.4	84.8	85.4	85.6	
			Average	84.6	85.0	84.7	85.8	85.0	85.0	**85.0**	83.8	85.0	85.1	84.5	86.1	84.6	84.0	85.0	85.1	85.4	86.0	86.0	84.4	85.2	85.3	**79.1**
10	L2384	HRC	Front	29.2	29.5	29.6	28.6	29.5	29.2	29.3	29.2	28.9	29.4	29.5	29.2	29.9	29.6	29.6	29.7	28.3	29.0	28.6	29.0	29.5	29.1	
			Rear	28.9	29.2	28.5	28.6	29.2	29.3	28.9	28.8	29.3	28.6	29.3	29.3	29.1	28.5	28.8	28.1	28.5	28.4	28.8	28.8	29.9	29.1	
			Average	29.0	29.4	29.1	28.6	29.4	29.2	**29.1**	29.0	29.1	29.0	29.4	29.3	29.5	29.1	29.2	28.9	28.4	28.7	28.7	28.9	29.7	29.1	**134.5**
11	L2408	HRC	Front	23.1	23.3	22.7	22.5	23.3	22.9	23.0	22.5	23.8	23.1	23.6	23.0	23.2	22.1	23.1	23.0	22.1	22.5	23.0	22.8	23.0	23.0	
8/18/10			Rear	22.4	22.7	22.4	22.3	22.7	22.2	22.5	22.1	22.9	22.2	22.5	23.0	22.5	21.5	22.8	23.0	21.5	22.8	22.7	22.1	22.5	22.1	
			Average	22.8	23.0	22.6	22.4	23.0	22.6	**22.7**	22.3	23.4	22.7	23.1	23.0	22.9	21.8	23.0	23.0	21.8	22.7	22.9	22.5	22.8	22.6	**116.1**
12	L2409	HRB	Front	95.7	96.2	95.7	95.8	96.2	96.0	95.9	94.9	96.0	96.1	96.0	96.4	96.2	95.5	95.8	95.8	95.5	95.8	96.0	96.0	95.9	96.0	
8/18/10			Rear	94.9	95.2	95.5	93.3	95.2	95.0	94.9	94.8	95.0	95.0	95.2	95.0	95.5	95.1	95.5	95.8	94.2	91.5	94.3	94.9	95.1	95.0	
			Average	95.3	95.7	95.6	94.6	95.7	95.5	**95.4**	94.9	95.5	95.6	95.6	95.7	95.9	95.3	95.7	95.8	94.9	93.7	95.2	95.5	95.5	95.5	**100.1**
13	L2415	HRC	Front	27.9	28.7	29.5	25.2	28.7	30.3	28.4	28.1	28.6	27.0	28.9	28.9	28.4	31.0	28.5	29.0	22.5	27.2	25.9	29.0	31.0	30.8	
8/13/10			Rear	26.8	27.7	28.2	28.0	27.7	24.2	27.1	26.0	27.0	27.5	28.3	28.5	26.2	28.1	28.0	28.6	26.3	28.7	29.0	23.1	25.1	24.5	
			Average	27.4	28.2	28.9	26.6	28.2	27.3	**27.7**	27.1	27.8	27.3	28.6	28.7	27.3	29.6	28.3	28.8	24.4	28.0	27.5	26.1	28.1	27.7	**130.1**
14	L2416	HRC	Front	23.1	22.5	21.9	22.4	22.5	23.4	22.6	22.4	23.0	23.9	21.9	22.8	22.9	21.4	22.0	22.2	23.8	22.2	21.1	23.4	23.3	23.6	
8/16/10			Rear	21.9	22.9	23.1	22.3	22.9	21.4	22.4	22.1	21.1	22.6	21.8	24.0	23.0	23.0	23.0	23.3	21.9	22.8	22.2	21.0	21.8	21.5	
			Average	22.5	22.7	22.5	22.3	22.7	22.4	**22.5**	22.3	22.1	23.3	21.9	23.4	23.0	22.2	22.5	22.8	22.9	22.5	21.7	22.2	22.6	22.6	**115.7**
15	L2417	HRC	Front	27.3	28.0	27.5	26.2	28.0	27.9	27.5	28.0	28.8	25.0	28.0	28.1	27.8	28.0	27.6	26.9	26.1	26.2	26.2	28.0	27.9	27.9	
8/13/10			Rear	25.9	26.8	26.1	26.9	26.8	23.8	26.0	25.7	26.0	25.9	26.8	26.8	26.8	25.3	26.1	26.8	26.8	26.9	26.9	24.0	22.8	24.5	
			Average	26.6	27.4	26.8	26.5	27.4	25.9	**26.7**	26.9	27.4	25.5	27.4	27.5	27.3	26.7	26.9	26.9	26.5	26.6	26.6	26.0	25.4	26.2	**127.1**

Attachment 1 (Cont'd)

Table A1.1. Hardness Results for Rolls-Royce Alloys

16	L2418	HRC	Front	26.8	27.7	27.8	27.3	27.7	24.5	27.0	26.0	27.4	27.1	27.5	28.5	27.2	27.5	28.1	27.9	27.2	27.8	27.0	24.0	22.5	27.0	
8/16/10			Rear	26.4	26.4	26.9	26.5	26.4	24.4	26.2	24.9	27.4	27.0	25.5	26.1	27.5	26.2	27.2	27.2	26.5	26.8	26.2	24.0	24.1	25.0	
			Average	26.6	27.1	27.4	26.9	27.1	24.4	**26.6**	25.5	27.4	27.1	26.5	27.3	27.4	26.9	27.7	27.6	26.9	27.3	26.6	24.0	23.3	26.0	**126.6**
17	L2436	HRC	Front	30.2	28.8	28.9	25.5	28.8	28.0	28.4	28.4	32.1	30.2	29.0	28.2	29.2	28.0	29.6	29.1	24.2	25.2	27.0	30.0	28.7	25.2	
8/13/10			Rear	27.1	27.7	28.7	28.8	27.7	24.6	27.4	25.1	27.1	29.0	26.0	28.9	28.2	27.2	30.0	28.9	28.0	32.3	26.2	23.0	25.1	25.8	
			Average	28.7	28.3	28.8	27.2	28.3	26.3	**27.9**	26.8	29.6	29.6	27.5	28.6	28.7	27.6	29.8	29.0	26.1	28.8	26.6	26.5	26.9	25.5	**130.6**
18	L2435	HRC	Front	28.8	28.9	29.0	28.9	29.0	29.9	29.1	28.8	28.7	29.0	29.2	28.7	28.8	29.4	31.5	28.9	25.0	25.7	24.7	29.0	29.2	28.2	
9/13/10			Rear	29.1	29.0	29.0	28.5	28.8	28.8	28.9	29.2	29.0	29.0	28.9	29.2	28.9	28.3	29.1	28.8	28.2	28.2	29.0	26.8	27.2	28.0	
			Average	29.0	29.0	29.3	26.8	29.0	28.1	**28.5**	29.0	28.9	29.0	29.1	29.0	28.9	28.9	30.3	28.9	26.6	27.0	26.9	27.9	28.2	28.1	**132.5**
19	L2411	HRB	Front	94.8	94.8	94.9	94.8	94.8	94.7	94.8	94.5	95.0	95.0	94.8	95.0	94.7	94.8	94.7	95.0	94.5	94.2	95.0	94.7	94.8	94.6	
8/18/10			Rear	93.2	94.6	94.3	93.1	93.8	94.0	93.8	91.0	94.6	93.9	94.8	94.2	94.8	92.3	95.0	94.5	93.2	93.2	93.0	94.5	94.8	94.9	
			Average	94.0	94.7	94.4	93.9	94.7	94.7	**94.4**	92.8	94.8	94.5	94.8	94.6	94.8	93.6	94.9	94.8	93.9	93.7	94.0	94.6	94.8	94.8	**97.6**
20	L2421	HRB	Front	82.1	80.7	82.0	80.7	80.7	82.1	81.4	80.7	82.7	83.0	79.2	81.8	81.0	81.6	81.7	82.7	78.8	81.2	82.0	81.6	82.8	82.0	
9/7/10			Rear	80.6	80.0	81.2	80.4	80.0	79.9	80.3	79.0	81.2	81.6	79.1	79.8	81.0	80.3	81.5	81.9	79.2	80.9	81.0	79.0	79.8	81.0	
			Average	81.4	80.3	81.6	80.5	80.3	81.0	**80.9**	79.9	82.0	82.3	79.2	80.8	81.0	81.0	81.6	82.3	79.0	81.1	81.5	80.3	81.3	81.5	**73.0**
21	L2412	HRB	Front	90.4	91.7	91.5	91.4	91.6	91.5	91.4	87.8	92.0	91.5	91.5	91.8	91.9	91.1	91.5	92.0	91.0	91.1	92.2	91.1	91.5	91.8	
8/18/10			Rear	91.7	92.0	92.0	91.4	91.9	91.8	91.8	91.1	92.0	92.0	92.0	92.0	91.8	91.8	91.8	91.3	91.0	91.2	91.9	91.8	91.7	92.0	
			Average	91.1	91.8	91.6	91.4	91.8	91.7	**91.6**	89.5	92.0	91.8	91.8	91.9	91.9	91.5	91.7	91.7	91.0	91.2	92.1	91.5	91.6	91.9	**91.2**
22	L2413	HRC	Front	21.4	21.9	22.2	22.5	22.2	22.5	22.1	21.5	21.0	21.8	22.8	22.1	22.6	21.8	23.2	23.3	21.8	22.0	22.2	22.3	23.2	23.0	
8/18/10			Rear	22.0	22.4	22.5	22.6	22.8	22.8	22.5	21.0	22.7	22.4	22.2	22.8	22.7	22.8	22.8	24.3	22.2	23.0	22.0	22.8	22.9	23.0	
			Average	21.7	22.5	23.0	22.2	22.5	22.9	**22.5**	21.3	21.9	22.1	22.5	22.5	22.7	22.3	23.0	23.8	22.0	22.5	22.1	22.6	23.1	23.0	**115.5**
23	L2433	HRB	Front	90.9	91.2	91.6	89.9	91.2	91.2	91.0	90.1	91.8	90.7	91.2	91.5	90.9	91.5	91.5	91.7	89.1	90.4	90.2	91.6	90.8	91.1	
9/10/10			Rear	90.5	90.0	90.0	91.7	90.0	90.3	90.4	90.3	90.3	90.8	89.2	90.6	90.2	89.4	90.5	90.2	91.7	91.7	91.8	90.9	90.8	89.3	
			Average	90.7	90.6	90.8	90.8	90.6	90.8	**90.7**	90.2	91.1	90.8	90.2	91.1	90.6	90.5	91.0	91.0	90.4	91.1	91.0	91.3	90.8	90.2	**89.4**
24	L2397	HRC	Front	26.0	26.3	25.7	25.7	26.3	25.0	25.8	26.0	26.0	26.0	26.0	27.0	26.0	26.0	26.0	25.0	25.0	26.0	26.0	24.0	26.0	25.0	
			Rear	28.0	25.3	26.7	25.3	25.3	25.0	25.9	29.0	29.0	26.0	25.0	25.0	26.0	27.0	27.0	26.0	26.0	25.0	25.0	24.0	26.0	25.0	
			Average	27.0	25.8	26.2	25.5	25.8	25.0	**25.9**	27.5	27.5	26.0	25.5	26.0	26.0	26.5	26.5	25.5	25.5	25.5	25.5	24.0	26.0	25.0	**124.6**
25	L2434	HRB	Front	93.2	93.3	93.3	93.3	93.5	93.5	93.4	93.5	93.0	93.0	93.0	93.8	93.2	93.5	93.8	93.2	93.8	93.5	94.5	93.2	92.6	93.6	
9/10/10			Rear	94.0	94.3	94.4	94.1	94.1	93.7	94.1	93.9	93.9	94.3	93.8	95.0	94.0	93.2	93.8	93.2	93.8	94.1	94.3	93.9	93.7	93.5	
			Average	93.6	93.8	93.5	94.0	93.8	93.4	**93.7**	93.7	93.5	93.7	93.4	94.4	93.6	93.4	93.8	93.2	93.8	93.8	94.4	93.6	93.2	93.6	**95.9**
26	L2386	HRC	Front	22.0	22.1	21.5	22.1	22.1	22.4	22.0	22.0	21.8	22.1	22.6	21.9	21.7	21.4	21.2	22.0	21.7	21.8	22.7	22.3	22.7	22.1	
			Rear	22.1	22.3	21.8	22.0	22.3	22.1	22.1	22.1	22.3	21.9	22.4	22.2	22.4	21.6	21.7	22.0	22.1	21.9	22.0	21.9	22.3	22.2	
			Average	22.0	22.2	21.7	22.0	22.2	22.3	**22.1**	22.1	22.1	22.0	22.5	22.1	22.1	21.5	21.5	22.0	21.9	21.9	22.4	22.1	22.5	22.2	**114.5**
27	L2423	HRB	Front	88.8	90.7	90.1	87.3	90.7	90.8	89.8	88.2	89.3	89.0	91.0	90.1	91.1	89.0	90.5	90.8	87.3	86.5	88.2	90.8	91.2	90.5	
9/7/10			Rear	89.6	88.7	89.5	89.7	88.7	89.3	89.3	90.2	89.2	89.5	89.5	88.2	88.5	88.5	90.1	89.8	90.2	89.6	89.4	89.7	88.3	89.9	
			Average	89.2	89.7	89.8	88.5	89.7	90.1	**89.5**	89.2	89.3	89.3	90.3	89.2	89.8	88.8	90.3	90.3	88.8	88.1	88.8	90.3	89.8	90.2	**87.0**
28	L2422	HRC	Front	21.1	22.1	21.7	21.9	22.1	22.1	21.8	20.0	21.8	21.6	21.9	22.4	22.0	20.8	22.0	22.4	21.4	22.3	22.0	22.2	22.0	22.1	
9/7/10			Rear	21.4	21.2	21.6	22.1	21.2	19.9	21.2	20.2	21.2	22.8	20.9	21.6	21.1	21.2	21.5	22.0	22.0	21.8	22.4	19.9	19.0	20.8	
			Average	21.3	21.7	21.7	22.0	21.7	21.0	**21.5**	20.1	21.5	22.2	21.4	22.0	21.6	21.0	21.8	22.2	21.7	22.1	22.2	21.1	20.5	21.5	**113.2**
29	L2424	HRB	Front	93.6	94.0	93.8	92.7	94.0	94.0	93.7	93.5	93.2	94.2	93.2	93.5	95.2	93.2	93.5	94.7	92.2	92.8	93.2	94.5	93.1	94.5	
9/7/10			Rear	93.5	93.4	92.9	93.7	93.4	93.2	93.3	93.5	93.2	93.8	93.0	93.6	93.6	92.7	93.1	92.9	94.8	93.1	93.1	93.0	93.2	93.4	
			Average	93.6	93.7	93.4	93.2	93.7	93.6	**93.5**	93.5	93.2	94.0	93.1	93.6	94.4	93.0	93.3	93.8	93.5	93.0	93.2	93.8	93.2	94.0	**95.5**
30	L2429	HRB	Front	92.9	94.9	95.1	94.3	94.9	95.0	94.5	94.2	93.2	91.2	94.8	94.9	95.0	94.2	95.0	96.0	94.0	95.2	93.8	94.7	95.0	95.2	
9/13/10			Rear	96.2	96.3	96.6	96.9	96.3	96.7	96.5	96.6	95.9	96.0	95.4	96.0	97.5	96.4	96.5	96.9	96.8	96.8	97.2	98.0	96.7	95.4	
			Average	94.5	95.6	95.8	95.6	95.6	95.8	**95.5**	95.4	94.6	93.6	95.1	95.5	96.3	95.3	95.8	96.5	95.4	96.0	95.5	96.4	95.9	95.3	**100.3**

Attachment 1 (Cont'd)

Table A1.1. Hardness Results for Rolls-Royce Alloys

31	L2430	HRC	Front	24.0	23.4	23.1	22.6	23.4	23.4	23.3	23.9	24.1	23.9	23.0	23.1	24.0	22.8	22.7	23.8	22.8	22.0	22.9	23.0	23.6	23.6	
9/13/10			Rear	22.8	22.3	21.8	22.0	22.3	21.5	22.1	23.3	22.1	23.0	22.2	22.9	21.7	21.2	22.2	22.0	22.0	22.0	22.0	21.0	21.5	22.0	
			Average	23.4	22.8	22.5	22.3	22.8	22.5	**22.7**	23.6	23.1	23.5	22.6	23.0	22.9	22.0	22.5	22.9	22.4	22.0	22.5	22.0	22.6	22.8	**116.1**
32	L2398	HRC	Front	26.3	26.7	26.0	26.0	26.7	22.3	25.7	26.0	27.0	26.0	26.0	27.0	27.0	26.0	26.0	26.0	26.0	26.0	26.0	22.0	21.0	24.0	
			Rear	25.7	26.0	26.0	25.7	26.0	24.7	25.7	26.0	26.0	25.0	26.0	26.0	26.0	26.0	26.0	26.0	25.0	26.0	26.0	25.0	25.0	24.0	
			Average	26.0	26.3	26.0	25.8	26.3	23.5	**25.7**	26.0	26.5	25.5	26.0	26.5	26.5	26.0	26.0	26.0	25.5	26.0	26.0	23.5	23.0	24.0	**123.9**
33	L2420	HRB	Front	96.6	96.9	96.7	95.0	96.9	96.5	96.4	97.9	96.0	96.0	97.1	96.5	97.0	96.0	97.2	97.0	94.2	95.7	95.0	96.0	96.3	97.2	
8/16/10			Rear	97.2	95.9	96.0	94.9	95.9	95.2	95.9	98.7	96.5	96.4	96.5	95.3	96.0	95.2	96.1	96.7	93.0	95.8	96.0	95.7	94.1	95.9	
			Average	96.9	96.4	96.4	95.0	96.4	95.9	**96.2**	98.3	96.3	96.2	96.8	95.9	96.5	95.6	96.7	96.9	93.6	95.8	95.5	95.9	95.2	96.6	**102.0**
34	L2419	HRB	Front	94.9	95.8	94.2	94.2	95.8	95.3	95.0	93.8	95.1	95.8	97.8	94.5	95.0	93.0	94.8	94.8	93.4	94.4	94.8	95.6	95.0	95.2	
9/7/10			Rear	95.4	95.4	95.0	95.3	95.4	94.9	95.2	94.0	96.0	96.1	95.9	95.4	95.0	94.7	94.3	96.0	95.0	95.0	95.9	95.0	94.8	95.0	
			Average	95.1	95.6	94.6	94.8	95.6	95.1	**95.1**	93.9	95.6	96.0	96.9	95.0	95.0	93.9	94.6	95.4	94.2	94.7	95.4	95.3	94.9	95.1	**99.4**
35	L2399	HRB	Front	96.7	96.0	96.3	96.0	96.0	96.0	96.2	98.0	96.0	96.0	96.0	96.0	96.0	95.0	96.0	98.0	96.0	96.0	96.0	96.0	96.0	96.0	
			Rear	97.7	95.7	97.3	96.0	95.7	96.3	96.4	99.0	99.0	95.0	95.0	96.0	96.0	98.0	98.0	96.0	96.0	96.0	96.0	96.0	97.0	96.0	
			Average	97.2	95.8	96.8	96.0	95.8	96.2	**96.3**	98.5	97.5	95.5	95.5	96.0	96.0	96.5	97.0	97.0	96.0	96.0	96.0	96.0	96.5	96.0	**102.4**
36	L2425	HRB	Front	89.5	88.7	87.9	88.7	88.7	89.1	88.8	89.4	90.0	89.0	90.2	88.9	87.1	88.5	86.8	88.3	88.8	88.6	88.6	90.0	88.4	89.0	
9/10/10			Rear	87.6	88.3	88.3	87.9	88.3	89.0	88.2	86.9	88.0	88.0	87.4	88.8	88.8	88.2	87.8	88.8	87.2	88.2	88.3	88.1	88.9	89.9	
			Average	88.6	88.5	88.1	88.3	88.5	89.1	**88.5**	88.2	89.0	88.5	88.8	88.9	88.0	88.4	87.3	88.6	88.0	88.4	88.5	89.1	88.7	89.5	**85.1**
37	L2426	HRB	Front	97.0	97.6	97.2	96.7	97.6	98.5	97.4	98.0	96.1	97.0	97.8	97.0	98.1	97.2	97.5	96.8	96.4	97.0	96.8	98.5	98.4	98.5	
9/10/10			Rear	96.8	97.6	97.2	98.7	97.6	97.8	97.6	96.5	96.8	97.2	98.0	97.3	97.6	97.0	97.2	97.5	98.0	99.1	99.0	97.5	97.5	98.3	
			Average	96.9	97.6	97.2	97.7	97.6	98.1	**97.5**	97.3	96.5	97.1	97.9	97.2	97.9	97.1	97.4	97.2	97.2	98.1	97.9	98.0	98.0	98.4	**105.7**
38	L2427	HRB	Front	89.3	89.5	89.2	90.2	89.5	89.9	89.6	89.5	88.9	89.6	89.8	89.4	89.4	89.5	88.6	89.4	89.9	90.6	90.0	89.3	90.3	90.2	
9/13/10			Rear	89.3	87.7	87.6	88.0	87.7	87.9	88.0	88.0-8!	89.0	89.5	87.8	87.0	88.3	88.0	88.0	86.7	86.9	88.5	88.7	87.8	88.1	87.8	
			Average	89.3	88.6	88.4	89.1	88.6	88.9	**88.8**	89.5	89.0	89.6	88.8	88.2	88.9	88.8	88.3	88.1	88.4	89.6	89.4	88.6	89.2	89.0	**85.7**
39	L2400	HRB	Front	94	94	96	94	94	94	94.5	94	95	94	94	95	94	94	96	97	94	95	94	94	94	94	
			Rear	98	95	97	95	95	94	95.7	99	98	98	94	95	95	97	96	99	95	95	95	95	94	94	
			Average	96	95	97	95	95	94	**95.1**	97	97	96	94	95	95	96	96	98	95	95	95	95	94	94	**99.4**
40	L2428	HRB	Front	95.8	96.4	95.9	94.0	96.4	95.5	95.7	96.1	95.3	96.1	97.1	96.2	96.0	95.8	96.0	96.0	92.0	94.9	95.0	96.0	95.0	95.6	
9/13/10			Rear	95.8	95.4	95.8	96.8	95.4	95.6	95.8	94.8	95.7	97.0	95.0	94.9	96.3	95.4	95.8	96.1	96.6	96.9	96.8	95.9	94.9	96.0	
			Average	95.8	95.9	95.9	95.4	95.9	95.6	**95.7**	95.5	95.5	96.6	96.1	95.6	96.2	95.6	95.9	96.1	94.3	95.9	95.9	96.0	95.0	95.8	**101.0**
41	L2431	HRB	Front	94.1	93.9	94.0	93.5	93.9	94.5	94.0	94.1	94.1	94.1	94.1	94.0	93.5	93.9	94.0	94.0	93.2	93.5	93.8	94.8	94.2	94.5	
9/10/10			Rear	94.2	93.9	94.4	93.8	93.9	94.0	94.0	94.8	93.4	94.5	93.8	94.1	93.8	94.5	94.6	94.0	93.2	93.5	94.8	93.9	93.9	94.1	
			Average	94.2	93.9	94.2	93.7	93.9	94.2	**94.0**	94.5	93.8	94.3	94.0	94.1	93.7	94.2	94.3	94.0	93.2	93.5	94.3	94.4	94.1	94.3	**96.7**
42	L2432	HRB	Front	97.0	97.7	97.7	96.9	97.7	97.9	97.5	96.6	97.2	97.2	97.8	97.2	98.0	97.8	97.5	97.9	96.6	97.0	97.1	97.3	98.1	98.2	
9/10/10			Rear	96.7	96.4	97.4	96.6	96.4	97.0	96.8	98.0	96.0	96.1	96.5	96.3	96.5	97.5	97.5	97.2	98.0	96.1	95.6	97.0	97.9	96.1	
			Average	96.9	97.1	97.6	96.7	97.1	97.4	**97.1**	97.3	96.6	96.7	97.2	96.8	97.3	97.7	97.5	97.6	97.3	96.6	96.4	97.2	98.0	97.2	**104.6**
43	L2437	HRB	Front	96.3	95.6	96.7	96.1	95.6	96.0	96.1	95.8	96.0	97.1	95.8	94.9	96.1	97.8	96.2	96.1	96.0	96.1	96.2	97.0	95.5	95.6	
8/16/10			Rear	98.2	97.9	97.0	97.7	97.9	95.8	97.4	97.8	99.5	97.2	97.0	97.0	99.8	95.8	97.2	97.9	96.0	97.9	99.2	94.0	96.2	97.2	
			Average	97.2	96.8	96.8	96.9	96.8	95.9	**96.7**	96.8	97.8	97.2	96.4	96.0	98.0	96.8	96.7	97.0	96.0	97.0	97.7	95.5	95.9	96.4	**103.6**
44	L2438	HRB	Front	98.1	97.1	98.1	97.6	97.1	97.6	97.6	98.0	98.0	98.2	97.2	97.0	97.1	97.4	98.0	98.9	97.5	97.5	97.8	97.6	97.8	97.5	
8/13/10			Rear	96.3	96.9	99.2	96.6	96.9	95.5	96.9	96.0	97.9	95.0	96.4	97.1	97.1	99.1	99.9	98.7	96.5	96.2	97.2	95.0	95.9	95.5	
			Average	97.2	97.0	98.7	97.1	97.0	96.6	**97.2**	97.0	98.0	96.6	96.8	97.1	97.1	98.3	99.0	98.8	97.0	96.9	97.5	96.3	96.9	96.5	**104.9**
45	L2439	HRB	Front	101.1	100.1	100.6	99.3	100.1	99.4	100.1	102.0	100.9	100.4	100.1	100.0	100.1	101.5	100.0	100.2	99.2	98.5	100.2	100.0	98.8	99.4	
8/16/10			Rear	100.2	100.2	100.0	98.5	100.2	100.4	99.9	99.9	100.2	100.5	100.0	99.7	100.9	99.8	100.1	100.0	97.8	98.0	99.8	101.5	100.1	99.7	
			Average	100.7	100.1	100.3	98.9	100.1	99.9	**100.0**	101.0	100.6	100.5	100.1	99.9	100.5	100.7	100.1	100.1	98.5	98.3	100.0	100.8	99.5	99.6	**112.9**

Attachment 1 (Cont'd)

Table A1.1. Hardness Results for Rolls-Royce Alloys

45	L2439	HRB	Front	101.1	100.1	100.6	99.3	100.1	99.4	100.1	102.0	100.9	100.4	100.1	100.0	100.1	101.5	100.0	100.2	99.2	98.5	100.2	100.0	98.8	99.4	
8/16/10			Rear	100.2	100.2	100.0	98.5	100.2	100.4	99.9	99.9	100.2	100.5	100.0	99.7	100.9	99.8	100.1	100.0	97.8	98.0	99.8	101.5	100.1	99.7	
			Average	100.7	100.1	100.3	98.9	100.1	99.9	**100.0**	101.0	100.6	100.5	100.1	99.9	100.5	100.7	100.1	100.1	98.5	98.3	100.0	100.8	99.5	99.6	**112.9**
46	L2401	HRC	Front	31	30	30	30	30	29	30.1	32.0	31.0	31.0	31.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	28.0	29.0	29.0	
			Rear	31	30	30	30	30	30	30.1	30.0	30.0	32.0	29.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	31.0	
			Average	31	30	30	30	30	30	**30.1**	31.0	30.5	31.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	29.0	29.5	30.0	**137.8**
47	L2440	HRB	Front	93.9	96.8	96.7	96.1	96.8	96.6	96.2	92.8	94.5	94.3	96.8	96.9	96.8	96.5	96.8	96.7	96.3	95.9	96.1	96.7	96.1	97.0	
9/7/10			Rear	97.0	97.3	96.8	97.1	97.3	97.2	97.1	96.8	97.2	97.0	97.8	96.7	97.5	97.0	96.5	97.0	96.8	98.1	96.4	96.8	97.4	97.5	
			Average	95.4	97.1	96.8	96.6	97.1	96.9	**96.6**	94.8	95.9	95.7	97.3	96.8	97.2	96.8	96.7	96.9	96.6	97.0	96.3	96.8	96.8	97.3	**103.3**
48	L2444	HRC	Front	22.4	23.0	22.4	22.8	23.0	22.7	22.7	22.4	22.5	22.2	22.9	23.1	23.0	22.0	23.0	22.1	22.4	23.3	22.7	22.9	23.1	22.2	
9/7/10			Rear	20.9	21.1	21.2	21.6	21.1	21.2	21.2	20.2	21.5	21.0	20.6	21.8	20.9	20.8	20.8	22.0	21.0	22.0	21.7	21.8	20.8	20.9	
			Average	21.6	22.1	21.8	22.2	22.1	22.0	**21.9**	21.3	22.0	21.6	21.8	22.5	22.0	21.4	21.9	22.1	21.7	22.7	22.2	22.4	22.0	21.6	**114.2**
49	L2442	HRC	Front	23.5	22.8	21.9	21.7	22.8	22.1	22.5	23.8	22.8	24.0	22.1	24.2	22.1	21.5	21.5	22.6	22.1	21.3	21.8	20.8	22.5	23.1	
9/7/10			Rear	20.8	21.0	20.9	22.2	21.0	19.6	20.9	19.7	21.5	21.2	20.1	22.0	21.0	20.8	21.0	20.9	21.9	20.9	23.7	19.0	19.6	20.2	
			Average	22.2	21.9	21.4	22.0	21.9	20.9	**21.7**	21.8	22.2	22.6	21.1	23.1	21.6	21.2	21.3	21.8	22.0	21.1	22.8	19.9	21.1	21.7	**113.6**
50	L2443	HRC	Front	23.4	23.2	23.7	20.2	23.2	23.0	22.8	22.5	23.7	24.1	22.1	23.9	23.7	23.5	23.8	23.9	18.0	23.9	18.7	22.8	23.1	23.0	
9/7/10			Rear	24.6	24.5	24.9	20.4	24.5	24.4	23.9	24.0	24.9	25.0	24.0	24.4	25.2	24.8	25.0	24.9	20.8	20.0	20.5	24.0	24.5	24.7	
			Average	24.0	23.9	24.3	20.3	23.9	23.7	**23.4**	23.3	24.3	24.6	23.1	24.2	24.5	24.2	24.4	24.4	19.4	22.0	19.6	23.4	23.8	23.9	**117.7**
Calabration Block HRB 74.6 ± 1.0			**Date**	**8/13/10**	**8/16/10**	**8/18/10**	**9/7/10**	**9/9/10**	**9/10/10**	**9/13/10**																
				74.0	74.6	75.2	74.8	74.0	74.5	74.8																
				74.7	74.8	74.9	75.8	74.0	74.8	74.8																
				74.5	74.0	75.0	75.4	74.2	74.5	75.0																
			Average	**74.4**	**74.5**	**75.0**	**75.3**	**74.1**	**74.6**	**74.9**																
Calabration Block HRC 25.4 ± 1.0			**Date**	**8/18/10**	**9/7/10**	**9/9/10**	**9/13/10**																			
				24.9	25.4	24.8	25.1																			
				25.0	25.2	25.2	25.5																			
				25.3	25.1	25.2	25.8																			
			Average	**25.1**	**25.2**	**25.1**	**25.5**																			

Attachment 2
Examples of Optical Metallography for Rolls-Royce Alloys

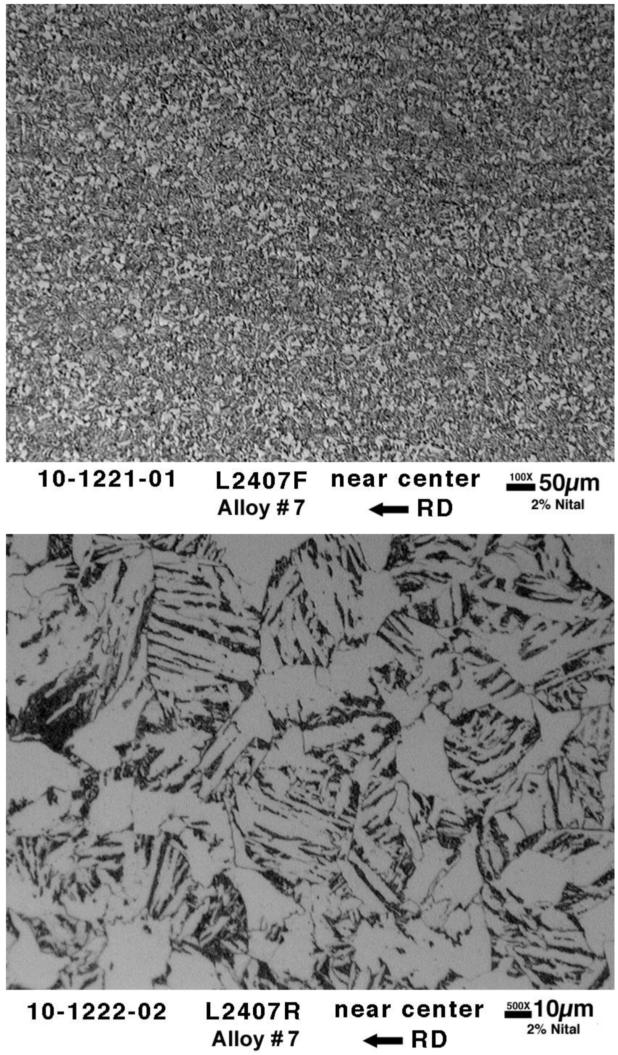

Figure A2.1. Optical micrographs of RR alloy no. 7, showing a generally bainitic microstructure with some ferrite. The hardness of this alloy correlates to an estimated ultimate tensile strength of 86.0 ksi (592 MPa).

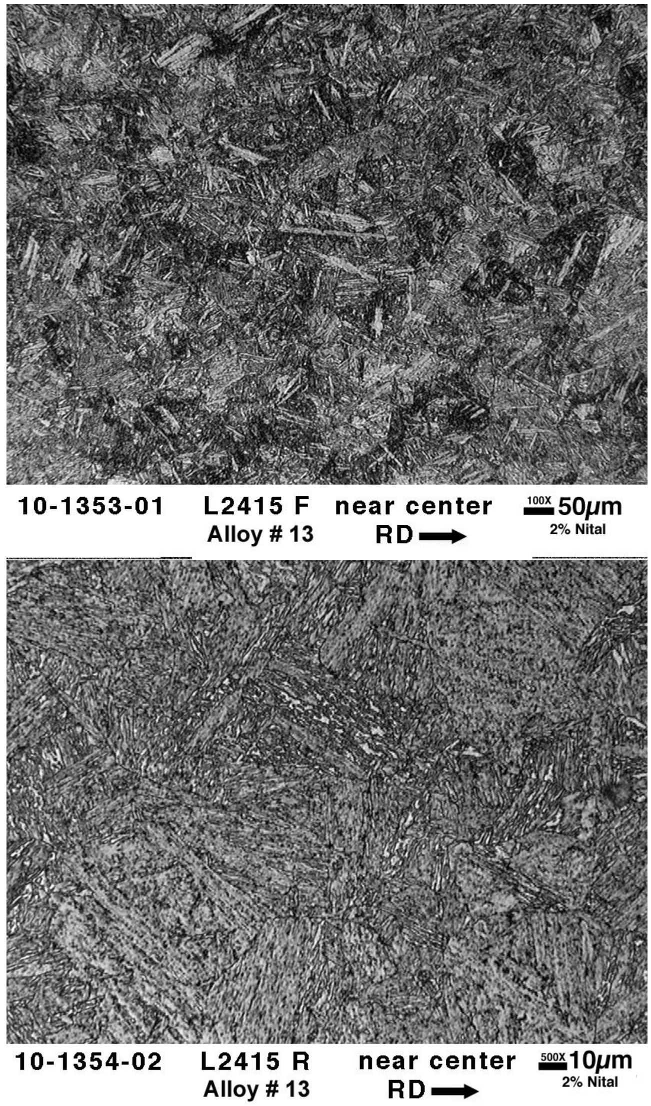

Figure A2.2. Optical micrographs of RR alloy no. 13, showing a bainitic microstructure with some martensite. The hardness of this alloy correlates to an estimated ultimate tensile strength of 130.1 ksi (896 MPa).

INTERNAL DISTRIBUTION

1. J. T. Busby
2. S.R. Greene
3. G. E. Ice
4. D. Ingersoll
5. R. K. Nanstad

EXTERNAL DISTRIBUTION

R. Szilard, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3860, (Ronaldo.Szilard@inl.gov)
P. Finck, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3860, (Phillip.Finck@inl.gov)
R. Reister, GTN Bldg, 1000 Independence Ave, S.W. Washington, DC 20585, (Richard.Reister@nuclear.energy.gov)