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BORALCAN™ SNAP-IN®: NEUTRON TRANSMISSION TESTING, STATISTICAL ANALYSIS

Matt Eyre, NETCO, Lake Katrine, NY, USA

Jean-Alain Laurin, Rio Tinto Alcan, ARDC, Jonquière, Qc, Can

Richard Krutzik, Manufacturing Sciences Corporation, Oak Ridge, TN, USA

Pierre Marchand, Rio Tinto Alcan, Montréal, Qc, Can

ABSTRACT

Neutron absorber materials are used for cask storage as well as for transportation of nuclear fuel. Furthermore, high density storage of fuel in commercial nuclear reactor pools relies on neutron absorber material to assure fuel sub-criticality. Analysis of regulatory required sub-criticality margin relies on the assurance of a uniform distribution of the absorber, usually boron-10, and meeting or exceeding the minimum specified boron-10 areal density[1] (grams/square centimeter). The usual form of the neutron absorber is rolled sheet or extruded shapes of a boron containing matrix.

The aim of this paper is to review, using statistical analysis, the variations of the neutron transmission ratio associated with the variations coming from casting, rolling and measurement of the end product areal density of Rio Tinto Alcan's (RTA) Boralcan™ material as used in the production of NETCO Snap-In® spent fuel storage rack inserts. Rio Tinto Alcan will perform the controls and tests associated with casting of Boralcan™ billets. Manufacturing Sciences Corporation (MSC) will perform the controls and tests associated with rolling and cutting of sheets. NETCO will perform the uncertainty measures associated with the measurement of the Boralcan™ sample coupon neutron transmission ratio and boron-10 areal density.

INTRODUCTION

BORALCAN™

Boralcan™ is a Metal Matrix Composite (MMC): aluminum alloy with nuclear grade B_4C addition used as neutron absorbing material for:

- spent fuel dry storage baskets made from rolled sheet or extruded shapes,
- spent fuel wet pool racks made from rolled sheet.

[1] Areal density is Density x Thickness, or $\rho_{AD} = \rho \times t$ such that rho is the density of boron-10, and t is the thickness of this volume in the direction of interest. Areal density has the units of g/cm².

The use of Boralcan™ MMC material is attractive due to its high capability to capture neutrons as well as for its low density, superior stiffness and strength.

Based on many years of experience in the manufacturing of aluminum-based MMC materials, Rio Tinto Alcan has developed a novel liquid mixing process and associated downstream fabrication technologies for the production of Boralcan™, which can now be cast, extruded or rolled into almost any desired shape. A variety of Boralcan™ materials incorporating a range of Al matrix alloys and B_4C loadings are now available for use in an extensive series of applications.

Common Boralcan™ alloy matrices used are W1100N.xxB, W6351N.xxB

The volume B_4C found in the matrix is specific to each project and can reach as high as 30% v/v.

Corrosion resistance is certainly a key factor in wet pool applications and is very important in dry storage and transport applications due to the initial flooding of the cask/canister during the loading, drying, and sealing operations. An accelerated corrosion resistance test of the Boralcan™ material was performed under the following conditions as part of material qualification:

- BWR and PWR pool environment,
- in contact with 304 L, Inconel 718, zircaloy,
- 16 and 25% v/v B_4C, flat and bent sheet,
- up to 8000 h at 195^{o}F (90°C), equivalent to 17 years at 80^{o}F (27°C).

Post-test examination led to the following conclusions:

- typical corrosion rate: -0.01 to 0.04 mils/year (0.25 to 1.0 µm/year),
- identical corrosion rate for Boralcan™ 16 and 25% v/v B_4C,
- no differences between BWR and PWR environments,
- no difference when exposed to galvanic conditions,
- no localized corrosion (pitting) observed.

APPLICATION OF BORALCAN™ IN NETCO SNAP-IN®

NETCO selected Boralcan™ as the fabrication material for Snap-In® inserts delivered to a number of US commercial nuclear power plants.

The NETCO Snap-In® is a patented neutron absorbing product, which restores the reactivity hold down capability of spent fuel storage racks with degraded neutron absorber material or augments the neutron absorber effectiveness due to changes in the design basis fuel assembly.

Snap-In® inserts are installed in fuel storage cells using simple tooling, which is operated above the pool from the spent fuel pool bridge. Once installed, the Snap-In® inserts become an integral part of the fuel rack allowing fuel to be readily moved in and out of the storage location. Snap-In® inserts solve problems such as Boraflex degradation at a fraction of the cost of re-racking or accelerated dry storage.

The NETCO Snap-In® insert is a one-piece chevron, shaped safety related component, made entirely of an aluminum boron carbide MMC. The insert, which is approximately as long as a fuel assembly, is installed into a Spent Fuel Pool (SFP) storage cell and resides between the fuel assembly and two adjacent storage cell walls. The insert is shaped to fit tightly against the storage cell walls and is held in place within the storage cell by the friction force between the insert and storage cell wall as well as by the spring-like flexure force exerted by the installed insert on the fuel cell wall. The thickness of the insert is such that it can be placed within the space that exists between the fuel cell and the fuel assembly external envelope. Once installed, the insert does not interfere with the insertion or removal of the fuel assembly. Inserts are installed using an installation tool which is designed to be compatible with the insert and the SFP fuel cell.

The principal safety function of the spent fuel pool and of the fuel racks is to maintain the stored fuel assemblies in a safe, sub-critical configuration. The purpose of the inserts is to ensure an adequate sub-criticality margin inside the fuel storage rack. In addition to providing criticality control, installation of the inserts into the fuel rack requires that all other functions and conditions of the spent fuel pool necessary to safely store fuel be maintained. Accordingly, the Snap-In® insert is an important safety component.

As a safety related component, the NETCO Snap-In® insert has a number of critical characteristics:

- part and material traceability,
- dimensions, shape and specified bend angle,
- insert retention force,
- ^{10}B areal density.

CASTING OF BORALCAN™ MATERIAL BY RIO TINTO ALCAN

For the purposes of this paper, the authors studied a number of material production lots associated with the first NETCO Snap-In® project. For this project, each heat (lot coming from the same furnace batch) of Boralcan™ was cast by Rio Tinto Alcan at Dubuc Works[2], in 2011. Each heat weighed approximately 5000 kg, which is the largest heat size for aluminum B_4C metal matrix composite (MMC) producers. The Boralcan™ material was cast into 16 logs, each 5500 mm long. Logs were then cut into 8 billets.

[2] Dubuc Works is situated in Chicoutimi, Québec, Canada.

Below is a schematic of the Boralcan™ fabrication process.

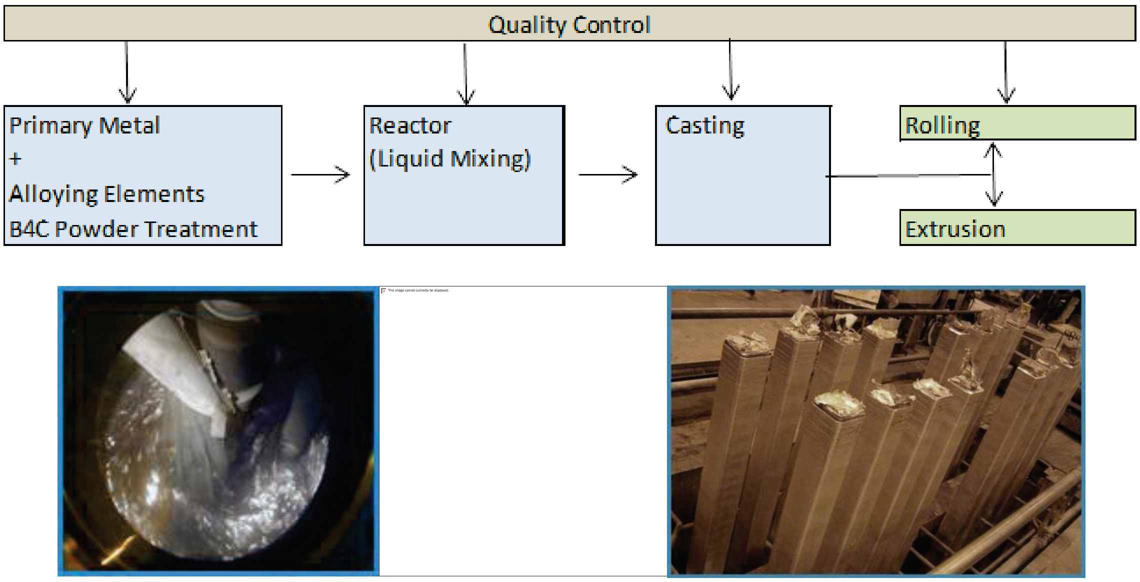


Figure 1. Boralcan™ fabrication process

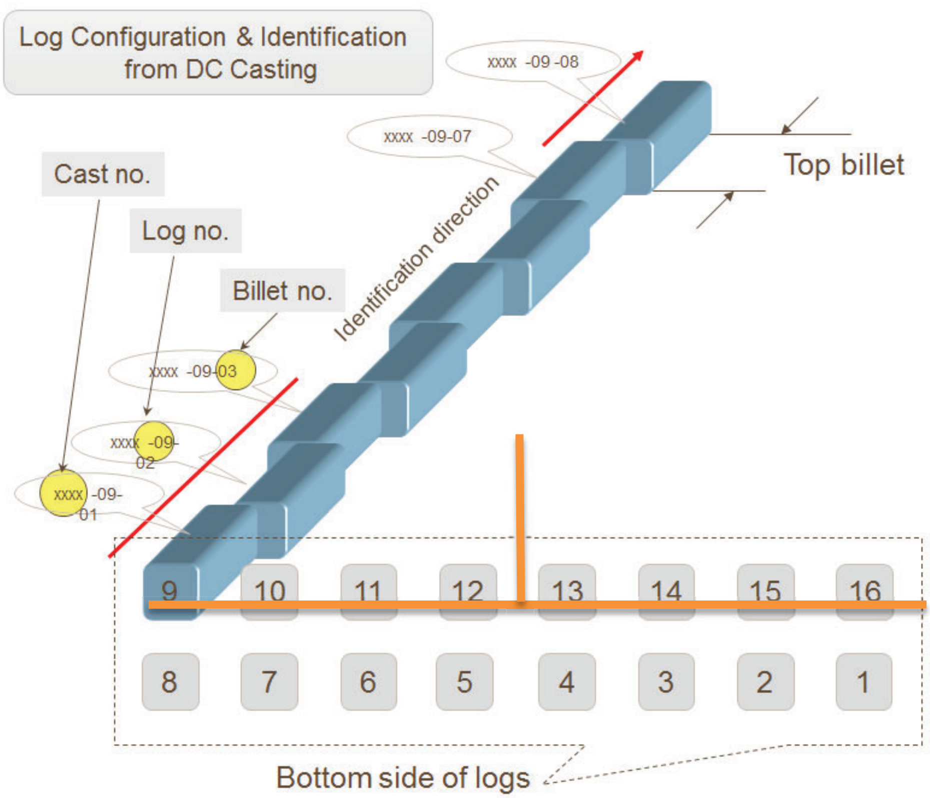
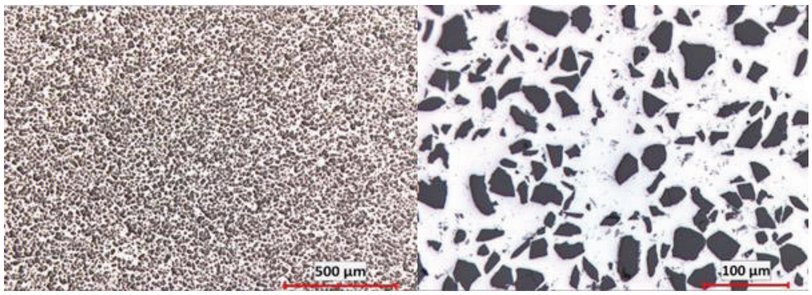


Figure 2. Log and billet configuration

During casting, the Rio Tinto Alcan personnel measure the melt material to see if it is in compliance with the design specification.

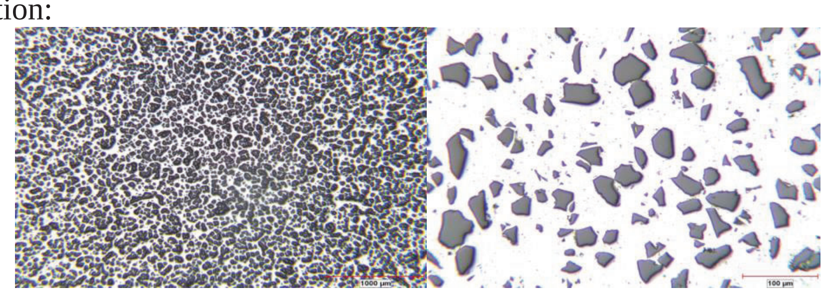
Subsequent to casting, the Rio Tinto Alcan personnel examine the material to ensure that the B_4C particles are homogeneously distributed. Below is an example of the B_4C distribution within the aluminium alloy matrix of Boralcan™ 23% v/v B_4C.

As-cast condition:



25 X 200X

As-rolled condition:



25 X 200X

Figure 3. Magnification of as- cast and as-rolled Boralcan™

The B_4C distribution is uniform across the thickness of the material, either rolled or extruded.

FORMING OF BORALCAN™ INTO SNAP-IN® BY MSC

Rolling

Manufacturing Sciences Corporation hot-rolled the 6 in (152 mm) (Height) x 6 in (152 mm) (Width) x 28 in (711 mm) (Length) billets of Boralcan™ on a 4-high rolling mill down to 0.075 in (1.9 mm) thick sheets – an 8000% reduction in thickness. The billets were hot-rolled to a near-finished thickness and then cold-rolled to final gauge. The rolled plates were annealed prior to forming into Snap-In® inserts.

Bending up to 90°

Manufacturing Sciences Corporation has found that Boralcan™ offers the following benefits as the starting material for rolling:

- excellent surface finish on the cast billet, thus eliminating the need to scalp the billet surface prior to rolling – maximizing yield and saving processing time;

- exhibits minimal edge cracking as a result of the thickness reduction, maximizing the yield of the finished plates from a billet;
- the homogeneous chemistry within each heat of material minimizes the variation of mechanical properties after processing. Manufacturing Sciences Corporation performed a tensile test on each billet, and the material has had zero material rejection due to a failure to meet the required mechanical properties.

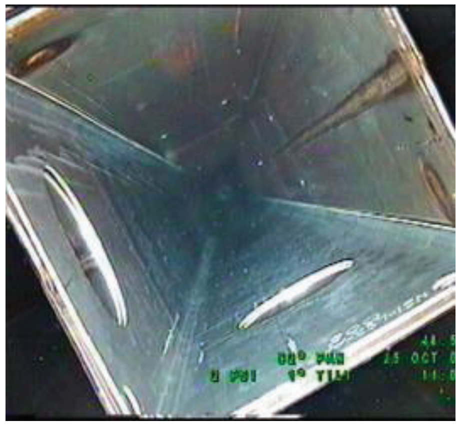


Figure 4. Boralcan™ material bent in a Snap-In® insert

As demonstrated by the photomicrographs (Figure 3) of the cast and wrought (rolled) Boralcan™, each exhibits a homogeneous distribution of the boron carbide within the metal matrix.

Fabrication Testing

For this Snap-In® project, the fabrication testing sample size for the areal density was 100%. Each sheet of Boralcan™ material used to manufacture the inserts had an associated traceable test coupon, which was removed and subjected to areal density testing to demonstrate compliance with design requirements.

Criticality Safety

As stated earlier, the principal safety function of the spent fuel pool storage racks is to maintain the stored fuel assemblies in a safe, sub-critical configuration. The purpose of the inserts is to ensure an adequate sub-criticality margin.

Thus, the K_{eff} of the spent fuel storage racks loaded with maximum reactivity fuel shall not exceed 0.95, at a 95 percent probability, at the 95 percent confidence level[3].

95% confidence is commonly misinterpreted as 95% of the time. In this case, it means that if 100 identical procedures were conducted (N random samples from the same population and same statistical analysis), 95 of the 100 intervals would contain 95% of the population.

[3] Rule 95-95: This term is generally used to refer to an interval or upper/lower limit. In this case, 95/95 means that with 95% confidence, 95% of the population from which the sample was taken will fall within the interval.

To meet the criticality safety requirements noted above, the areal density of each insert must meet or exceed the specified minimum areal density, as identified in the spent fuel pool criticality safety analysis.

STATISTICAL ANALYSIS STUDY OF BORALCAN™

The objective of this paper is to evaluate the stability of the areal density of the Snap-In® material product from the Boralcan™ material.

The case study focuses on a production lot for the LaSalle Unit 2 Snap-In® project. Four heats were selected for the statistical study: Heats 6812A, 6825A, 6838A, and 6840A.

For this study, each billet was rolled by MSC in individual sheets at a given thickness of 0.065 in (1.9 mm). Coupons were withdrawn for each sheet for quality assurance testing of thickness and areal density. The thickness measurement was performed by MSC with a micrometer (measurement precision of +/-0.0001). The design for the LaSalle Unit 2 Snap-In® project required a minimum areal density of 0.0087 g/cm^2 and a thickness of 0.065 in $\pm$0.005 in.

Coupons for areal density testing were transferred to the NETCO lab at Penn State University. Measurements for the study heats were performed from January 10th to August 18th 2011, on a quantity of 200-250 coupons per heat.

For the purpose of the study, the boron carbide density is expressed in volume density (VD) where: VD = AD / t given in g^{10}B/cm^3.

The Minitab software was used for this statistical study case (average, standard deviation, capability, CPK, etc.). The variation of VD is expressed in percentage of the average VD of each individual heat.

A sensitivity study, named gage R&R, was performed on a selected number of coupons in order to identify any bias in the measurement method of the areal density.

RESULTS

The four heats used for testing have all coupons above the minimum areal density (AD) requirement. The average AD of the four heats varies from 111 to 116% above the minimum areal density requirement of 0.0087 g/cm^2, while the process capability index (Cpk) is above 1.6, indicating how close the minimum values are relative to the specification. Typically, a Cpk value of 1.33 and above is considered as within control 4 sigma or higher.

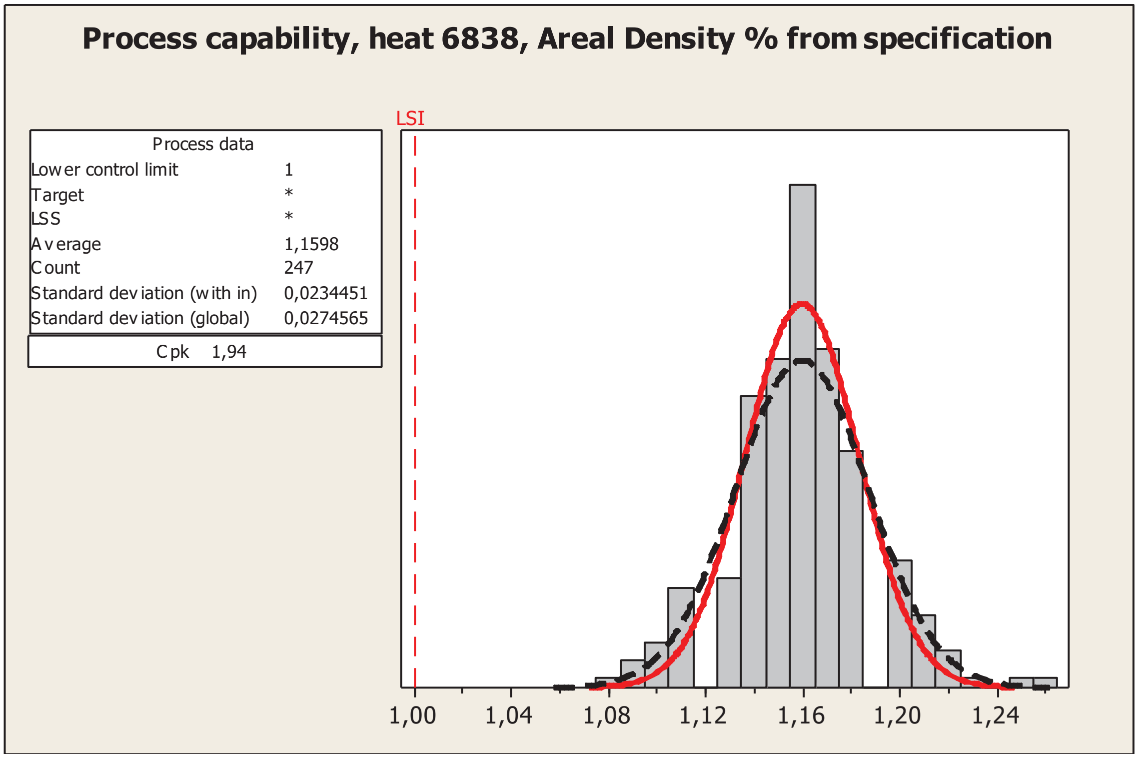


Figure 4 : Heat 6838, process capability relative minimum areal density (coupon AD/ minimum AD)

The following table presents a summary of percentages relative to specification.

Table 1. Summary table of areal density

Heat #	**6812**	**6825**	**6838**	**6840**
Number of samples	255	203	247	244
AD measurements Date	2011-01-10	2011-06-02	2011-08-17	2011-08-17
AD measurements Date	2011-02-28	2011-06-03		2011-08-18
AD measurements Date	2011-03-01			
Spec AD ($g^{10}B/cm^2$)	0.0087	0.0087	0.0087	0.0087
Min AD ($g^{10}B/cm^2$)	0.0098	0.0097	0.0101	0.0100
Avg AD ($g^{10}B/cm^2$)	0.0100	0.0101	0.0109	0.0103
Max AD ($g^{10}B/cm^2$)	0.0120	0.0119	0.0137	0.0127
Avg AD (% spec)	113%	111%	116%	115%
Min AD (% spec)	102%	105%	108%	103%
Max AD (% spec)	120%	117%	126%	123%
Interval min-max AD (% spec)	18%	12%	18%	20%
Std dev AD (%)	2.6%	2.0%	2.8%	3.1%
Cpk	1.6	1.8	1.9	1.6

All four heats have a Cpk value above 1.33, which indicates a comfortable margin between the minimum measured areal density and the minimum specified by the designer.

The %AD values are expressed as a % relative to the project specification value of 0.0087 $g^{10}B/cm^2$.

<u>Gage repeatability and reproducibility (R&R)</u>

In order to determine how much the product variation is due to the measurement system variation, a number of 22 samples were selected from Heat 6838A to perform a gage R&R study.

The repeatability of the measure was evaluated by repeating the areal density measurements three times on each individual coupon during the same day. The reproducibility was evaluated by performing a series of measurements on different dates.

The first series of measurements was performed on May 1st, 2013. The second and third series were performed on May 21st, 2013.

The following figure shows the results of the analysis.

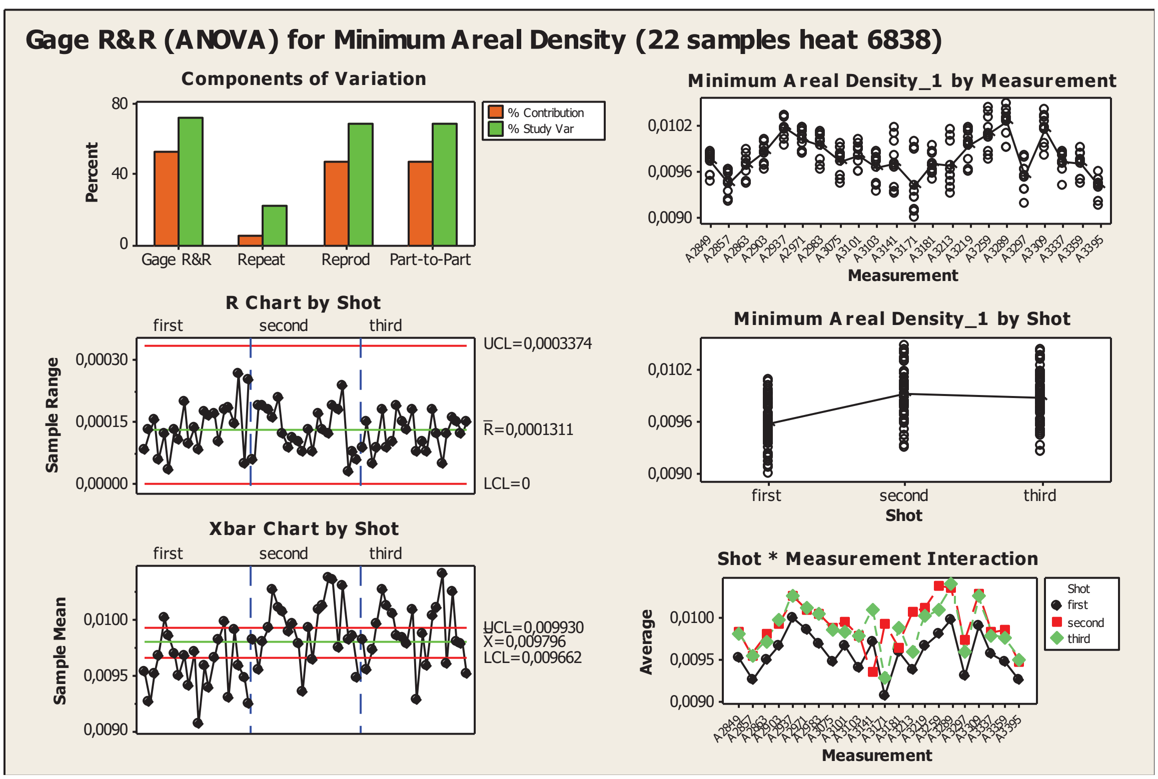


Figure 5. Gage R&R summary graphs

Areal density measurements were taken at the reactor facility at Penn State University. As noted above, the average minimum areal density may vary. The designer must take note of and consider the neutron absorber panel fabrication tolerances and quality assurance measurement accuracy in the specification of the material requirements. Conversely, the material supplier must understand the basis of the neutron absorber designer's specification to provide a material that will meet or exceed the design requirements in the finished product.

The graph "components of variation" shows a variation of the gage R&R equal to the part-to-part variation. There is a significant variation coming from the measurement system. The "repeatability" variation is low but the "reproducibility" variation is high.

The detail of the repeatability variation is given by the "R Chart by Shot" chart where differences between areal density measurements taken during three different days are shown. Since the difference between the highest value of a measured part and the lowest value of the same part does not exceed the upper control limit, then that gage study is considered repeatable.

A good part-to-part variation is given by the "Xbar chart by shot" chart. The gage study is considered acceptable when about 50% of the data are out of the control limits. However, the reproducibility variation is not low compared to the part-to-part variation. The variation of the reproducibility is detailed in the graph "Minimum Areal Density_1 by shot" which compares the distribution of the AD during each different measuring day. This graph shows that there are significant differences in the patterns generated by each measuring day of the same samples. The difference between the first date and the second is 3.5%, and only 0.5% between the second and the third series of measurements taken the same day. The last graph illustrates that the first series of measures shown in black is systematically below the two others.

ANALYSIS

To consider the effect of the thickness, the areal density (AD) evaluation is reported as volume density (VD). To facilitate the evaluation, each coupon reading is converted into % Average Volume Density (%VD) of the heat (VD coupon/VD average of the heat). It is expected that the variation caused by the thickness will be reduced by considering the volume density instead of the areal density.

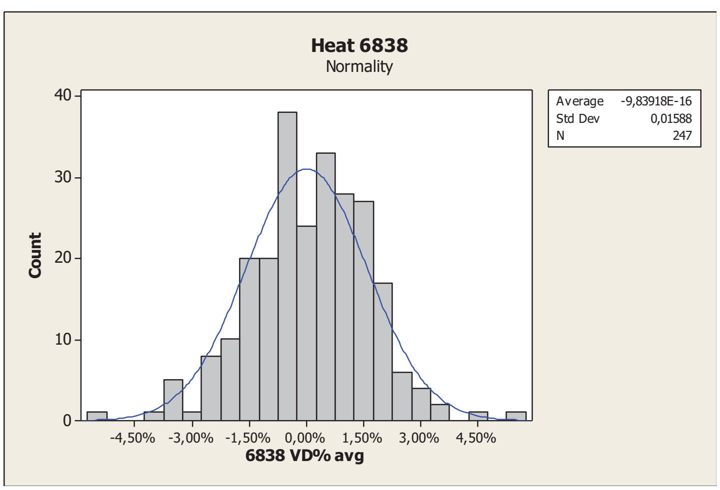


Figure 6. Heat 6838 Volume density of coupons relative to VD average of the heat expressed in percent

Table 2 presents the VD value of the four heats and the date of measurement of the coupon areal density

Table 2. VD value of the four heats

Heat #	6812	6825	6838	6840
Number of samples	255	203	247	246
AD measurements Date	2011-01-10	2011-06-02	2011-08-17	2011-08-17
AD measurements Date	2011-02-28	2011-06-03		2011-08-18
AD measurements Date	2011-03-01			
Min VD ($g^{10}B/cm^3$)	0.054	0.055	0.056	0.055
Avg VD ($g^{10}B/cm^3$)	0.058	0.057	0.061	0.060
Max VD ($g^{10}B/cm^3$)	0.064	0.060	0.065	0.064
Min VD (% avg)	-6.5%	-4.8%	-8.3%	-7.9%
Max VD (% avg)	11.0%	4.5%	5.5%	5.8%
Interval min-max VD (% avg)	17.5%	9.3%	13.8%	13.7%
Std dev VD (%)	3.0%	1.3%	1.7%	2.5%
Std dev AD (%)	2.6%	2.0%	2.8%	3.1%
Std dev improvement (AD-VD)	-0.3%	0.7%	1.1%	0.6%
Std dev improvement (%AD)	-13%	34%	39%	20%

Since the impact of the thickness is taken into account, the variations expressed in standard deviation of the VD should reduce. This is the case for three heats where the standard deviation in Table 2 was reduced by 0.6 to 1.1%, which represents a reduction of 20 to 39% of the standard deviation. On the contrary, a standard deviation increase from 2.6 to 3.0% can be observed for Heat 6812. This heat had an AD measurement taken on three different days, which, based on the gage R&R study, shows a 3.5% variation. When considering only the measurements taken in March, which contains the majority of the measurements, the standard deviation is now reduced to 1.9% instead of 3.0% and becomes more in line with other heats.

In order to evaluate if there are statistical differences between logs, which refers to the position on the casting table, and billets, which refers to beginning to end of the cast, graphs of main effect plots are used with assessment of the statistical significance.

Below are the graphs presenting the main effect plots of the four heats studied.

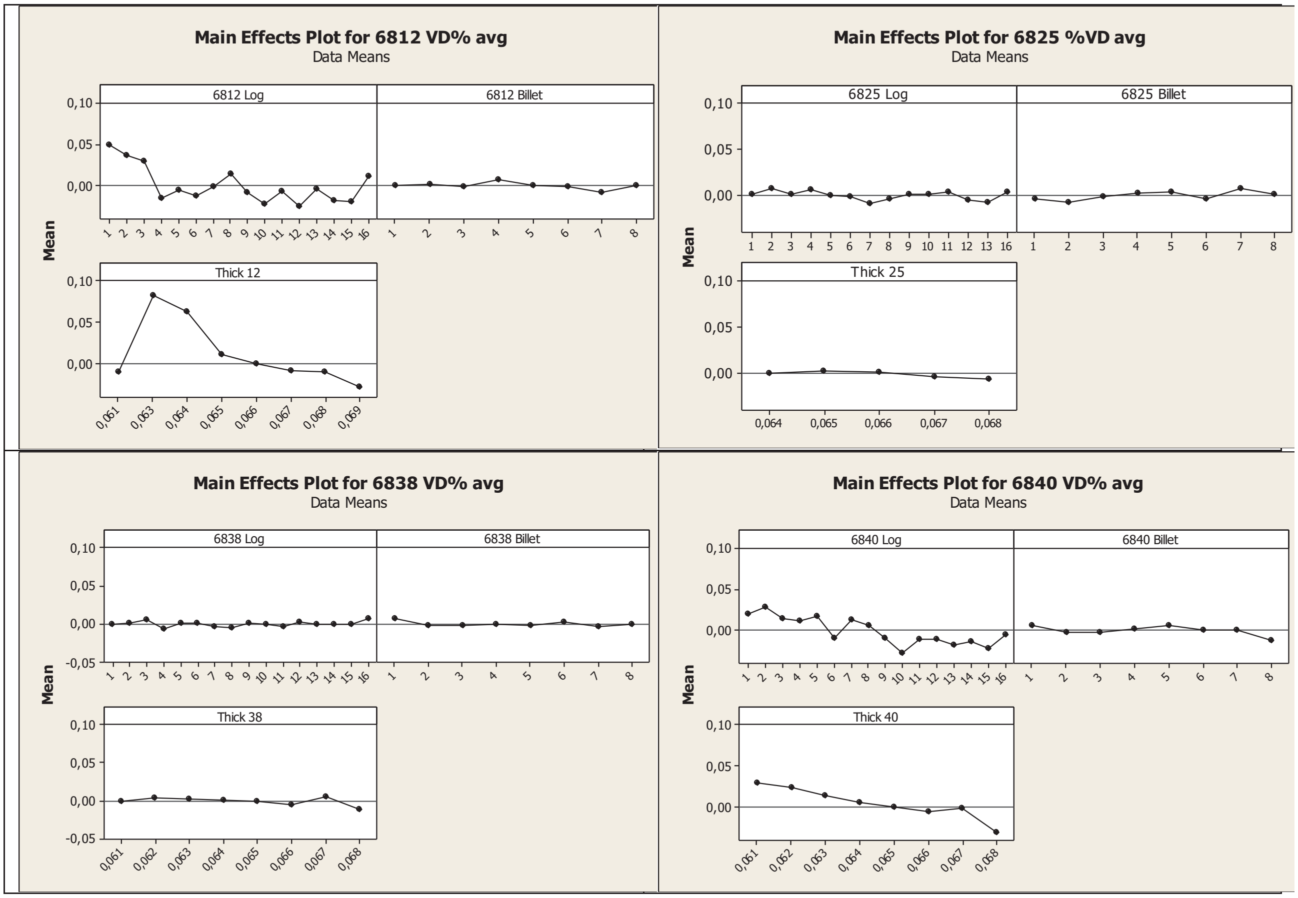


Figure 7.Main effect plots of the four heats

These graphs in Figure 7 show the main effect plot of the VD % average variation as a function of:

- log position on the casting table
- billet position in the log length
- sample thickness

In a perfect world, all graphs should have results aligned on the 0.00 horizontal line.

Due to natural variances, it is expected to obtain results which will be distributed around the central line.

It is expected to have the main effect plot variation of the volume density related to thickness well aligned to the zero line since the thickness variation of the final plate is independent of the log position, the billet position, or the material itself, and coupons thickness impact is removed by calculation from AD to VD. Heats 6812 and 6840 exhibit surprising variations. Results of Heat 6812 are discussed later. No specific reasons were found for Heat 6840.

The main effect plot variation of the volume density related to log position shows uniformity in Heats 6825 and 6838. Similarly to the main effect plot related to thickness, Heats 6812 and 6840 show variability between logs. For Heat 6840, no detailed exploration was made to identify the source of variation of VD for logs which were cast side-by-side. Log 2 has the highest VD average and is cast next to Log 15, which has the lowest VD average of the group. This is quite surprising since those two molds are fed from adjacent metal distribution troughs 125 mm (5 in) apart. The largest distance observed between feed points is that between logs 1 and 4, and between 5 and 8 where no differences were observed. The VD average is showing a higher value on logs with even position numbers. Referring to Figure 2, it shows that the odd and even log positions are in front of each other and feed from the same central metal feeding system. In spite of those variations, all results of areal density measurements are well above the minimum AD specification and the heat shows a CpK of 1.6

The main effect plot variation of the volume density related to billet position shows uniformity in all four heats. Therefore, there are no variations throughout the duration of the cast. The Rio Tinto Alcan MMC fabrication process has features to maintain uniformity of the particle distribution. In the case of Boralcan™, the process is facilitated by the fact that B_4C particle density is very close to liquid aluminum density (2.5 vs. 2.4 g/100 mL respectively) compared to other MMCs with addition of SiC and Al_2O_3.

The following Table summarizes the analysis of the main effect plot chart.

Table 3. Summary evaluation of main effect plots

HEAT #	6812	6825	6838	6840
Graph distribution	8 outliers (high side)	2 outliers (1 each side)	2 outliers one confirmed thickness measurement error	1 outlier (low side)
Comments Graph Log	high values (Jan) low values (March)	stable, statistically identical	stable, low variation when thickness measurement error removed	high values (logs 1-8) low values (logs 9-16)
Comments Graph Billet	stable	stable	stable	stable
Comments Graph Thickness	high values (Jan) low values (March)	stable	stable	stable but small trend with the thickness

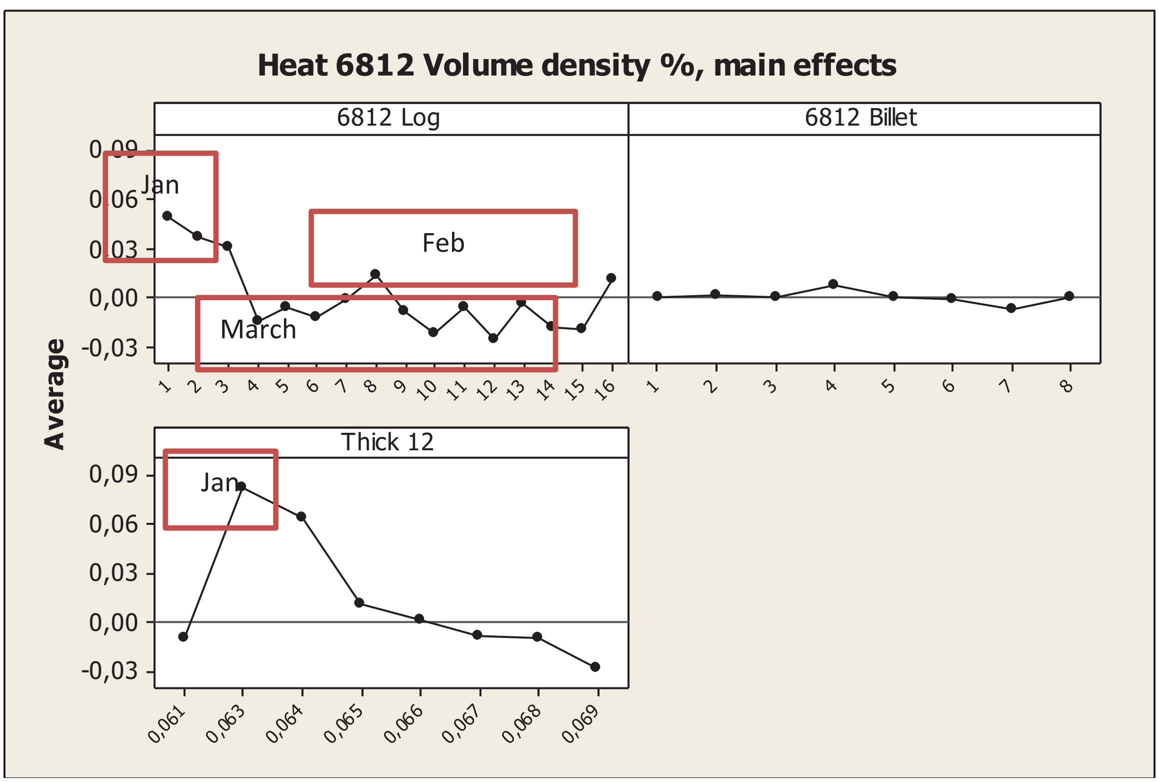


Figure 8. Main effect plots – comments on Heat 6812

However, when comparing the day during which the areal density was measured for Heat 6812A, it can easily be observed that there is an impact introduced by the measurement sequence. The measurement taken in January shows higher values, compared to those measured in February, less impacted but still higher than the measurements taken in March. This variation can be seen on the graph of the logs, where Logs 1, 2 and 3 show an individual average being higher, and full complete logs were processed and measured during the same sequence. The impact of measurement bias is not seen at billet level since coincidently the full log containing eight billets were all processed and measured during the same sequence.

CONCLUSIONS

The main safety function of the spent fuel pool storage racks is to maintain the stored fuel assemblies in a safe, sub-critical configuration. The authors have demonstrated through statistical analysis that Boralcan™ maintains consistent nuclear properties within a heat of 5000 kg and from heat-to-heat.

All coupons tested from the four heats have exceeded the minimum areal density (AD) requirement. The average AD of the four heats varies from 111 to 116% above the minimum areal density requirement of 0.0087 g/cm^2, while the process capability index (Cpk) is above 1.6, indicating how close the minimum values are relative to the specification. This consistency and repeatability has made Boralcan™ the neutron absorber material of choice for designers, fabricators and end users.

Areal density testing has demonstrated that the standard deviation varies from 2.0 to 3.1% between heats. When the ^{10}B volume density is calculated to eliminate the effect of thickness variation, the standard variation within a heat ranges from 1.4 to 3.0%. Part of the variation can be attributed to the repeatability and reliability of the measurement process. Evaluation performed with a gage R&R study identified that a testing bias of 3.5% may exist between set-ups or measurement sequences.

The use of Boralcan™ as a neutron absorbing material offers the following benefits:

For the designer:

- By proper specification of the material boron-carbide content, Rio Tinto Alcan can consistently provide Boralcan™ within the target areal density goal.
- Boralcan™ maintains consistent nuclear properties within a heat and from heat-to-heat given a single spec requirement as evidenced by the 100% areal density testing performed by NETCO.
- A 5000 kg heat size having consistent nuclear and mechanical properties minimizes the number of heats and reduces the variation of the material used in the finished product.

For the manufacturer:

- Boralcan™ is formable. The insert manufacturer, MSC, can achieve the tight manufacturing tolerances required by the NETCO Snap-In® designers.

- The Boralcan™ material has a visibly homogenous distribution of boron carbide in the as-cast and as-rolled state, which ensures consistent mechanical properties. MSC had zero rejections due to failure to meet mechanical properties.
- Areal density testing is one of the last insert fabrication checks and is performed once all fabrication processes are completed. Failure to meet the areal density requirement has a significant impact on the overall cost and schedule.

For the end user:

- Corrosion resistance is a key factor for wet pool applications and is very important in dry storage/transport applications due to the initial flooding of the cask/canister during loading, drying and sealing operations. Boralcan™ performance has been tested and characterized for these applications.
- The use of Boralcan™ allows the designer and fabricator to efficiently specify material lowering overall cost.
- Product consistency minimizes schedule disruption due to failures during fabrication or failure to meet areal density requirements after fabrication is completed.

ACKNOWLEDGEMENTS

Mr. Stéphane Paré, for statistical study interpretation at Rio Tinto Alcan, ARDC.

Mr. Ashleigh Quigley, for measurements of areal density at Penn State University.

Thickness measurements performed by MSC

APPENDICES

None.

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Minitab Software.