52nd Annual St. Louis Refractories Symposium: Refractories for the Ferrous Industry – Past, Present, and Future

C. E. Semler

The US Annual Refractories Meeting, was held at the customary venue, adjacent to the St. Louis, Missouri airport, on 30–31 March 2016. The weather was good and there were blossoms on the Spring trees – and there was no snow. The attendance was 208 this year, compared with 203 in 2015 and 210 (record) in 2014. The roster of attendees included people from 11 foreign countries. The technical program, which was organized by co-chairs, Bill Davis (Harbison Walker Intl.) and Simon Leiderman (U.S. Steel Research & Technology), included 16 papers.

Fig. 1 Group of Planje Award winners in attendance (f.l.t.r.): R. Bottjer, J. Witte, R. Bradt, K. Weisenstein, R. Volk, Bjørn Myhre (2016 Winner), C. Semler, M. Stett, J. Smith, L. Trostel, H. Johnson, and L. Krietz (Courtesy of Eileen DeGuire, American Ceramic Society)

2016 Planje – St. Louis Award

The 2016 Planje – St. Louis Award was presented to Dr Bjørn Myhre, who works in the R&D Department of Elkem Silicon Materials, Norway, which he joined in 1989. His extensive research has focused on castables, including various aspects of microsilica, self-flow, mullite formation, and microsilica-gel bonding. He first attended the Annual St. Louis Symposium in 1994 and spoke on particle packing. As the 2016 Awardee, he spoke about particle sizing and control thereof, castable heatup, and explosion, with video examples. Fig. 1 shows Dr Myhre and previous Planje – St. Louis Award winners, who attended the 2016 meeting.

Blast furnace refractories

The technical program began with Mike Alexander (Riverside Refractories/US) giving "An Overview of Blast Furnace Hearth Construction", in which he indicated that refractory design, operating methods, monitoring, and remedial actions have permitted operators to achieve campaign lives of 20 years, and longer. For example, Kawasaki Chiba no. 6, Japan, achieved production of 60 Mt in 21 years (1977–1998). Examples of three other blast furnaces were discussed, to illustrate details of their design and performance. He mentioned furnace productivity, burden quality and distribution, and instrumentation and control, as important considerations. There are two schools of thought on hearth design, i.e., thermal and ceramic. The hearth is monitored by thermocouples and cooling water analysis. Hearth isotherms in the range 1150–1350 °C are used to monitor the lining condition. For decades, titania, as ilmenite, titania-doped clay, etc., have been added to blast furnaces to control/lower hearth temperatures. By utilizing the increasing experience and technology, it can be expected that blast furnace life and productivity will continue to increase.

Ashley Hampton (Vesuvius/US) presented the "Changes in North American Blast Furnace Operations and their Effect on Casthouse Refractory Practice from 70's to Present". There have been many changes in blast furnace operations in North America since the 1970's, which have resulted in far greater output and efficiency, and have put increased demands on the refractories in the troughs. Whereas the decline of blast furnace iron-making has frequently been predicted, that has not happened due to the ongoing improvement in productivity. In 2014, there were 21 blast furnaces in the USA and 8 in Canada. The improved production in North America mainly involved retrofitted 2 taphole furnaces, although there are also many high output 1 taphole

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Tab. 1 Breakdown of daily output of iron in North America blast furnaces

Daily Output [t/d]	Number of Blast Furnaces
<3000	3
3000–6000	18
6000–9000	7
>9500	1

furnaces. The breakdown of daily output of iron in North America blast furnaces is shown in Tab. 1.

She discussed the change in casthouse design to an iron pooling design for higher output furnaces, to minimize or eliminate cooling/heating shocks associated with draining the trough, and the various refractory improvements that were made, from A–SiC–C ramming mixes to low-moisture A–SiC–C castables, that can be repeatedly repaired (endless lining concept). Today, trough campaigns of several million tons of iron throughput are routine. Trough castable installation by shotcreting is more widely used in North America than other markets, because of the prevalence of 1 and 2 taphole furnaces, which limit the repair time.

Future improvements mentioned were: (a) wear measurement of castables, without draining the trough, using laser profiling or continuous monitoring with mounted probes, (b) precast shapes with optimum properties, for high wear areas, based on manufacture under optimum conditions, and (c) use of improved pneumatic gunning products, based on low-cement castable technology, which are more effective as interim repair materials.

A paper by Glenn Biever (retired) of Vesuvius/US), on the "Evaluation of Anhydrous Taphole Clay" – a Historical Review", was presented by his colleague Sam Bonsall. This talk reviewed the demise of water-based taphole clays, in favour of anhydrous taphole clay mixes. Water-based mixes with raw fireclays and other calcined aggregates were used from the 1940s to 1958, when coke breeze and coal tar pitch were added to the mixes. These new taphole mixes were more complex and couldn't be prepared on the cast house floor, thus a conversion to commercial-made mixes began.

Before 1960 there were no multi-taphole blast furnaces, and in 1950, the average daily iron production was ~850 t, which increased to ~1450 t in 1964. With this increase in iron production through, the performance demands increased for the water-based taphole clays and associated operations problems increased. Early trials of anhydrous taphole clays had problems with the equipment designed for the water-based mixes, but successful trials were achieved in 1974–1975.

Because of the great benefits of the anhydrous taphole clays, material, equipment, and procedure changes were made, and the old test for water-based materials had to be changed to properly evaluate/compare the anhydrous products. Over time the anhydrous mixes have evolved as needed, including environmentally-friendly ("green") mixes. Based on many improvements, anhydrous taphole clays meet the demands of the blast furnaces that now produce an average of 3000–4000 t/d, and more, of iron.

Refractories for steelmaking

Vanessa Mazzetti-Succi and Tom Vert (ArcelorMittal – Dofasco/CA) presented "Steelmaking Refractories – 2030 Dream Scenario". ArcelorMittal employs 220 000 people in 60 countries and their refractory engineers want to know, "what types of refractories will make my job easier, and prevent a breakout 100 % of the time". Based on forward-thinking vision, they proposed the following 5 possibilities:

1. A monitoring system with data input from multiple sources, on a reliable, ongoing basis, that would show wear rates, repair consumption rates, live cost/ton tracking, and projection of refractory life.
2. Monolithics that set at extremely cold temperatures; for example, down to –40 °C.
3. There is an increasing need for clean steel production. This means that there is an increasing need for refractories that reduce the size and quantity of inclusions in steel. Presently it is a goal of refractories to be inert to the steelmaking process, but it would be a major advance if refractories could actively remove inclusions.
4. Steelmaking is a batch process that involves thermal cycling which causes thermal shock cracking of refractories. The cracking can be major and/or minor, and will lead to wear that can be accelerated with penetration and dissolution along the cracks. The future goal is to have refractories that may develop micro-cracks which don't spread or propagate.
5. Currently the testing of steelplant refractories does not simulate the real life-cycle in service and therefore can't be used to predict their performance. So there is a need for qualification tests that can be used to predict performance in service without the need for risky in-plant trials.

Refractory consultant Ruth Engel discussed the "Roles and Effects of Metals in Carbon-containing Refractories", as related to needed oxidation protection. The first mention of metal addition for oxidation protection of a refractory was in a 1935 patent (U.S. 2,013,625 by Ross Tacony Crucible Co.), but the technology for MgO–C bricks was not implemented until the 1980s, for example U.S. patent 4,407,972 by Dr Bo Brezny, Armco Steel in 1983, with the addition of Mg metal. As MgO–C bricks were improved, with increased carbon, and the addition of graphite, which had to be protected from oxidation, much research was done on additives, such as Al, Si, Mg, alloys, carbides, borides, and nitrides, to evaluate the many and complex reactions as a function of atmosphere and temperature, and their role in dense zone formation. Research has shown that additives can increase or decrease porosity (directly affecting slag resistance) and increase strength (Fig. 2). The development of alumina-containing (A-C, A–M–C, A–SiC–C) products, utilizing additives for oxidation protection, did not occur until there was a need for improved slide gate refractories. In addition to the benefit of metal additions, there are also disadvantages, such as hydration, and gas-pressure cracking of MgO–C bricks. For the addition of Al to A–SiC–C castables, the generation of hydrogen gas after placement, has resulted in major safety issues, with serious incidents that have occurred in service. Development trends for C-containing products now include the reduction of carbon and the use of nanomaterials technology.

Dr Peter Quirmbach (DIFK/DE) spoke about "Evaluation of Refractories Influence on Inclusion Formation in Clean Steel Production". With the increasing production of more high-quality (clean) steels, an important objective is to minimize the number and size of oxide and non-oxide inclusions. The refractory lining of metallurgical vessels is one source of oxide impurities. Given the oxygen affinity of alloy elements or deoxidizing agents in molten steel, reoxidation occurs to form fine, hard oxide inclusions, which reduces the quality of the steel. The general re-oxidation reaction for Al is: 3MeO (s) + 2Al (in steel) = 3 Me (in steel) + Al_2O_3 (s).

To date, the determination of a refractories potential to re-oxidize has been limited by the lack of a suitable test. But the thermal extraction of carrier gas offers a possible method to determine the re-oxidation potential for refractory materials; this method has been used to examine the stability of gunning mixes. This method defines the total oxygen content of samples at extremely high temperature ≤2800 °C by a reduction reaction that releases CO which can be analysed to indicate the quantity of oxygen released. And the calculated quantity of oxygen released could be used as a quantitative indicator of the re-oxidation potential for refractory oxides.

Because of the melting of mineral phases at the very high test temperature, the thermodynamics of the pertinent reactions were evaluated, indicating that a temperature of 1600 °C and pressure of $2{,}4 \times 10^{-5}$ bar would insure that graphite and Al have the same activity for oxide reduction. So test equipment was set up, including an ultrahigh vacuum furnace with graphite lining (T = ≤1800 °C) and a pressure range of 10^{-6} bar ≤p ≤1 bar, connected with a mass spectrometer for precise gas analysis. Ni is used as a fluxing agent to accelerate the reactions.

Results of the pressure-dependent thermal extraction of oxygen from pure oxides, have correlated with their estimated stabilities. Silica showed the highest oxygen release, followed in decreasing order by mullite, periclase, spinel, and corundum. The tests at negative pressure gave a significantly higher oxygen signal. So this test method has indicated that real oxidation potential can be measured, using larger samples (1–6 g) than prior Leco tests with 20 mg samples. Additional tests will be conducted with natural raw materials and reference refractory materials to obtain data on the re-oxidation potential of various real materials.

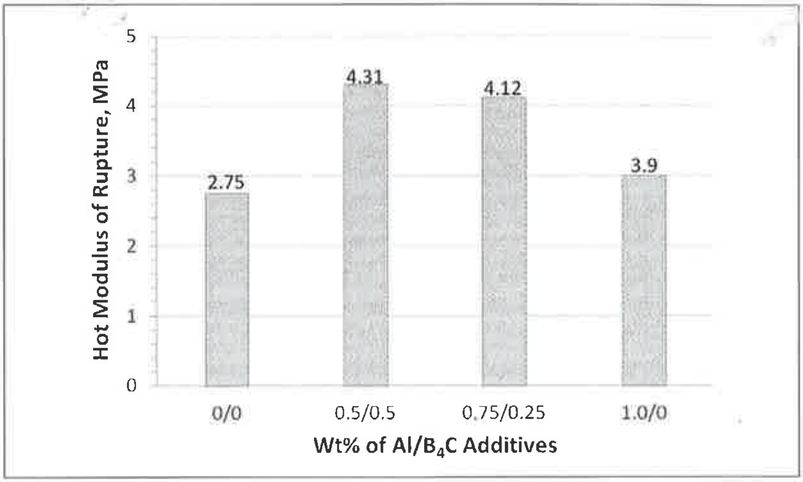

Fig. 2 Graph showing the effect of Al and B4C antioxidant additives on the 1400 °C HMOR of a 94 %MgO–C brick. The combination of additives proved to be more effective in increasing the hot strength of the brick. Reference: M. Bag and Dr R. Sarkar, Dept. of Ceramic Engineering, National Inst. of Technology, Rourkela/IN, MSc Thesis, 73 p., 2011

Ladle and tundish refractories

Dr Andreas Buhr (Almatis/DE) reviewed the "Trends in Clean Steel Technology and Refractory Engineering". Buhr emphasized that the development of steel-producing technology is a key driver for development of new and improved refractories. There are more than 2000 steel grades on the market now, many of which are high purity steels ("clean steel") with tight composition specifications. The production of the many grades of steel is made possible by the treatment in the ladles. In the past, ladles were only transport vessels, and now they are reaction vessels. The residence time of molten steel in ladles has increased, and refractories must withstand slag attack by aggressive, metallurgical reactive slags. So high purity alumina-spinel or MgO–C bricks have replaced andalusite and bauxite in ladle linings. The number of European steelworks with andalusite or bauxite wear linings in ladles has markedly declined, as follows: 2000–8, 2002–6, 2004–5, 2006–1, 2008–0. He reviewed the needs

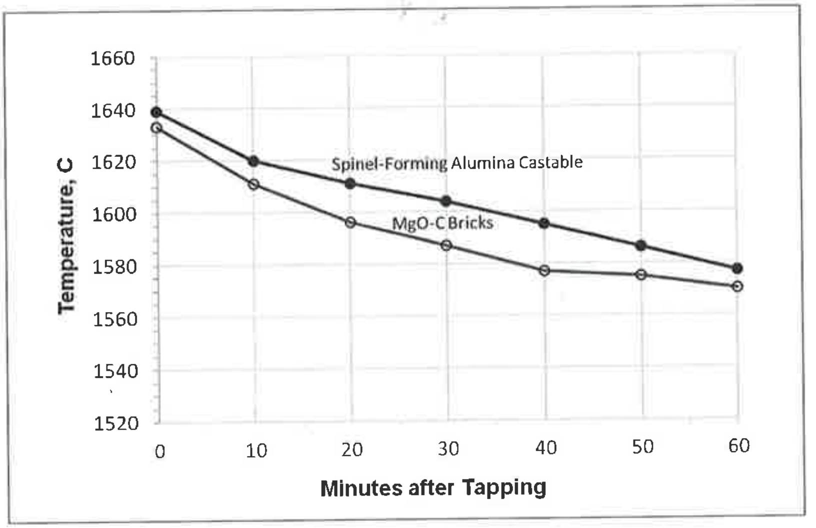

Fig. 3 Plot of the steel temperature change in a 180 t ladle with sidewall linings of spinel-forming alumina castable vs. higher thermal conductivity MgO–C bricks. These data illustrate that there are differences in ladle lining concepts that need to be considered in the economic evaluation.
Data from R. Exenberger for voestalpine ladles, Steel Academy, 2012

Tab. 2 Calculated ladle shell temperatures for several different lining configurations

New Lining				
6" Hot Face Brick	Intermediate Layer	3" Backup Brick	Insulation	Shell Temp.
A–M–C	None	70 % Alumina	None	407 °C
A–M–C	1" Dry Vibratable	70 % Alumina	None	377 °C
A–M–C	1" Dry Vibratable	70 % Alumina	3 mm, silica	310 °C
MgO-10 % C	None	90 % MgO	None	574 °C
MgO-10 % C	1" Dry Vibratable	90 % MgO	None	503 °C
MgO-10 % C	1" Dry Vibratable	90 % MgO	3 mm, silica	376 °C
MgO-10 % C	1" Dry Vibratable	90 % MgO	5 mm, alumina	350 °C
Used Lining				
3" Hot Face Brick	Intermediate Layer	3" Backup Brick	Insulation	Shell Temp.
A–M–C	None	70 % Alumina	None	440 °C
A–M–C	1" Dry Vibratable	70 % Alumina	None	413 °C
A–M–C	1" Dry Vibratable	70 % Alumina	3 mm, silica	335 °C
MgO-10 % C	None	90 % MgO	None	613 °C
MgO-10 % C	1" Dry Vibratable	90 % MgO	None	531 °C
MgO-10 % C	1" Dry Vibratable	90 % MgO	3 mm, silica	390 °C
MgO-10 % C	1" Dry Vibratable	90 % MgO	5 mm, alumina	362 °C

and performance of various refractories for the ladle sidewall and bottom for making clean steels, and given the tight composition specifications for clean steels, there is increased need for the refractories to be "inert".

Steel is constantly cooling in the ladle, as illustrated in Fig. 3, and it is very costly to compensate for this temperature loss, to insure the right temperature for casting. Heat losses can be reduced by covering ladles, but that can't be, or isn't done in steelworks. The cost of heat loss can be >50 % of the ladle refractory cost. Every ladle now has an insulating layer. And for a 200 t steelmaking ladle, if the refractory lining thickness is reduced, the volume of steel processed is increased. For example, a reduction of the ladle lining thickness of 10 mm will permit 2,5 more tons of steel. Consequently, the ladle lining thickness has been reduced in many European steelworks, with special attention to the permanent lining, including microporous or vermiculite-based boards that require temperature protection. With the disadvantages of multi-layer permanent linings, CA_6 materials (two available densities) have shown promise as an alternative. Functional refractories like porous plugs and well blocks are an essential aspect of ladle lining design. Currently the standard refractory for well blocks is alumina-spinel castable with the highest quality of tabular alumina. And for porous plugs, tabular alumina-spinel materials provide the desired thermal shock resistance based on the different thermal expansion coefficients. The role of ladles is very important, and their successful performance is directly related to the use of engineered refractory linings and functional components. A. Buhr noted that the refractory cost for steel ladles is 1,50–2,00 EUR/t of steel.

Robert Doty (IMACRO Inc./US) spoke on the subject of "New Higher Temperature Resistant Microporous Insulation for Molten Iron and Steel Refractory Applications – Focus on Steel Ladles". The increasing use of refractories in steel ladles with higher thermal conductivity and longer processing time has led to interface temperatures >1000 °C, which is the use limit for microporous silica insulation that has been effectively used for years. A new microporous alumina-based insulation has been developed, that can withstand temperatures up to 1200 °C. Successful trials have been conducted in various iron and steel applications, including steel ladles. For reference, he presented the thermal conductivity and thermal expansion (unused) data for bricks and monolithics that were used in the design of steel ladle linings.

According to published specifications (AISE Technical Report No. 9) for ladle sidewall and bottom steel, the maximum service temperature is 371 °C (700 °F). Calculated ladle shell temperatures were shown for several different lining configurations, for both new and used conditions, including the examples shown in Tab. 2.

R. Doty presented actual shell temperature data for multi-layer trial linings, similar to the designs shown above, in electric furnace shop ladles, which showed that the shell temperature continuously increased each month for the trial; for 3 mm 1000 °C silica insulation the shell temperature continuously increased from 440 °C in month 1 to 511 °C in month 8, and for 5 mm 1200 °C insulation, the shell was cooler, going from 408 °C in month 1 to 458 °C in month 8.

Dr Gary Hallum (COMAT/US – Division of CCPI, Inc.) discussed the "Raw Materials used in Tundish Linings and their Effect on Performance". He noted the many functions of a tundish lining as follows:

1. Maintain steel cleanliness
2. Resist slag attack
3. Protect the permanent lining
4. Provide an insulating layer to maintain steel temperature
5. Maintain a friable layer to permit easy removal of steel skull.

Steelmakers continue to push for longer tundish lining life. The porous character of tundish linings is essential for its success, and if it can resist densification in service, due to sintering and/or liquid phase creep, it should have good performance until the end of its useful life. So using a variety of MgO materials, Hallum studied the effect of starting materials on the ability of a porous structure to resist densification.

Tundish linings are typically represented to customers by the MgO [%] in the mix, with little thought about the kind of MgO. To the customers, the tundish mixes are dirt, and "dirt is dirt". But refractory engineers know that raw materials are not all equal. G. Hallum chose to test 10 magnesites (0,35 –2,57 range of CaO/SiO_2) and 3 olivines. Samples of varying porosity were fired at 1350 °C for 3 h, and then tested for thermal expansion under load (TEUL), to 1550 °C, with a 3 h hold. He showed graphs to illustrate the differences in yield point and creep for the materials, alone and in combination. For example, 50 : 50 mixes of Chinese dead-burned magnesite (DBM) 92 and olivine showed a significant difference in yield/creep at 1550 °C, based on the olivine source, in the order Greece (least), Norway, and China (most). He concluded, that the strain rate and resulting densification is dependent on the MgO content of the sample, and the strain rate can be decreased by the addition of olivine, although olivine alone densifies rapidly due to liquid formation, which he explained by phase diagram. He found that the addition of inorganic bonding agents reduced the ability of a DBM to resist sintering and densification, and porosity also plays a big role in densification of mixes under load. Further study is planned to consider other variables such as the effect of slag, particle sizing, etc.

Aggregate, spinel, C-pickup and more

Dr Shangzhao Shi (Materials Technology Innovation, Katy/US) spoke about "Spherical Refractory Aggregates for Easy Installation and High-Performance Refractories". Refractories are little-known products, which usually are hidden from view as they perform their critically important functions.

But in reality, refractories are high-tech engineered materials that enable profitable and efficient, high-temperature industrial production of all metals, cements, glass, ceramics, chemicals, petrochemicals, and many more commodities.

Over the decades, the bonding matrix has been a focus of refractory engineering. Given the fact that the aggregate/matrix interface makes a significant contribution to the properties and performance of refractories, and 60 % of the world's refractory production is "aggregate", it is definitely worthwhile for more attention to be given to value-added, engineered aggregates. In China, research is being done to produce novel types of value-added, engineered aggregates for use in refractories. For example, dense balls, hollow balls, microspheres, spheres with surface features, and other types. It is expected, that these new types of aggregates will have benefits for self-flow castables, taphole clay, and lightweight insulations. For castables, spherical aggregates could reduce water demand and give higher packing density to improve strength and corrosion resistance. For insulating aggregates, it will be possible to control the pore type (closed or interconnected) and the pore size distribution. And aggregates could be made with specific properties (strength, thermal expansion, thermal conductivity, etc.) to meet the specifications defined by microstructure design/modeling programs.

Arthur Mangualde (Magnesita/BR) discussed "In-situ Spinel Formation in Alumina-Magnesia Systems". The spinel formation reaction has been widely studied, as indicated by the large number of papers that have been published around the world. It is known, that refractories with either pre-formed or in-situ formed magnesium aluminate ($MgAl_2O_4$) spinel have high corrosion resistance, especially in contact with basic slags. And spinel will easily form when MgO and Al_2O_3 are present together in mixes at temperature >1200 °C, the reaction is accompanied by a volume increase of 8,2 %. He discussed a study of how the MgO content and grain size, and the alumina grain size, affect the spinel formation to provide useful data for the design of alumina-magnesia materials.

Samples were made using coarse, sized white fused alumina (WFA), <600 µm dead-burned MgO, and <300 µm or <600 µm WFA. Samples were fired at 1200, 1400, and 1600 °C respectively for 5 h, permanent linear change (PLC) and crushing strength were determined. The results showed that not only the amount or grain size of MgO, or the firing temperature, are important, the amount of alumina in the matrix is very important to the volume expansion of the material. If there is enough alumina to react with MgO in the matrix, the spinel reaction will readily proceed. If there is not enough alumina present, the MgO will react with the alumina grain boundaries. But if prior reaction has occurred at the grain boundaries, there can be a barrier to MgO diffusion, so the reaction tendency may be less. It was concluded that for a well-designed Al_2O_3–MgO refractory, with in-situ spinel formation, the amount of fine alumina, as well as the grain size and amount of MgO should be defined. Because the use temperature of the material affects the amount and rate of spinel formation, it also plays an important role, and must be considered.

Mariella Zefferer (RHI AG/AT) presented "Slide Gate Refractories and Systems: Adapted Solutions for High Quality Steel". The production of high-quality steels places high demands on slide gate refractories and systems in terms of process reliability, safety, quality, and performance. And the contamination of steel during the casting process from ladle to mold should be kept as low as possible. Her talk reviewed the ongoing development of slide gate systems and refractory components, including the new Interstop ladle gate type S, optimisation of the casting channel of the inner nozzle and well block, and two component collector nozzle.

The new plate design is beneficial, with more efficient use of the refractory material, and reduced cost. Also the design gives increased operational safety by insuring that cracks initiate and propagate in a controlled manner. The optimised casting channel results in homogeneous, continuously increasing velocity of steel flow, without the creation of areas of turbulence, which minimize the effects that contribute to refractory deterioration or re-oxidation of steel. In practice, small and compact collector nozzles have outperformed collector nozzles with larger wall thickness. Thermomechanical modeling was done for 3 different types of collector nozzle to evaluate/compare the stress levels, and permit optimization of the design and material. The concept of a compound collector nozzle is to separate the tasks of corrosion resistance and resistance to crack formation between the inner and outer components. The long-term use of compound collector nozzles in practice has shown improved service life, reduced crack formation, and additional operational safety.

Dr. Matthias Rath (spumix Dämmstoffe GmbH/AT) described the "Development of a Novel Hybrid Method for Producing Macroporous Ceramics". The production of porous materials with 10 %–90 % porosity, low density, and low thermal conductivity dates back to the last century. Early production of porous materials involved incorporation of combustible materials. This was followed by the replica technique using sacrificial artificial (plastic/polymeric foam, etc.) or natural templates. Then came direct foaming where porous structure is created by (a) direct introduction of air, (b) gas created by chemical reaction, and (c) gas created by liquid evaporation.

The new hybrid method described by M. Rath involves a combination of the direct foaming and replica techniques. The processing includes two stages, with ceramic powder, water, and additives in stage 1, and heavy ceramic slurry, water, and one or more additives in stage 2. In stage 1, a lightweight ceramic foam is produced from a primary slurry and pressurized air. In stage 2, the template light foam is blended with ceramic slurry to give foams with the desired properties. The wet ceramic foam is cast and dried before firing. Drying is done in the range 40–100 °C; the temperature depends on the water content and the type of binder. After drying, the green body is fired to the material-appropriate temperature, in the range 1000–750 °C. This process is applicable to a wide range of ceramic raw materials, such as fireclay, andalusite, mullite, alumina, zirconia, and more. Depending upon the additives used, the structure of the foams can be changed. Further work is planned to study the effects of other additives.

Bin Wu (Purdue University, Center for Innovation/US) discussed their activities using virtual reality visualization of blast furnaces. In 2005 they created computerized hearth models of two blast furnaces, using actual measured data. Currently they have hearth models of most US blast furnaces. By tracking the actual furnace operations, they can monitor the conditions that provide a balance between refractory wear and operating efficiency. Blast furnaces use a lot of fuel, and by monitoring the operation, they can optimise the coke use. They can also evaluate the burden distribution, and do training with a virtual model of a blast furnace. The options for using this technology are only limited by the imagination of the users. They have done more than 150 projects, and have saved companies tens of millions of dollars.

Andrew Russo, student of Prof. Jeff Smith, et. al (Missouri Univ. of Science & Technology/US), spoke on "Kinetics of Carbon Transfer from Magnesia-Graphite Ladle Refractories to Ultra-Low Carbon (ULC) Steel". Given the widespread use of MgO–C/graphite refractories in steel ladles because of their multiple desirable properties, they also have drawbacks, including the fact they transfer carbon to the molten steel. ULC steels are particularly sensitive to C-pickup, and interstitial carbon increases the strength of steel, but decreases its ductility. The C-pickup of ULC steels is detrimental in forming and drawing operations, where ductility must be a maximum. Thus the final carbon content of ULC steel is specified as <50 ppm.

Lab study of carbon transfer involved refractory dip tests in a vacuum induction furnace at 1600 °C, under an Ar atmosphere. Refractory core samples (1,27 cm diameter) were taken from commercial MgO–C refractories with 4, 6, 10, and 12 mass-% carbon respectively.

Three different conditions were tested: steel without slag, steel with slag, and steel with MgO-saturated slag. Results showed that in the absence of slag, C-pickup from the 10 and 12 mass-% C respectively MgO–C refractories was controlled by the penetration of steel into the refractory.

For the 4 and 6 mass-% C respectively samples, the steel showed no C-pickup with no slag present, because steel could not penetrate the closely packed (dense) brick structure. C-pickup was controlled by corrosion of the refractory at the slag line, when slag was present.

The controlling mechanism is convective mass transfer of MgO into the slag. The measured C-pickup in these tests was shown to be in reasonable agreement with the C-pickup calculated by the proposed mechanisms for C-transfer to steel.

Dr Ron O'Malley (Missouri Univ. of Science and Technology/US) gave an overview of the activities at the Peaslee Steel Manufacturing Research Center (PSMRC), based on funding of about USD 750 000/a. They have seven active projects, in which 280 students are involved. Three of the projects relate to refractories, including non-metallic inclusion technology, reduction of nozzle clogging, and ladle/refractory interactions in ultra-low carbon steels. A new project is planned to consider the next generation slagline refractories.

Business and social gathering of the refractories family

Following the first day technical programme there was an active social gathering of attendees, hosted by the following 28 companies: Almatis; Alteo; AluChem; American Ceramic Society; BassTech Intl.; Calucem, Inc.; Christy Minerals; Cilas Particle Size; Conitex Sonoco; DIFK GmbH/DE; Elkem Materials, Inc.; FESIL Sales, Inc.; FX Minerals; Great Lakes Minerals; IMERYS; Kerneos, Inc.; Kyanite Mining Corp.; Lancaster Products; Orton Ceramic Foundation; Possehl Erzkontor N.A.; PQ Corporation; RED Industrial Products; Refractory Minerals; TAM Ceramics; UltraTest GmbH/DE; Washington Mills; Zili USA; and ZIRCAR Ceramics, Inc.

Meeting Proceedings and 2017 Symposium

Most of the papers presented at the 2016 St. Louis Refractories Symposium are included in the Proceedings. This paper provides only a short review of the papers presented. Further details can be found in the written papers in the Proceedings. The 2017 St. Louis Refractories Symposium will be held in late March, with a 1½ day technical program that focuses on a popular contemporary topic, to be determined. Also, the Planje-St. Louis Refractories Award and the Allen Award (for Best Published Refractories Paper) will be presented.

Information about the 2016 Meeting Proceedings, the 2017 Symposium, and sponsorship can be obtained by contacting Patty Smith at Missouri University of Science and Techology (E-mail: psmith@mst.edu).