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EDUCATION

Refractories from fire to fire

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Abstract
A brief description of the evolution of the making and usage of crucible and heat containing linings to the development of today eco-designed refractories materials is offered to illustrate the gigantic steps the refractory constituency has accomplished. Eco for Ecological, Economical, Eco-Energetical. That is fire to FIRE.
To prolong Professor T. Planje's vision, the research and education needs are to be secured. This will require unified efforts of all stakeholders of our brotherhood. A brief description of FIRE's role for such a purpose is hence recalled, insisting on the implementation of the conception, design, implementation, organization approach to support the refractory industry needs for young innovators.

KEYWORDS
eco-design, education, FIRE, innovation, refractory materials

1 | INTRODUCTION

The objective of this short essay is to focus on the importance of refractory materials during three periods: the fire era, prior to 1960, then the period between 1960 and 1980, in reference to the Planje Symposium (!!) and lastly the first two decades of the 21st century, corresponding to the FIRE's evolutive era. This will put into perspective how professor Planje did contribute to the modifications of the refractory education syllabus, from the craftmanship to the scientific era, adopting Dr. Planje's mantra, the three elements essential to engineering success are: *materials, energy, and creativity*. To cope with our today context, of a globalized world, it will be analyzed how important it is to be concerned with the education of innovators to conceive eco-design of complex-engineered refractory materials. This constitutes the 3rd period, the so-called FIRE era with only a one-word mantra: *coopetition* (cooperation and competition).

2 | THE fire ERA PRIOR TO 1960

A long time ago as soon as humans had conquered fire the unrecorded history started then. The first refractory shapes were discovered under fire holes. It was observed that heat had transformed the earth clay in contact with the fire, and so the first crude bowls were obtained. Bigger fire places were built, then baking ovens (3000 BC) then convected-draft and forced-draft furnaces (4000–1000 BC) necessary to reach 1150 Celsius, enough to melt cast iron. The production of cast iron was closely related to the qualities of the refractory crucibles then used (a mixture of quartz and carbon fines and clays) close to the well-known plumbago crucibles (still in use in the iron foundries industry). However up to 1500 AC the technical knowledge was transferred by "show and tell" advice, from a master to an apprentice, mainly by human interaction. This was so when the industrial era started (around the 1800), and the refractory materials were developed by trial and error. The raw materials selection, beneficiation, and the manufacturing processes were kept as closed-shop secrets. The scientific description of refractories began in the early years of the 20th century. The American Ceramics Society was founded in 1899. The first phase diagram for oxides became available around 1920. And so, the ratio between craftmanship and scientific knowledge kept decreasing slowly but steadily until 1960.

3 | THE CRAFTMANSHIP TO THE SCIENTIFIC ERA (1960–1980)

This 20-year period was one of an unprecedented economic growth, where rapid changes in most of the industrial sectors took place. Progresses were made in manufacturing, automatization, robotization, and transportation. New triumphs in the rapid transmission of knowledge were being made by new invention of recording, broadcasting, reproducing speech, and images.

As a good example, let us recall Dr. Planje's career.[1] Dr. Planje had been promoted full professor in ceramic engineering in the School of Mining and Metallurgy at the University of Missouri Rolla (UMR) and named chairman of his department in 1955. He was then able to attract other collaborators with whom it was possible for him to extend the teaching of the scientific aspects at the detriment of the hands-on experimental periods. New courses, on thermodynamic laws and phase diagrams equilibrium in mineral structure, heat transfer, physical chemistry of solids, and liquids, were upgraded in the new syllabus he was able to implement.

I am not the appropriate person to review and comment on his own scientific contributions. Looking only at his curriculum vitae, he was already in 1964 both the dean of the Missouri School of Mining and Metallurgy and Director of the Space Science Research Center. For sure Professor Planje was the right man at the right place, in such a period where all engineering faculties in North America were asked to adjust their syllabus to match the spectacular advancements of sciences, technology, and rocketries. No wonder we do have to keep recognizing his accomplishments in the field of refractory ceramics, promoting the reputation of the academic world, always remembering his mantra: *materials, energy, and creativity*.

Men of his stature gave the refractories its letter of nobility at UMR.

4 | THE INTERIM PERIOD (1960–1980)

In between 1980 and 2000, the world economy kept changing rapidly. The exponential growth of knowledge and know-how brought about by the convergence of various technological domains with numerical algorithms lead to an unprecedented accumulation of goods, feeding a huge thirst for power and vital resources, in every domain. This was the period of world globalization. This impacted many industrial sectors including ours. Mergers, rationalization, and outsourcing as well as their repercussions on the research and education levels in universities in all western world were well documented[2–4] during the R. E. Moore Symposium at the 9th UNITECR meeting in 2005. On the other front, after 1980 industry, government and university programs were addressing the need to reform the engineering education and to narrow down the gap between industrial interests and university academics endeavors in both applied research and graduates' education.

5 | FIRE THE NEXT STEP FORWARD (2000–2020)

This now brings us to the FIRE concept. The last two decades were by analogy as exciting as what Professor Planje had to adjust to. The difficulty was not a matter of how to upgrade the scientific knowledge but how to recruit and ensure the quality of the human resources to fulfill the needs of our industry to innovate and to cope with issues concerning ecology, energy, and minimize the cheapest and fastest syndromes (still persistent in our industry). The challenge was to change the paradigm, in order to elaborate a new syllabus at the Master and PhD levels to distinguish between the scientific knowledge and the cultural and know-how knowledge. So, in creating FIRE, the goal was to achieve the balance between the two aspects.[5–7]

Scientific knowledge results from systematization and rationalization efforts; it is performed in our left-brain side, which is the intelligence locus. Scientists in search of new knowledge share their problems, so as to isolate a special limited field of inquiry. By narrowing the chosen region, the task is simplified, and all the intelligence can be concentrated on it. Adopting this method, the scientific knowledge has grown exponentially, but the education system has been abused by this scientific approach hypertrophy.

Cultural knowledge includes the totality of information concerning the technical tools, the work of arts and of literature preserved by social, political, economical structures, and the ideological systems conceptualized at different periods of the evolution of mankind. This information is shaped by emotional values, being by nature evanescent.

The dichotomy between the two types of knowledge has been addressed in the following way. The left hemisphere, the locus of the logos, in which lie speech, memory, and numerical analysis, registers what is visible in the world and tries to discover its laws, fractals, and orientations in time. The right hemisphere of the brain, the locus of emotions, in which lie the intuition, holistic view, uncertainties, artistic talents, governs the orientation in society. Living in such a globalized world, we are now at a point where it is urgent to readjust the ratio between the two sides of our brain. Yes, to tackle the ecological problems and the socio-economic disparities, right-brainers are needed to rule in the future. How FIRE academics adjusted, at the beginning of this era can be followed in Pirker et al.[8] and Rigaud.[9,10]

5.1 | The conception, design, implementation, and organization approach

One initiative was the formulation of such an approach, elaborated by Crawley et al. from MIT, Boston, USA, and revealed in a book published in 2007,[11] entitled: Rethinking Engineering Education. The conception, design, implementation, organization (CDIO) approach stands for to **c**onceive-**d**esign-**i**mplement and **o**perate complex, value-added products, processes, and systems to meet specific demands of users.

The philosophy of this approach is to capture the excitement about what engineers do, with a deep learning of the fundamentals of sciences, the skills and attitudes as well as the knowledge of how engineers contribute to society, all of it being taught in a way to sustain students' passion to progress. The approach must be built on stakeholders' inputs to identify the learning needs of the students and construct a sequence of integrated learning experiences to meet such needs, taking into consideration, internationalization, student mobility, and flexibility, and how government and multilateral initiatives, beyond its engineering education, do merge into a business and societal context.

In the western world at least, in the period 1960–2000, the engineering programs evolved first from more sciences and engineering until 1980, then to more and more sciences and computer sciences until 2000, at the detriment of personal, interpersonal, and systems building skills.

FIRE academics network started to follow a similar syllabus to the one the CDIO mentors had developed. The FIRE's MSc and PhD programs had to focus more on the personal and professional skills and attributes, as well as on the interpersonal skills, teamwork, and communications of its graduates, while the refractory industry had to compromise with the effects of globalization issues, as well as company restructuration and business context changes.[8–10]

It was agreed that an ideal program should specify the products, processes, and system building skills consistent with a program centered on innovations and should be validated by the program stakeholders (academics, manufacturers, suppliers, and users); with detailed learning outcomes for personal and interpersonal skills and details for the expected proficiency to be established at each level.

Of course, for FIRE to realize such a vision, many challenges had to be overcome, facing the cultural changes, in each academic poles of the network, the adjustments of the faculty competence, the alignment with the local and national standards and other initiatives in order to value collaboration in a competitive world. So, education as FIRE research programs had to operate in a real *COOPETITIVE* mode.

5.2 | The fire's network

FIRE, started in 2003, was incorporated in 2005 and has been able to develop, as a nonbricks and mortars network, of nowadays 10 academic institutions, spread in eight different countries (Austria, Brazil, China, France,[2] Germany,[2] Korea, Spain, and United States) with 14 industrial partners (manufacturers, users, and services suppliers) constituting a global chain of values from the raw materials to the recycled products with all the complexity of the business, legislative political, ecological, and economical laws to take into account.

The FIRE mission, goals, research, and education programs and definition of its networking values have been described at different times of its evolution[8–10] and are detailed on its web-page (http://fire-refractory.org).

In short FIRE funds international studies and research activities associated with manufacturers and users' interests to allow graduate students to obtain a degree in refractory materials. FIRE also supports financially academics institution promoting student exchanges and generating double (multiple) degree program certificates organized by two or more universities. FIRE pools the expertise, the experience, and the willingness of the worldwide most competent persons, installations, and companies in the field of refractories to tackle some innovative research programs with the *precompetitive spirit* required.

From this brief description, one can now appreciate to what extent the CDIO approach, and the FIRE development through the years has followed parallel paths. It allows FIRE partners to focus on the 21st century challenges, the eco-design of refractories.

6 | INNOVATIONS AND INNOVATORS

6.1 | What's innovation means?

There are so many forms of innovations! To understand one has to comprehend fully the meaning of patent rights, patent laws, business laws, international laws interfering with foreign exchanges policies, how to make profits in a chain of values for processing materials, how to implement and organize innovations, technology transfer (including the human values, communication skills, cultural biases), technology forecasting, strategic planning, including the economical, environment, and ethical aspects.

From an educational point of view, this constitutes an immense challenge to learn, to learn to learn, and to use in a rapidly changing world (keeping track of the ethical sense of justice, solidarity, and oneing). But there is no reason not to tackle the task, challenging the partners and students to develop, bit by bit, some of the needed innovations at our disposal right now: such as better high temperature insulating materials, ultra-high-temperature corrosion and erosion resistances of refractories for new processes such as near-net-shaped casting of steels.

To accustom FIRE students to such horizons, it is to be realized that several experiences have been attempted with some successes. In the 1990s at the Industrial Chair on Refractory of École Polytechnique, the precursor of FIRE, the graduate students in refractory engineering were introduced to courses on technological forecasting and later strategic and technological planning. Then within the FIRE network, another initiative of interest has been implemented at the Brazilian Sao-Carlos pole. There, a compulsory reading list of books is submitted to the students, to be discussed in classroom, with small groups of students being asked to write an essay on one of the subjects listed, closely related to innovation and business finances, and then to suggest how this would be applicable to the refractory industry. Many more initiatives of this kind must be taken.

6.2 | How to increase the innovation potential of fire graduates?

At first all refractory engineers should know the fundamentals of material sciences, the process engineering principles (mass balances, transport phenomena of gas, liquid and solid, kinetics of reaction) then know how to conceptualize, design, implement, and organize the best practices to manufacture and use the refractories, and finally know why the life cycle of such advanced engineering materials needs to be optimized to be profitable to all concerned in the chain of values (from the origin to the end, including recycling).

Then for those who have had the opportunity to obtain a FIRE's certificate, FIRE should increase its efforts to offer a wider list of extensive education services. It is here worthwhile to underline that such possibilities have been tested at three levels.

1. With the organization of two Summer Schools, one in Orleans, France, in June 2013 on fundamentals to explain the macro- and microstructure of refractories by phase diagrams, computational thermodynamics, kinetics, wetting, infiltration, reaction mechanisms, thermal, chemical and mechanical couplings. The second one in Turino, Italy, in June 2019,[12] on the reactivity and corrosion of ultra-refractories, thermal-structural composites, and industrial refractories, to bridge the gaps among the experts in the three fields and to learn from one another. A third type of FIRE Summer School will be tested in June 2022, in Aachen, Germany, as both a presential and a virtual event, with added values, one being the availability of extra videos to cover in more depth-specific aspects, under the overall title: eco-design of refractories. E for ecological, economic, and eco-energetic.
2. With the publication of peer-reviewed pedagogical and reference books, outlined by FIRE academics and industrial members. So far the list of books already published in the FIRE Compendium Series on the Refractory Technology contains: Volume I on Refractory Castable Engineering, in a single volume of 430 pages, authored by AP Luz, M. Braulio, and V. Pandolfelli, all from Sao-Carlos, Brazil; Volume II on Corrosion of Refractories, in three separated books, 2A on Fundamentals, with six authors; 2B on Testing and Characterization Methods with 12 authors; 2C on the impacts of corrosion with 29 authors, for a total of 43 different authors, 23 academics and 20 industrial experts and 1200 pages.[13]
3. With specialized training courses open to FIRE students but also to others attending the UNITECR meetings in Kyoto, Japan 2011; Vienna, Austria in 2013; and Santiago, Chili in 2018, and expected in Chicago, in 2022.

In each case, 1-, 2-, and 3-, different business strategies have been tested. It is time to evaluate them to create more opportunities and more contacts between FIRE alumni and professional partners, eventually other selected worldwide experts from outside the FIRE circles. It seems appropriated to learn from different sources of inspiration, to experience cultural differences, and to develop new global markets, with competing and conflicting priorities. Ultimately FIRE should share with others the benefits from the competitive edge each may possess. It may also be wise to contemplate other activities, more attractive at a local scale than at a global scale.

7 | CONCLUSION

Let us recognize that both Professor Planje and FIRE have been considered the same chain of values, using different wording: merging at UMR, minerals-mining-metallurgy-materials up to nuclear engineering, while FIRE is bringing the raw materials providers, the manufacturers of refractories products with the users of such products, and the academic institutions to work all together in a collaborative and competitive spirit successfully.

We must be thankful to Professor Planje for having given his letter of nobility to refractory education at UMR and today recognize that UMR has been one of the early founding members of FIRE since 2005.

It is still essential to develop more collaborative educative tasks in a coopetitive spirit with the proper business plan to support and widen such efforts. For the educative aspects, the academics must take the leadership, but the Industrial members must back them up to transcend the cultural limits and to suggest the appropriate courses to be included into a common FIRE syllabus of courses, insisting on creativity and innovations

To contribute to the continuous development of efficient refractories, more efforts should be devoted to actualizing the knowledge accumulated in the last decades and to disseminate the main results for the benefits of all concerned.

The existence of a network, such as FIRE or any other similar ones, is worthwhile to promote, for the refractory industry. The ATHOR project is a recent good example.[14]

In trying to close the circle, to recruit and train refractory engineers, it is mandatory to match the expectations of the younger's generation with their aspirations to lead and innovate, and to bring them to the highest cognitive levels of synthesis and evaluation, including their affectivity.

Any new education program or course in refractory engineering at the graduate level should focus on the global vision of the industry, the society, and our neighbors, to be concerned with the energy and environment requirements to create the "seductive attraction" to recruit the best young engineers while insisting upon the refractory industry actors' solidarity and friendliness characteristics, a trademark in our constituency.

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