Navigating uncertainty – Advancing pyrometallurgy through reliable new technology development

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To effectively develop innovative pyrometallurgical production technologies, it is essential that a well-structured framework be used. The purpose of such a framework is to enhance the success of producers and equipment suppliers by mitigating uncertainty and risk through a collaborative, methodical, and sophisticated process encompassing analysis, investigation, modelling, simulation, measurement, and testing. We consider – in the context of large extractive metallurgy plants – common causes of failure; important principles to abide by; the development process itself, and the collection of tools and methods that underpin these production technologies.

INTRODUCTION

The pyrometallurgical industry in South Africa and worldwide faces several challenges and threats. These include the constraints imposed by fluctuating electrical energy availability, diminishing raw material quality, and ever-tightening environmental regulations essential for combatting climate change. These factors, along with the need to remain competitive in challenging global markets, necessitate the development of cleaner and more efficient production technologies. It also means, however, that the task of designing and deploying new furnaces that can be started up and operated reliably in large, integrated plants is becoming more challenging.

Since new production technologies are an unavoidable reality as we make the transition to sustainable pyrometallurgy, we need to proactively reduce uncertainty and risk to limit the likelihood of failures and disasters. We can do this through close collaboration between role players such as researchers, technology developers, equipment suppliers and producers, and by appropriate use of sophisticated methods and tools. When we do this well, these partnerships can help to accelerate development, improve reliability, and ultimately safeguard hundreds of millions and even billions of dollars in future value. This can help to protect the interests of investors and funding agencies and ensure that the right capital is made available at the right time to further support successful project execution and sustainable metals production.

NEW PYROMETALLURGICAL PRODUCTION TECHNOLOGIES

Before considering the influence of new technologies and our recommended framework, this section considers what new ppt-tech-as are, and why they are needed.

What is it?

There is not always consensus regarding what constitutes a new ppt-tech-a. Pyrometallurgical operations involve a combination of (1) raw materials, (2) equipment, (3) process conditions, and (4) products. Significantly changing any one of these factors will confront an owner with the risks and difficulties associated with new technology. Failing to recognise this has resulted in severe challenges in projects around the globe over the years, as shown in A Framework for Reliable Development section.

Why develop it?

Why are new ppt-tech-as developed? The fundamental motivation is a combination of needs, opportunities, problems and threats. When producers in the metallurgical industry have a specific need, equipment suppliers may see an opportunity to develop and supply new technological solutions to serve these customers. A need may be the result of external factors that create problems for producers, or even threaten their existence. We refer to this as the context of ppt-tech-a development, as shown in ?????.

Of the factors that cause technology to be new, at least one – raw materials – is bound to keep changing, and likely at an increasing rate into the future. As high-grade ore bodies become depleted, lower-grade ore**s** have to be used. This is already a reality in the iron and steel industry (Wimmer, Fleischanderl, and Voraberger 2023). In addition, the recycling of waste materials from industry, vehicles, electronics, catalysts, and battery materials is becoming ever-more important (Tesfaye *et al.*, 2017; Makuza *et al.*, 2021). In both cases, new production technologies will likely be required. When raw materials change, it can result in significant changes to product materials and process conditions, which further increase the likelihood of new technologies.

Environmental aspects also drive new PPT development. Waste materials are increasingly creating problems that must be solved, climate change is a threat to our environment and future, and governments around the world are putting ever stricter environmental regulations in place that producers must comply with. Nevertheless, society has a permanent and growing need for metals. This creates business opportunities for producers to satisfy this need. Therefore, all the fundamental drivers for development of new ppt-tech-as are in place, and it appears that these will only strengthen into the future.

LARGE SMELTER PROJECTS

Large greenfield smelter projects have been executed for decades. Many of these projects have succeeded, but many others have failed. In this section, we discuss the realities of executing large smelter projects. Companies in the metallurgical industry have studied the key components and requirements for project success for as long as there have been such projects. Effective, structured approaches to enhance project success rates were developed as far back as the 1970s and 1980s (Hatch, Goode, and Noskiewicz 1974; E. W. Merrow, Phillips, and Myers 1981). It has been shown that the use of new technology in such projects can have a profound influence on project outcome. This section provides the background for the framework we propose.

Key Project Elements

According to Boom *et al.*, (2015, sec. 1.2) the key aspects of a project are the following:

Business case:

This is a clear description and analysis of the business opportunity that addresses the context within which the plant will have to exist.

Metallurgical concept:

This includes process flow sheets, mass and energy balances, and phase diagrams, which form the basis for progressively more detailed engineering effort as the project progresses.

Design of core process equipment and infrastructure:
Most of this work is usually contracted out to one or more equipment supplier.

Risk
It is well known that large greenfield smelter projects are "*fraught with risk*" (Boom *et al.*, 2015, sec. 1.3). Business opportunities are often substantial, but commensurate risks generally accompany the rewards being sought ... there is no such thing as a free lunch. The difficulties associated with these projects include:

1. Complex raw materials;
2. Uncertainties related to custom equipment and technologies necessitated by unique raw materials, products, project constraints and client requirements;
3. Energy-intensive processes;
4. Handling large quantities of materials;
5. Large-scale environmental impact that must be mitigated;
6. Large quantities of waste materials that must be treated, re-processed, or disposed of;
7. A competitive and cyclical global market;
8. Long lead times to fund, design, and build projects;
9. High capital cost; and
10. Limited windows of opportunity.

The success of these projects are directly related to the owner's ability to identify, understand, and mitigate these risks, either themselves or through the appointment of a competent owner's engineer and knowledgeable technical specialists.

Key Contributors to Project Success or Failure
This section presents results of studies related to large industrial projects. The authors propose different frameworks to assess project success or failure.

Criteria for Success or Failure
Before considering factors that contribute to project failure, it is important that we understand what success and failure mean. E. Merrow and Yarossi (1994) published their criteria for a successful project as one that:

1. Exceeds its budget by less than 10%;
2. Starts up no later than three months after the planned start-up date; and
3. Reaches 85% of design capacity within 12 months of start-up.

In a later work, E. W. Merrow (2011) relaxed the success criteria so that a successful project is considered to be one that:

1. Exceeds its budget by less than 25%;
2. Starts up no later than 12 months after the planned start-up date; and
3. Does not have significant production problems by the end of 24 months.

Wasmund *et al.*, (2011) viewed projects that reached their design capacity within three years as successful; projects that reached design capacity in more than three years as difficult, and projects that were closed due to an inability to get close to design capacity as failures.

Factors Contributing to Project Failure
Twigge-Molecey (2011) analysed 43 projects based on criteria initially published by E. Merrow and Yarossi (1994). When considering the projects that failed:

- More than 67% lacked a properly structured staged approach;

- More than 67% lacked continuity in the implementation team from concept to start-up;
- More than 40% had project development issues such as budget cuts and late scope changes;
- Roughly 50% involved significant use of new technology.

Wasmund *et al.* (2011) also analysed 23 projects that involved new technology. They found that seven of those projects (±30 %) were successful and reached their design capacity within three years; nine (±40 %) had difficult start-ups and took more than three years to reach design capacity; while the remaining seven (±30 %) could not reach close to their design capacity and were closed. This means that around 70% of projects that employed new technology either struggled or failed.
According to Harrison, Waters, and Patoine (2011), higher than expected ore variability and the first use of new technology contributed to failure.

New Technology
It appears that the use of new technology is indeed a significant potential stumbling block in large projects. The term 'new' can be subjective, though, and Boom *et al.*, (2015) identified different degrees of novelty, including:

- New to the world,
- New to the industry sector,
- New to the company, and
- New to the company staff.

Their classification of new technology risk is further clarified in Table I. Even the use of technology that is adapted from existing operations for major equipment, but that is new to a company can be a high risk.

Table I. New technology risk categories (Boom et al.*, 2015, Table 6-2)*

Scope of New Technology	**Minor**	**Major**	**Plant-wide**
Application	**Equipment**	**Equipment**	
Incremental to current operations, new to staff	Low	Medium	High
Adapted from current operations, new to sector or company	Medium	High	High
New or transformational	Medium to High	High	High

Wasmund *et al.,* (2011) identified eight key contributing factors to difficulties and failure when new technology is involved in a project:

1. Too many new elements in the project (e.g., new process technology steps, unfamiliar plant locations, new markets for the plant products, uncertain raw material sources, or a new business for the owners).
2. Inadequate pilot testing of new or newly integrated process steps.
3. Over-reliance on process equipment vendors and suppliers for design of new technology, or for equipment or systems that extend known operating ranges.
4. Insufficient financial and human resources for project development, implementation and startup, and to sustain operations.
5. Inadequate project teams or 'champions', either too weak to provide leadership or too strong to be objective.
6. Inadequate project stage-gating to ensure that defined targets and objectives are met at each project stage.
7. Insufficient attention to risk analysis, evaluation, and mitigation.
8. Poor knowledge of the overall business case, particularly the impact of marketing and product pricing, raw material sourcing, and the tradeoff between rewards and risks.

Finally, Coyne (2002), as referenced in Boom *et al*., (2015) provided a summary of what is required to reduce risk when employing new technology on a project, as shown in Table II. According to the author, these factors can greatly improve the probability of success in projects employing new technology.

Table II. Factors contributing to success when applying new technology (Boom et al. *2015, sec. 6.3)*

No.	Contributing Factor
1.	Appropriate process investigations, generally on the scale of a fully integrated pilot plant, to establish detailed process chemistry, effect of [internal] recycle [streams], effect of feed variations, input parameters for complete mass and energy balances, [and] all key process design criteria and to measure product quality.
2.	Test work and plant design based on the same feed material and ranges of characteristics as will be fed to the commercial plant.
3.	Use of equipment [in the pilot and demonstration scale plants] that has been commercially demonstrated at the same size and in a similar application in successfully operating plants.
4.	Avoidance of any first-of-a-kind equipment that needs to be manufactured to achieve a key process step unless it has been demonstrated at full scale on the expected range of feed material.
5.	Selection of materials of construction that are within proven ranges of application without regard to the cost; otherwise perform long term corrosion/abrasion testing of alternatives.
6.	An [implementation] team that is experienced in the design and operation of comparable facilities, as well as first-of-a kind projects, and that gives a balanced attention to the details of the innovative and conventional aspects of the plant.

A FRAMEWORK FOR RELIABLE DEVELOPMENT

In this section, we present a technology development framework (TDF), which we continue to develop (Zietsman, Weitz, and Sweeten 2020), and that we use to support our clients in the development of new ppt-tech-as, as depicted in Figure 1. This framework responds to the realities presented in Large Smelter Projects section, focusing on reducing uncertainty and identifying, mitigating, and where possible averting risks, to avoid disastrous outcomes that we believe can be foreseen and prevented. We do this in close collaboration with clients, through a structured process of analysis and investigation, with sophisticated yet practical modelling and simulation tools. Through these partnerships we help to accelerate the development process while improving its reliability, and ultimately to protect hundreds of millions and even billions of dollars in future value.

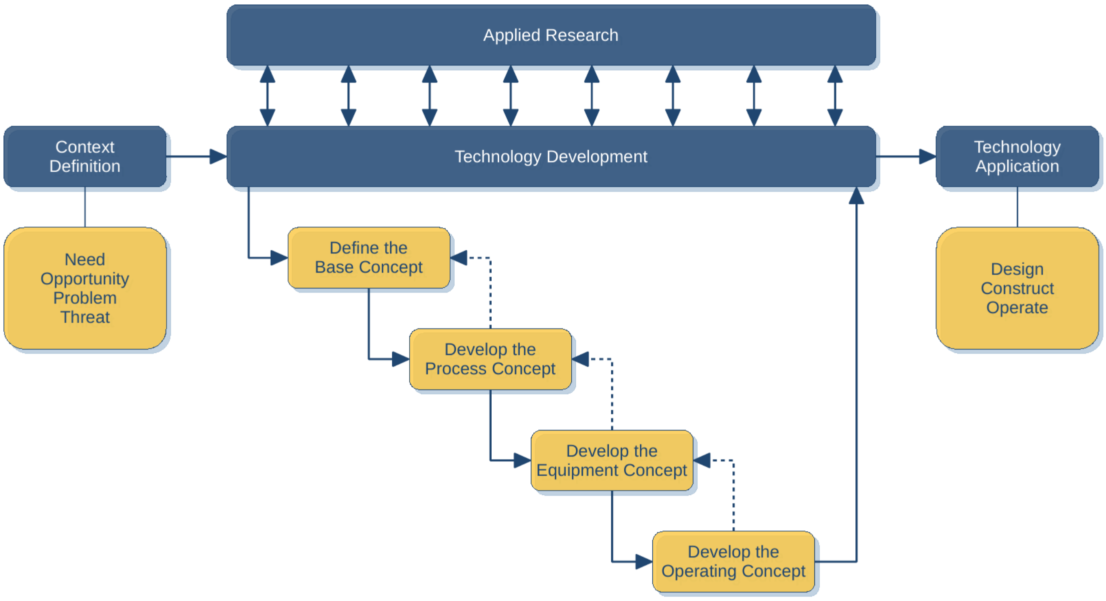

Figure 1. An overview of Ex Mente's pyrometallurgical production technology development framework.

Guiding Principles

The TDF is based on a set of guiding principles, which drives our approach to support clients. We have learnt this over many years, based on the realities of technology development projects, both good and bad.

There are no shortcuts:

High-temperature processes are inherently complex and fraught with uncertainty and risk; believing the opposite is a fallacy. These challenges can all be dealt with effectively, but it takes diligence and structured thinking.

Harsh perspectives now are better than harsh realities later:

We are sometimes asked to review concepts on which a client's team has spent substantial effort and time. It can be quite disheartening when such concepts are shown to be flawed or unfeasible. Learning of such problems early on is, however, much less painful than starting up a furnace with fatal flaws.

Failure is inevitable:

When developing new technology, we venture into the unknown ... and it is a bit like feeling our way in the dark. In this process we are bound to make mistakes and to fail, since this is a natural part of learning, and of life. Society in general has a negative perspective on failure and making errors. We don't, since it is part of the human condition.

When you fail, fail quickly and cheaply:

Since failure and making mistakes are inevitable, we can choose to go about the learning and development process wisely ... to fail well. Critical assessment of a new concept is less costly than struggling to commission a difficult furnace. Analysing a process with a comprehensive prpg-meb model to find flaws is easier than running a pilot smelting campaign. Failing on pilot scale is preferable to failing on an industrial plant. Changing furnace feed configurations in a multiphysics model is much less frustrating, costly, and time-consuming than having to redesign and replace existing equipment within the constraints of an existing building. Doing the right things at the right time is our choice, and we can use it to move forward rapidly and reliably.

Integration is a key requirement for success:

Part of the complexity of furnaces originates from the interactions between materials, process, equipment, and operation. If we 'marry' these aspects from concept through to detailed design, we can create robust and reliable plants. If we neglect these matters, the end result may be a difficult-to-operate, unreliable, and frustrating plant that is unable to compete in an unforgiving global commodity market.

The entire lifecycle needs care:

One of our clients mentioned that their furnace was designed to operate at, for example, 70 MW, but it was not designed to get there. Such problems have caused many years of struggling to ramp up furnaces to full production, which can be disastrous for the owner. It is, however, entirely possible and, of course, critically important to account for the commissioning, start-up, ramp-up, shut-down, re-start, and normal production stages of a furnace's life cycle from concept through to detailed design.

Use the right tools at the right time to answer questions:

Selecting appropriate tools for answering questions at different stages of the development process provides valuable opportunities to fail well. A carefully designed research and development plan should employ a combination of literature reviews, simple calculations, financial models, process models, multiphysics models, laboratory experiments, and pilot-scale test work. Each of these tools have distinct strengths and weaknesses, and they have to be employed with discretion. Each of them has merit when applied at the right stage of development.

The Development Process

Core to our perspective is that context definition, applied research (AR), technology development (TD), and technology application are distinct activities, each of which need to be addressed with care to ensure that large smelter projects can be completed successfully, and metals can be produced sustainably.

Defining the context well provides clarity and focus on development and helps us to say no quickly and avoid meaningless work. It provides an early opportunity to fail well.

The development process starts with the simplest and most impactful aspects first, working towards more detailed matters such as design and operation, as explained in Table III. TD progresses by first developing the simplest and most impactful aspects, and progressively working towards more detailed matters such as design and operation. Due to the inherent complexity and uncertainty, the process is iterative. The concepts that need to be developed are briefly described below:

1. In defining the base concept, we take a high-level view on the process flow sheet. We consider aspects such as the raw materials, the sources of energy, operating conditions, and the range of product compositions that are required and achievable with the inputs.
2. The process concept builds on the base concept by analysing the process, materials, and process conditions in more detail, deciding on a containment concept, and assessing process dynamics.
3. To develop the equipment concept, we decide on the reactor concept, as well as the subsystems like feed, electrical, tapping, and gas cleaning. Instrumentation and control, as well as maintenance concepts are also developed on a high level.
4. For the operating concept, we consider how the process units and plant as a whole will be operated during all stages of its life; including commissioning, start-up, ramp-up, normal operation, shut-downs, and re-starts.

During development, it is inevitable that the team will encounter things that they don't know or understand. These questions need to be solved through AR, focused on supporting the development process. For many years, the term 'research' has not had a positive connotation in the industry. It is, however, a crucial requirement for rapid, reliable, and successful technology development.

During the development stages, different aspects of feasibility are continually assessed, different aspects are identified and analysed, and different tools and methods used, as shown in Table III. This rigorous, staged, and iterative approach limits risk and accelerates progress.

Table III. Commonly neglected stages in developing pyrometallurgical production technologies

Define the need, opportunity, or problem			
Description	Assess Feasibility	Identify Analyse	Tools and Methods
Analyse and describe the opportunity by considering the market, client needs, as well as financial, economic, environmental, and technological aspects.	Economic Financial Technical Physical	Own capabilities Own capacity requirements risk	Financial modelling, market analysis, economic analysis
Define the base concept			
Description	Assess Feasibility	Identify Analyse	Tools and Methods
Devise the technology concept on a basic level, considering the process flow sheet, raw materials, energy sources, products, operating conditions, and the process mass and energy balance.	Financial Technical Physical	Requirements Risk	Process modelling, thermochemistry material test work, laboratory test work

Develop the process concept			
Description	Assess Feasibility	Identify Analyse	Tools and Methods
Devise a robust process concept by analysing the process, materials and process conditions, deciding on a containment concept, assessing process dynamics.	Physical Technical	Core process functions Material properties Requirements Risk	Process analysis, Process modelling, Material test work, Thermochemistry Laboratory test work, Pilot test work
Develop the equipment concept			
Description	Assess Feasibility	Identify Analyse	Tools and Methods
Decide on a reactor concept, and subsystems like feed, electrical, tapping, and gas cleaning. Also, address instrumentation and control, and maintenance.	Financial Technical Physical	Requirements Risk	Mechanical design, Electrical design, Thermochemistry process modelling Multiphysics modelling Pilot, test work
Develop the operating concept			
Description	Assess Feasibility	Identify Analyse	Tools and Methods
Consider how the process unit/units and the plant will be operated during normal commissioning, start-up, ramp-up, normal operation, shut-downs, and re-starts.	Financial Technical Physical	Requirements Risk	Process simulation, Plant simulation, Pilot test work

Deliverables

The term 'technology' tends to be abstract and vague. However, when a business invests in the development of a technology, there needs to be a clear and concrete set of deliverables, which will ultimately become the technology asset. The structured process that we describe in The Development Process section should therefore deliver tangible items, such as those shown in Table IV.

Table IV. Important deliverables of a pyrometallurgical production technology development process

Technology Items	**Project Templates**
Technology handbook	Design criteria specification
Requirement specification	Financial model
Financial model	Risk register
Risk register	Process mass and energy balance model
Process mass and energy balance model	Basic engineering specification
Process simulator	Detailed engineering specifications
Reactor multiphysics models	Commissioning plan operating manual
Plant simulator	

We distinguish between two deliverable categories. The first, technology items, relates to the technology itself, and not its application. The technology handbook is the central tool in the development process, but the other listed items also have crucial parts to play. The second category, project templates, are focused on deploying a technology through projects. These tools can assist equipment suppliers, for example, to become more cost competitive, reliable, and faster to produce, all of which are beneficial to the producers.

CONCLUSION

The pyrometallurgical industry will continue to be challenged by change as we move into the future. This is, most fundamentally, due to changing raw materials and increasing environmental constraints. For these reasons, new production technologies will have to be developed, likely at an ever-increasing pace.

The history of our industry has shown that the application of new technology poses a real and substantial risk to successful project execution and sustainable metals production. The framework that we present in this paper is a set of practical principles, tools and methods to assist with reducing uncertainty and risk, and ultimately to accelerate progress and produce reliable returns on capital investment.

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