

Campaign Life Extension of Ironmaking Facilities

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INTRODUCTION

Ironmaking assets, including mission-critical equipment and structures, are commonly exposed to extremely harsh operating conditions, which degrade their condition over time and can ultimately result in costly repairs and downtime. Pressurized and non-pressurized components in ironmaking facilities are often used for 50+ years after construction, exceeding their original design lives and requiring careful attention to their condition and remaining campaign life.

Even within the design life, ironmaking assets are commonly subjected to changes in operating conditions that may vary from those considered in the design. This may include increases in operating temperatures and pressures, either due to upset or unanticipated operational conditions, or due to purposeful changes in the process which may be associated with raw material quality, upgrades, or retrofits to system components, or increases in production beyond that originally envisioned. In addition to changes in these key parameters, many ironmaking components are subject to cyclic loading which can lead to fatigue cracking and excessive deformation through ratcheting. General harsh service during site maintenance and repair activities can also cause acute damage due to impacts or other accidental conditions / events.

Many ironmaking system components operate without redundancy. Breakdown or severe damage to components such as sinter machines and coolers, mixers, hot blast mains, bustle pipes, furnace shells, and gas cleaning systems may lead to major downtime and cost, as they cannot be bypassed to perform extended maintenance or repair in-service.

The overall operating regime of these systems means that understanding the asset condition and remaining life at any given time is critical to minimizing the operational risk. Rigorous assessment of campaign life for components, operating units, and overall plants, is a valuable methodology to identify key risks and determine appropriate strategies for campaign life extension. This may include quantitative assessment considering the provisions of API 579-1 / ASME FFS-1 [1], “Fitness-for-Service”. FFS-1 provides recommendations based on long-developed experience and safe practices associated with pressure vessel, piping, and storage tank industries, which can be extended to other types of equipment. FFS-1 incorporates by reference the design-by-analysis provisions of ASME VIII-2 [2], “Rules for Construction of Pressure Vessels Division 2 – Alternative Rules”, covering stress analysis and various damage mechanisms such as yielding, buckling, rupture, fatigue, and creep. Fitness-for-service principles can also be applied to evaluate suitability of components for changes in the operating conditions compared to the original conditions. This methodology is also invaluable for aging assets where the original design documentation or calculations may not be available.

Although ASME FFS-1 and VIII-2 do not cover refractory systems, these are also critical components to many ironmaking assets and must be considered as part of campaign life assessment and extension. Hatch evaluates these systems using in-house best practices that have been proven through industrial guidelines and past experience.

This paper will provide an overview of a campaign life extension approach applicable to ironmaking facilities, providing several examples in which this methodology has been successfully used to extend the life of key components, and significantly reduce operating and sustaining capital costs for these facilities. This methodology is also applicable to adjacent assets such as those used in raw material production and agglomeration, steelmaking, and rolling.

KEY IRONMAKING ASSETS

Ironmaking includes a host of different assets, including critical systems such as (but not limited to): raw material agglomeration equipment such as sinter machines and sinter coolers, cold blast systems, blast stoves, hot blast mains and bustle pipes, tuyeres, blast furnaces, off-gas cleaning systems, and more. All these systems must work in tandem to produce iron, and the loss of service of one can compromise the entire ironmaking operation, leading to downtime and major production interruptions which are both challenging and costly to mitigate. A schematic of the blast furnace, blast air system, and gas cleaning system is shown below, and it is noted that there are many other relevant systems and assets not pictured.

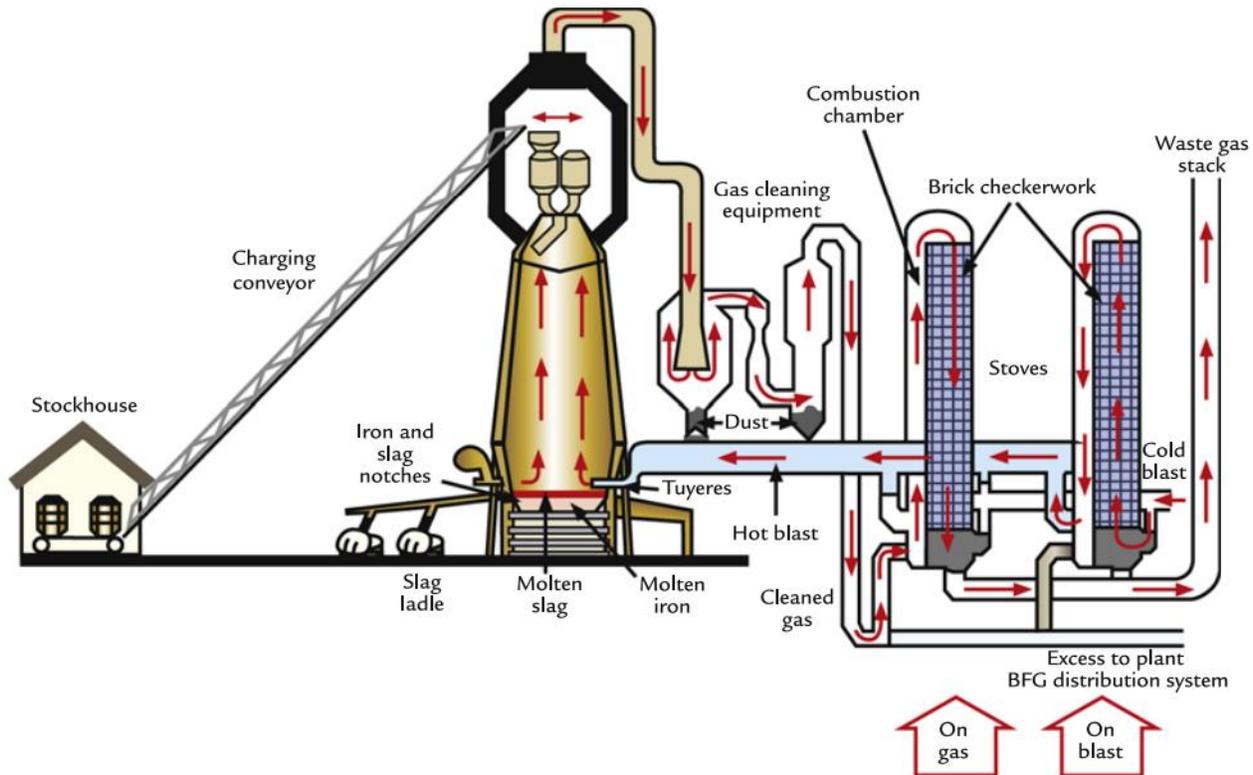


Figure 1. Schematic of blast furnace and some associated facilities [3]

In some cases, problems manifest in only one specific area or asset, and can be addressed in isolation. However, in other cases, the root cause of damage may be systemic and may affect multiple components of the system, requiring a holistic assessment approach. A system-wide, holistic approach is also key when assessing overall design changes such as increases in operating temperature or pressure, or when evaluating the system for key concerns and risks to the overall campaign life.

COMMON DAMAGE MECHANISMS AND RISKS

In-service ironmaking assets are at a high risk of damage from a variety of mechanisms which can cause degradation or failure of steel components such as furnace shells, stove shells, blast air and off gas ducts, and numerous others. Damage mechanisms for steel components can typically be assessed using the provisions of ASME FFS-1. Some key damage causes / mechanisms for steel components include, but are not limited to:

- **Mechanical overloading.** Mechanical loads due to weight of the equipment and contents can cause local yielding, rupture, buckling, or other damage. This can be particularly problematic at discontinuities such as openings in shells, corners, welded attachments, and others. This type of damage may be a result of factors such as incorrect original design, increase in loading over the life of the asset, or accidental damage due to repairs and alternations.
- **High temperatures.** Short-term and long-term high temperature events, such as flame impingement and shell overheating due to refractory loss, may damage the steel microstructure and reduce its strength or

other properties affecting its future performance. Higher temperatures can lead to creep damage, particularly in carbon steel equipment. It is important to note that in some locations, such as the top of bustle pipes, dust build-up or inaccessibility may limit the ability to capture creep damage in inspections. This is particularly problematic where dust build-up serves both to increase local temperatures in the steel and to hide the higher temperatures or steel damage.

- **High and cyclic pressures.** Operating pressures are commonly quite high and regularly cycle, which can lead to fatigue damage and cracking of steel shells, causing gas leakage and potentially leading to structural failure and collapse. Operating pressures may be increased over the lifetime of the equipment. For an aging system which may have already sustained other forms of damage, this can cause performance issues and require attention to mitigate.
- **Corrosion.** Environmental and process exposure result in corrosion, which is a common and widespread issue for ironmaking facilities. Equipment is commonly designed with appreciable safety margins (corrosion allowances) on installed thickness, but corrosion can still result in major thickness loss that could compromise the structural integrity of assets, especially those operating beyond the original design life. This can be more critical in areas exposed to higher temperatures or harsher environments (e.g. process gases), or in local areas prone to dust and moisture build-up.
- **Stress Corrosion Cracking (SCC).** SCC is a damage mechanism commonly seen in hot blast stoves, in which there may be high concentrations of NO_x. Shells should be designed with an impermeable layer to protect the shell, or with insulation that maintains the steel temperature above the gas dewpoint. If these actions are not taken, significant stress-corrosion cracking can occur.

As noted previously, ASME FFS-1 does not cover refractory components. However, the condition of refractory must be considered alongside the condition of steel components. Refractory is subject to many similar damage mechanisms, including mechanical overloading, high temperatures, thermal shock, abrasion and chemical attack from components of the process (hot blast air, hot metal, off-gases, etc.).

In an ironmaking facility or operating unit, many of these damage causes and mechanisms may be occurring in different areas, or in combination in some areas. Campaign life extension of individual assets must consider all applicable damage mechanisms. In assessing and potentially extending the overall campaign life, for example the life of the blast furnace, all areas and applicable damage mechanisms must be considered together.

CAMPAIGN LIFE ASSESSMENT AND EXTENSION METHODOLOGY

Campaign life assessment and extension may typically involve two broad categories:

1. Specific pieces of equipment which do not affect other systems. The need to assess the fitness-for-service and extend campaign life of these components may be related to specific damage events (e.g. process upset condition and overheating), recurring issues (repeated shell cracking or refractory failures), or in some cases, damage where the root cause is not immediately clear. This can also include process changes that are confined to one piece of equipment.
2. Events or conditions that affect several systems. This may include changes in process conditions, such as furnace process modifications that affect the furnace refractory and shell as well as downstream components such as the off-gas system, and is also applicable for general assessment of aging plant equipment and systems (overall audits to identify problematic areas which may have shorter campaign life and implement mitigations).

Assessment steps may differ somewhat between these categories, but are generally similar in principle:

1. Review actual equipment operating conditions as well as any planned changes compared to original design; this may affect multiple assets or systems.
2. Prepare detailed accounting of any previous damage (nature, timing), remediations performed, understood causes, as well as previous records of maintenance, inspection, component replacements, and other work. In some cases this data is not readily available, which makes an assessment less precise – operators should strive to keep these records for all core equipment.
3. Prepare inspection plans to determine current condition of the system, for aspects that are not already understood. Inspections should be completed by certified / qualified inspectors, and preparations must be made to make inspection areas safe and accessible.

4. Root cause analysis should be performed to determine causes of any damage (or potential damage in case of changes in condition). This is key to preventing future reoccurrence of similar damage, or occurrence of new damage due to changes in condition.
5. Perform fitness-for-service assessment of areas that are damaged or affected by changes to service conditions. For steel components, ASME FFS-1 should be used. Based on this, determine whether the equipment is safe to continue operation.
6. If equipment is safe for continued operation, determine the remaining campaign life. If the equipment is not safe to continue operation for the desired campaign life, develop campaign life extension actions such as remediation / repair plans (e.g. addition of repads, stiffeners, local replacements, or other strengthening measures).
7. Develop an inspection / monitoring / maintenance plan. Inspections should be calibrated to allow projection of the remaining life through measuring damage rates. This could include a combination of automated monitoring such as thermocouples or strain gages to capture data on an ongoing basis and periodic in-person where needed. Ongoing maintenance, such as dust cleaning, corrosion cleaning, painting, etc., should also be considered.

EXAMPLE 1: BLAST FURNACE SHELL DESIGN IMPROVEMENTS TO EXTEND CAMPAIGN LIFE

In aging blast furnaces, the steel shell often accumulates damage to high mechanical and thermal stresses as well as reduced material strength caused by loss of refractory and local overheating. Partial or full furnace rebuilds may include replacement of either part or all of the furnace shell, with the intention to allow for campaign life extension of the furnace overall, with improved reliability. The blast furnace shell includes many attachments and discontinuities such as tuyere openings, nozzle locations, stove pipe openings, maintenance doors, offtake connections, and others. If the design of these areas is not performed carefully, cracking and other damage can occur locally and lead to onerous maintenance, repairs, and ultimately compromised campaign life of the blast furnace and associated production loss.

In one example, an aging blast furnace was approaching the end of its life and a new shell was designed, to be implemented during a furnace rebuild to extend the campaign life of the ironmaking facility. Although the previous shell was not subject to heavy damage, a refined shell design was considered in order to optimize the future campaign life and to accommodate a new feed system. The new design layout is shown in Figure 2, with proposed design improvements including a modified top cone and feed system, added maintenance doors (shell openings), and adjusted shell profile with reduced thickness compared to the original design.

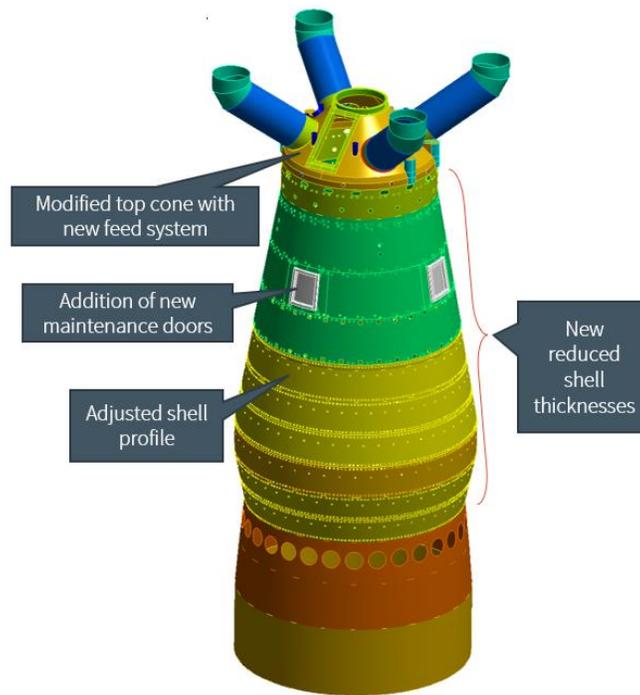


Figure 2. Furnace shell with proposed design improvements

To ensure the integrity of the new shell for the extended campaign life, considering the modifications to the shell profile, opening arrangement, and thickness, an engineering design assessment was performed using the provisions of ASME VIII-2. This assessment focused closely on details of the new shell design, to identify locations that would potentially limit the campaign life through overstress, fatigue, and other damage of the shell.

The assessment was performed using ANSYS Workbench commercial finite element software. Use of finite element software allowed for explicit consideration of critical geometric details, including closely spaced holes, which would otherwise not be addressed properly (under-conservative) or addressed using excessive conservatism (inefficient use of materials and more costly implementation). This assessment found a number of local regions requiring adjustments in configuration and/or local reinforcements, as shown in Figure 3. Only minor and targeted design modifications and reinforcements were needed to achieve a new shell design with significantly improved design campaign life.

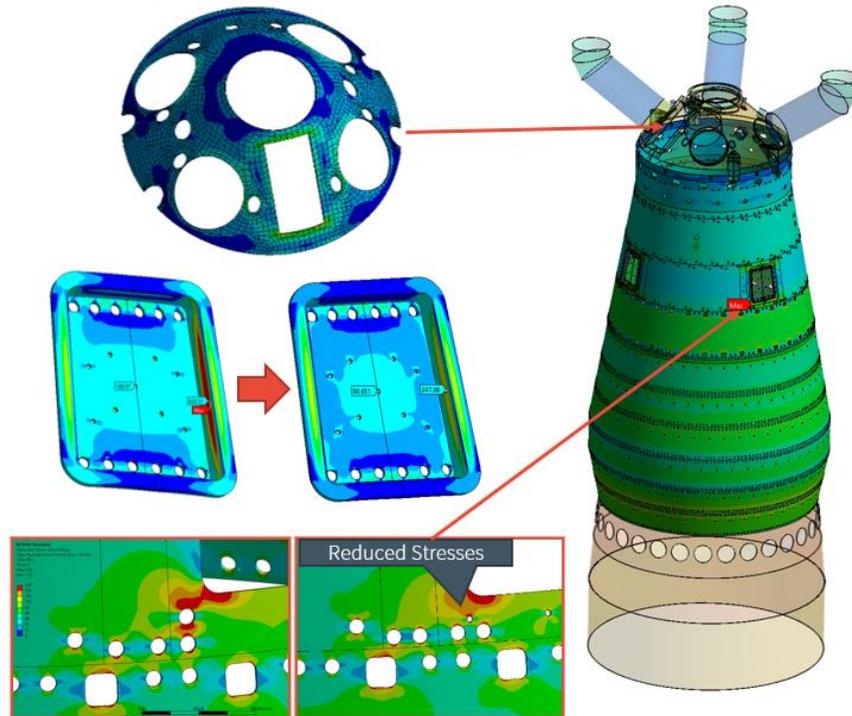


Figure 3. Finite element model (right) and stresses in top cone (left top), improvements to reduce stress in maintenance door (left middle), and improvements to reduce stress at closely spaced openings (left bottom)

The final design, considering the fitness-for-service and campaign life extension approaches described in this paper, met code requirements and mitigated potential future damage which would have compromised the campaign life extension of the blast furnace. This allowed for confidence in implementation of the new design, with optimized fabrication and installation costs.

EXAMPLE 2: SINTER COOLER FITNESS-FOR-SERVICE AND CAMPAIGN LIFE EXTENSION

Ongoing damage and degraded condition, particularly due to operation outside the original design parameters, can lead to situations in which the owner operates an asset without a clear knowledge of the remaining campaign life. In these cases, there is a severe risk of unexpected downtime, potentially resulting in the need to fully replace a piece of equipment, but without certainty of how soon this replacement may be needed.

In one example, a rotating sinter cooler had been in operation for approximately 35 years. The sinter cooler was supported by 80 trucks and wheels running on a circular rail. Various damage mechanisms had been evident over the campaign life, including structural failures in ring beams and other steel components, misalignments between cells of the cooler, and damage to the concrete base underneath the rail. The owner had identified the sinter cooler as being near the end of its

campaign life but was not certain of the risk level and remaining life. It was decided to perform two studies in parallel: one to assess the requirements to replace the sinter cooler completely, and one to assess the fitness-for-service of the sinter cooler and understand the requirements to be able to extend the campaign life. This paper focuses on the campaign life extension.

Initial steps included data gathering regarding the historic operation and condition of the sinter cooler, past capacity increases, previous repairs, load monitoring, and numerous other information. Understanding that misalignments had occurred over the life of the asset, a detailed inspection was performed, including 3D laser scanning to develop a point cloud and 3D model, as shown in Figure 4.

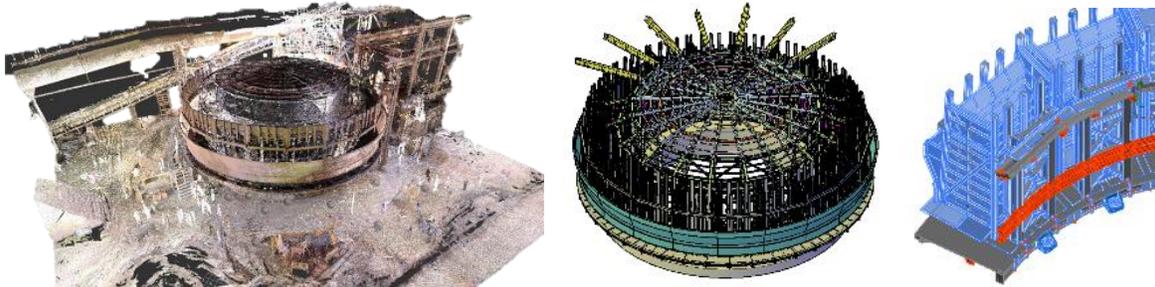


Figure 4. Sinter cooler point cloud (left), overall 3D model (centre), and structural model (right)

Using the available information and numerical tools, root cause analysis of past failures was performed, and three key root causes of damage were identified:

1. Unevenness in the rail surface
2. Vertical misalignment in the rotating structure
3. Lack of circularity of the rotating structure in the horizontal plane

These root causes, combined with a lack of flexible element or suspension between the rotating structure and the trucks, resulted in highly variable loads between trucks, with some wheels carrying many times the average, and others carrying zero or nearly zero load. This caused damage such as deformation and yielding of the structure, failure of connections, failure of rails, and local failure of the concrete base below.

Fitness-for-service assessment of the structure, using ANSYS Workbench commercial finite element software, considered two conditions: (1) “as-designed” condition without damage or misalignment, in which all truck / wheel loads were equal, and (2) “as-built” (current) condition with damage and unevenness / misalignment explicitly considered and high variability between truck /wheel loads, based on the point cloud and 3D model. Comparing the results of these two assessments found that in the “as-designed” condition, stresses were typically below allowable limits, indicating no fatal flaw in the original design. However, unevenness and misalignment resulted in very high local loads and stresses in the “as-built” model which were responsible for the observed damage.

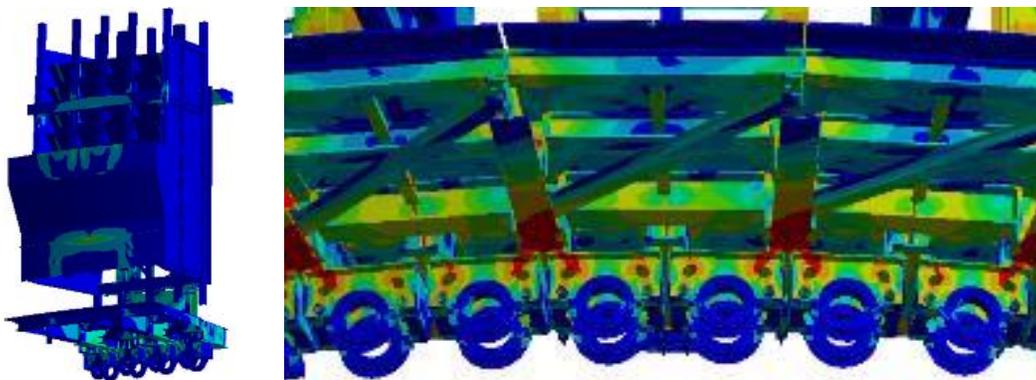


Figure 5. Low stresses in nominal / as-designed condition (left); high stresses in key areas in as-built condition (right)

Based on this evaluation, recommendations were developed to extend the campaign life to the next furnace reline shutdown, including improvements to the shimming and load equalization procedures for the trucks, adjustment of horizontal guide wheel positions, and targeted minor structural reinforcement. Potential for implementing increased flexibility between the rotating structure and trucks was investigated, but it was ultimately found that improved load equalization procedures were a more robust and economical solution. A structural health monitoring plan was also developed, to maintain the condition and capture any new challenges.

Application of the campaign life extension approach described in this paper allowed the owner to continue operation with clear knowledge of the root causes of problems and the remaining campaign life, with implementation of the targeted recommendations at a fraction of the cost and labor efforts that would have been required to replace the equipment.

EXAMPLE 3: OVERALL FACILITY CAMPAIGN LIFE EVALUATIONS

In many plants, problematic assets may be addressed on a case-by-case basis as their campaign life becomes a critical concern, as in previous examples. However, this may obscure the overall picture of the plant or operating unit remaining campaign life, as assets in the poorest condition receive substantial attention, while assets in moderate (or unknown) condition may not receive attention until their condition degrades and they fail unexpectedly. This issue can be addressed through systematic campaign life evaluations and development of condition “heat maps” and campaign life extension strategies. This type of evaluation is extremely valuable for identifying key drivers for major interim repairs and relines / rebuilds of key components, which are major events with respect to cost, logistics, and safety.

In one example, an integrated steel plant had a number of operating units including two blast furnaces, melt shop, and sinter plant. Major outages and repairs were tentatively planned for these areas, but clarity was needed on the key drivers for the outages and the flexibility of the timing, to be able to optimize the overall repair planning and business case.

To assess the campaign lives of the operating units / facilities, a systematic approach was taken including key steps:

1. Development of a Work Breakdown Structure (WBS) and definition of the scope of assets being investigated
2. Preliminary prioritization of the assets based on their criticality, to determine the required level of information gathering and technical assessment for each (see Figure 6).

Classification	Criteria	Information Gathering	Technical Assessment
Priority 1 (Critical)	Area identified as critical or unsafe	Detailed data collection	More detailed technical assessment
Priority 2 (Potentially Critical)	Area agreed as not currently critical but could impact campaign life	Some information gathering required beyond verbal / qualitative feedback	Less detailed technical assessment
Priority 3 (Non-Critical)	Area agreed as not currently critical and not expected to impact campaign life	Verbal / qualitative feedback to come from client in workshops	High-level (conceptual) feedback and assessment

Figure 6. Example matrix of criticality

3. Information gathering through site visits, workshops, interviews, maintenance and repair reports, and other available documentation describing the historic and current condition
4. Technical assessment of each asset. Level of detail required for the technical assessment could range from qualitative review and comparison to benchmarks for non-critical assets, up to detailed fitness-for-service assessment for the most critical assets.
5. Consolidation of technical assessments for all assets, to determine overall campaign life of each operating unit based on its key drivers.
6. Development of recommendations for immediate campaign life extension actions, and prioritization of actions to be done during more major future outages (see Figure 7).



Figure 7. Example categories for prioritization of actions

This approach provided the owner with a thorough and actionable set of recommendations for campaign life extension and provided valued inputs to the timing of critical outages such as interim repairs and furnace relines. Some examples include:

- Quantification of assets deemed to be in poor condition but with uncertain remaining life
- Determination of more detailed required assessments in key areas (e.g. structural analysis, fitness-for-service) either at the current time or in the future
- Identification of synergies between required repairs, to optimize implementation (e.g. sharing of cranes between major repairs needed in close proximity)
- Recommendation of detailed and systematic health monitoring programs to extend campaign life of critical assets
- Confirmation of the feasibility of deferring major shutdowns to allow for additional planning, engineering, procurement, and construction planning, allowing for safer and more effective shutdown periods

CONCLUSION

Ironmaking equipment and facilities are commonly exposed to extremely harsh and variable operating conditions, which can lead to damage of steel and refractory components and cause unplanned downtime, which disrupts production, reduces reliability and safety, and increases costs. It is therefore critical to have a systematic approach for assessing the fitness-for-service of in-service assets as well as the remaining campaign life, and developing strategies to extend the campaign life if needed.

The campaign life assessment and extension approach given in this paper is a systematic and flexible way of addressing uncertainty in campaign life and damage to key ironmaking assets, as well as those in adjacent applications such as raw material production and agglomeration, steelmaking, and rolling. This approach allows for quantitative assessment using ASME FFS-1, and determination of the suitability of facilities or parts thereof, for continued operation. The examples have demonstrated the application of this approach to some key ironmaking facilities.

Proper assessment, maintenance, repairs, monitoring, and outage planning are critical to the reliable operation of any ironmaking facility. Using this approach, plants can maximize asset life and minimize downtime, reducing the overall cost of operation.

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