BLAST FURNACE HEARTH MANAGEMENT[1]

Jean-Paul Simoes[2]
Gilles Kass[3]
Philipp Bermes[4]
Giorgio Avanzino[5]
Carlo Morelli[6]
André Oliveira[7]

Abstract
The proper management of hearth related phenomena is essential for safe and stable blast furnace operation. Assuring good liquid flow and drainage is one of its most important functions, whereas monitoring its wear and erosion is vital to achieve a long lifetime. In general, mathematical models use indirect measurements of the major hearth parameters to support the operator in the assessment of its internal state. The present paper presents the latest developments of Paul Wurth's level 2 automation system, BFXpert™, supporting the blast furnace operator in this task. The Hearth Lining Model included in BFXpert™ is an online mathematical model monitoring the hearth's thermal status and the evolution of the wear profile. The use of specific temperature measuring probes increases the model's predictability. In case of high wear, the information given by the model helps the operator to take appropriate counter-measures in due time, before hearth wear becomes critical. The Hearth Liquids Model (HeLiMo) monitors the drainage behaviour of the hearth and keeps track of the hot metal and slag quantities and levels, based on a continuous mass balance of produced and tapped liquid quantities. The implementation of the different models and tools in a common platform eliminates interface and compatibility problems. The early detection of phenomena and anomalies avoids perturbations and enables preventive actions, contributing to enhanced plant productivity and availability.
Keywords: Blast furnace; Hearth; Level 2; Models.

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2 Head of BF Plant & Process, Paul Wurth S.A., Luxembourg
3 Senior Project Engineer, Paul Wurth S.A., Luxembourg
4 Project Engineer, Paul Wurth S.A., Luxembourg
5 System Engineer, Paul Wurth Italia S.p.A., Genova
6 Senior Project Engineer, Paul Wurth Italia S.p.A., Genova
7 Metallurgy Process Analyst, Paul Wurth do Brasil, Belo Horizonte

1 INTRODUCTION

Efficient hearth management is essential to ensure stable blast furnace operation, since disturbances in this part have an impact on overall blast furnace operation and productivity. An adequate understanding of the internal state of the hearth, characterised by numerous factors and variables that are mostly interrelated, is therefore required. Hearth management consists in the challenging task of monitoring and controlling these factors.

Undisturbed drainage and liquid flow have to be assured by controlling hearth permeability, which is influenced by various parameters such as coke bed voidage, deadman movements, slag and hot metal levels or available hearth volume. The latter is again influenced by skull formation: although skulls will contribute to protect the refractory lining, an excessive growth of skull will limit the available hearth volume which can affect productivity.

In parallel, the condition of the hearth lining has to be monitored closely to detect increased rate of wear and erosion, avoid premature wear and thereby maximise campaign length.

Hearth phenomena mostly evolve progressively over time. Nonetheless, disturbances can entail rapid changes in some cases, requiring prompt action by the operator.

As direct measurements of the parameters characterising the internal state of the hearth are generally very complex, mathematical models using indirect measurements are used to support the operator in his assessment. The latest process models and tools developed by Paul Wurth provide the required continuous assistance to achieve top class hearth performance. The process models are part of BFXpert™, the Paul Wurth blast furnace level-2 system.

2 BFXpert™

BFXpert is Paul Wurth's advanced process control system that consists of a modular set of powerful on-line and off-line models on a common platform including SACHEM® expert system as well as BFXpert RULES and other utilities. BFXpert covers all areas of blast furnace ironmaking such as charging, blast and injection, tapping and supervision.

It provides diagnostics as well as recommendations to assist blast furnace managers, process engineers and operators in their daily tasks to safely achieve the target production at optimised cost as well as ensuring a longer campaign life.[(1)]

The benefits obtained by the use of BFXpert are the following:

- routine tasks are handled or respectively cross-checked
- continuous training and increased process awareness of operators
- improved operational stability 24 hours a day and 7 days a week
- early detection of process phenomena or plant anomalies enabling preventive actions
- improved safety through fewer incidents lowering the risk of human, environmental and equipment hazards
- increased plant availability, thus increased production capacity
- improved product quality, thus improved slag granulation and steel shop operation
- reduced overall energy consumption (blast furnace and hot stoves area)
- extended campaign life.

BFXpert models and tools are designed and developed in-house, beneficially combining Paul Wurth blast furnace process know-how, along with long expertise in automation technologies and hearth design. They are a powerful support tool for efficient BF operation, including major hearth management issues.
The models related to hearth management are the Hearth Lining Model, the Hearth Liquids Model (HeLiMo) and various functionalities included in the expert system SACHEM.
An additional tool is BFXpert RULES, a real-time rule based system for process control. It makes use of the in-depth process knowledge available at blast furnace plants by providing a way to implement such knowledge directly into the level-2 automation system. BFXpert RULES is complementary to the Sachem expert system, as it allows covering operations specific for individual blast furnaces and corresponding site organizations.

3 HEARTH LINING MODEL

3.1 Online Model

In order to operate the furnace safely, it is necessary to continuously monitor the hearth thermal status and assess the extent of hearth wear based on thermocouple readings, heat flux measurements across the lining and monitoring of thermal losses in the cooling system.
This is a crucial issue in particular at the end of the furnace campaign, when the actual wear profile may be critical and the moment for a blast furnace shutdown has to be decided accordingly.
The Hearth Lining Model included in BFXpert is an on-line mathematical model, which uses the hearth temperature measurements to monitor the hearth thermal status and provides an estimate of the hearth lining wear profile. In case of wear, this information helps the blast furnace operator to take appropriate counter-measures in due time, before the hearth wear becomes critical.
The model is activated automatically on a cyclic basis, usually once per day, without any operator intervention, apart from possible modifications of the input options (such as disabling of unreliable thermocouples). These can be easily set by means of the human-machine interface, when required.
The model results are displayed graphically. Different display options, such as 2-dimensional vertical or horizontal sections, 3-dimensional view, or time evolution, can be selected by the operator.

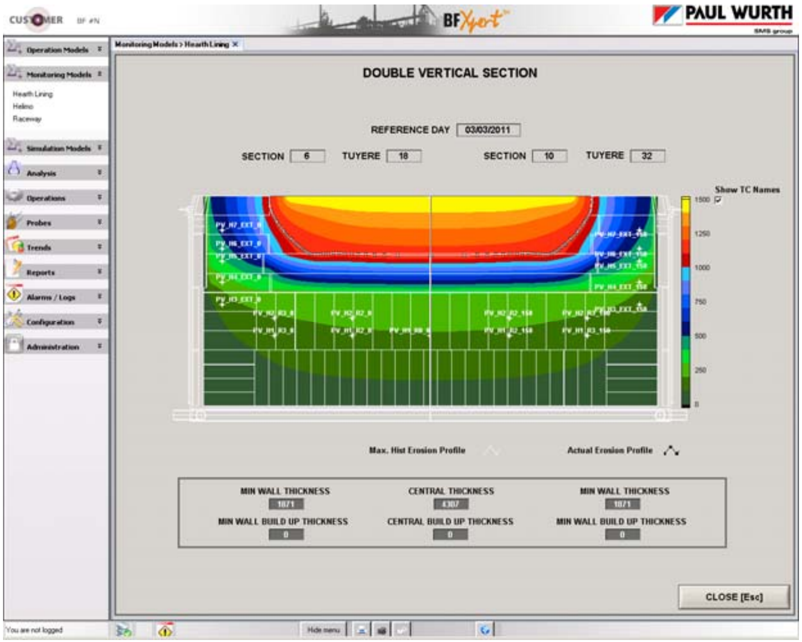

Figure 1: Hearth Lining Model screen for the 2-D visualisation of model results.

The model, based on a well-founded physico-mathematical background, includes the calculation of the temperature distribution inside the hearth, and a self-tuning procedure introduced to align the calculation results to the actual plant conditions.(2)
The model keeps track of the time evolution of the thermal and erosion profiles, and therefore takes into account the build-up of adherent relining material, from the beginning of the campaign onwards.
The hearth thermal status is described by means of the Fourier equation of heat transmission:

$$div\,[\lambda(T,x)\cdot grad(T)] = 0$$

The coefficient $\lambda(T, x)$ is the thermal conductivity of the hot metal and of the lining materials in the considered layers, x is the space and the solution T is the temperature distribution inside the hearth.
The thermal conductivity is a function of temperature T as well as of space x, because of the presence of different materials in the hearth lining, as well as of the discontinuity between hot metal and lining material.
The time dependence is not considered, having assumed steady state conditions.
The first calculation step consists of the numerical solution of the above Fourier two-dimensional equation of heat transmission in steady state conditions.
The second step is the self-tuning procedure, i.e. the correction of the adjustable model parameters, to minimise the deviation between calculated and measured temperatures.
The considered model parameters are defined and used for the evaluation of the value $\lambda(T, x)$ relevant to the actual hot metal thermal conductivity in different areas of the hearth. They are self-tuned to minimise the cost function:

$$\sum(T_{meas} - T_{calc})^2 + f(u)$$

where T_{meas} is the set of mean measured temperature values, T_{calc} is the set of calculated temperature values (corresponding to the given thermocouples positions), and $f(u)$ is a cost on the deviation between the actual values of the considered model parameters, and their optimal reference values.

The hearth is represented as a set of two-dimensional vertical sections, for each of which the above calculations are applied; the definition of the current wear profile is based on the position of the 1140 °C isotherm (approximately corresponding to the crystallisation temperature of the hot metal).
The final result is obtained by the iterative application of these two steps. This procedure, applied to a significant set of vertical two-dimensional sections, produces a three-dimensional representation of the hearth, showing its wear profile and thermal status.
The Paul Wurth Hearth Lining Model is highly appreciated for on-line monitoring purposes, but it can be also beneficially used for off-line applications at the end of the blast furnace campaign.

3.2 Off-line Application of the Hearth Lining Model at the End of the Blast Furnace Campaign

The Hearth Lining Model can be applied off-line to study the end-of-life conditions of the hearth. This may be required in case of existing furnaces and old installations, to support plant managers and process engineers during this critical phase and provide useful information for their decision-making, possible actions and, at last, for the preparation of the shutdown procedure. The off-line application is implemented and executed on the basis of the historical data, as well as of the required geometrical and physical data.
Targets of this kind of studies are basically:

- Evaluation of the erosion profile, in order to plan some intervention or practise that help the reconstruction of the lining and may therefore prolong the furnace campaign.
- Evaluation of the erosion profile and available hearth volume, to support the definition of the drilling conditions for salamander tapping. These values will be used for the planning of the drilling hole and for the evaluation of the salamander volume to be discharged.

Being an off-line application, to be executed retroactively, some simplifications on input data are needed:

- Selection on thermocouples: validation analysis of the thermocouples data on the entire hearth life, to identify the ones that show a correct behavior, and avoid to affect the adaptation algorithm with misleading information.
- Selection on time: a very reduced subset of the huge amount of measured data is used. This reduced set of data is normally chosen in correspondence with some minimum and maximum average temperature, observed at some particular moment of the hearth life.

Of course the results are normally less accurate than the on-line application, but nevertheless very useful for the scope. A recent off-line application has been done by Paul Wurth before the shutdown of the ILVA Blast Furnace #1 in Taranto - Italy, which occurred in December 2012, in order to evaluate the hearth conditions and the corresponding salamander volume. A comparison of the model results and the measured values is reported on Figure 2.

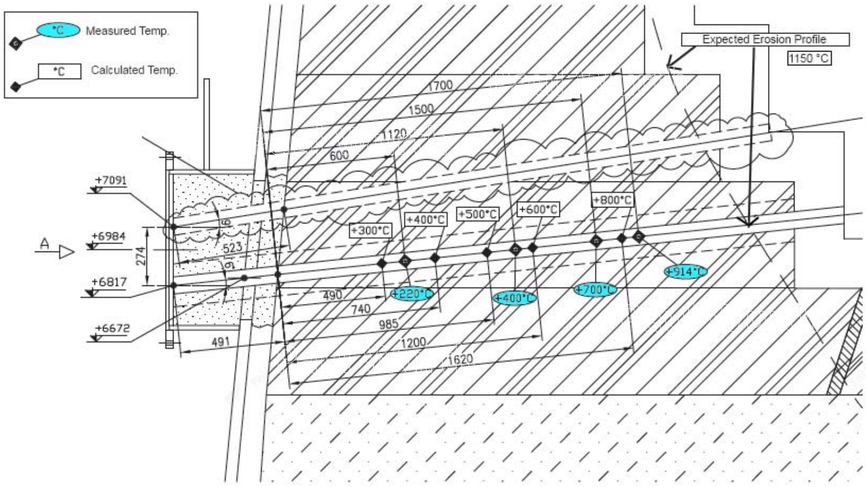

Figure 2: Comparison of the model results and the measured values.

The results of this study were beneficially used to support and monitor the blast furnace shutdown procedure. The findings were in good agreement with the salamander conditions of the just blown-out furnace.
Paul Wurth, based on his consolidated BF process know-how and technological expertise, can provide profitable support and consultancy services to ironmaking producers, at the end of the furnace campaign, including the above described off-line application of the Hearth Lining Model.

3.3 Advanced Probes for Hearth Temperature Measurement

The Hearth Lining Model will provide accurate results if the temperature readings that serve as basis for the calculations are reliable, are installed in sufficient number and their positions are properly distributed and known with precision.
In some cases, the reliability of the temperature measurements can be affected by the appearance of discontinuities like brittle layers, originating from physical-chemical attack mechanisms within the hearth lining. Such discontinuities can modify the temperature profile along the furnace wall and act as an additional thermal resistance. By adopting standard thermocouples and their usual arrangement at the outer periphery of the hearth walls, the above discontinuities may remain undetected and affect the accuracy of the wear profile calculation.
Paul Wurth proposes advanced temperature measurement probes to improve the temperature surveillance of the hearth and give the possibility to detect possible discontinuities within the temperature profile. These *Multipoint Thermocouple Sensor Probes* or *MTP*s, consist in a combination of several temperature measurements in a single probe. Several thermocouple wires are installed in a perforated, hot metal and slag resistant ceramic rod up to their predefined insertion length. Additionally, the ceramic rod is incorporated in a super-micropore carbon protection tube, which renders the probe break-out proof. The probe allows deeper penetration inside the hearth wall to enable extended measurement of the temperature profile, while maintaining the integrity and safety of the lining. The result is a further increase in the predictability of hearth wear monitoring.

4 HeLiMo (Hearth Liquid Model)

HeLiMo estimates the amount of molten hot metal and slag inside the hearth, based on continuous mass balances of produced and tapped liquid quantities. The necessary input values originate from blast furnace data and from the SHAFTRACK model included in BFXpert. SHAFTRACK is used in order to provide the hearth liquids model with batch information such as chemical composition in the lower parts of the blast furnace.

HeLiMo calculates the residual mass of hot metal and slag remaining in the hearth after tapping and its accumulation in time. Based on this information and the hot metal production rate, the model permits a prediction of the time remaining before closing the tap-hole and the time until the next tap.

The model manages all relevant tapping information enabling monitoring and thus providing uniform tapping conditions. Besides the cast information, it supervises and stores data concerning the tap-hole, the instrumentation and the injection mass.

Calculation of the heights of hot metal and slag in the hearth is realized by continuous mass-balancing of hearth liquids. This function is supported by a sophisticated system of on-line and off-line corrections to prevent any diverging between calculated and real values and to ensure at all time the accurate working of the model.

Additionally it takes into consideration the hearth voidage degree, the available space for hot metal and slag, by automatically calculating this important factor based on long-term casting information.

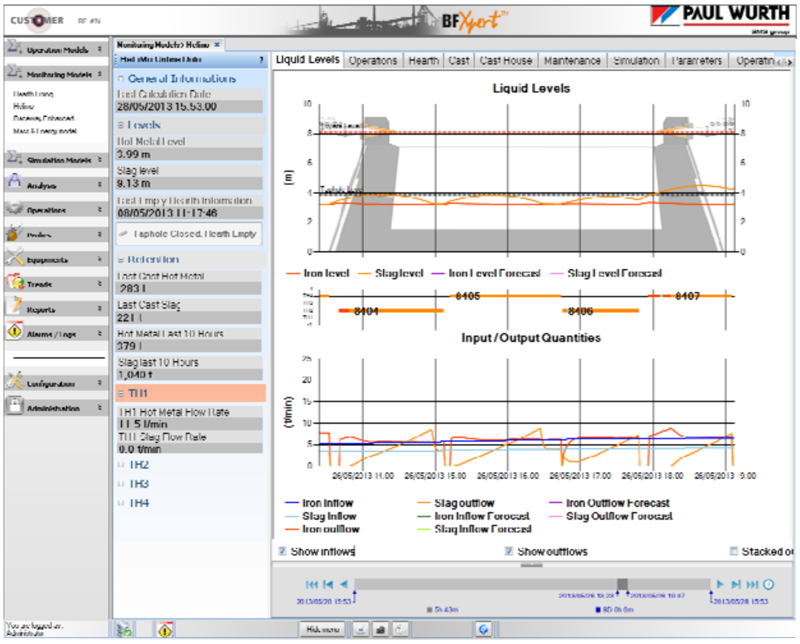

Figure 3: HeLiMo main screen.

A simulation environment is included that permits optimisation of the tapping practise. Based on a freely defined tapping sequence, a simulation is launched which features the same mathematical core as the operational part of HeLiMo. It permits to evaluate the effect of parameter changes such as production rate, tap hole order, tap durations, drill bit diameters, inter-tapping time or overlapping tapping

on the tapping sequence and the liquid levels in the hearth. The results are presented in every detail for a user defined time span, for example 24 hours.
Further included in HeLiMo is a module for cast house maintenance. The amounts of hot metal and slag are individually counted for all runners, skimmers and tap holes. It is combined with the functionality to input all maintenance works performed on the runners. In case runners are equipped with thermocouples, a representation of temperatures and remaining lining depth is also available. Additionally a database for all other cast house information concerning the tap-hole, the instrumentation and the injection mass is provided within HeLiMo. With the combination of all these functionalities HeLiMo provides an automated platform for the management of cast house information and maintenance.
The model is adapted to a wide range of possible cast house instrumentation and can even be used in absence of online measurements of hot metal and slag outflow.
Summarising the information from cast-house together with an insight view on the conditions inside the blast furnace hearth, HeLiMo provides a powerful tool to diagnose the tapping process and to evaluate corrective actions in case of unsatisfying hearth drainage conditions.
HeLiMo provides the following outputs and functionalities:

- Liquid levels:
  - The levels of hot metal and slag in the hearth are displayed as trend on the model's main screen and as figures in the model sidebar.
  - In order to prevent high liquid levels and irregular tapping practise to interfere with the blast furnace operation, targets can be set to generate alarms and warnings based on liquid levels.
- Graphical representation of recent tapping operation:
  Active tap hole, begin and end of tap, slag appearance and cast number can be reviewed at a glance.
- Input / output quantities:
  Input quantities are based on tracking charged material down to the hearth, whereas output quantities can result from an online measurement or a calculation of the model itself if for example no online measurement of hot metal outflow is available.
- Retention:
  Hot metal and slag retained in the hearth for the last cast and cumulated for a definable time span.
- Cast cycles:
  HeLiMo also features a display of the input and output quantities on a per-cast basis allowing the identification of inter-cast time and imbalances between produced and tapped amounts of hot metal and slag.
- Pressures:
  The model informs about pressure readings in bosh and bustle main as well as presenting a calculated pressure balance on the hearth coke.
- Hearth oxidation degree:
  From chemical analyses HeLiMo evaluates the oxidation degree of the hearth, giving valuable information about the amount of unreduced material entering the hearth.
- Heat losses:
  Hearth and bosh heat losses information is provided for further analysis of hearth conditions.

- Casts forecast:
  Up to 4 hours of forecast for the hot metal and slag inflows, outflows & levels.
- Slag appearance time prediction:
  Optimal opening and closing times prediction for the current and next tap.
- EMF:
  Existing EMF measuring equipment can be integrated into HeLiMo generating strong synergies between both methods of evaluating hearth liquid levels.
- Runner wear evaluation:
  Estimation of runners lining wear based on thermocouple measurements.
- Cast information:
  To review the past operation HeLiMo collects and displays the available information of recent casts, including remarks, dates, amounts, analyses and silicon / temperature relationship.
- Cast house:
  In addition to the cast information, HeLiMo also displays a summary of drilling machine, clay gun and clay information.
- Maintenance:
  - Total quantity of hot metal and slag per runner, skimmer and tap hole is traced.
  - Performed maintenance is saved in cast house management functionality of HeLiMo.
- Tapping simulation & optimisation:
  - Simulation environment for optimisation of tapping practise.
  - Freely defined sequences.
  - Evaluate result of changes such as higher production rate, tap hole order, tap durations, drill bit diameters, inter-tapping time or overlapping tapping on the tapping sequence and the liquid levels in the hearth.

5 SACHEM

SACHEM[3,4] is a knowledge based process control system, integrated within the BFXpert platform, that continuously assists the operator to operate the blast furnace according to a best practise philosophy.
SACHEM is made of multiple software processes and a database. The processes are specialized in data acquisition, verification, invalidation and self re-validation, model computation, signal analysis, recognition of phenomena, generation of alarms and warnings, action recommendation and elaboration of synthesized information. In order to guarantee the best results, SACHEM includes several rule-based on-line automatic invalidation functionalities that ensure data consistency.
The functionalities integrated in SACHEM related to hearth management are complimentary to the Hearth Lining Model and HeLiMO. Whereas the hearth lining model computes the wear profile generally once per day and is used to monitor hearth wear in the long term, SACHEM manages short-term phenomena by analysing data continuously and reacting on excessive levels or fast changes in hearth temperatures or heat fluxes. In case of abnormal deviations, SACHEM will generate alarms and warnings that allow the operator to take immediate action.
The forecast function for hot metal temperature and silicon content allows the operator to act based upon the future evolution of the furnace, which further contributes to ensure stable hearth operation and maintain overall process stability. The implemented thermal models that allow this forecast function take into account

the actual thermal state of the furnace and its future prediction. These models are self-adaptive to the current blast furnace behaviour with the target to minimise fuel consumption while maintaining the hot metal temperature stable.
Besides the above mentioned functionalities with direct relation to hearth phenomena, the supervision of the blast furnace by SACHEM ensures stable operation conditions, which highly contribute to reduce wear and load on the hearth and all equipment, thanks to lower process fluctuations and less stoppages.

Figure 4: SACHEM - Thermal balance and temperature forecast screen.

6 CONCLUSIONS

Constant and profitable use of level-2 process models and monitoring tools is a key factor to improve operators' performance during their daily tasks, and beneficially support their prompt and efficient decision-making process.
This also applies to the blast furnace hearth, a crucial area of the plant affecting the furnace campaign life, the productivity, and the quality of the tapped hot metal.
BFXpert, Paul Wurth's level-2 system for blast furnaces, is intended to successfully meet above expectations and beneficially support operators, as well as process engineers, to achieve and maintain higher performances of hearth management, thanks to the following embedded models:

- Hearth Lining Model, concerned with the monitoring of the hearth thermal status and long-term wear profile
- HeLiMo (Hearth Liquid Model), concerned with cast house operation, maintenance and precious support for better tapping practises
- SACHEM hearth functionalities, aimed at providing information about short-term phenomena and recommendations for possible immediate actions

The models have proven to be powerful tools supporting the operator in his pursuit of increased hearth performance and provide:

- Early detection of process phenomena or plant anomalies enabling preventive actions.

- Extended campaign life.
- Improved operational stability.

These advantages finally result in one major benefit, which is a tangible reduction of production costs.

REFERENCES

1 SIMOES, J-P.; TOCKERT, P.; BERMES, P.; ODICINO, G.; MORELLI, C.; HANSEN, F.; HAUSEMER, L. BFXpert™ - The Benefits of Paul Wurth's Integrated Blast Furnace Level 2 System. ABM 2010, 40th International Meeting on Ironmaking and 11th International Symposium on Iron Ore, Sept.19-22, 2010, Belo Horizonte, MG, Brazil, pp.667-679.

2 BISIO, G.; FONTANA, P.; BAROZZI, S.; MORELLI C. Alcune considerazioni sui fenomeni termofluidodinamici nel crogiolo dei moderni altoforni. 46° Congresso Nazionale Associazione Termotecnica Italiana, Gaeta, Italy, 1991.

3 THIRION, C.; ODICINO, G.; FONTANA, P. Improving BF operation through SACHEM® (Intelligent Supervision System) and process optimization models. ABM 3rd International Meeting on Ironmaking, São-Luís, Brazil, 2008.

4 HELLEISEN, M.; GIROLDINI, F.; CARMICHAEL, I.; THIRION, C. Optimized use of BLT® and PCI with intelligent supervisor assistance SACHEM®. 5th European coke and iron-making congress. Stockholm, June 12-15, 2005.