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THE IMPLEMENTATION OF AN ONLINE MATHEMATICAL MODEL OF BILLET REHEATING IN AN OFU FURNACE

IMPLEMENTACIJA SIMULACIJSKEGA MODELA ZA SPREMLJANJE OGREVANJA GREDIC V OFU-PEČI

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We present the implementation of an online mathematical model for billet reheating in the OFU walking-beam furnace at the Štore Steel d.o.o. steelworks in Slovenia. For the real-time operation of the simulation model the data about furnace charging and real-time measurements in the furnace are needed. The simulation model is connected to the existing information system of the OFU furnace, which can ensure the required data. The simulation is performed for all the billets (up to 125) that are currently charged in the furnace. The modeling of the reheating process in a gas-fired walking-beam furnace consists of descriptions of complex partial mechanisms. For the validation of the model, measurements of the billet reheating in the OFU furnace were made. These measurements involved a test billet and five trailing thermocouples. The comparison of the measurements and the simulation results, which are stored in a local database, shows good agreement across the whole temperature range of the reheating process. For a user-friendly presentation of the simulation-model results we developed a graphical user interface. This GUI allows the selection of particular billet from a visualization on the screen of the billets in the furnace. The temperature field and the history of reheating for individual positions of the billet in the furnace are shown for the selected billet. The system has been used online in the production process since May 2006.

Key words: simulation of reheating, billet reheating, real-time simulation, reheating furnace, walking-beam furnace

V prispevku je opisana implementacija simulacijskega modela za spremljanje ogrevanja gredic v OFU-peči v valjarni Štore-Steel, d. o. o. Simulacijski model za delovanje v realnem času potrebuje podatke o trenutnih meritvah temperatur con peči in podatke o založitvi peči, zato je povezan na obstoječ informacijski sistem OFU-peči. Simulacija se izvaja v realnem času za vse gredice, ki so založene v peči (do 125). Modeliranje ogrevnega procesa v plinsko ogrevani koračni peči je sestavljeno iz obravnave kompleksnih delnih mehanizmov. Vrednotenje simulacijskega modela je bilo izvedeno z meritvami ogrevanja gredice v OFU peči. Meritve ogrevanja so bile izvedene med proizvodnim procesom na preizkusni gredici s petimi vlečnimi termoelementi hkrati. Primerjava izračuna in meritev kaže dobro ujemanje v celotnem poteku ogrevanja. Rezultati simulacije se shranjujejo v lokalno bazo podatkov. Za uporabniško prijazen prikaz rezultatov simulacije je bil razvit grafični uporabniški vmesnik. Ta omogoča izbiro poljubne gredice med prikazanimi gredicami, ki so založene v peči. Za izbrano gredico se prikaže trenutno temperaturno polje in celotna zgodovina ogrevanja po posameznih položajih v peči. Sistem se v rednem proizvodnem procesu uporablja od maja 2006.

Ključne besede: simulacija ogrevanja, ogrevanje gredic, simulacija v realnem času, ogrevna peč, koračna peč

1 INTRODUCTION

A computer-controlled hot-rolling process for steel billets requires high-quality reheated billets in terms of time, temperature, thermal profile and furnace atmosphere. When the furnace operates in steady-state conditions the reheating history of every billet is very similar; this type of operation can normally not be achieved. During the normal, non-steady-state, production process various transient operating conditions occur in the furnace : planned and unplanned stoppages in the mill's operation, changing steel grades with varying drop-out temperatures and different thermodynamic properties, changing the stock dimensions, etc. During this kind of transient operation every billet is reheated under different reheating conditions. Therefore, the reheating history of almost every billet is different. For transient-type furnace operation information about the temperature field for all (up to 125) billets in the furnace is very important for successful furnace control and operation. Unfortunately, however, existing measuring methods cannot provide the temperature fields of billets in the furnace. Nevertheless, by using trailing thermocouples it is possible to measure the reheating at a few measuring points inside the test billet. By contrast, measurements using optical pyrometers or thermal cameras in the furnace only give information about the surface temperature of the billets. The use of an online simulation model is the most appropriate way to acquire the real-time temperature fields of billets in the furnace.

In the Štore Steel, d. o. o. steelworks a continuous walking-beam furnace (**Figure 1**) is used for the reheating of steel billets. The furnace has three control zones. The material flow through the furnace is discontinuous, with fixed walking-beam steps. The furnace has 125 billet positions; however, it is possible to charge only every second or every third walking-beam

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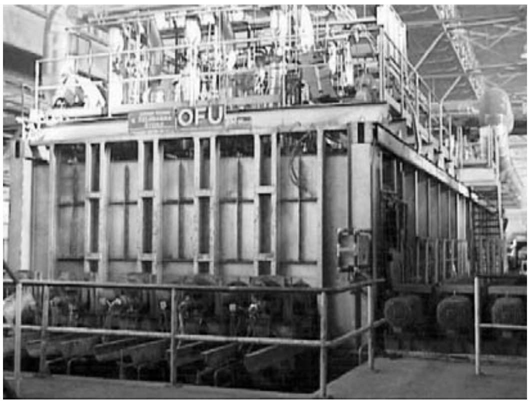

b


Figure 1: a) OFU walking-beam furnace, b) billets in the furnace
Slika 1: a) OFU-koračna peč za ogrevanje gredic, b) gredice v peči

step in order to shorten the residing time of the billets in the furnace.

In recent years, simulation models of reheating furnaces that calculate the actual temperature distribution in the stock have been developed with increasing computational power. The current state of the art are one- or two-dimensional calculations of the stock temperature [1,2,3,4]. However, the first attempts were made to calculate the stock temperature in three dimensions [5,6,7] for different types of reheating furnaces, but not in real-time. A 3D online simulation model of reheating in a walking-beam furnace is presented in [8]. The implementation of an online simulation model in a pusher-type furnace is presented in [9].

In this paper we present the implementation of the 3D online simulation model of the OFU walking-beam furnace.

2 EXPERIMENTAL WORK

The implementation of the simulation model for the online operation of the furnace includes the development of modules to provide real-time measuring data from the furnace, to provide and recognize the current furnace charge, to provide the thermal properties of different steel grades, to store the simulation results in a database, and to present the simulation results in a user-friendly form.

2.1 Mathematical model

The online mathematical model used in the implementation is presented in detail in [8,10]. The determination of the temperature fields of the billets is based on algorithms that include the main physical phenomena associated with the reheating process in a natural-gas-fired walking-beam furnace. Thermal radiation represents the dominant contribution of heat transfer in a high-temperature reheating furnace. The heat exchange between the furnace gas, the furnace wall and the billet surface is calculated using the three-temperature model of Heiligenstaedt.[11] Heat radiation between the surfaces inside the furnace (the furnace-wall surfaces and the billet surfaces) is described using a view-factor matrix. This matrix is obtained before the simulation using the Monte Carlo method. The heat conduction in the billets is calculated using a 3D finite-difference method. The algorithms in the model are optimized to allow a real-time simulation.

2.2 Obtaining the real-time data

For the online operation of the simulation model the real-time data of furnace charging and furnace measurements are needed. The simulation model is connected to the existing furnace-process computer of the OFU furnace (**Figure 2**), which provides the real-time data about furnace-charging measurements in the furnace. Both computers are connected by an Ethernet connection. The data transfer is performed with ASCII files using file-transfer protocol (FTP).

A data file "OFU.DAT" is generated every 30 s by the OFU furnace-process computer. It contains both online measurement data and charging data. The measurement data include:

- Date and time of the measurements
- Temperature measurements of the three control zones
- The gas/air flows of individual control zones
- Oxygen measurements
- Pressure measurements
- Measurements of the recuperator temperatures.

The charging data are written in table form and include information about current positions and other important information about the billets in the furnace. The data for an individual billet in the table consist of:

- Billet position
- Working order
- Serial number of the billet in the working order
- Steel grade
- Billet dimensions
- Date and time of charging

The "OFU.DAT" file is transferred from the furnace-process computer to a computer with the simulation model at regular intervals (i.e., every 20 s) by the process "ftp-transfer", which runs on the computer with the simulation model. After the transfer the file is

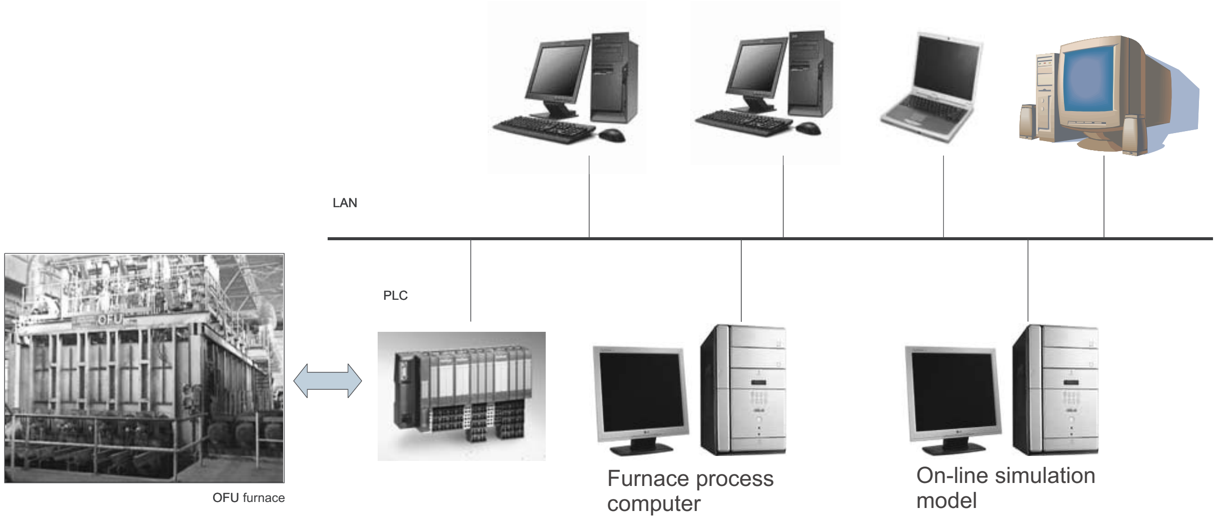

Figure 2: The connection of the simulation model to the OFU furnace-process computer
Slika 2: Povezava simulacijskega modela s procesnim računalnikom OFU peči

deleted on the main process computer. The intervals for transferring the data file have to be shorter than the intervals for writing the data to the file to prevent data loss.

2.3 Thermal properties data

The thermal properties (the specific heat and the heat conduction) of steel billets have a significant influence on the reheating process. Generally speaking, these properties are temperature dependent. In the model the tables are written in ASCII files. In the production process different steel grades with different thermal properties are reheated in the furnace; however, some of them have similar thermal properties. Therefore, all types of steel grades are classified into main groups, and for these groups the thermal properties were measured or obtained from the literature. The automatic classification is based on a uniform classification table, where the corresponding steel group is written for each steel grade in the table. When the billet is added to the charging list the corresponding steel group is recognized on the basis of the steel billet's grade. The system then reads from the files the temperature-dependant specific heat and the heat-conduction tables for the recognized steel group. These data are used for the calculation of the thermal conduction inside the billet.

2.4 Automatic recognition of the charging events

The system is capable of automatic recognition of the charging events and the charging interventions of the furnace operator on the basis of a comparison between the billet-charging table and the charging file. At the end of the event-recognition process the charging table and charging file have to be harmonized. The recognition of charging events is a three-stage process.

In the first stage every billet in the charging table is tested to see if it is present in the charging file. The billets that are absent are deleted from the charging table; their reheating history is saved in the archive directory.

In the second stage every billet in the charging file is tested to see if it is on the charging list. The billets that are absent are added to the charging list and a new file with billet data is opened and filled with the initial data.

After the first and second stages we can be sure that the same billets are included in the charging list and in the charging file. In the third stage the billets in the charging list are sorted into the same order as in the charging file. The position of every billet in the charging list is compared to that in the charging file. If the position is different, then the position in the list is changed and the current calculated temperature field and the position data are written in the reheating file of that billet. The same algorithm is used for single and for double charging and also for transitional operations: single-to-double and double-to-single charging.

2.5 Database structure

All the results of the simulation model are stored in a local database named "**ofu**" (**Figure 3**). The system uses the open-source database system MySQL. The database can be accessed locally by the online simulation model and the human-machine interface (HMI) or through an Ethernet connection by PC workstations in the local area network (LAN).

The database consists of data tables. At every simulation step (30 seconds) the simulation model creates the data table "ofu_online" (**Figure 3**). The records in the table correspond to the billets in the furnace. Each record in the table includes basic billet data (Working order, Serial number in the working

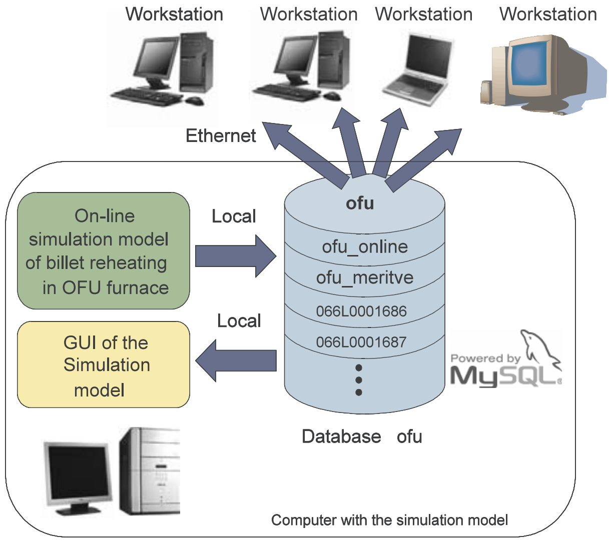

Figure 3: Database structure and availability
Slika 3: Struktura in dostopnost baze podatkov

order, Steel grade, Billet width, Billet height, Billet length, Charging time, Real-time of last calculation, Number of the walking-beam step, Position in the furnace, Residing time at the position, Residing time in furnace) and the characteristic points of the last-calculated temperature field of the billet (**Figure 4**).

In cases when the charging situation in the furnace is changed (new billet charged, billet discharged, walking-beam step) the simulation model writes changes into the "Working order tables" (the names of the tables are working-order names, i.e., "066L0001686"). For those billets for which the position is changed the model writes the record of the last calculated temperature field into the table with the name that corresponds to the billet working order. The record has the same fields as the record for the table "ofu_online". Therefore, the "Working order tables" include the position-dependent history of reheating in the furnace for all the billets of the working order.

When new measurements from the furnace are available (every 30 seconds) the simulation model adds

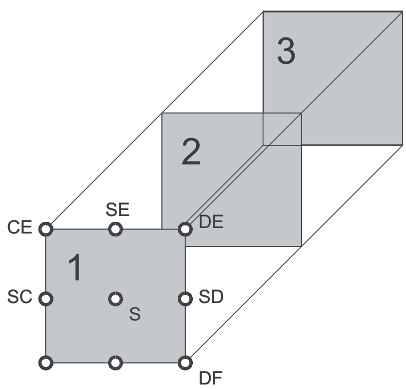

Figure 4: Characteristic points on the billet cross-sections
Slika 4: Karakteristične točke na prerezih gredice

the record with the measurement data to the data table "ofu_meritve" (**Figure 3**). The record consists of the following: Time of measurement, Temperature zone 1, Temperature zone 2, Temperature zone 3, Fuel-consumption zone 1, Air-consumption zone 1, Fuel-consumption zone 2, Air-consumption zone 2, Fuel-consumption zone 3, Air-consumption zone 3, Furnace pressure, Oxygen probe 1, Oxygen probe 2, Oxygen probe 3, Combustion-air temperature, Waste-gas temperature before recuperator, Waste-gas temperature after recuperator.

2.6 Human-machine interface

The human-machine interface (HMI) (**Figure 5**) was developed for the user-friendly presentation of the real-time results of the simulation model. The HMI process runs parallel to the simulation model. The HMI gets all the data from the "ofu" database. There are two modes of HMI operation: real-time and archive.

When the HMI runs in real-time mode the top view of the furnace containing charged billets is shown in the upper part of the window (**Figure 5**). The billet is selected with a mouse click. In the lower part of the window are detailed data about the selected billet: Working order, serial number, steel grade, dimensions, etc. The calculated temperatures of the characteristic points on the cross-section are presented numerically and using a thermal scale. Different diagram presentations, such as the reheating temperatures of three selected points in the billet, the temperatures of individual furnace-control zones, the gas consumption of individual control zones, the oxygen content, the pressure in the furnace, the holding time of a billet at a particular position in the furnace (**Figure 6**), can be selected. The archive mode allows a preview of the reheating process

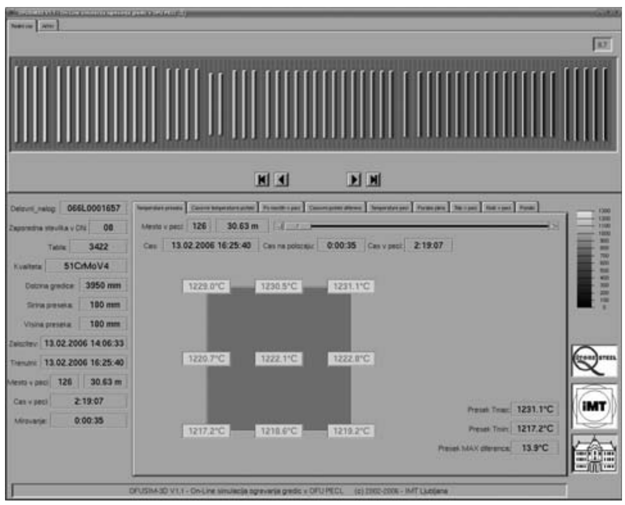

Figure 5: The human-machine interface of the simulation model – calculated temperatures of characteristic points of the cross-section
Slika 5: Grafični uporabniški vmesnik simulacijskega modela – izračunane temperature karakterističnih točk prereza

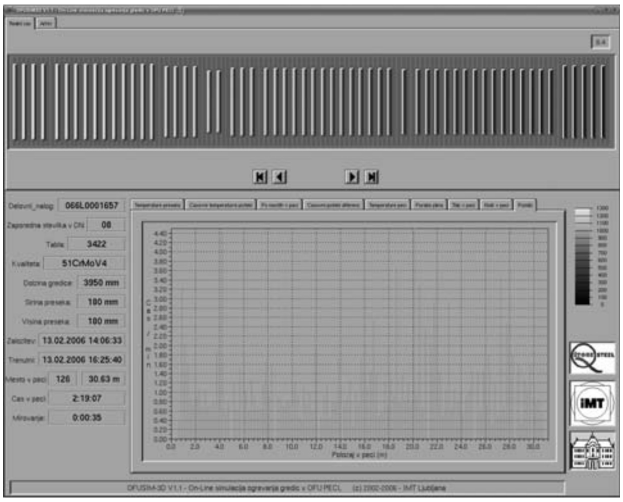

Figure 6: The human-machine interface of the simulation model – diagram of the residing time of the billet at a particular position in the furnace
Slika 6: Grafični uporabniški vmesnik simulacijskega modela – diagram časa zadrževanja gredice na posameznem mestu v peči

of already-reheated billets. Billets in the archive list are sorted by discharge time. The HMI is developed using the XFORMS graphical library.

3 RESULTS AND DISCUSSION

The model was validated on the basis of measurements from the OFU walking-beam furnace at the Štore Steel steelworks in Slovenia. The test billet (CK45 steel grade, dimensions 140 mm x 140 mm x 3500 mm) was reheated during the normal production process. The temperature measurements were performed using five trailing thermocouples (Type K, ϕ = 4.5 mm, L = 35 m). These five thermocouples were mounted inside a test billet, as shown in **Figure 7**. Thermocouple TC1 was mounted 10 mm under the upper slab surface; TC2 was mounted 10 mm from the left billet surface, 70 mm deep; TC2 was mounted 10 mm from the right billet surface, 70 mm deep; TC4 was mounted 10 mm from the bottom billet surface, 130 mm deep; and TC5 was mounted in the centre of the billet.

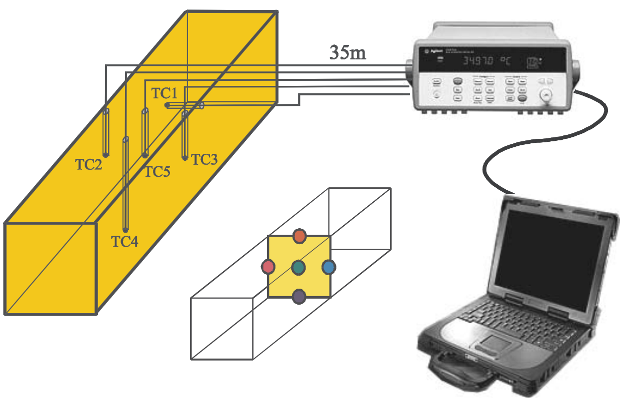

Figure 7: Measuring points in the test billet
Slika 7: Merilne točke na preizkusni gredici

The simulation model was compared with the measurements at all five measuring points, TC1, TC2, TC3, TC4 and TC5. The model was tuned by adjusting the temperature profile of the furnace's ceiling and sidewalls. After tuning the model, all the parameters of the model were observed to be real physical values. Good agreement was obtained between the measured and the calculated temperatures at all five comparison points for the whole reheating process (**Figures 8 and 9**). The graph was divided into two graphs–the first for the time interval 0–60 min (**Figure 8**) and the second for the time interval 60–120 min (**Figure 9**) – in order to distinguish between the measured and the calculated values. The small vertical lines at the bottom of the graphs show the walking-beam step intervals of the furnace.

The validation phase shows that the developed algorithms of the simulation model for billet reheating in

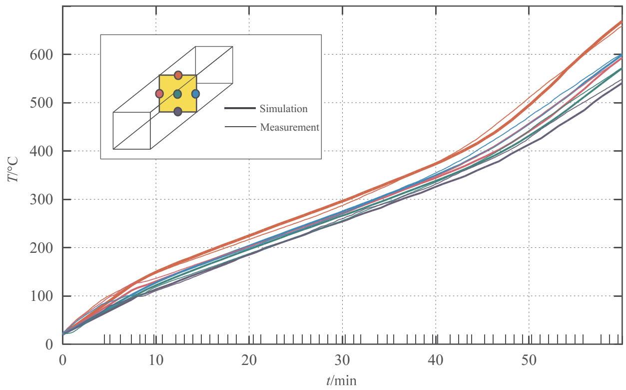

Figure 8: Validation of the simulation model for the test billet (material: CK45, 140 mm x 140 mm x 3500 mm) for the time interval 0–60 min
Slika 8: Vrednotenje simulacijskega modela na preskusni gredici (material: CK45, 140 mm x 140 mm x 3500 mm) v časovnem intervalu 0–60 min

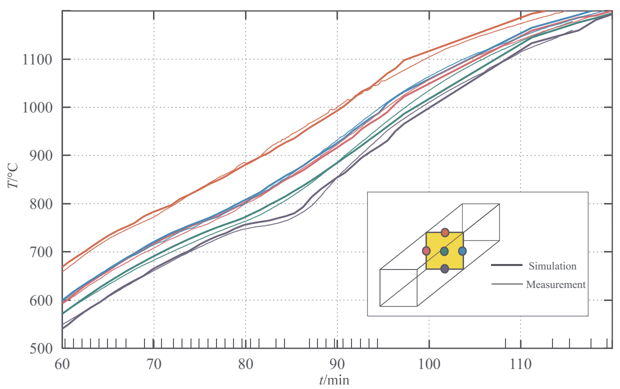

Figure 9: Validation of the simulation model for the test billet (material: CK45, 140 mm x 140 mm x 3500 mm) for the time interval 60–120 min
Slika 9: Vrednotenje simulacijskega modela na preskusni gredici (material: CK45, 140 mm x 140 mm x 3500 mm) v časovnem intervalu 60–120 min

the OFU furnace are in good agreement with the real physical behavior of the reheating process.

The system was developed using only open-source solutions, and the Linux platform ensures stable running of the system. The system has been used online in the regular production process at the Štore Steel, d. o. o. steelworks in Slovenia since May 2006.

4 CONCLUSIONS

The implemented system allows online monitoring of non-measurable values (the 3D temperature fields of billets in the furnace). The system is connected to the furnace-process computer to ensure real-time measuring and charging data from the furnace.

The simulation model's results are stored in an SQL database, which allows internet access to the data. Good agreement between the measured and the calculated heating curves shows that the model includes the main physical phenomena occurring during the reheating process in the OFU walking-Beam furnace. The developed HMI allows a user-friendly presentation of the simulation model's results. The system has been used online in the regular production process at the Štore Steel, d. o. o., steelworks in Slovenia since May 2006.

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