Sensors for crystallisation control in vacuum pans - a review of Fives Fletcher experience over the past 25 years

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**abstract**

Boiling massuscule in a vacuum pan requires simultaneous regulation of its dissolved solids concentration, crystal content, consistency and supersaturation. A key challenge in pan boiling is measuring the necessary massuscule properties for controlling these parameters. Fives Fletcher has been supplying electronic sensors for vacuum pan crystallisation control for more than 25 years and has been at the forefront of the considerable developments that has taken place in the technology during this time. The paper reviews the developmental history of online sensors with specific emphasis on conductivity, radio frequency and microwave technology. Information on practical aspects of the use and application of these so-called 'brix' probes is presented. An evaluation of the current developments is also given and includes some recommendations for controlling both batch and continuous vacuum pans.

*Keywords:* crystallisation, microwave sensors, probes, radio frequency, sugar

**Sensores para el control de la cristalización en los tachos de vacío - una reseña de la experiencia en Fives Fletcher en los últimos 25 años.**

Hervir la masa cocida en un tacho de vacío requiere una regulación simultánea de la concentración de sólidos disueltos, del contenido de cristales, de la consistencia y de la sobresaturación. Un desafío fundamental para la ebullición en los tachos es poder medir las propiedades de la masa cocida necesarias para el control de dichos parámetros. Fives Fletcher ha provisto sensores electrónicos para el control de la cristalización en tachos de vacío por más de 25 años manteniéndose a la vanguardia de los considerables desarrollos que se han logrado en la tecnología durante este período. Este trabajo reseña la historia del desarrollo de los sensores en línea con especial énfasis en la tecnología electrónica, de radiofrecuencia y de microondas. Se presenta información en los aspectos prácticos del uso y la aplicación de las llamadas sondas "brix". También se presenta una evaluación de los avances actuales y se incluyen algunas recomendaciones para controlar tanto los tachos por tandas como los continuos.

**Sensores para control de cristalización en concentradores a vacío - una evaluación de la experiencia de Fives Fletcher al largo de los últimos 25 años.**

A ebullición de la masa cocida en un concentrador a vacío exige regulación simultánea de la concentración de sólidos disueltos, del contenido de cristal, a su coherencia y a su supersaturación. Un dos principales desafíos de la ebullición en concentradores es la medición de las propiedades de la masa cocida necesarias para el control de dichos parámetros. A Fives Fletcher fornece sensores electrónicos para control de la cristalización en concentradores a vacío há más de 25 años e tem estado na vanguardia da considerável evolución que ocorreu nessa tecnologia durante este tempo. O artigo revê a história do desenvolvimento de sensores de forma onda especial ênfase na tecnologia de condutividade, radiofrequência e microondas. Informações sobre os aspectos prácticos da utilização e aplicação de sondas chamadas "brix" são apresentadas. Uma avaliação dos desenvolvimentos atuais também é apresentada, e ela inclui algumas recomendações para o controle de concentradores a vácuo em lote e contínuo.

**Introduction**

A common aim of any sugar factory, be it cane, beet or refinery, is to maximise the efficiency of crystallisation at the vacuum pan boiling stage. This entails maximising purity drops and at the same time producing sugar of the desired quality in terms of pol, colour, crystal size and regularity. To achieve efficient boiling in a vacuum pan requires simultaneous regulation of the massuscule dissolved solids concentration, crystal content, consistency and supersaturation.

Obtaining a reliable measure of the necessary massuscule properties for controlling these parameters has been one of the key challenges for pan boiling (Rein, 2007). To this end, a variety of different types of transducers have been used for pan boiling control. They include online refractometers; nuclear density meters as well as devices measuring boiling point elevation and massuscule viscosity. However, the most successful and popular transducers are those which measure the electrical properties of a massuscule. These consist of conductivity, radio frequency and microwave devices.

The availability of reliable transducers such as these has, as Hugot (1986) reports, provided a "scientific" basis for control of the sugar-boiling process to replace previous reliance on the "mysterious art" of the pan boilers. This has produced substantial
improvements in sugar recovery and crystallisation efficiency through improved sugar quality (particularly in uniformity of crystal size) and in effective capacity of vacuum pans and centrifugals. Hugot (1988) concludes that modern standards of performance would indeed be impossible without such instruments.

Conductivity transducers

The practical application of conductivity measurement for pan boiling control was pioneered in Java, in the 1920’s and 30’s, by Honig and Alewijn (Hugot, 1986 and van der Poel et al., 1998).

Conductivity is the ability of a solution to pass an electric current. The amount of current flowing is roughly proportional to the number and mobility of the ions present in the solution. Since viscosity has a retarding effect on the mobility of ions in solution the conductivity of a massecuite is dependant on both mother liquor concentration and massecuite consistency, such as that resulting from increasing crystal content (Rein, 2007).

Conductivity can be measured reliably by relatively simple instruments and as a result has been widely used for controlling vacuum pans boiling ‘B’ and ‘C’ massecuites where the ash content is sufficiently high and comparatively consistent. The lower ash content in higher purity products (e.g. ‘A’ and white sugar massecuites) means there is a greater effect of ionic content variations on the absolute reading of conductivity and this makes it unsuitable as a control signal for these products.

Another drawback of conductivity transducers is that they require a high level of management and maintenance, for the following reasons;

- They require frequent recalibration in order to maintain reliable repeatable results. This results from unpredictable changes in the juice non-sugar composition consequently affecting the conductivity of the massecuites.

- The electrodes require frequent cleaning because they are susceptible to scaling and also suffer from erosion of the metal due to the electrolytic action. The reason that conductivity probes are especially sensitive to scale or encrustation build up is because at the low measuring frequency (1 to 2 kHz) of the signal even a thin layer deposited on the electrodes is sufficient to produce a significant effect on the results.

Radio frequency transducers

Radio frequency (RF) probes are transducers which measure the electrical properties of sugar solutions at higher frequencies, ranging from 10 to 45 MHz. This higher signal frequency means that, compared with traditional conductivity sensors, these probes are effectively not susceptible to scaling and can tolerate some level of encrustation without their readings being affected. They can also operate with high purity massecuites.

It was the need for repeatable, reliable measurements for controlling continuous vacuum pans (CVPs), especially those being used for boiling high purity massecuites, which was the main impetus that led to the successful commercial development of radio frequency probes for use in sugar processing. Monotrac and Duotrac probes are the two highly successful RF transducer products, marketed by Fives Fletcher, which were developed specifically for this application. They have also proven to be equally successful for use in batch vacuum pans and other brix control applications in a sugar factory.

Monotrac radio frequency probes

The Monotrac RF probes were specifically developed to provide a cost effective alternative to conductivity probes for continuous vacuum pan control. The Monotrac probe produces a radio frequency signal of approximately 10 MHz which is passed through the massecuite, using the probe tip as an antenna. The probe produces a signal proportional to both the series resistance and series capacitance, with the values of capacitance and resistance being ranged to represent the dielectric loss due to the impurities of the massecuite. As crystal growth progresses and mother liquor brix increases during a pan boiling cycle, the mean free path of the loss resistance decreases resulting in a reduction in RF losses. The output of the Monotrac transducer is proportional to dielectric losses and therefore to both the brix and crystal content of the massecuite.

The Monotrac system uses a simple analogue method of measurement and does not require the complication of a microprocessor. This gives the probe a significant advantage in terms of manufacturing cost and also increases its reliability and makes it much simpler to operate and calibrate.

In order to incorporate design improvements several version of the probe have been produced over the years, with the latest being the Monotrac Mk III probe. The device consists of a transducer, a probe and an interconnecting cable; it is a two-wire device that draws its power from the 4 to 20 mA instrumentation loop. The probe is usually supplied with a handheld calibrator that enables the user to calibrate the probe for the required duty (see Figure 1).

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**Figure 1.** Fives Fletcher Monotrac RF probe
There are four options that can be chosen for the physical configuration of the actual Monotrac probe. There are short and long versions of the probes and either of these can be supplied with quick release or screwed fittings. The quick release version is mainly intended for use in continuous vacuum pans, as it allows for easy removal of the probe for cleaning to remove any encrustation build-up. For batch pans, where pan steaming keeps the probe free of encrustation build-up, a 2” BSP screwed fitting version is available. The short version of the probe is designed to enable it to be installed underneath the calandria of a batch vacuum pan whereas; the longer version is designed to reach into the middle of a CVP downtake for measuring in the optimum location.

The Monotrac has proven to be accurate, repeatable and reliable in operation with some installations having used the same probes for nearly 20 years. Fives Fletcher has now sold more than 2,500 Monotrac probes and they still represent one of the best choice and cost effective options for vacuum pan control, particularly for multi-compartment continuous vacuum pans. However, the Monotrac probe cannot be used for refinery white sugar massecuites. This is because the probe measurement requires a certain level of impurities in the massecuites and so they can only be reliably used on massecuites having less than ±94 purity.

**Duotrac radio frequency probes**

The Duotrac probe was developed by Tongaat Hulett with the prime intention of devising a transducer that would give a “better method of measuring massecuites conditions” in continuous vacuum pans boiling high purity A-massecuites (Radford and Cox, 1986). The probe does of course also have applications for general brix control and in batch pan boilings of all purities. It was, however, in white sugar boilings that this probe found its niche market. The development history and the technology of the probes utilisation for refined sugar massecuites vacuum pan control have been well documented in two Sugar Industry Technologists papers (Radford et al., 1987 and 1988).

The Duotrac probe (see Figure 2) is able to compare changes in the massecuites impedance to a tuned circuit at radio frequencies (27 MHz) and produce two 4-20 mA outputs; one related to the series resistance of the massecuites and another related to the series capacitance of the massecuites. These two signals can be closely correlated with massecuites and mother liquor brix as well as with the crystal content of a massecuites. This means the probe can be used to control all aspects of vacuum pan control and as a consequence has been a highly successful product with over 1,000 units sold worldwide. The successful introduction of microwave probes for pan boiling and brix control has meant that these devices have now largely replaced the Duotrac unit in the market place.

**Microwave transducers**

In 2000 Fives Fletcher formed a partnership with Hydronix Ltd. to develop and promote a new probe using a promising new kind of measurement based on microwave technology. Hydronix has been in business since 1988 and is the world leader in using microwave measurements for assessing the moisture content of concrete during its production. They were considered to have promising potential for use in sugar manufacturing since their sensors were tough enough to survive the operational requirement of being used in concrete mixers in the construction industry and had a proven ability to provide accurate measurements. They have been shown to be accurate for moisture measurement in both wet and dry concretes to within ±0.1%.

Following successful laboratory and factory trials this new probe, the Hydronix HT01, was launched for sale in 2001 and following several design improvements a second version, the Hydronix HT02 model, was released in September 2008. Over 600 units of the original HT01 probe have been sold worldwide and currently over 185 units of the HT02 model have been sold.

**Measurement principles**

The microwave measurement technique relies on the interaction of microwaves on the water molecules with changing (high frequency) electromagnetic fields (Laffan, 1998). Considering the properties of the water molecule with its two positively charged hydrogen atoms positioned on one side and the negatively charged oxygen on the other, as shown in Figure 3, it can be seen that the molecule is electrically a dipole. One of the properties of water is that only a few molecules are ionized, about one in 550 million water molecules are dissociated and so effectively all the water molecules can be considered dipoles. To begin the explanation of how microwave measurement works the effect of electrical currents on a water solution needs to be considered (see Figure 4). A water solution, such as a massecuites that is being boiled in a vacuum pan, will contain both ionised and non-ionised dissolved materials. Under normal conditions, all these molecules and ions will be randomly orientated as shown in Figure 4A. The non-ionised material, like sugars and the majority of the organic non-sugar impurities are
Figure 3. Water molecule dipole arrangement

not affected by the electric field. If this material is subjected to a DC electrical current, the charge sensitive molecules, like water (bi-polar) and ions, will be attracted by the opposite charges and so line up as shown in Figure 4B. The cations will be drawn towards the cathode and the anions towards the anode. The water molecule, being bi-polar, will be aligned in the relevant direction. If the solution is then subjected to a low frequency oscillating AC current, the ionic material will oscillate backwards and forwards following the change in polarity, while the water molecules will turn around by 180°, as they are subjected to each pulse as shown in Figure 4C.

If the frequency of the AC current is increased the rate of pulsing will increase and if this is extended into the microwave range, a point will be reached where the water molecules have difficulty in maintaining just turning over action and start to spin. These highly energised water molecules in the process of spinning then collide with neighbouring material generating heat and absorbing energy, as occurs in a microwave oven for example. However, the inertia and friction caused by the ionic materials hinders rapid linear motion and as the ionic content of material increases the electrical effect on the mechanical motion, i.e. energy absorbed, becomes less. Therefore the quantity of energy absorbed will mainly be a function of the amount of water present in the solution and therefore, measuring this at a suitably high frequency provides a technique for measuring moisture content of a solution.

The Hydronix single head sensor technology

Unlike most other techniques for microwave measurement, where separate transmitters and receivers are used, the Hydronix sensors are single head devices. Conventional attenuation techniques for microwave measurement, i.e. those that depend on separate transmitters and receivers, require the transmittal of a narrow beam of high frequency (1-10 GHz) through the material and then detecting the attenuation (or energy absorbed) in the receiver. In contrast the single head sensor, developed by Hydronix, radiates a lower frequency electromagnetic field into the material (800 MHz) from an antennae placed beneath a ceramic plate (see Figure 5).

This lower operating frequency of the Hydronix sensors means the signal has a greater penetration depth into the material from the antennae or resonator. The benefit of sensors using these techniques is that there is greater flexibility in how they may be used. For example they are not dependent on having to maintain a fixed distance between the antennae and so can be located at the end of a long probe, penetrating deep into a vessel, therefore locating the sensor at the optimum position for representative measurements of the material. It is also now possible with this one design of sensor to measure the brix of the material in pans, evaporators, melters, mangle, bins, mixers, no matter what the purity of the product.

In order to obtain maximum sensitivity of measurement the Hydrotrac probe is also designed to operate at resonant frequency, such that a standing wave is established (in the antennae) which requires the minimum input of energy – as with pushing a swing.
you only need to give it a little push at the right time to keep it swinging. This technique is known as "resonating cavity" in which the material forms part of the cavity (Laffan 1998). With increasing moisture, two factors change; firstly, the resonating frequency decreases, as illustrated in Figure 6, from a frequency value of 11 to 12. The second change is a reduction in the amplitude of the wave (in Figure 6 this is from a1 to a2). The sensor uses digital techniques to measure a combination of these two effects. The signal is then "linearised" and following some signal conditioning and calibration correlation a meaningful moisture (or brix) reading is obtained. The signal is then "linearised", and together with signal conditioning and calibration facilities, turns the measurement into a meaningful moisture (or brix) reading (Laffan, 1998).

The Hydrotrac microwave probe

As noted earlier the current version of the Hydrotrac probe is the HT02 model (see Figure 7). Improvements in the new model include a higher temperature specification rating for the electronic components and a new ceramic plate sealing arrangement. To provide installation flexibility and compatibility the Hydrotrac probe has been designed with body dimensions that allow it to fit into the same housing as those of the Duostrac and Monotrac probes.

The new ceramic plate sealing arrangement is illustrated in Figure 8 and employs a mechanical seal using two "O" rings to replace the former method, which used a glue sealant that had the disadvantage of gradually deteriorating over time.

The Hydrotrac probe offers a high degree of flexibility for the output signals. It has two 4-20 mA (or 0-20 mA) outputs and, since there is a temperature sensor in the probe tip, each of these outputs can be configured to give a choice of brix, moisture or temperature values as output signals. The probe also has an RS485 serial data connection to allow communication between the probe and a laptop, PC or PLC control system as required with three connection options. These are illustrated in Figure 9 and comprise an RS485/RS232 interface (which is supplied as standard with the probe), a RS485 to USB interface and a RS485 to Ethernet connection.

The Hydrotrac probe is provided with a software package, called HydroCom, which includes user-friendly interface facilities for selecting and using probe set-up parameters, diagnostic services and for calibration. The probes are supplied pre-calibrated so that they all operate the same when they leave the factory. This calibration comprises adjusting the resonant frequency output (called unscaled units) so that it is 0 in air and 100 in pure water. The relationship between unscaled units and brix has been established through comprehensive laboratory and factory testing on a broad range of high, low and intermediate purity products. This testing established that the relationship between the unscaled unit
reading and brix follows a curve having an exponential relationship with A, B, C and D calibration parameters. The probes are supplied with calibration parameters to match the standard curve established through this testing.

**Site calibration.** Since every material has different electrical properties some on-site calibration is required in order to get perfectly precise readings. The HydroCom software provides facilities enabling quick and easy calibration adjustments.

**Figure 10. HydroCom calibration page**

These not only include provisions for entering laboratory results and producing new coefficients (see Figure 10) they also comprises trending and data logging facilities.

**Practical application notes**

**Installation of probes**

All Fives Fletcher probes have been specifically designed to enable the sensing part of the instrument to be located in the vacuum pan at a point where there is good circulation, in order to ensure the probe is measuring a representative sample of the product in the vacuum pan. This is a particular advantage when compared to those designs of probe which have measuring sensors located close to the vacuum pan side-wall. In this case friction losses or encrustation build-up in the layer of masseselective adjacent to the pan wall can cause stagnant areas and pockets of poor circulation which can translate into an unreliable or unrepresentative signal of the product brix.

When installing a probe consideration should also be given to where other components of the vacuum pan such as the feed system, jigger steam lines, pan discharge valves and other instruments, all of these can cause local eddy currents or vapour bubbles which can cause disturbances or interferences with the probe signal.

Generally for batch vacuum pans the probes are installed in the pan saucer at about a half radius in from the outside edge. For continuous vacuum pans the probes are generally installed two thirds along the length of each compartment so as to measure the brix leaving the compartment and just below the horizontal plane where the downtake is at its narrowest and the maximum circulation point.

The Monotrac and Duotrac probes come in two different insertion lengths, 229 mm and 349 mm. Although there is only one insertion length, of 355 mm, for Hydrotrac probes an additional sleeve arrangement has been used by clients on occasion, when it was found necessary to have a shorter insertion length. Typical probe installation positions for batch and continuous vacuum pans are illustrated in Figure 11.

**Practical aspects on calibration of probes**

The practical aspects of collecting representative samples of the product that correspond to the readings taken at the probe sensing position present one the biggest challenges for correct calibration of the probe signals. This can be particularly fraught with problems, especially with batch vacuum pans where generally only a proof stick is available for getting samples from the pan.

**Monotrac probe calibration.** Monotrac probes are
not calibrated to give a brix output, instead the signal represents a “massecuite consistency” value ranging from 0 to 100. Each set of probes is supplied with a calibrator which can be used to check 0 and 100 output values, which is the only calibration required for these probes. This is quick and easy to do and is one aspect which makes the application of these probes so effective and simple. For continuous vacuum pans there needs to be regular “brix curve” checks carried out, in order to ensure that the probes in each compartment are controlling to the optimum brix values.

**Hydrotrac probe calibration.** As noted earlier the differences in “electrical” properties of the products being processed means the preset calibration factors will need to be adjusted on-site to give precise brix output values. For batch vacuum pan calibrations, although obviously the more samples that can be collected the better, it has been found in practice that taking 4-5 samples evenly spread out across the brix range of the pan cycle is sufficient for the HydroCom software package to calculate an accurate best fit curve and establish the new coefficients (A, B, C & D) for the probe. These new coefficients should be written to the probe and a further set of samples taken to establish if there is a close correlation between the laboratory brix and the probe brix. If all the samples are within ±1.0 degree brix of the laboratory we can consider that the probe is calibrated. Trying to calibrate the probe closer than this will be difficult due to sampling and analytical errors. Generally the probe can be successfully calibrated within 1-3 sets of samples being taken.

An interesting feature of the HydroCom software is that it has a facility to recalculate the brix of the seeding point for batch vacuum pans when the coefficients have been changed and the probe is following a different calibration curve. This new brix for seeding can be entered in to the pan control system either to warn the operator to seed the pan or open an automatic seeding valve.

**Operational notes.** The Fives Fletcher range of probes have provided a remarkably cost effective and efficient means of measuring the complex combination of parameters involved with controlling the consistency of all types of massecuite in a vacuum pan; and they have, as a result, brought about a major transformation to the technology of pan boiling. These probes offer a factory the full range of opportunities for pan control from the most basic massecuite consistency indication only, through automated liquor feed control and to complete and full automation of all operations. The Monotrac probe signal has generally been found to only vary by about 4 to 5% over a season due to the influence of product impurity changes and is therefore a very stable and repeatable signal. The effects of purity changes on a Hydrotrac probe is even less although it has not been fully evaluated. Figure 12 gives an interesting graph showing the progress of a Hydrotrac probe outputs of massecuite unscaled value, brix and temperature over a refinery boiling in a batch vacuum pan.

**Probe cleaning.** For batch vacuum pans the regular steaming-out of the pan after striking is sufficient to keep the probes free of any encrustation build up, which means they should be maintenance free. In a continuous vacuum pan there is a gradual accumulation of sugar encrustation on the sensing tip of the probes which, unless periodically removed, will eventually affect the probe readings. For this reason Monotrac and Dupotrac probes are generally supplied with “quick-release” fittings which enable them to be quickly and easily removed for manual cleaning. With these facilities a probe can be easily cleaned within 2-3 minutes, which means it is therefore not a particularly time-consuming task. The Hydrotrac probe has to be cleaned in-situ, which can be done with a simple water or steam spray that can be either manually operated or set to operate automatically at timed intervals. Probe cleaning schedules are very often found to be excessively cautious with the probes being unnecessarily frequently cleaned. This arises from a generally excessive concern from factory management towards probe cleanliness and the consequent adoption of “rather safe than sorry” policy. In very many cases the intervals between cleaning could easily be extended to around twice that practiced on average, but since there is no real consequence to this except the extra effort required it is not expected that the situation will change significantly.
New developments

Determining heat transfer coefficient of a continuous vacuum pan. Massesuite temperature measurements provided by Duotrac (Love et al., 2001) and Hydrotrac probe can and have been used in several Fives Fletcher continuous vacuum pan installations as an aid for the online measuring of the heat transfer coefficient of the calandria heating surface. The heat transfer coefficient, \( k \), is calculated using equation: \( Q = K' A' \Delta t \). The parameter \( Q \) is the heat duty, is calculated from the measured condensate flow rate and the latent heat which can be calculated from a formula based on the measured calandria operating pressure. The parameter \( A \) is the heating surface area of the vacuum pan. The \( \Delta t \) parameter is the temperature difference between the heating steam in the calandria and the massesuite. The heating steam temperature can be calculated from the measured calandria operating pressure whilst the massesuite temperature is measured by the Hydrotrac probe. An example control screen print-out is shown in Figure 13.

Determining massesuite supersaturation. Two of the critical stages in batch vacuum pan boiling are adding slurry at the correct seeding point with the second being the grain establishment stage which immediately follows the first. During the establishment of the grain, since the crystal content is very low and the evaporation rate high, it is necessary to either add water, or close the steam valve, to ensure the supersaturation is controlled so that it does not go too high or too low and control formation of additional crystals or dissolution of those just formed. In the past this regulation was left to the skill of the pan boiler to judge. It is now possible to use a factory's control system software to process the Hydrotrac brix and product temperature signals for generating a supersaturation value which can then be used for regulation of the vacuum pan. The supersaturation calculation will require manual input of values such as the product purity and some other constants (e.g. solubility coefficients), and as long as the material being processed is reasonably constant a repeatable supersaturation value can be obtained. Using this system can give a supersaturation value for graining and also for control of the grain establishment phase. This means that a better accuracy of control is achieved and will enable the production of a better quality crystal product.

Conclusions

The development of Fives Fletcher / Tongaat-Hulett continuous vacuum pan some 25 years ago has spawned a very successful range of vacuum pan sensors. The Monotrac, Duotrac and Hydrotrac range of transducers have proven to give excellent and reliable control of both batch and continuous vacuum pan boiling. The Hydrotrac probe represents the state of the art in on-line brix and moisture measurements and has largely taken over the Duotrac market. The Monotrac probe provides the most efficient and cost-effective solution for pan control when determination of actual on-line brix values are not essential and the purity of the product is less than around 90-94.

Acknowledgements

Fives Fletcher would like to acknowledge the pivotal role played by its technology partners, Tongaat-Hulett Sugar, Concontrol and Hydronix in the critical development, supply and support functions of the Duotrac, Monotrac and Hydrotrac probes respectively. The authors wish to acknowledge work of John Thalwall, Tony McKay, Colin Sanders and Eddie Sheppard on whose work much of this paper has been based.

* This paper was presented at the 2010 Sugar Industry Technologists annual conference in Savannah, Georgia, USA.

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