Technical Whitepaper
Sonic V – Acoustic Pulse Reflectometry (APR) Inspection System

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Sound Wave Inspection Systems

Contents

1.   SCOPE

This document will provide insight into Acoustic Pulse Reflectometry (APR) technology used in Sound Wave Inspection System's SONIC V, and it's application on inspecting Heat Exchangers (HEX) and boiler tubes.

2.   APR Technology Overview

In order to perform inspection of HEX or boiler tubes utilizing APR, we need 3 components: Source of acoustic pulses (loudspeaker), receiver of acoustic waves (microphones), and the object of inspection (tube). Principle behind the APR is to inject an acoustic pulse into the air enclosed by the tube, which will propagate down the tube axis. Any change in the cross section in the path of the pulse will create reflected waves, which will propagate back up the tube. These changes of inner diameter (ID) cross section can be caused by obstacles inside the tube, wall loss on the ID of the tube, through wall holes (TWH), but also structural events on the tube such as U-bend, rolling of the tube to tube sheet, end of tube (EOT). Some of these structural changes can be seen in Figure 1.

Figure 1: Schematic description of typical blockage and ID wall loss in a tube

Reflections that are created can be measured and analyzed, and from signal interpretation we can understand if there are any discontinuities in the tube ID cross section uniformity, and we can understand their type, position and size.

3. Physical Principles of the APR

Acoustic waves in air are longitudinal waves: particle velocity is parallel to the direction of wave propagation. In free space, acoustic waves can propagate in all directions. However, in a confined space, such as a tube whose transverse dimensions are small with respect to the minimal wavelength, such waves will propagate solely along the tube axis.

Up to a certain "cut-on frequency", a wave propagating in a tube can be considered a plane wave, i.e. wave fronts are flat and the pressure fluctuations are uniform over the cross section of the tube. This kind of wave is the most convenient wave to measure, since it suffices to measure it at one point in the cross section. Most commonly this is performed by a microphone embedded in the tube wall so as not to create a disturbance in the tube. Above the cut-on frequency, higher order modes of propagation are excited. These modes have different wave velocities, and in addition when they occur the pressure is no longer uniform over the cross section. It is difficult both to excite these modes in a controllable manner and also to measure them, therefore they are usually avoided in APR systems. The plane wave mode of propagation is also referred to as the lowest order mode. The cut-on frequency of the first higher order mode is given by the equation:

$$(1) \qquad \frac{1.84 * c}{\pi * d}$$

where c is the speed of sound in air, and d is the inner diameter of the tube. This frequency is determined by tube diameter and the speed of sound, becoming lower as the tube becomes wider. To avoid the complications created by higher order modes, APR systems are usually designed to create an excitation signal that is limited to a maximal frequency that is below this cut-on.

4. Attenuation of Acoustic Waves in Tubes

Acoustic waves propagating in a tube will experience attenuation due to friction at the tube wall. The equations governing attenuation as discovered by Kirchoff and later formulated in more mathematically tractable approximations by Keefe (1984), show attenuation to be dependent mainly on the ratio of wavelength to tube diameter. Attenuation increases with frequency, therefore a wideband pulse excited at one end of the tube will gradually lose its high frequency content, becoming gradually more smeared in the time domain.

5.   Effect of Tube Defects on APR Measurement

Acoustic waves within a uniform tube will propagate down the tube, experiencing only the gradual attenuation described above. However, any internal change in cross section of the tube will split the wave into two components: a reflected and a transmitted component. Several types of cross-sectional change can occur: an increase in cross section due to wall loss, a through wall hole, and a reduction in cross section due to full or partial blockage. When dealing with the lowest order mode, only the change in overall cross section has an influence on the reflected and transmitted wave, regardless of the particular shape. In the case of a hole, for instance, the area of the hole determines the reflection, whether it is round or elongated. The same holds for reduction in cross section – whether it is localized or uniformly distributed over the circumference of the tube has no importance.

The reflection and transmission caused by an abrupt change in cross section can be modeled easily through the reflection and transmission coefficients. Given a wave propagating down a tube with cross section S1, which then encounters a tube with cross section S2, the reflection coefficient R is given by:

$$(2) \quad R = \frac{S1 - S2}{S1 + S2}$$

And the transmission coefficient T by:

$$(3) \quad T = \frac{2 * S1}{S1 + S2}$$

From (2) it can be seen that an increase in cross section (S2>S1) causes a negative reflection, whereas a decrease in cross section (S2<S1) causes a positive reflection. In heat exchanger tubes, typical defects such as blockages and wall loss cause local changes in cross section. A typical blockage will be composed of two successive discontinuities: a reduction of cross section at the beginning of the blockage, and an increase back to the nominal cross section where the blockage ends. A wall loss defect is the opposite: an increase in cross section followed by a decrease. Furthermore, the amplitude of a reflected pulse is determined by the value of the reflection coefficient R, thus it can be used to determine S2 if S1 is known. Theoretical signatures of these defects can be seen in Figure 2.
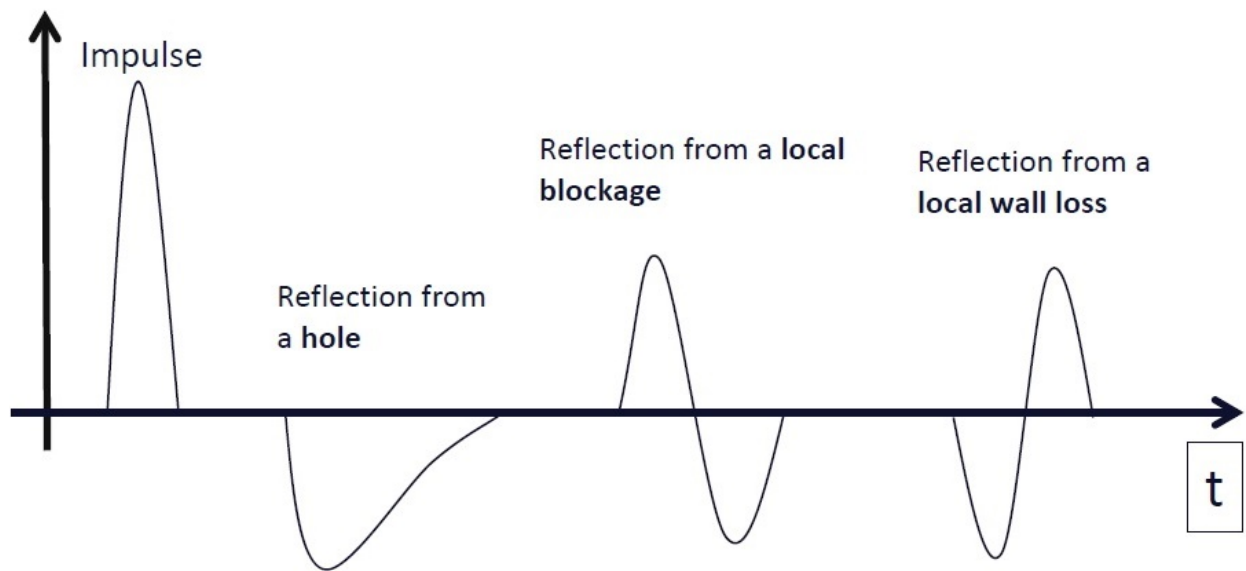
Figure 2: Theoretical signatures of most common defects

From equation (2) it can be inferred, that the reflections from blockage and wall loss defects will have typical signatures. Assuming a positive pulse is sent down the tube, when it encounters a blockage it will cause first a positive reflection followed by a negative one, whereas a wall loss defect will cause the opposite: a negative pulse followed by a positive one.

6.   Effect of Impinging Impulse Bandwidth on System Resolution

The pulses in the above figures represent a schematic picture of the excitation impulse. To enhance axial resolution of an APR system, an ideal pulse would be as narrow as possible. This is because it is necessary to distinguish reflections from closely spaced defect. If for example the pulse is too wide, the positive reflection from the beginning of a blockage might merge with the negative reflection from the end of a blockage, in effect cancelling each other to a large degree. Basic Fourier theory tells us that to obtain a narrow pulse in the time domain, its spectrum must be as wide as possible. The effective limit on the bandwidth is determined both by the loudspeaker creating the pulse and on the first cut-on frequency in equation (1). In the Sonic V system, the spectrum of the pulse extends to about 8 kHz, corresponding to the inability to distinguish between defects separated by less than 2cm. In addition, resolution gradually decreases down the tube due to attenuation, since higher frequencies decay more rapidly than lower frequencies. Thus the reflections from further defects become smeared in the time domain.

7.   *Optimization of the Excitation Impulse*

In a practical APR system, as in any physical system, background noise will always be present. The common measure for quantifying the disturbance caused by noise is SNR – Signal to Noise Ratio, which is simply the RMS of the signal divided by the RMS of the noise. SNR is usually quantified in decibels, or dB:

$$(4)\ SNR[dB] = 20 * \log(\frac{As}{An})$$

To improve SNR, the average signal amplitude must be increased as far as possible, though there are practical constraints on the attainable value. Increasing pulse width is one option, though as seen above, this has a detrimental effect on resolution. Another option is to increase pulse height, though the amplifier and loudspeaker capabilities limit this option too.

Sonic V APR implementation employs another method that combines the advantages of repeating a measurement multiple times, yet nevertheless keeps measurement time down to a few seconds. This method is based on the use of a signal called a "Maximal Length Sequence" (MLS), a form of pseudo-noise composed exclusively of the values +1 or -1. The theory behind MLS sequences is well known and used also in other applications. An MLS sequence is always of length 2N-1, where N is an integer. For example, if N=10, the sequence will be 1023 samples long, taking up only 23 thousands of a second to transmit, at a typical sampling rate of 48 kHz. For N=14 the sequence will by 16,384 samples long, taking about 1/3 of a second to transmit. The value of N can be selected in software in the Sonic V system. Typically it is set to 13, and the measurement repeated several times, giving a total measurement time of approximately 10 seconds.

Extracting the pulse response from the measured MLS signal requires a correlation computation. Mathematically, it is a linear operation, and thus any nonlinear distortions in the system will create spurious peaks in the resultant signal, which could be misinterpreted as defects. Evidently it is very important to keep nonlinear distortions to a minimum. The component most susceptible to such distortions is the loudspeaker, which becomes nonlinear when driven at high amplitudes. Therefore there are two conflicting demands on the excitation signal: on the one hand, it is beneficial to increase signal amplitude in order to increase SNR, yet on the other hand, increasing it too much leads to nonlinear distortions. The optimal amplitude is the one at which the nonlinear noise and background noise balance to achieve the highest overall SNR.

8.   Analysis of APR Signals

After acquiring the measurements it is necessary to analyze them carefully in order to extract all the available information regarding defects and tube condition. Three main stages in the analysis of APR measurement are Detection, Classification and Sizing.

8.1 Detection

It is important to stress that the single most important goal of the detection phase is to ensure that any possible defect is flagged. The main challenge in the detection phase is to decide which features of a given signal represent actual defects, as opposed to random fluctuations due to ever-present background noise. Several factors can contribute to this noise: ambient noise, internal noise and fluctuations caused by reflections off residual fouling and tube surface roughness. Regardless of the source, it is necessary to determine the actual background noise level and use it to determine a threshold of defect detectability, which we term here the "noise threshold", seen in red lines in Figure 3.
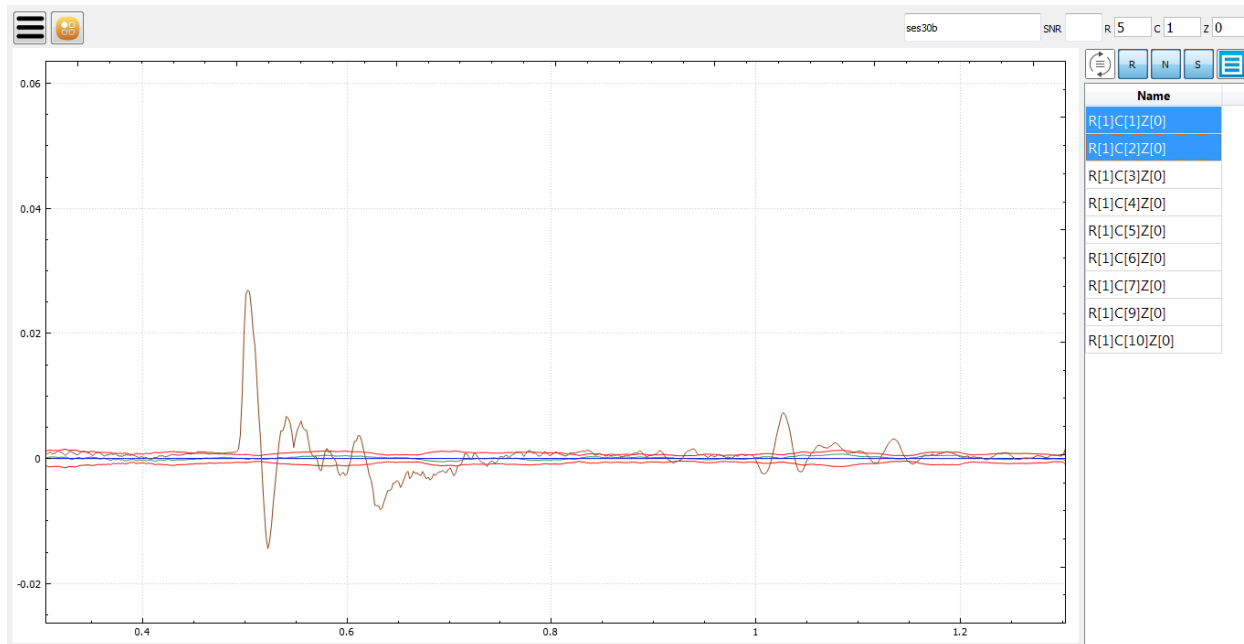

Figure 3: Blockage on tube R[1]C[1] seen against reference signal and neighbor tube signal

Calculating this threshold is performed by carrying out a statistical analysis over the entire ensemble of measurements. Any reflections crossing this threshold are considered to represent defects. It is noteworthy that the noise threshold varies with distance along the tube, mainly due to reflections from residual fouling which is not necessarily uniform. Finally, the statistical analysis used to determine the noise threshold can be carried out in several ways. The simplest is to calculate the standard deviation

across the ensemble of measurements at each point along the tube, however more complex methods can be used.

8.2. Classification

The second stage of the analysis is defect classification. Peaks that extend beyond the noise threshold are classified by comparing them to signature templates derived from the schematic examples shown in Figure 2. This procedure is complicated by the fact that there still remains a large degree of variability in reflection shape due to variations in axial length of the defects, for example, or irregularity in defect morphology.
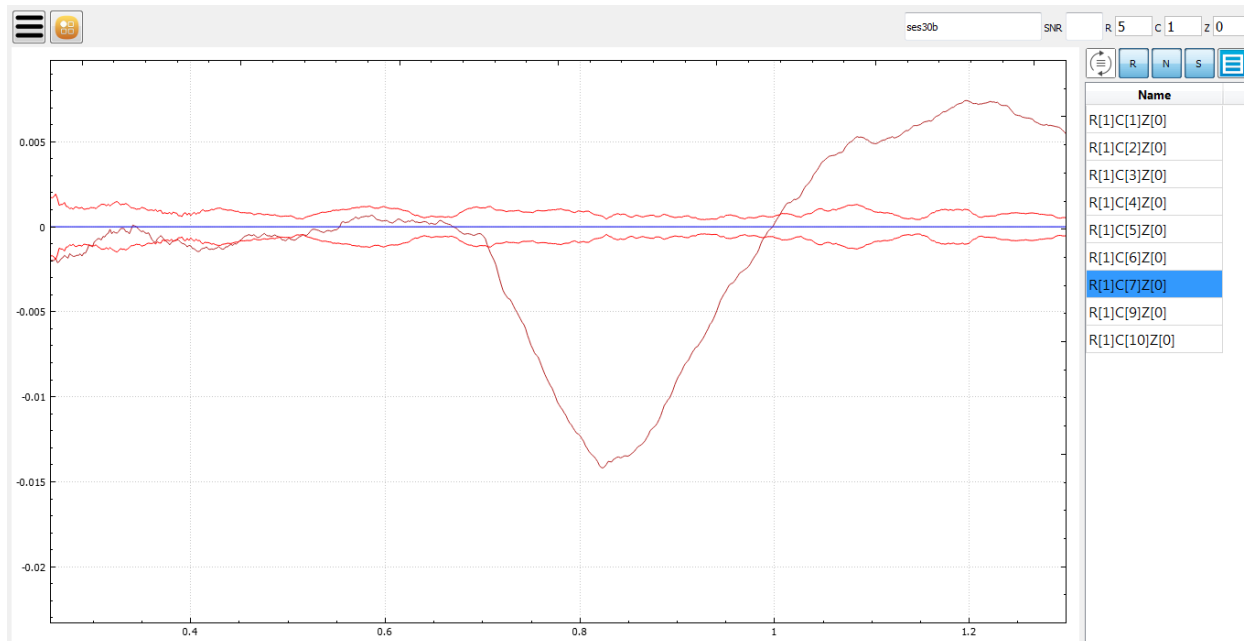

Figure 4: A Through Wall Hole seen in Sonic V analysis software

The difficulties encountered in this phase are usually related to the degree of cleanliness of the tubes being detected. Excessive debris and fouling can create a multitude of spurious reflections that can interfere with the reflections off defects, especially small ones.

In applying APR, as in any NDT technology, tough calls can occur. As long as the number of such cases can be kept marginal, the best policy for dealing with them is to flag them and bring them to the operator's attention, rather than forcing them to fit into one of the existing categories.

8.3.   Sizing

Acoustic theory enables accurate simulation of all defect types detectable by an APR system. Wall loss and blockage signatures can be calculated based on equation (2), while through wall holes can be simulated based on the works of Sharp et al. (1997). The idea behind sizing is therefore straightforward: after defect signatures are detected and classified, they are matched to signatures derived from the theoretical simulations.
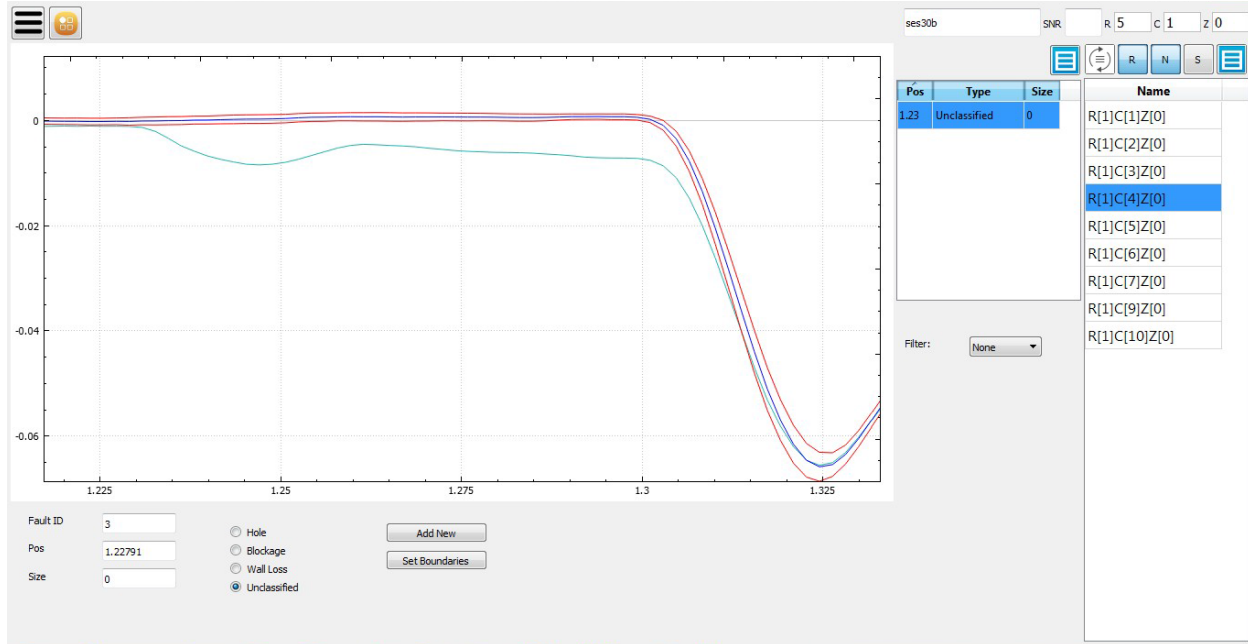

Figure 5: End-Of-Tube Erosion seen in Sonic V sizing software module

9. APR Capabilities in Tubes Inspection

Ideally, a tube inspection technique should provide several key properties: high sensitivity and accuracy are extremely important, at the same time providing a high level of consistency regardless of the operator. System design should facilitate short inspection time while providing objective and highly consistent data interpretation criteria, and be applicable to a wide variety of tube materials and dimensions. Finally, it should require minimal technical knowledge and experience to implement properly and consistently, and should require minimal pre-inspection preparation of the tubes.
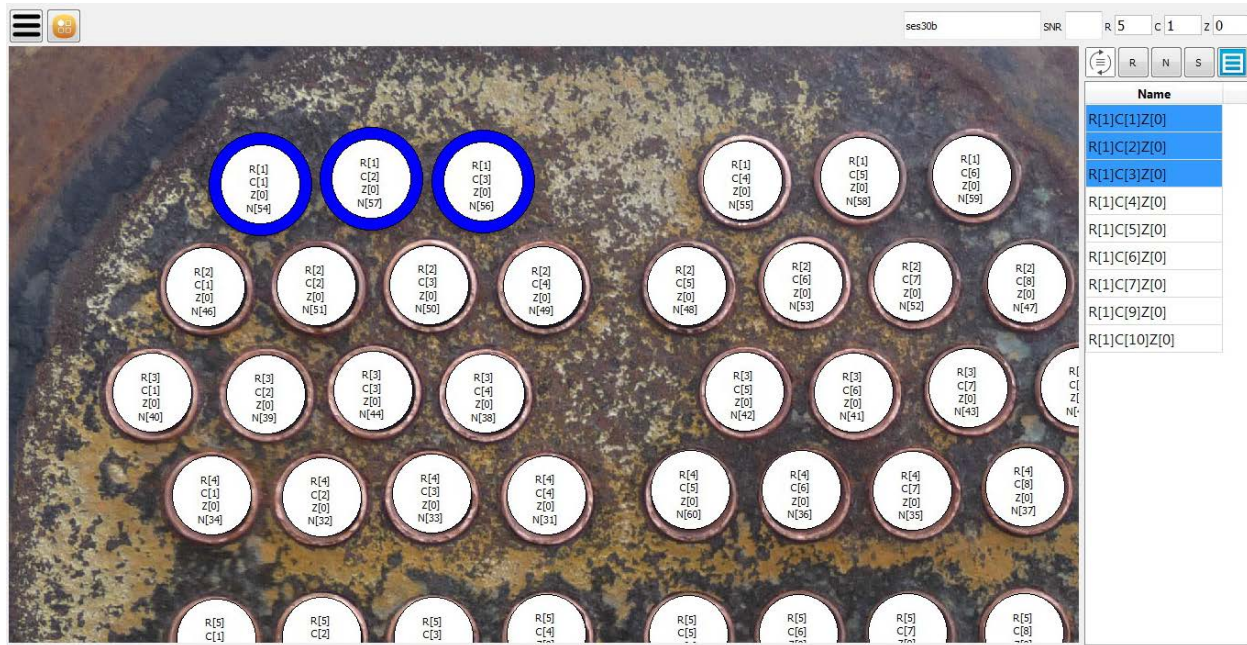

Figure 6: Quick automated map preparation using on-site digital photo

In this light, several core principles governed all the technological decisions in developing the Sonic V APR system:

1. Non traversing inspection

2. Short inspection time per tube

3. Detection of all ID faults relevant to the industry.

4. Minimal sensitivity to tube material, dimensions and configurations

5. Minimal dependence on operator judgment.

The following Table 1 describes the most important characteristics and capabilities of Sonic V system.

APR Advantages	APR Limitations
High speed measurement: 10 seconds per tube	Doesn't detect any pure OD defects
Automated measurement process, not dependent on the operator	Overall inspection results depend on the cleanliness level of the tubes.
Highly sensitive to holes and blockages (holes and wall loss defects have separate signatures)	Lower precision on sizing of small wall loss defects (pitting)
Not dependent on the material: APR can test any material	Can't detect cracks of any orientation
Non dependent on the shape of the tube: Can test U-tubes (only one pass required), spiral, fin fan tubes, etc.	Provides no circumferential resolution
Sound waves are used as a "virtual probe" for non-traversing inspection. No parts that can get stuck, damaged, or possibility of damaging the equipment that is being inspected	
Only tool apart videoscope that can quantify blockages	

Table 1: APR advantages and limitations

Reference

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