Deformation kinetics of layered personal protective material under impact via terahertz reflectometry

Anis Rahman[a], Aunik Rahman[a] and Mark A. Mentzer[b]
[a]Applied Research & Photonics (ARP), 470 Friendship Road, Suite 10, Harrisburg, PA 17111. Phone: 717-623-8201, Fax: 717-566-1177, email: a.rahman@arphotonics.net; [b]Neuroscience Applications Group, LLC, Dept. SIG, 11 S. Somerset Avenue, Crisfield MD 21817

ABSTRACT

Terahertz dynamic scanning reflectometry (TDSR) was used for measuring layered materials' deformation kinetics spectra. Multi-layered materials are used for protective devices such as helmet and body armor. An in-situ measurement of deformation profile and other dynamic characteristics is important when such material is subjected to ballistic impacts. Current instrumentation is limited in their abilities to provide sub-surface information in a non-destructive fashion. A high sensitivity TDSR has been used to measure dynamic surface deformation characteristics in real-time (in-situ) and also at post deformation (ex-situ). Real-time ballistic deformation kinetics was captured with a high speed measurement system. The kinetics spectra was used to compute a number of crucial parameters such as deformation length and its propagation profile, the relaxation position, and the macroscopic vibration profile. In addition, the loss of mass due to impact was quantified for accurate determination of the trauma causing energy. For non-metallic substrates, a transmitted beam was used to calibrate mass loss, a priori, of the laminate layers due to impact. Deformation kinetics information may then be used to formulate trauma diagnosis conditions from blunt hit via the Sturdivan criterion [1]. The basic difference in the proposed approach is that here diagnostic criteria are inferred by measuring the helmet itself; no need to draw blood or any biopsy from the patient.

Keywords: Terahertz reflectomtery, kinetics spectrum, layered materials, helmet deformation

1. INTRODUCTION

Most trauma detection methods available today are based primarily on biological detection (e.g., either of a biomarker, or some sort of cellular biochemical, or neurochemical). A different approach is proposed where the diagnostic criteria are inferred by measuring the helmet itself; no need to draw blood or any biopsy from the patient. For example, it takes some specific amount of energy on the skull for trauma that is imparted through the helmet during a collision. For a moderate hit which may generate only stigma but not trauma, a specific biomarker is not likely to be present. Consequently, use of a biomarker approach may not be feasible for less than trauma hits. We propose to measure the energy imparted by the helmet to the skull either in real time or by testing the helmet after impact. This energy, termed as the Sturdivan energy [1] may then be used to formulate a diagnostic protocol for classifying the trauma/stigma/concussion conditions. Currently a technique called digital image correlation (DIC) is used for characterizing the layered material before making the helmets [2]. But the DIC is simply based on the measurement of the surface of the helmet, and is neither sensitive to delamination of the interior layers nor to any loss or gain of mass due to the impact. However, since it is the interior of the helmet that imparts energy to the skull causing trauma etc. Therefore, it is crucial to monitor the interior delamination of a helmet's trauma generating volume, which cannot be probed by DIC. With terahertz, one can probe the surface as well as the delamination of the interior layers. In addition, any loss or gain of mass due to delamination may also be determined via a calibration library. This information is crucial for accurate determination of the energy which could then be used in the diagnosis process.

In the followings we review the requirements of deformation characterization for less-than-lethal impact, the so called blunt criterion prescribed by Sturdivan [1]. The experimental procedure is outlined with brief description of the terahertz source and detection system. The materials under test, ballistic experiments and results are described subsequently, followed by summary and conclusions.

2. EXPERIMENTAL

As outlined in Fig. 1, a high speed measurement system is deployed for capturing the kinetics during the ballistic impact. Here the target is placed at a fixed position and the terahertz beam is incident at a known angle, θ. The layered materials

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used for helmet are transparent to terahertz but a significant portion is also reflected from different layers of the target. Therefore, measurements may be conducted both in reflection and in transmission. Here we have deployed both the transmission and reflection measurements, where, the reflection kinetics is utilized for the deformation and velocity profile computation and the transmission kinetics is deployed for determination of any change in mass due to impact. Some details of the experimental setup were described elsewhere [3].

A series of live shot experiments were conducted at the Army Research Laboratory's Survivability/Lethality Analysis Directorate (Aberdeen Proving Ground, MD 21005) facility. Here, either a multi-layered panel or an actual helmet (called "target" in Fig. 1) was mounted on a sturdy platform. The target was subjected to ballistic shots of pre-calculated velocity. The kinetics spectra were captured in real-time.

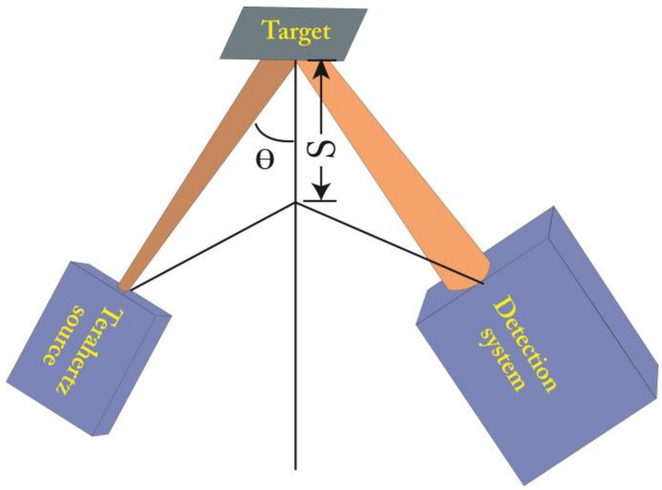


Fig. 1. Deformation kinetics measurement system via terahertz reflectometry. The terahertz is generated by an electro-optic dendrimer based CW source [4].

3. RESULTS AND DISCUSSION

3.1. Results of live firing test

The test results and findings are summarized in Table 1. This experiment yielded a bigger picture about the robustness of the technique and sets the stage for a THz test protocol for trauma diagnosis. Two different kinds of panels and a helmet (total 18 shots) were tested. Thus, the results demonstrate that the proposed terahertz technology is suitable for a bio-marker-less diagnostic tool. Column 1 of Table 1 lists the number assigned to a particular live shot. Column 2 indicates the mode of measurement, i.e., either in reflection or in transmission, while Column 3 gives a brief description about the nature of the short and related observation. The actual kinetics spectra corresponding to respective shots are given in Table 2.

3.2. Computation of parameters

Once the maximum displacement is read off of the kinetics spectrum utilizing the calibration curve (not shown here), the deformation propagation profile is calculated from the kinetics spectrum (see Fig. 2). From this profile the next most important parameter to calculate is the velocity profile of deformation. Here the following boundary conditions are utilized. Initially the target is at rest; therefore, the initial velocity, v_0, is zero. As the deformation propagates, the propagation accelerates and then at the maximum deformation the velocity is again zero. If the target recoils (in the opposite direction), the velocity again increases and then comes to zero when the target stops at the relaxed position. So one can utilize the fundamental physical principle, the Newton's law for uniformly accelerated motion:

$$S = v_0 t + \frac{1}{2} a t^2,$$

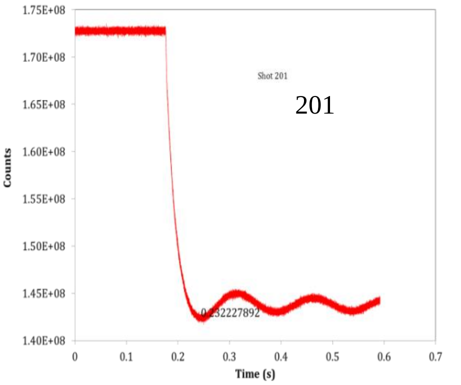
where, S is the deformation (see Fig. 1), a is the acceleration and t is the time. Since $v_0 = 0 \rightarrow S = \frac{1}{2} a t^2 \rightarrow a = 2S/t^2$. Knowing the acceleration, a, one can then determine the velocity, v, from,

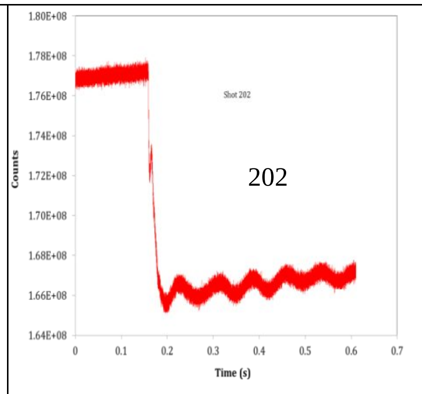
$$v^2 - v_0^2 = 2aS \quad (1)$$

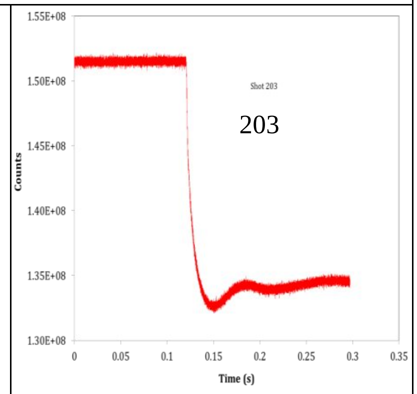
Table 1. Summary of observation of different shot experiment. Kinetics spectra are shown in Table 2. Each shot was taken on a different panel on an unaffected region of the panel.

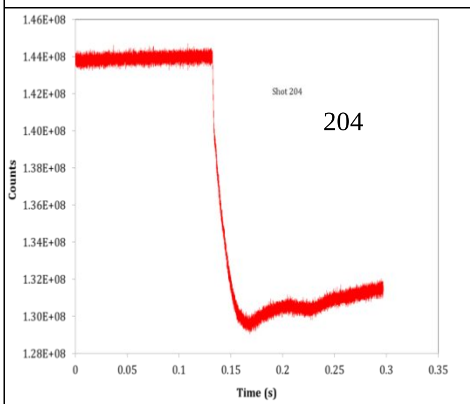
Shot#	Mode	Comment
201	Reflection	Typical reflection kinetics spectrum of a multi-layered panel. The spectrum is used for computing deformation and propagation profile, and other parameters. The vibrations in the tail end of the spectrum (at 0.2s onward) are indicative of vibration of the mounting platform.
202	Reflection	Typical kinetics but two distinctly different slopes with an upward shift in the fast decay region that indicates shaking of the mounting platform during the shot.
203	Reflection	Typical kinetics acquired over a shorter period (0.3 s)
204	Reflection	Two or more slopes in the fast decay region indicative of movement of composite layers in groups (clusters) leading to subsequent delamination of internal layers.
205	Reflection	Similar to shot 204 but a bigger variation in reflected intensity is indicative of a bigger deformation depth.
207	Reflection	Incomplete data due to data acquisition synchronization error
208	Reflection	More than one slope in the fast decay region is indicative of movement of a cluster of layers as opposed to the whole panel and subsequent delamination of internal layers.
209	Reflection	Typical kinetics similar to shot 204. Two or more slopes in the fast decay region indicative of movement of composite layers in groups (or clusters) leading to subsequent delamination of internal layers. See Fig. 2 for analysis.
210	Reflection	This shot is on a helmet. The helmet was mounted with a clamp system that could not be made very sturdy. So this spectrum cannot be interpreted unless further helmet shot is taken
301	Transmission	Incomplete data due to acquisition start error
302	Transmission	Typical transmission kinetics except the initial portion was not captured due to synchronization error in data acquisition. Some loss of mass due to the bullet shot causes an increase of the transmitted intensity. A priori calibration of mass vs. transmission may be used to quantify the loss of mass due to the ballistic event.
303	Transmission	Typical transmission kinetics profile. Once calibrated with respect to transmission vs. mass change for a given panel, this curve will quantify the loss of mass during ballistic deformation.
304	Transmission	This kinetics shows the flaw in mounting apparatus. The oscillatory nature of the platform holding the panel is clearly visible
305	Transmission	While this curve shows initial increase of power, indicative of mass loss due to impact. However, the moving panel and its vibrations due to weak mounting are responsible for the decrease in transmission.
306	Transmission	Resembles a typical transmission kinetics spectrum. Once calibrated with respect to transmission vs. mass change, this curve will quantify the change in mass during ballistic deformation
307	Transmission	This shot was done with BB ball instead of a bullet as was in the previous cases. Kinetics was inconclusive due to vibration of the unstable mounting platform.
308	Transmission	Also a BB ball shot. Transmission increased immediately after shot. The oscillatory pattern is due to vibration of the mounting platform. However, the transmission takes off towards the end because this shot actually went through the panel creating a hole that caused the increased transmission.
309	Transmission	Also a BB ball shot. This shot is very similar to typical transmission kinetics. However, the BB ball got stuck in the panel that caused a sharp decrease in the transmission.

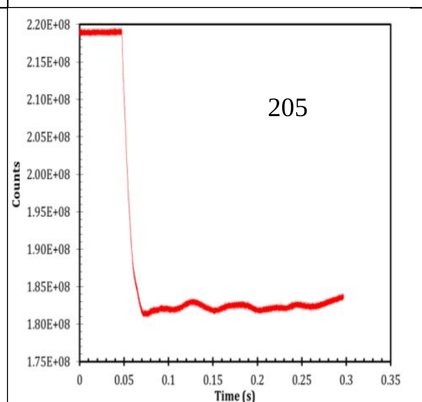
Table 2: The kinetic spectra below were measured in reflection. The X-axis is the time of duration and the Y-axis is the reflected intensity (counts). Shot number is arbitrary, mainly for identifying the shot corresponding to the comments in Table 1.

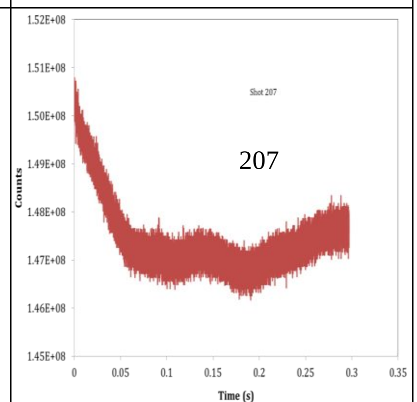


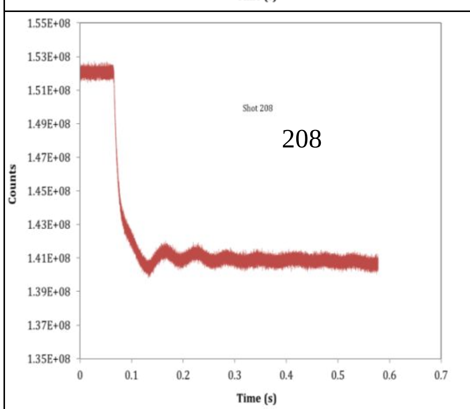


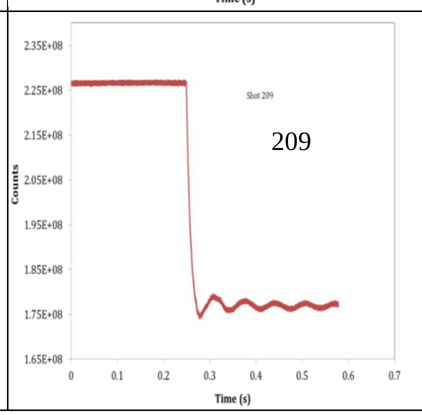












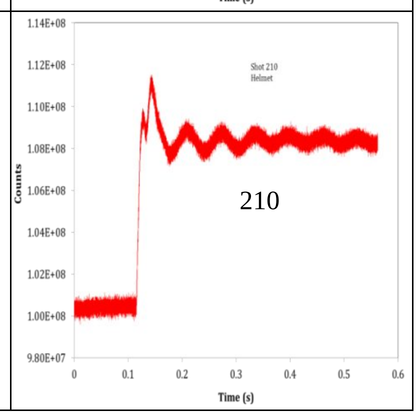
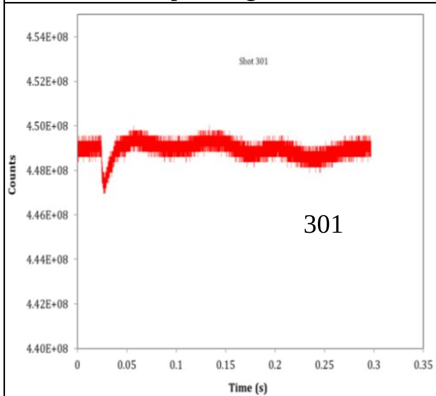
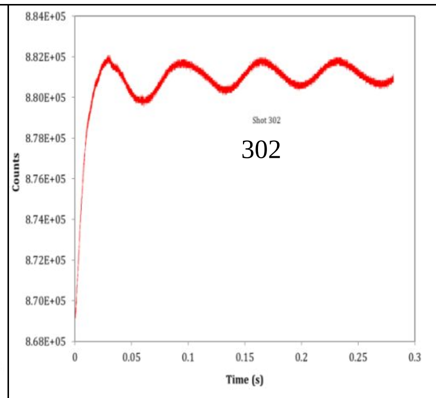
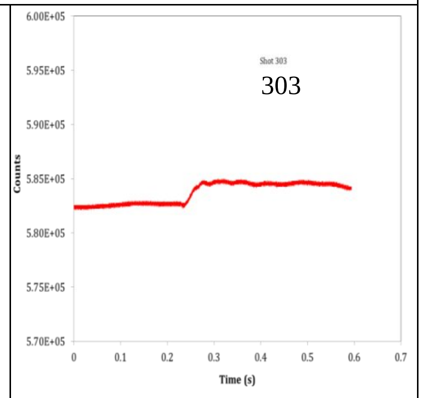
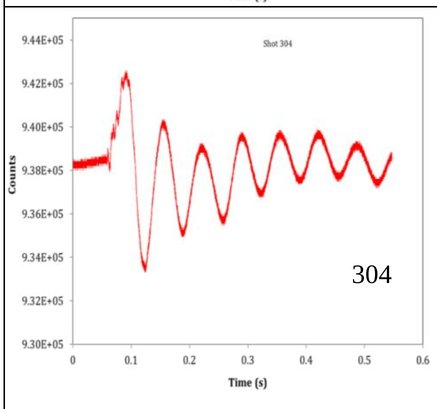


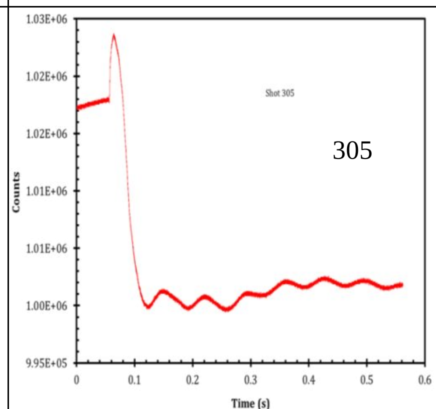
Table 2 (contd.): The kinetic spectra below were measured in transmission. The X-axis is the time of duration and the Y-axis is the reflected intensity (counts). Shot number is arbitrary, mainly for identifying the shot corresponding to the comments in Table 1.

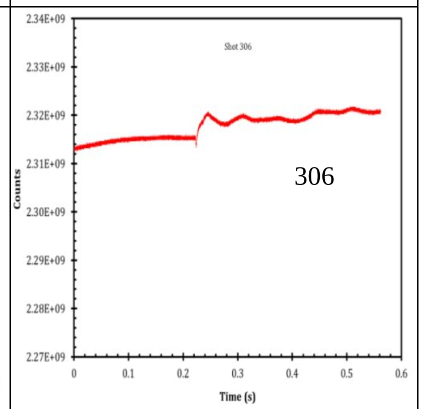


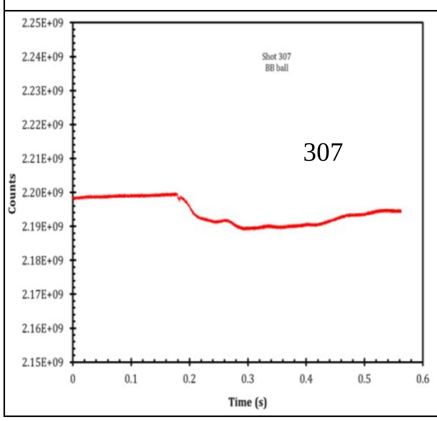


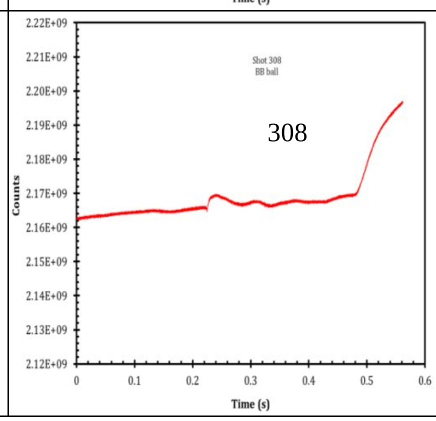












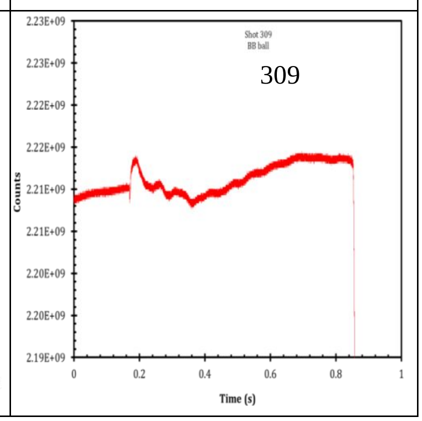


Fig. 2 displays the calculated deformation profile from the kinetics spectrum (shot 209, Table 1) and the velocity profile calculated from Eq. (1). Here the kinetics spectrum was de-noised with a curve-fitting routine and then a moving average was adapted for calculating velocity profile. Since the deformation calibration for this sample was not done ahead of time, the information available from a simultaneous digital image correlation (DIC) measurement [see reference 2] was used to calculate the deformation profile. The velocity profile of Fig. 2 reveals that the deceleration of the panel after the initial acceleration (between time 0.26s and ~0.28s) exhibit several small accelerations (indicated by the upward shots or "kinks" in the blue curve) followed by small decelerations. This is indicative of the clusters of layers are moving together as opposed to the whole panel; i.e., a few layers forming a cluster and being delaminated whose motion is captured by the kinks in the velocity profile. Altogether 4 clusters are visible following the initial deceleration of the panel. It is notable here that being able to apply the Newton's law of motion lends credibility to the approach that does not depend on any empirical formula.

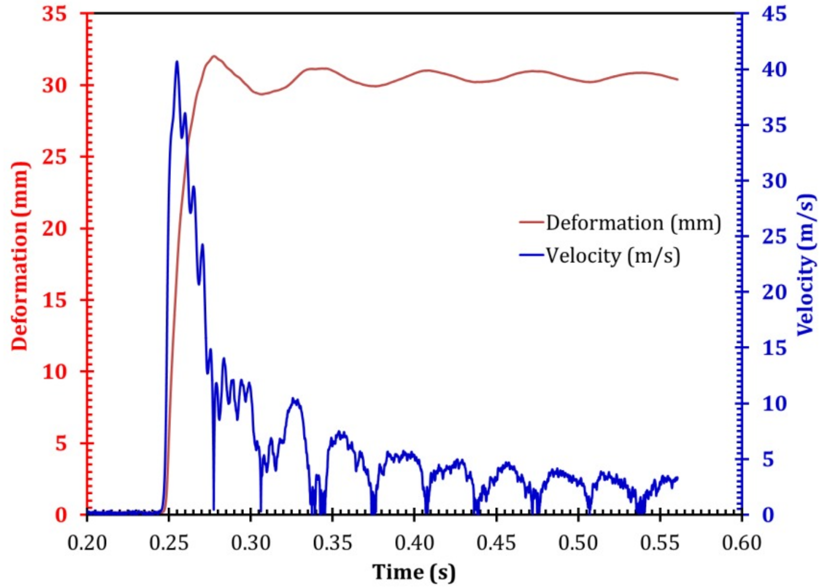


Fig. 2. Analysis of shot 209 in Table 2. Deformation profile (left Y-axis) calculated from the kinetics spectrum with a depth of 34 mm (from DIC under identical conditions). Calculated velocity profile of deformation is shown in blue (right Y-axis).

4. CONCLUSIONS

Real-time terahertz reflection kinetics spectra of ballistic events have been used for determination of deformation profile and velocity profile of deformation for layered materials used for making personal protective device such as helmet and body armor. Live firing test data have been analyzed. The Newton's law of motion for uniform acceleration was deployed for the computation. The velocity thus experimentally determined provides ability for accurate calculation of Sturdivan energy which then may be used for formulating criteria leading to non-invasive diagnosis of trauma/stigma and/or concussion for less-than-lethal ballistic impact. In addition, change in mass of the trauma generating segment of a helmet can be simultaneously determined from a priory calibration of the layered material from the transmission kinetics spectrum.

5. REFERENCES

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