Stress Relaxation in Plastic Molding Compounds

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Abstract

Viscoelastic materials for plastic encapsulated molding compounds invariably exhibit a time-dependent stress response to an imposed constant strain, which is called stress relaxation. Stress relaxation tests with molding compounds used to encapsulate microcircuits have been performed to measure the time dependent non-linear constitutive relation between stress and strain as a function of temperature and imposed strain. In an effort to improve the design process, a methodology using short time stress relaxation tests can be used to provide long-time design information.

The goal of this study is to characterize the non-linear viscoelastic behavior of the encapsulated molding compound during environmental conditions that microelectronics devices have possibly experienced in their lifetime in order to help in developing new design including material selection and process and to inform that it is necessary to include the effect of curing shrinkage as well as viscoelastic behavior for better estimation for stress and deformation such as warpage in device.

Introduction

The main advantages of plastic-encapsulated microelectronics (PEM) are low cost, compact size, light weight, and ease of processing [1, 2]. In the past, PEMs have been used in commercial and telecommunication devices, which have a large manufacturing base. With major advantages in cost, size, weight, performance, and availability, plastic packages have reached 97% of the market share of worldwide microelectronics sales, although they still encountered formidable challenges in gaining acceptance for use in government and military applications. In fact, it was only in the early 1990s that the industry dispelled the notion that hermetic packages, such as ceramic types, were superior in reliability to plastic packages, in spite of their low production and procurement volumes [3].

One of the main trends in plastic packaging is to move toward thinner packages with fine-pitched leads. While reducing package thickness results in lower die stresses, it can also lead to greater warpage after molding. Most concerns of all are the bending and twisting of packages caused by molding induced stresses because they can affect back-end process steps, such as trim and form and may eventually reduce production yield due to non-coplanarity, which makes the packages difficult to be mounted on printed circuit boards [4]. Excessively warped packages may also lead to tensile stresses on the die surface that, in the presence of flaws could lead to die cracks due to the nature of the brittle material [5, 6]. Post-molding warpage is often used as an indicator of residual die stress when developing new molding compounds [7] and to indicate whether the molding process is stable.

A PEM consists of many different materials. Some properties of commonly used materials in PEM packages are presented in Table 1. Due to the unsymmetrical geometry, material construction, and CTE mismatch of different parts of the package, thermal stress and deformation, such as warpage, can occur inside the package, while it is being manufactured and surface mounted or being used [8, 9].

Table 1 Some Properties of Commonly Used Materials in PEMs [10, 11]

Property / Component	Material Type	Coefficient of Thermal Expansion (ppm/^{o}C)		Elastic Modulus (10^{10}dynes/cm^2)		Glass Transition Temperature (^{o}C)
		25^{o}C	215^{o}C	25^{o}C	215^{o}C	
Lead frame	Copper	16 - 18	16 - 18	1190	1190	-
	Alloy 42	4 - 5	4 - 5	145	145	-
Molding Compound	Epoxy/ Silica	10 - 25	40 - 65	15	1	110 - 200
Chip	Silicon	2.3	2.3	166	166	-

Modification of design features like materials or structure of a package may be necessary, not only for stress reasons, but for its thermal performance improvement or cost effectiveness. Molding compound manufacturers constantly try to improve the recipes of new encapsulants for lower CTE and elastic modulus [12, 13], which can lead to significant reduction in residual stresses. However, it is important to remember that while the effect of adding filler is to reduce the CTE of the molding compound, it may increase the elastic modulus. The benefit derived from lowering the CTE may be partly offset by an increase in stress due to the higher elastic modulus of the modified compound.

Problem Definition

In order to design for packaging improvement, it is very important to predict or anticipate the stress or deformation effect of an incremental change in one or more material or geometric parameters, in addition to the stress state inherited after initial fabrication of an electronic package. Nevertheless, the stress and deformation in PEMs may not be simply calculated or measured at a specific moment because there exists curing shrinkage, and they are time dependent due to viscoelastic material properties. The occurrence of molding compound curing shrinkage is not an entirely new concept [14], though its effect on package stress is not widely reported in the literature. It is generally assumed that the package is not subject to significant levels of stress during curing because the viscoelastic modulus or stiffness of the molding compound is a factor of 10 lower at 175°C than its room temperature value (See Figure 1). But the curing shrinkage of the molding compound should not be ignored, although it is minor when compared to the more dominant shrinkage given by CTE [15].

In viscoelastic materials, energy dissipation causes the strain to be out-of-phase with the applied stress by an angle between zero and 90 degrees. This phase shift between stress and strain, defined as the phase angle, is measured and used along with the sample geometry and driver energy, required to produce the strain within the material, to calculate the viscoelastic properties of the sample. A flexural bending mode of deformation is used to produce the strain within the sample. Based on this theory, the stiffness of a viscoelastic material can be separated into two components: a real part, which is the elastic modulus, and an imaginary part, which is the damping or viscous components. The separation of these two components describing two independent processes within the materials-elasticity (energy storage) and viscosity (energy dissipation)- is the fundamental feature of dynamic mechanical analysis (DMA). The ratio of samples loss to storage properties is tan delta, which is another parameter used to characterize the material [16]. Figure 1 shows the viscoelastic properties, such as elastic (storage) modulus, viscous (loss) modulus, and tan delta in encapsulated molding compounds interested in this study.

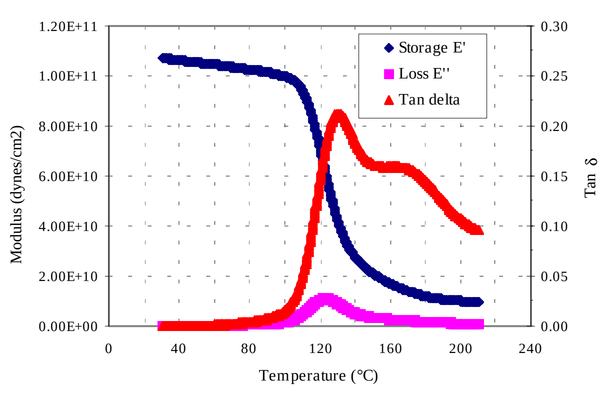


Figure 1. Viscoelastic Modulus of Plastic Molding Compound

Yeung et al. [17] studied the viscoelastic property of a PEM and found that a viscoelastic model predicted the warpage of an IC package more accurately than an elastic model. Nakamura et al. [18] found that for a laminated epoxy-aluminum beam, the deformation and residual stresses obtained by assuming thermoviscoelastic behavior showed close agreement with the experimental values, and they were quite different from the elastic solutions. Xiong et al. [19] conducted to evaluate the viscoelastic effect on energy release rate and mode mixity of an edge crack through viscoelastic finite element analysis.

Stress relaxation due to the viscoelastic effect that occurs by molecular diffusional motion, which becomes more rapid as the temperature increases. The epoxy is a cross-linked system with a well-defined glass transition temperature. The temperature dependency of the modulus in such materials is related to its cross-link density.

In this paper, the viscoelastic properties of a filled epoxy molding compound are investigated with the DMA. The objective is to determine the time- and temperature-dependent elastic modulus because it plays a significant role in inducing the variation in stress and deformation of PEM packages during subsequent mounting and operating services [20].

Experimental Procedures

To determine the stress relaxation modulus of EMC, a series of DMA tests were conducted using Perkin Elmer Dynamic Mechanical Analyzer 7E. Three-point bending tests were performed with beam-type specimens, which have dimensions of 15 x 6.35 x 1.6 mm (LxWxH). The tests were performed with various testing conditions as shown in Table 2. In this table, the "strain" is defined as the ratio of the loading deflection to the span of the specimen. The testing procedures are given as follows:

1. Preheat the chamber to a selected temperature.
2. When the chamber temperature reaches the set value, wait until the temperature becomes stabilized, usually in less than one minute.
3. The loading, which is a specified deflection, is then applied to the simply-supported sample.
4. When the deflection reaches the intended value, fix the position of the loading ram.
5. Take readings of the reaction force on the loading ram over a certain time period, typically more than 4 hours.

Table 2. Test Conditions of Stress Relaxation Modulus of EMC

Temp / Strain	75°C	100°C	140°C	170°C	200°C
0.1%	X	X	X	X	X
0.25%	X	X	X	X	X
0.5%	X	X	X	X	X

From the time history of the force recording, the stress relaxation response of the specimen can be characterized.

From the beam theory, for the three-point bending with a center load, the maximum deflection (loading), δ, can be expressed as

$$\delta = \frac{PL^3}{48EI} \quad (1)$$

Under a fixed δ, the time dependent modulus can be obtained from

$$E(t) = \frac{P(t)L^3}{48\delta I} \quad (2)$$

where *P(t)* is the time history of reaction force on the loading ram; *I* is the second moment of area of the beam cross-section, and *L* is the span of the simply-supported specimen.

In the present study, the molding compound under investigation is EME-7351TQ (1044154). The basic material properties and molding/post-cure conditions of this EMC are given in Table 3 and Table 4.

Table 3. Thermo-mechanical Properties of EMC

Properties		EME-7351TQ (1044154)	Notes
Filler content	Wt.%	-	175°C
Epoxy Resin System	-	New Biphenyl	
Spiral Flow	Inch	39	
Gel Time	Sec	26	
Hot Hardness	Shore-D	75	
CTE1	ppm/°C	10	Boiling, 24hr
CTE2	ppm/°C	41	
Tg	°C	140	
Flexural strength	$dynes/cm^2$	$20.1*10^8$	
Flexural modulus	$dynes/cm^2$	$2314.8*10^8$	
Specific gravity	-	1.96	
Water sorption	Wt.%	0.16	
Na^+	ppm	1.2	
Cl^-	ppm	22.4	

Table 4. Mold and Post Cure Conditions

Properties		EME-7351TQ (1044154)
Transfer pressure	$dynes/cm^2$	$85*10^7$
Mold temperature	°C	175
Cure time	sec	90
Post cure temperature	°C	175
Post cure time	hr	6

Results and Discussions

In this study, the measurement of the stress relaxation response was done with the conventional DMA testing procedure, which has a 5°C/min heating rate and a constant loading displacement at 1Hz frequency.

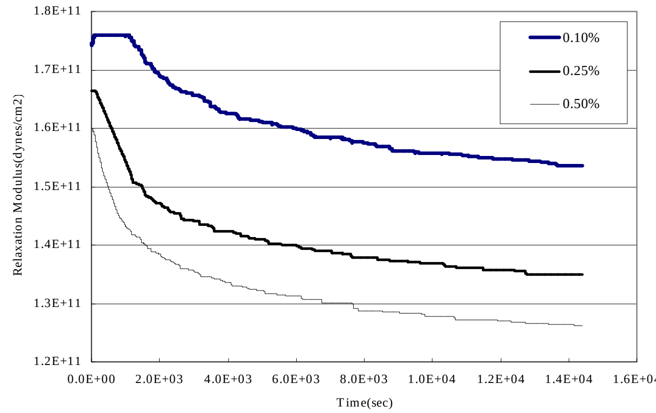
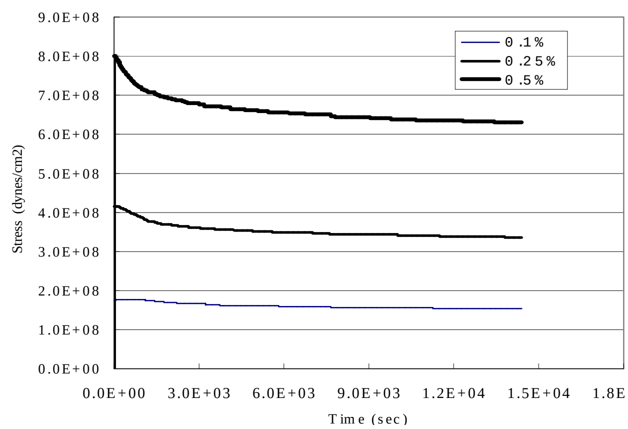


Figure 2. Relaxation Modulus Curves at 0.1-0.5% Strains at Reference Temperature of 75°C



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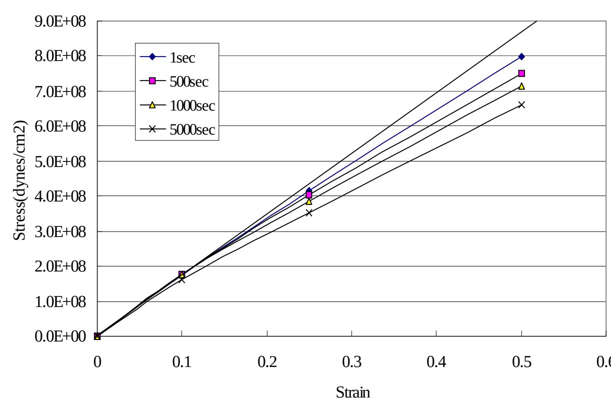

Figure 4. Non-linear Relation of Stress vs. Strain at 75°C

Figure 2, 3, and 4 show the testing results of stress relaxation and stress and strain curves at 75°C under three imposed strains of 0.1%, 0.25%, and 0.5%. Non-linear viscoelastic behavior has been observed. As time passes, the EMC shows a more prominent nonlinear constitutive relation. The relaxation modulus decrease as the applied strain increases at a fixed temperature. The drop rates in relaxation modulus at 0.25% and 0.5% of the strain application are higher than the one at 0.1% up to 2,000 seconds.

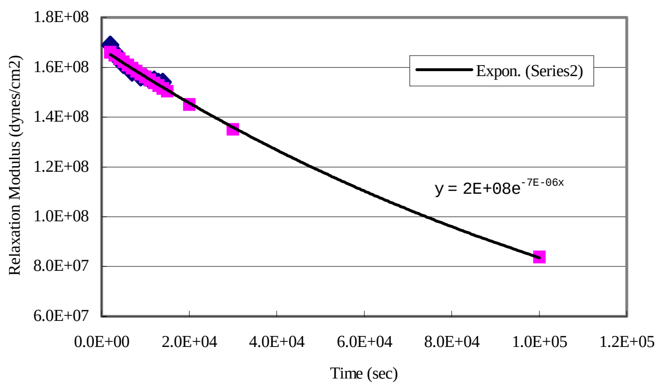

Figure 5. Curve Fitting of Relaxation Modulus under 0.1% Strain Application at 75°C

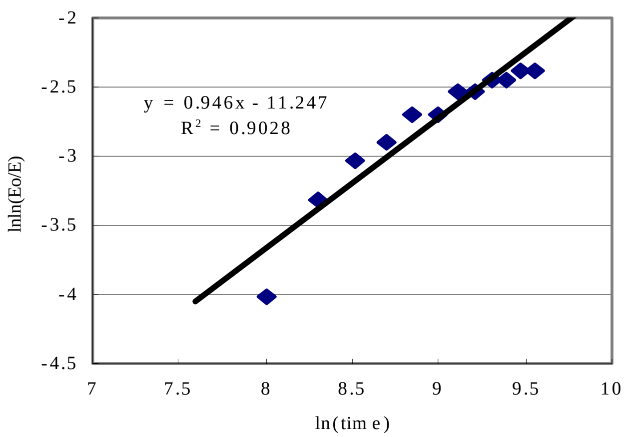

Figure 6. lnln(Eo/E) versus ln(time) under 0.1% Strain Application at 75°C

In the present study, the least square curve fitting routine (Figure 5) was implemented for data analysis. From the log-log relation (Figure 6) of relaxation modulus and time under 0.1% strain application at 75°C, an exponential model can be defined as

$$E = E_0 \exp[-(\frac{t}{\tau_r})^{\beta_r}] \quad (3)$$

where E_0 is the initial relaxation modulus(dynes/cm^2), 1.69E+8, τ_r is the characteristic relaxation time(sec), E+11.889, and β_r is the relaxation shape parameter, 0.946. It means that the drop of one order in relaxation modulus takes about $10^{11.9}$ sec. at 75°C.

At 100°C (Figure 7), the difference in the drop rates of relaxation modulus is not noticeable among various strain

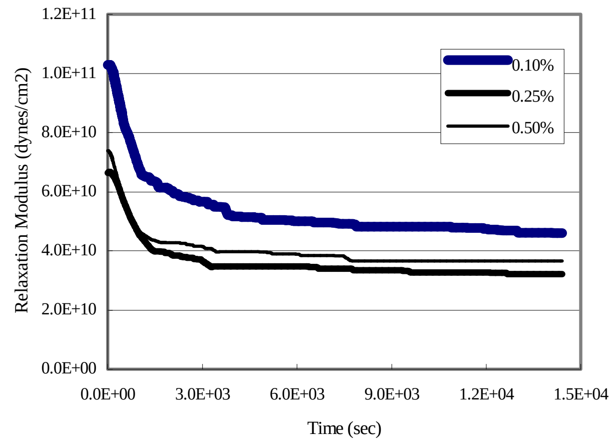

Figure 7. Relaxation Modulus vs Time of 0.1, 0.25, and 0.5% Strains at 100°C

loadings. The difference between modulus remains at about $2*10^{10}$ dynes/cm^2 all the respective to each saturated values of relaxation modulus, which takes less time to reach than the cases at 75°C. Relaxation modulus drops most before 3,000 seconds at this temperature. It seems that the relaxation response at this temperatue behaves independently of strain loading. It is unexpected to note that the modulus at 0.25% strain appears to be slightly less than that at 0.5%.

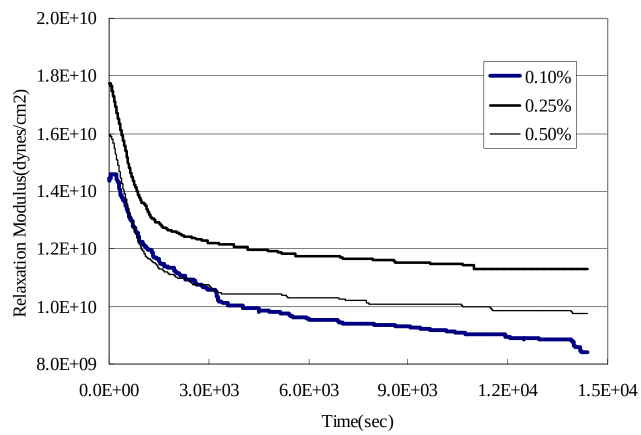

Figure 8. Relaxation Modulus vs Time of 0.1, 0.25, and 0.5% Strains at 140°C

Figure 8 shows the relaxation modulus versus time with 0.1%, 0.25%, and 0.5% strain loading at 140°C. Unlike the cases at 75°C and 100°C, 0.1% strain loading gives smaller relaxation modulus than 0.25% and 0.5%. The drop rate of relaxation modulus with 0.1% strain loading continued until the test ended. Above this temperature the relaxation modulus does not show much difference for various applied strain loadings and does not behave with tendency depending on strain (Figure 9). It is very obvious that the testing temperature influences the behavior of relaxation modulus more than the applied strain, particularly for temperatures above 140°C. There is no evidence at all that relaxation modulus changes depend on an applied strain. It means that linearity holds between stress and strain at these temperatures.

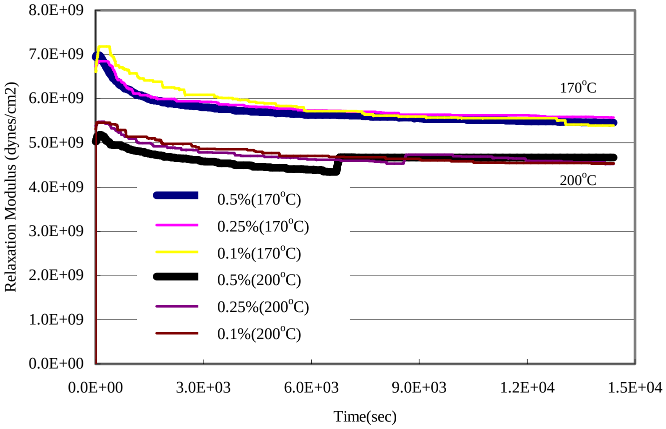

Figure 9. Relaxation Modulus at 170°C and 200°C in 0.1, 0.25, and 0.5% Strain Application

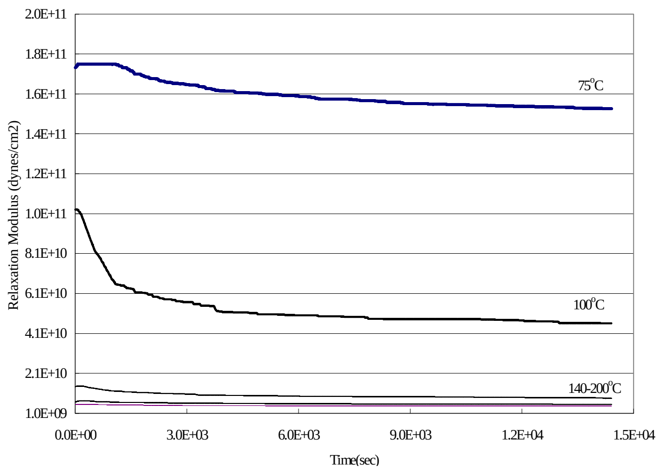

Figure 10. Relaxation Modulus of 0.1% Strain Application at 75-200°C

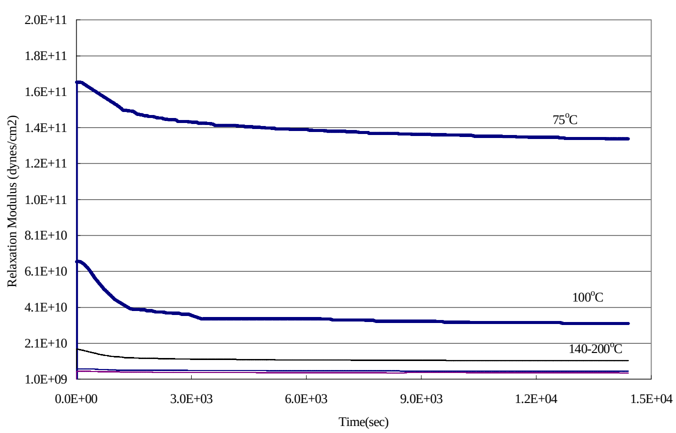

Figure 11. Relaxation Modulus of 0.25% Strain Application at 75-200°C

From Figures 10 and 11, it is evident that a big drop of relaxation modulus exists between 75°C and 100°C. Above 140°C, the relaxation modulus does not change much during the test. This phenomenon reveals that the glass transition temperature may be a dominant factor for the viscoelastic behaviors of EMC.

It should be noted that a duplicate test was done with 0.5% strain, loading at 140°C. Repeatability shows less than 5% error (Figure 12).

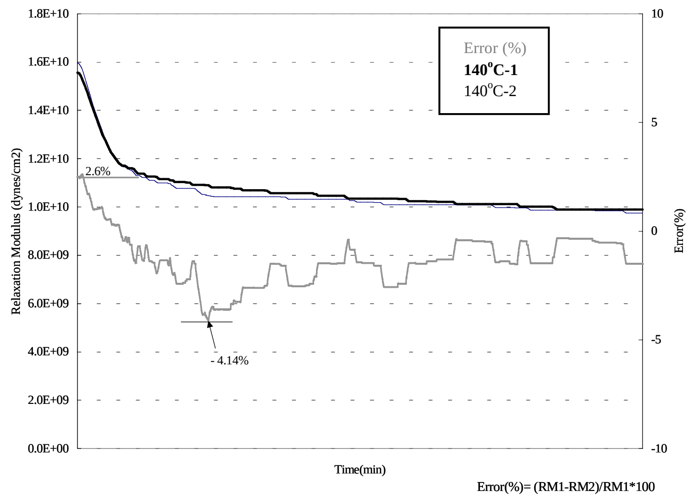

Figure 12. 0.5% Strain Application in Repeatability Test (RM: Relaxation Modulus)

Conclusions

In the present study, the stress relaxation modulus of a filled epoxy molding compound, Sumitomo EME-7351TQ, has been measured for temperatures ranging from 75°C to 200°C. The mechanical behavior of EMC exhibits time and temperature dependence, not only above the glass transition temperature, but also below it. The stress relaxation might continue over an extended period of time.

It was observed that, below 140°C, the modulus of relaxation depends on both temperature and strain loading. The tested EMC shows non-linear viscoelastic characteristics and nonlinearity characteristics between stress and strain is getting more significant as time passes at 75°C. Above 140°C, the drop rate and difference in modulus are not noticeable and the modulus decreased slightly as temperature increased during testing.

The results of the study can be used for the better prediction of computational stress analyses of PEMs. When the environmental temperature is relatively low, stress relaxation depending on both temperature and strain loading should be considered. On the other hand, for high temperature process, such as reflow soldering, lead or leadfree, the relaxation modulus mainly depends on the temperature. As a result, the modeling of EMC constitutive relation may become simpler.

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