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Resistance Strain Gauge Technique for High-Temperature Measurement

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Abstract. The article deals with problems of high temperature strain gauge measurements. A preliminary experimental work for purpose of mastery of this technique after a longer break has been kicked off in VZLÚ. Initially, possibilities of usage of commercial products are verified. Technical difficulties, historical milestones and up-to-date trends related to such measurement are shortly mentioned in the first section. Some achieved experimental results are presented in the second part of the article.

Introduction

A high-temperature measurement is one of the most challenging kind of strain-gauging. There are problems not only with endurances of the gauges and their wiring. The electric resistance strain gauges are temperature sensors simultaneously, so they generate an additional portion of the voltage output signal during fluctuations of the ambient temperature, unrelated to a mechanical loading. This so called *apparent strain* is influenced by many effects [1], which cannot be purely and separately described. It is necessary to consider both temperature changes of strain gauge characteristics causing a virtual strain and a real deformation of the structure due to its corresponding themal expansion, moreover influenced by different material coefficients of the gauge and the used adhesive. Generally, the apparent strain can be expressed:

$$\varepsilon_{app} = \left[\left(\alpha_m - \alpha_g \right) + \frac{TC}{GF} \right] . \Delta T \tag{1}$$

where

α_m …	coefficient of thermal expansion of the structure to which the gauge is bonded
α_g …	coefficient of thermal expansion of the gauge filament
GF …	gauge factor
TC …	temperature coefficient of resistance of the gauge filament
ΔT …	temperature change

All these parameters are not constant, but usually nonlinearly depending on the temperature. Therefore the resulting voltage response of the strain gauge mounted on a non-mechanical, only thermal loaded structure is troublesome to describe in closed mathematical term and more likely diagrams, established experimentally, are used. It is also evident, that the resulting apparent strain characterization is unique for each individualistic system: Strain-gauge type – means of its attachment – material of the testing part. Just properties of the used adhesive play the big role in the characteristics of whole sensor system – ideally, the value of its coefficient of thermal expansion should be closely similar the values of the materials of both the testing part and the gauge filament. This requirement is often uneasy to fulfil completely, because the primary property of the adhesive material must be to withstand very high temperatures without failures. Therefore, general characteristics given by strain gauge producers should be verified, just as in the case of in-house-made gauges. A typical example of testing of new strain gauge types is published in [2-4].

On the other hand, the sophistication of the evaluation process depends on purposes of the measurement strongly. Indisputably, an accurate measurement of (quasi-)static loading is the most complicated, because in this case all effects must be compensated and therefore excellent knowledge of characteristics of the mounted strain gauge should be at the disposal. A measurement of only dynamic component of the loading is simpler – a correction for the gauge factor corresponding the current temperature is sufficient, because we do not consider absolute values. And a checking of a dynamic behavior of rotors can be paradoxically an example of the modest evaluation because only resonance peaks and corresponding rotational speeds are requested, although such measurement on blades of gas turbines is, from the point of view of service conditions (temperature up to 1000 °C, centrifugal acceleration of about 60 000 g and high vibration), extremely harsh. First attempts were performed as early as 1940s, just few years after the invention of the resistance strain gauges, and nowadays these measurements are often considered to be routine – at least for leading industrial concerns [6]. By contrast, the performance of a static measurement still encounters non-excellent strain gauges, so a research in this respect continuously goes on.

The progress of high temperature strain-gauging in VZLÚ was related to development of jet engines (M 701 type), turboprop engines (M 601 and M 602 types) respectively, in Czechoslovakia during the years of 1958 – 1992 [7]. It was difficult to reach world-wide standards with limited resources in the period of the embargo on delivery of modern technologies for the countries of the Soviet bloc: All the more some original simple, but effective solutions surprised [8]. The experimental verification of vibration of the compressor and turbine blades of the M 701 jet engine, designed for the L-29 training aircraft, was the first task, because there were no reliable methods for computation of natural frequencies of blades, especially for higher modes, in 1950s. In 1980s the thermodynamic cycle of the M 602 engine was designed for the tempreatures up to 1000 °C (with cooled blades) even, however the two decade break consequential the politic and economic changes after 1989 caused heavy losses of knowledge. A re-activated interest in testing of new engines appears recently again. Nowadays, all past experiences are collected and in the first phase it was decided that applications of commercially obtainable products will be checked.

Short Review of History and Contemporary Technique

Strain Gauges. At the beginning each user usually manufactured own high-temperature strain gauges. Their grids were winded using a suitable resistance wire just on the intended place, because there were no proper back-carriers, high temperature resisting. The paper saturated with asbestos was used at temperatures up to 300 °C only. Subsequently, a few of strain gauge types has been commercially available since the late 1950s, commonly made from Nichrome V or Kanthal (Fe-Cr-Al) alloy both wire and foil design. They are the free-filament type in all cases and although the foil gauges have some benefits in comparison with the wire gauges, their bonding is an exacting art, mastered by few only. Other introduced materials for commercial high temperature strain gauges made by the company Hitec are Pt-W alloys. The best properties are expected with using a special Pd-13Cr alloy, because of its excellent structural stability up to 1200 °C [9]. In addition, special compensatory elements from platinum are designed for the gauges intended for the precise static measurement. High-Tech sensors fabricated by means of sputter deposition directly onto test article with very small thickness (so called *thin-films*) must be also mentioned [10], with advantages of negligible mass and minimal disturbance of the gas flow over the surface of measured turbine blade leading to minimal impact on the thermal, strain and vibration patterns that exist in the operating environment.

Attachment. An appropriate adhesive for instalation of the strain gauges must withstand intended high temperatures. In the past, a cement based on ceramics had to be used for the target temperatures in the range from 400 °C to 900 °C only. The development of own cement in VZLÚ evoked an alchemical process [8], including secrecy of the formula. The reaching for necessary thermal expansion (closed to values typical for metal alloys) and brittleness is the most important problem. Several trade-marks of cements specialized for bonding of hot temperature strain gauges have been appeared since the beginning ´60s. In Europe the Brimor cements were famous. However, the temperature limits of similar kind of the ceramic cements are up to 750 – 800 °C and a success of the measurement performed on turbines at higher temperatures is uncertain, more likely depending on an uncommon batch of the product.

Another solution is the mounting the strain gauges using thermal spray alumina (Al_2O_3) coats by ROKIDE® system. Contrary to plasma or flame spray of a powder material this system (originally patended by american company Norton) applies a special gun, in which the sprayed material supplied in the form of a rod is quite melted in an oxygen/acetylene flame, but the thermal loading of the substrate (and the mounted strain gauge herein) is relatively low – less than 60 °C. The attachment of the sensors is functional up to 1000 °C reliably and the positives of the process far out weigh the negative involved, for example a certain porosity of the sprayed material can lead to an oxidation of the gauge filament. Around the world this technique has been received as standard solving since 1960s [11 - 12], but in Czechoslovakia probably never was proved in the aircraft industry.

Of course, it should be note that with regard to absence of a carrier in the case of high temperature strain gauges it must be created an insulating layer, whether in the form of thin sprayed alumina or ceramic cement. For better results in the case of the ROKIDE technology it is often recommended to apply a precoat of other material which is more compatible to the substrate because of adhesion (e.g. NiCoCrAlY coating for the nickel-based superalloys).

Leading wires and their instalation are an individual theme. Problems related to their thermal endurance and reliability can be often larger than in the case of strain gauges himself. In the area of high temperature affection some kinds of thermocouple wires must be usually used and the leads may be replaced by common Cu-wires as far as in colder localities. The wires must be often protected by means of additional thermal isolation (asbestos fibres) or covering of the welded stainless steel foil.

Experiments

At first, fractional tests of some selected ceramic cements were performed. Older products of GA-100 and CR 760 types and contemporary models GC cement and DKS-8 were tested. Our past experiences were confirmed again – the temperature limits claimed by manufacturers are often very „optimistic“ values, differing from the reality. These limits are usually established according to the decreasing curve of the insulation resistance as a function of temperature for selected value (for example: 10 MΩ), which makes a broad range for an individual interpretation. But the problem can be simpler: The thermal expansion of the cement can be, compared to metal alloys, dramatically different. For example, the temperature limits of using of GC cement and DKS-8 type are very high – over 1000 °C, but considering their coefficient of thermal expansion they are not suitable for bonding metals (see Table 1) and the strain gauge strips away from a metal surface (mechanically unloaded) approximately at 500 °C.

Table 1. Coefficients of thermal expension [ppm/°C].

temperature basis [°C]	metal alloy			ceramic adhesive				
	Haynes 230	Nimonic 80A	Kanthal A-1	Brimor U529	GC cement	DKS-8	PBX	Al_2O_3 (99,5%)
20 – 200	11.8	13.3	11	11.1	2.7	4.7	13	8.4
20 – 600	12.8	15.0	13	13.6				
20 – 1000	13.6	18.1	15					

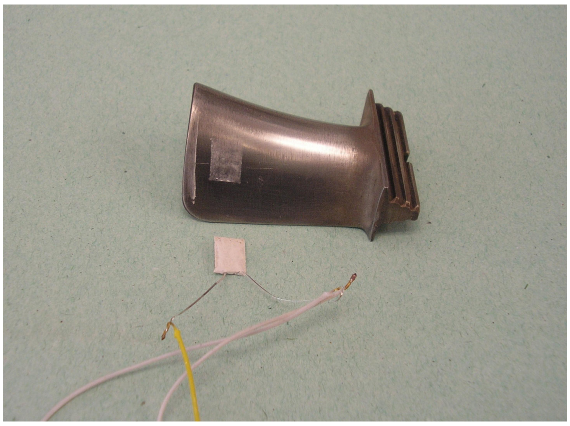

Fig. 1. Failure of the strain gauge mounted with using of the DKS-8 cement.

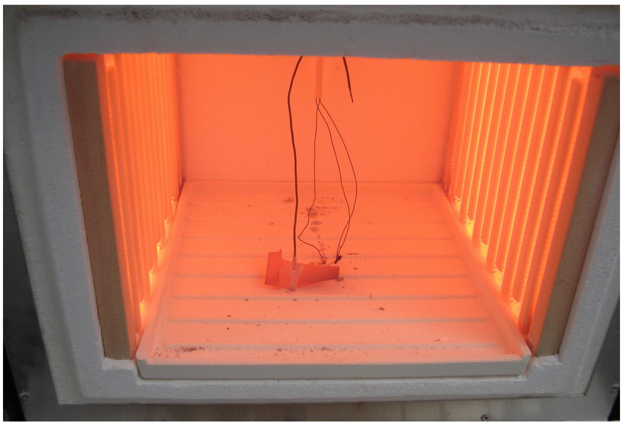

Fig. 2. Specimen with mounted strain gages and its wiring in the Omega Lux furnace.

Two models of common commercial high temperature strain gauges were used for the tests: Vishay ZC-NC-1262-120 is a foil gauge made from Kanthal alloy and equipped with Nichrome ribbon leads, its gauge factor is 2.80 and dimensions 1.57 x 1.93 mm (Fig. 3). BLH electronics HT-212-2A is a wire gauge made from Nichrome V alloy, its gauge factor is 2.03 and dimensions 3.2 x 1.6 mm (Fig. 4). The nominal resistance of both models is 120 Ω.

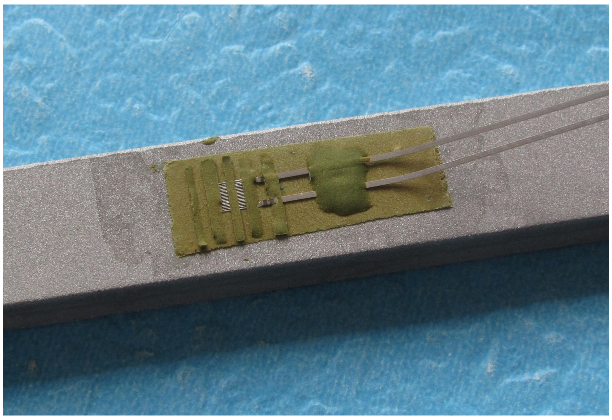

Fig. 3. ZC-NC-1262-120 strain gauge mounted on the Haynes 230 alloy specimen with using of the PBX cement.

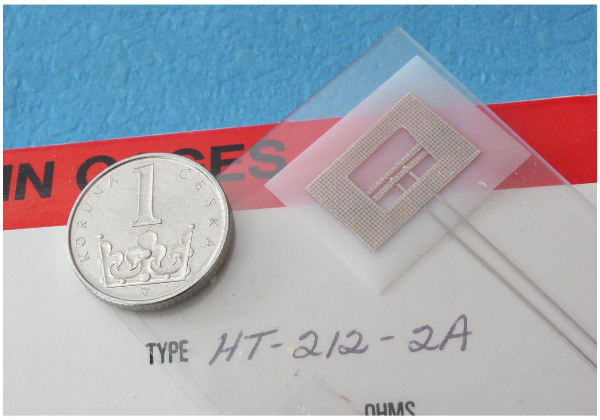

Fig. 4. Size of the HT-212-2A strain gauge.

Haynes 230 alloy was chosen as a substrate material to complying with the typical material properties in the range of nickel-based superalloys, from which hot parts of the turbine engines are usually made (Table 2). Changes of their mechanical properties in dependence on the temperature, namely the modulus of elasticity, are also interesting (Table 3).

Table 2. Nominal chemical composition (weight percent) of some important superalloys (Ni as balance).

Ni-alloy	Cr	Co	Ti	Al	Fe	Mo	W	other
Haynes 230	22	max 5	---	---	max 3	2	14	
Nimonic 80A	20	max 2	2.5	1.4	max 3	---	---	
Nimonic 105	15	20	1.5	4.7	max 1	5	---	
Inconel 713LC	12	---	0.8	6.5	---	4.5	---	Nb 2.1
Inconel 718	19	max 1	1.0	0.5	18	3	---	Nb 5.0
René 125	8.5	10	2.5	5.0	---	2	8.0	Ta 4.0

Table 3. Dynamic modulus of elasticity [GPa] of some important superalloys.

Ni-alloy	RT	200 °C	400 °C	600 °C	800 °C	1000 °C
Haynes 230	211	202	190	177	164	150
Nimonic 80A	219	210	197	183	165	141
Inconel 713LC	197	186	179	168	155	135

The tests were performed using two furnaces of the OMEGA LUX LMF – A550 type (see Fig. 2). The specimens were always equipped with K-type thermocouples for purpose of the measurement of the actual temperature near strain gauge position. Three-wire configuration of the quarter bridge strain gauge circuit was always used; the wires in the interior of the furnace were made from Nickel (originally a product for thermocouple wiring), outside common from copper. Signals from the sensors processed by the ESAM Traveller 2 measuring device were led to the Dewetron 2010 computer equipped with the DAQ card and software applications built on the LabVIEW platform. The data was recorded with the period of 10 seconds.

The verification process of various high temperature strain gauge attachment systems consisted of thermal endurance tests of the strain gauges and especially their mounting (the assessment of temperature limits) and tests to establish curves of the apparent strain and finding drift and zero-shift characteristics. The knowledge of long time characteristics (creep, life-time) is not necessary at present, because of typically short-time testing of engines. Likewise, a verification of gauge-factor changing was not performed in this first phase, because a special reliable loading fixture with high-temperature warming of the specimen is necessary.

PBX cement. This ceramic cement (originally in 1960s produced by the company Allen, nowadays Vishay supplies it) was screened for the reason that its manufacturer declares sufficiently high thermal expansivity (see Table 1), although the temperature limit of using of this cement is 650 °C only. Results of measurements performed on three specimen (i.e. instalations of strain gauges) look relative reliable and reproducible – an exhibit of apparent strain curves is in Fig. 5 – and they are in agreement with the data given by manufacturer or found in literature. However, the real scatter of the measured values of apparent strain for example at about 520 °C (Fig. 5) is in the range of a few hundreds $\mu m.m^{-1}$, which in consideration of levels of a common operating mechanical loading can make results of corrected measurement dubious.

It is evident, that this type of strain gauges (i.e. Vishay ZC-series), manufactured from „common“ Kanthal A-1 alloy, is not very suitable for purpose of the accurate static measurement. It is well-known [9], that these iron-chromium-aluminium alloys exhibit microstructural instability in the temperature range from 400 °C to 550 °C, therefore they are sensitive to heating and cooling rates at which the gauges pass through this transition temperature range. Fig. 6 demonstrates this effect. In order to improve posibilities of the static measurement, a development of an ideal material for the high temperature strain gauges still goes on. For example, the strain gauges made from the above mentioned Pd-13Cr alloy, equipped with appropriate compensatory elements, provide levels of the apparent strain up to 300 μm.m^{-1} only, in the temperature range up to 800 °C.

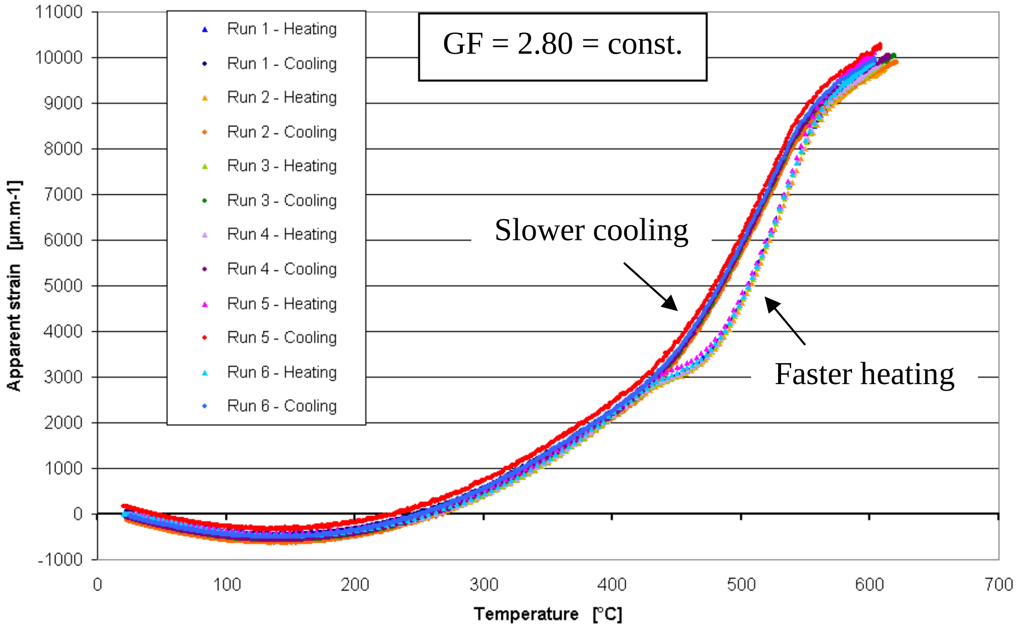

Fig. 5. Apparent strain measured on the specimen no. C3 (Vishay strain gauge).

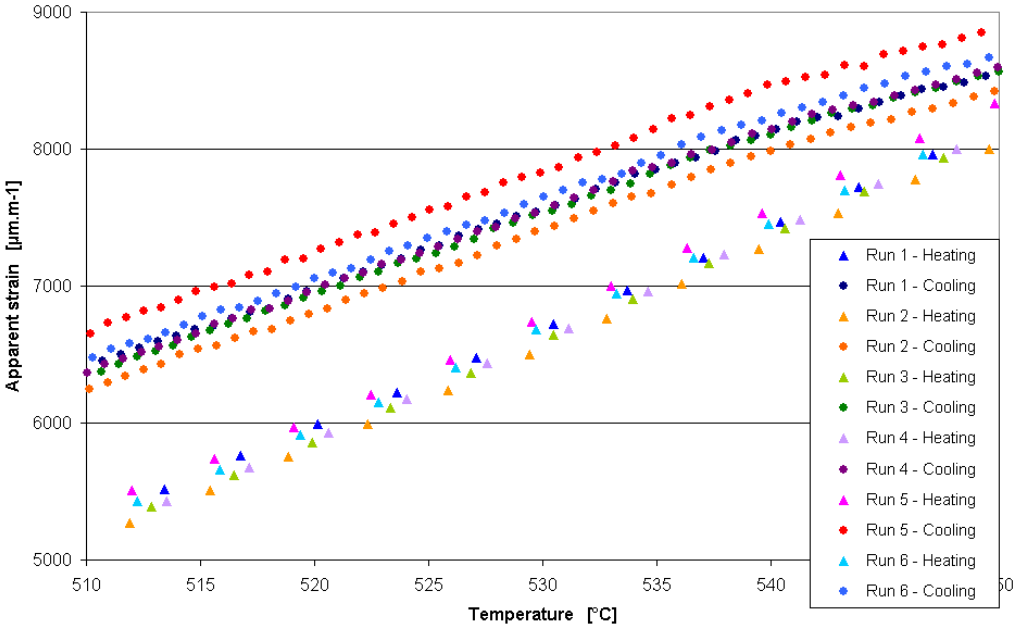

Fig. 6. Detail of the graph in Fig. 5.

Flame spraying. A co-operation with a company owning the ROKIDE® system has been established to verify possibilities of this technique. For purpose of a reference testing the first six specimens were prepared, equipped with both types of strain gauges fifty-fifty. Fig. 6 shows a typical mounting. It must be noted that for the present a standard quality of alumina was used; no special material that is specified for installation of strain gauges, characterized by higher purity and leading to lower roughness and porosity. This fact, together with the first experiences of the operator, could lead in inconsistent results. The specimens assessed visually as the best were characterized by a good stability of strain gauge output behaviour. Apparent strain curves of the best strain gauge installation are in Fig. 8; the data obtained from the second specimen shows a greater scatter. But abnormal variations appeared during repeated temperature cycles (heating-cooling) in the case of other specimens, and so it was evident some quick progressive degradation of these strain gauges. However, the mechanical endurance of the mounting of the strain gauges was excellent. All specimens withstood the temperatures above 1000 °C for number of hours without peeling from the substrate surfaces.

Fig. 7. Strain gauge ZC-NC-1262-120 mounted on the Haynes 230 alloy specimen with using of the ROKIDE technology of flame spraying.

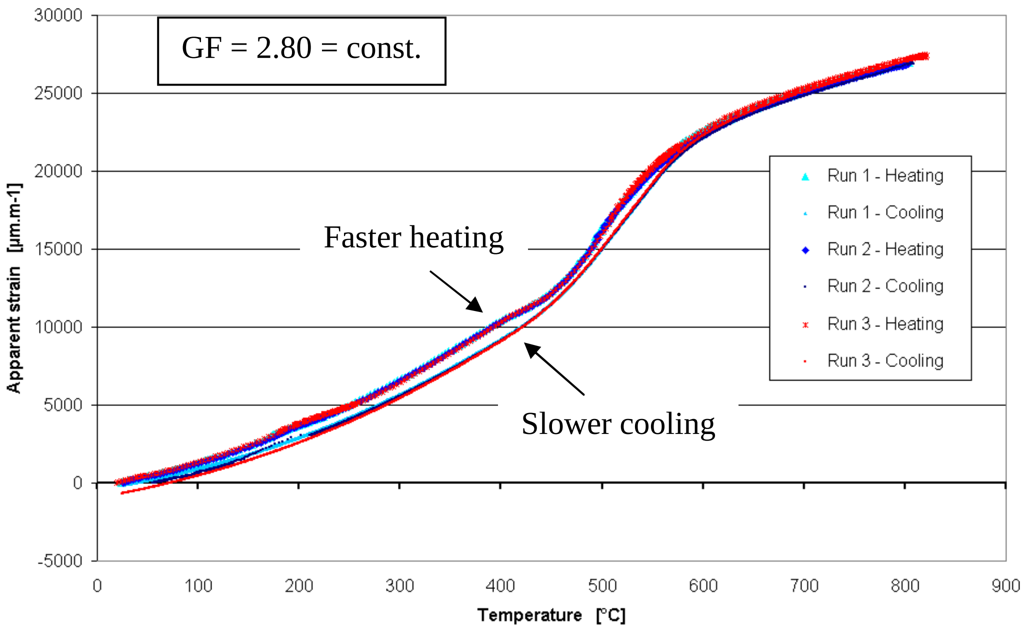

Fig. 8. Apparent strain measured on the specimen no. R1 (Vishay strain gauge).

Conclusions

The first tests confirm thermal endurance of the gauge mounting with using the ROKIDE technique up to 1000 °C. However, repeatability of the apparent strain curves up to 500 °C is somewhat poorer than in the case of the installation using the cement PBX, probably due to higher roughness of the base coat spray or porosity of the cover-coat and subsequent oxidation process of the strain gauge. Therefore the process of installation of the strain gauges must be improved. On the other hand, some negatives are not serious for short dynamic measurement. However, the flame sprayed process can also change the values of gauge factor [5], so in this respect the next phase of testing should be managed.

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