Radiation Characterization of Optical Frequency Domain Reflectometry Fiber-Based Distributed Sensors

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***Abstract*— We studied the responses of fiber-based temperature and strain sensors related to Optical Frequency Domain Reflectometry (OFDR) and exposed to high γ-ray doses up to 10 MGy. Three different commercial fiber classes are used to investigate the evolution of OFDR parameters with dose, thermal treatment and fiber core/cladding composition. We find that the fiber coating is affected by both thermal and radiation treatments and this modification results in an evolution of the internal stress distribution inside the fiber that influences its temperature and strain Rayleigh coefficients. These two environmental parameters introduce a relative error up to 5% on temperature and strain measures. This uncertainty can be reduced down to 0.5% if a pre-thermal treatment at 80°*C* and/or a pre-irradiation up to 3 MGy are performed before insertion of the fiber in the harsh environment of interest. These preliminary results demonstrate that OFDR fiber-based distributed sensors look as promising devices to be integrated in radiation environments with associated large ionizing doses.**

***Index Terms*— Optical fiber sensors, radiation effects, temperature measurement, strain measurement**

I. Introduction

THE development of new technologies to enhance and reinforce safety in nuclear power plants (NPPs) is today the subject of various studies. Fukushima accident can be considered as a turning point because it highlighted several weaknesses in the monitoring, under accidental conditions, of NPP parameters such as temperature, pressure or radiation doses. Nowadays, with the building of new reactors based on nand for enhanced sensors is increasing for the control of these environmental parameters in harsh environments [1].

In the panorama of different techniques, optical fiber-based sensors have attracted much interest over the last decade. They offer several advantages such as small size and light weight that coupled with the multiplexing capability give the possibility to substitute several older discrete sensors and cables with one fiber. These properties of optical fibers give some benefits such as reducing the nuclear waste or decreasing the sensor time [2] [3]. However, it is well known that radiation degrades fiber responses by inducing point defects that increase the optical losses along the fiber and change the refractive index [2].

Among the different optical fiber sensing techniques, those based on light scattering are the most investigated: from Fiber Bragg Gratings (FBGs) for discrete measurements [4] to Brillouin [5], Raman [6] [7] and Rayleigh [8] for distributed measurements. The choice of one technique with respect to the others depends on the characteristics and the sensor profile of use. Whereas Raman sensors are sensitive only to temperature, Brillouin and Rayleigh ones can be used to monitor both temperature and strain evolutions along the sensing fiber. These two kinds of sensors however differ by the spatial resolution they offer that varies from about one meter in Brillouin up to few µm in the case of Rayleigh sensor based on OFDR.

Here we use OFDR to investigate the dependence on the parameters involved in distributed temperature and strain measurements on radiation dose and thermal treatments. An OFDR fiber-based sensor uses the Rayleigh scattering signature of the fiber under test in both unperturbed (reference) and perturbed states. The scattered profiles from the two datasets are cross correlated along the perturbed portion of the fiber to obtain the spectral shift in this part of the fiber caused by a temperature and/or strain change. Rayleigh spectral shift exhibits linear temperature and strain dependencies through Equation (1):

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta\nu}{\nu} = C_T \Delta T + C_\varepsilon \varepsilon \qquad (1)$$

where λ and ν are the mean optical wavelength and frequency respectively; C_T and C_ε are temperature and strain calibration coefficients with typical values of $6.48\cdot10^{-6}\ ^{o}C^{-1}$

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and $0.780\mu\varepsilon^{-1}$ for Germanium-doped silica core fibers [9]; ΔT and ε are the applied temperature and strain changes, respectively.

Our recent works have investigated the vulnerability of OFDR fiber sensor to ionizing radiation [10] [11]. The study in [10] reports the characterization of C_T and C_ε and deals with the permanent γ-radiation effects up to 10 MGy on five different fibers classes, from radiation resistant to radiation sensitive ones. It is shown that the scattering mechanism at the basis of OFDR technique for the monitoring of temperature and strain is unaffected (changes below 5%), thus authorizing acceptable precision on the distributed measurements. The investigation, performed on a germanosilicate optical fiber [11], demonstrates that *in situ* distributed temperature measurements are not affected by transient radiation effects during both irradiations up to 1MGy and recovery processes. Those results have revealed that OFDR is a powerful technique possessing an almost unaffected response by radiations opening the way to the development of new NPPs security systems for which an urgent needs is observed since Fukushima's accident. However, both in [11] and in [12] it is reported that distributed measurements can be affected by the packaging (including coating, metallic tubes, bridles …) of the sensor resulting in errors caused by an inaccurate calibration.

Several studies have been devoted to the investigation on coating effects in various conditions to examine its mechanic resistance in presence of external strain [13], when thermal treatments are performed [14] [15] or in presence of ionizing radiation [16]. The axial strain induced stresses in double coated optical fibers was studied in [13] by the viscoelastic theory showing that the coating influences the induced stresses proportionally to the applied perturbation and they depend on the coating material's properties. The temperature influences the coating/glasses interaction: typical plastic coating with high Young's modulus substantially increases the temperature sensitivity [17]. For a standard double acrylate coating it becomes clear that the mismatch of the thermal expansion coefficient between silica glass and the secondary coating induced internal strain into the optical fiber by a thermal shrinkage that occurs at ~90*°C* corresponding to the transition temperature, T_g, of the secondary coating. The thermal contraction in the longitudinal direction disappears when the secondary coating is aged under temperatures above T_g [14] [15].

These investigations reveal the effect of a perturbation on a coated optical fiber and show that the interactions coating/fiber move to a stabilization that changes the distribution of the internal stress along the fiber diameter. The stress profile in a fiber is a function of several parameters and it was calculated in [18] for a Ge-doped and a Er-Ge-Al-doped optical fibers showing that along the fiber profile there are different zones of tension or compression that are dopants dependent.

Also radiation has an impact on the coating; Fig.1 is a typical example picture of optical fiber samples with a double acrylate coating non-irradiated and irradiated at different γ doses from 1 to 10 MGy: the evolution of the color is clearly evidenced even to a naked eye. A previous study [16] reveals that these changes improve the mechanical properties and fiber strength parameters up to 2 MGy of radiation but, to the best of our knowledge, there are no results on the effects of radiation on the coating in relation with its temperature response.

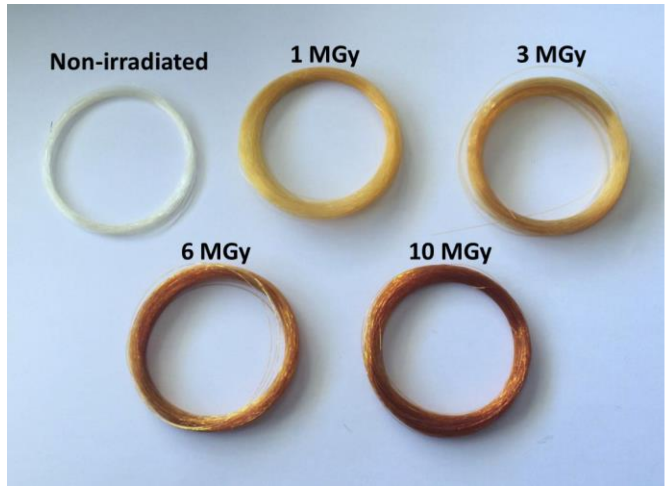

Fig. 1 Fibers photo of non-irradiated sample and irradiated at 1MGy, 3 MGy, 6 MGy and 10MGy to highlight the degradation of the coating due to the radiation.

The purpose of the present work is to improve the understanding of radiation effects for OFDR sensors. In particular, to go deeply into the influence of fiber design on the sensitivity of C_T and C_ε coefficients to radiation, we compare three single mode fibers with different dopants in core and cladding and with a double acrylate coating. We perform consecutive thermal treatments in order to stabilize the coating/glass configuration; this approach will give us the possibility to overcome packaging linked problems (i.e. the influence of the coating on the performance of distributed OFDR sensors) and to estimate the effects induced by the radiation on C_T and C_ε and on distributed temperature and strain measurements.

II. Materials and method

A. Investigated samples

We investigate the response to radiation of three commercial single mode fibers from Prismian/Draka manufacturer: the first (SMF-Ge1) is a step index single mode fiber, doped with germanium in the core with a cladding of common silica and widely used in the telecom and sensor market; the second one (SMF-Ge2) is a single mode fiber, doped with germanium into the core with a pure silica cladding that improves its hardness to radiation and the third fiber (SMF-F) is a single mode fiber doped with fluorine in the core and more heavily doped with F in its cladding. The three fibers have a Dual Layer Primary Coating (DLPC) resisting up to 85 *°C*.

B. Irradiation facilities

The γ-ray irradiations were performed using a ^{60}Co source facility (BRIGITTE) in SCK-CEN (Mol, Belgium) [19]. The accumulated dose on our samples varies from 1 MGy up to 10 MGy(SiO_2), the dose-rate and the temperature ranging from 10 to 30 kGy(SiO_2)/h and from 30°*C* to 50°*C*, respectively. For each of the three fibers described above we obtain four different samples to characterize irradiated at 1, 3, 6 and 10 MGy, as well as the non-irradiated sample.

C. Distributed temperature and strain measurements

Distributed sensing measurements were done, post irradiation, with an Optical Backscatter Refectometer (OBR) 4600 from Luna Technologies. OFDR distributed sensing measurements were performed to deduce C_T and C_ε presented in Eq. (1) and therefore calibrate the sensor responses to these two parameters.

To this aim we developed two experimental setups to measure the OBR response when the temperature (or the strain) applied to the fibers evolves. C_T and C_ε coefficients, for all the three investigated fibers in both non-irradiated and irradiated samples, are extracted from the experimental results and compared. In all measurements described below the laser source was tuned over a range of 21 nm around a central wavelength of about 1550 nm (with an accuracy of 1.5 pm), yielding a nominal spatial resolution of the Rayleigh scattered pattern of ~40 µm.

Temperature calibration was done in an oven controlled by a type K thermocouple; C_T was deduced from the slope of the relative Rayleigh spectral shift with temperature in the range from 30 °*C* up to 80 °*C* with a ΔT of 5 °*C*, waiting a half hour at each temperature after its stabilization. Maximum temperature is related to the maximum temperature the acrylate-based coatings can resist without impacting the fiber properties. For such experiments, all the samples of the same fiber type, both non-irradiated and irradiated at 1, 3, 6 and 10 MGy, were spliced in series to perform the temperature treatment at the same time; the entire segment was ~10 m long.

Strain parameter was precisely induced by stretching the fiber with a translation set up coupled to an adapted tensile gauge for both the evaluation of the applied constraint and its stability during the measurement. The strain applied along the fiber is given in the relation: $\varepsilon=\Delta L/L$, were L is the length of stretched fiber (~50 cm). This measurement method was applied to all fiber samples, one after the other, under similar conditions. The coefficient C_ε was deduced from the slope of the Rayleigh spectral shift with strain in the range from ~0 $\mu\varepsilon$ up to 4000 $\mu\varepsilon$.

An example of obtained curves is reported in Fig. 2 for temperature and strain calibration in SMF-Ge1 fiber.

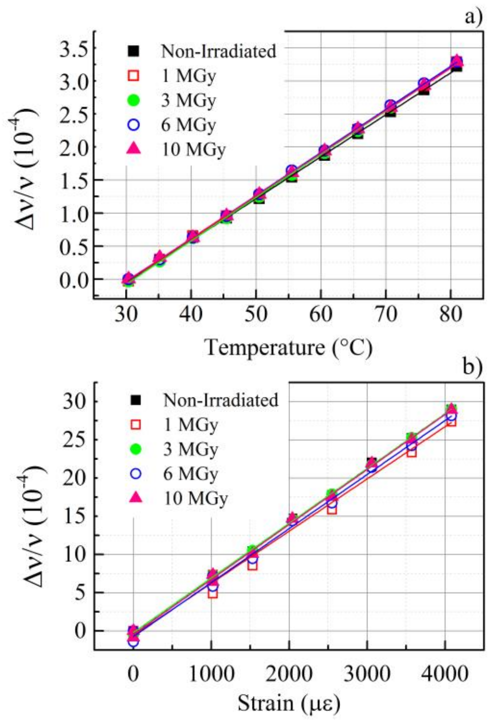

Fig. 2 Relative Rayleigh spectral shift dependence on temperature (a) and on strain (b) for SMF-Ge1 pristine and samples irradiated at 1MGy, 3MGy, 6MGy and 10MGy. These curves are shown for one point for each fiber in the considered range chosen to calculate C_T and C_ε.

To better understand the effects of radiation on OFDR calibration coefficients we study the stability of C_T and C_ε with three consecutive thermal treatments. The temperature profile is that of temperature calibration (i.e. from 30 °*C* up to 80 °*C* with a ΔT of 5 °*C*). We measured C_T and C_ε in as drawn sample (corresponding for the C_T to the sample after the first temperature calibration and further named as N-T) as well as in the sample after one, two and three thermal treatments.

III. Experimental results

Fig. 3 shows C_T evolution with thermal treatments for (a) SMF-Ge1, (b) SMF-Ge2 and (c) SMF-F in non-irradiated and irradiated samples. We detect in all the samples the maximum variation of C_T between the non-thermally treated fiber (i.e. C_T obtained after one calibration) and the fiber after the first thermal treatment. The next treatments slightly affect the C_T value that stabilizes at the third treatment.

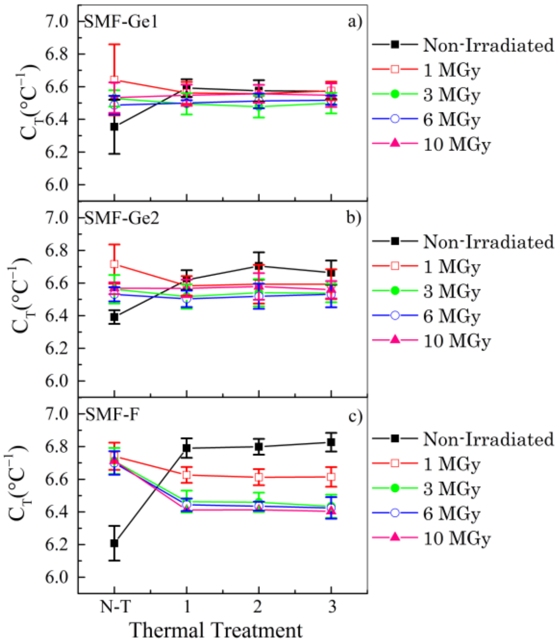

Fig. 3 Temperature coefficients (C_T) after consecutive thermal treatments of SMF-Ge1 (a), SMF-Ge2 (b) and SMF-F (c). We report C_T non-irradiated (black points), 1 MGy (red points), 3 MGy (green points), 6 MGy (blue points) and 10 MGy (pink points) irradiated samples.

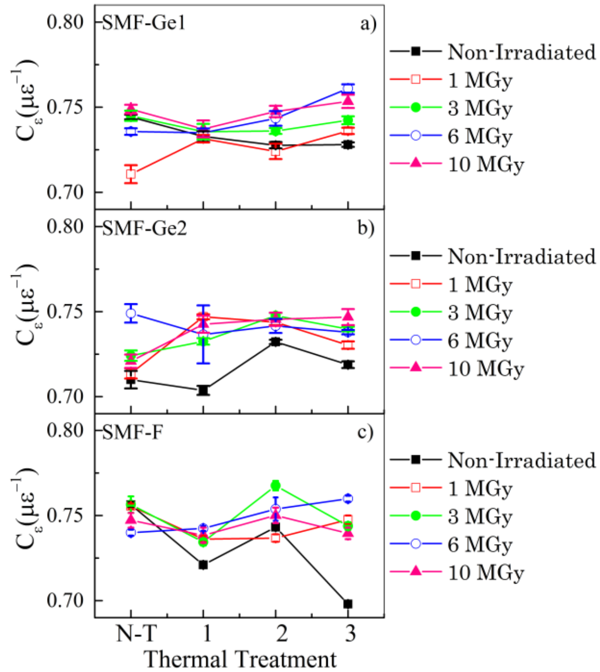

Fig. 4 Strain coefficients in non-thermally treated and treated SMF-Ge1 (a), SMF-Ge2 (b) and SMF-F (c). We report C_ε of non-irradiated (black points), 1 MGy (red points), 3 MGy (green points), 6 MGy (blue points) and 10 MGy (pink points) irradiated samples.

We highlight the positive influence of the irradiation in the stabilization of C_T. In particular we find that for the three fibers the non-irradiated sample behavior differs from the irradiated ones: C_T value increases between non-thermally treated fiber (i.e. C_T obtained after one calibration) and the fiber after the first thermal treatment of about 4% in SMF-Ge1 and SMF-Ge2, and of about 10% for pristine SMF-F samples. In irradiated fibers C_T value decreases between the non-thermally treated fiber and the fiber exposed to the first thermal treatment with amplitude depending on the fiber composition and on irradiation doses. SMF-Ge1 and SMF-Ge2 samples exhibit variations between the first and the second thermal treatments which decrease with increasing the dose: we observe 2% of variation at 1 MGy, 1% for 3 MGy and below 0.5% at 6 MGy and 10 MGy samples. We observe a different behavior for SMF-F for which C_T variations in irradiated samples are lower than in the non-irradiated one. In fact, they increase with the dose: 1.7% for 1 MGy, 3.8% for 3 MGy, 4.0% for 6 MGy and 4.7% for 10 MGy. After the first thermal treatment C_T stabilizes with variation lower than 0.5%.

Strain characterization is reported in Fig. 4. We performed the calibration on non-irradiated and irradiated samples at the four doses of 1MGy, 3MGy, 6MGy and 10MGy. Investigated samples were also thermally treated to investigate the stabilization of C_ε with such a treatment on the fiber. The samples were treated at the same time of temperature calibrations in order to characterize non-treated fiber and samples after one, two and three thermal treatments. Fig. 4 shows the obtained coefficients for (a) SMF-Ge1, (b) SMF-Ge2 and (c) SMF-F. We note that there is no effect of thermal treatment on the determination of C_ε: the values are scattered with a maximum variation between two consecutive thermal treatments of 2.9% for SMF-Ge1, 4.7% for SMF-Ge2 and 4.9% in the case of SMF-F. These variations are not reduced by treating the fiber as in C_T and permit a relative error up to the 5% on strain measurements.

IV. Discussion

From temperature and strain characterization we are able to study the evolution and stabilization of C_T and C_ε in three single mode optical fibers with a double acrylate coating. Temperature calibration points out the positive influence of a pre-treatment and improves the performances of optical fiber sensors by stabilizing the temperature coefficients. We find that C_T changes between the as drawn samples and the sample after one thermal treatment in both non-irradiated and irradiated ones (e.g. we obtain the 10% of variation in the case of SMF-F non–irradiated); then temperature coefficients stabilize with variations lower than 0.5% for treatments successive to the first one. This effect, according with [14] and [15], can be explained by the influence of thermal treatment on the coating which is subjected to a dilatation that releases stress into the fiber. It considerably decreases after a first thermal treatment showing that this first thermal treatment is probably mandatory before the OFDR sensor calibration. In the case of strain coefficient we are not able to extrapolate the thermal treatment effects being the values scattered with a variation between two consecutive thermal treatments up to 5%. We suppose that this variation is due to the accuracy on the determination of C_ε, since our strain setup does not allows us a precision on induced strain as high as the oven with the temperature.

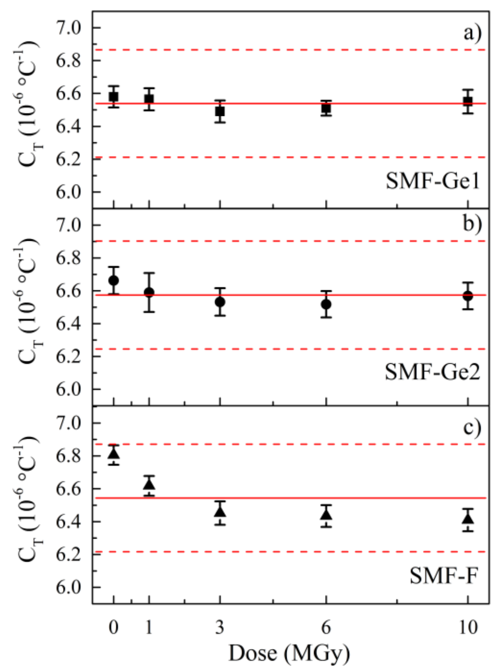

Fig. 5 Temperature coefficient as a function of irradiation doses in (a) SMF-Ge1, (b) SMF-Ge2 and (c) SMF-F. Solid line in the middle indicates the average values of the coefficients and space between dotted lines in each graph indicates a variation of 5% from average values.

Moreover, we observed the irradiation influences the behavior of temperature coefficients: in the non-irradiated sample C_T increases after the first thermal treatment, whereas in irradiated samples it decreases. The explanation is linked to the radiation induced changes in the properties of the coating which affects the calibration of the fiber sensors. To better understand the effects of radiation we report the evolution of C_T and C_ε with radiation dose. These data are an average of the coefficients obtained without taking into account the non-treated fiber in which coefficients have been observed to be unstable.

Fig. 5 shows C_T as a function of the dose for SMF-Ge1, SMF-Ge2 and SMF-F. We note that C_T is not affected by radiation in SMF-Ge1 where the variations are lower than the error on the measurements (0.5%); in SMF-Ge2 and SMF-F however it decreases with increasing the irradiation dose with variation between non-irradiated and 10MGy irradiated fiber of 1.5% in Ge2 doped and 5% in F-doped fiber. These variations are more important between non-irradiated and 1MGy and 3MGy whereas the coefficient does not change after 3MGy up to 10MGy.

Similar is the case of C_ε, shown in Fig. 6, where no clear trend of this parameter with radiation is observed in SMF-Ge1. In contrast, SMF-Ge2 and SMF-F exhibit a strain coefficient that increases with increasing radiation dose with variation between non-irradiated and 10MGy irradiated fiber of 5% in GeF doped and 2% in F-doped fiber. Also in this case we note a stabilization of the coefficient after 3MGy (variation lower than 0.5%).

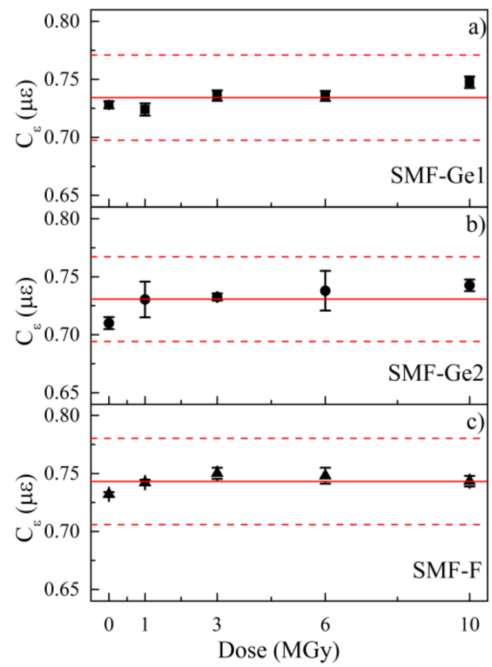

Fig. 6 Strain coefficient as a function of irradiation doses in (a) SMF-Ge1, (b) SMF-Ge2 and (c) SMF-F. Solid line in the middle indicates the average values of the coefficients and space between dotted lines in each graph indicates a variation of 5% from average values.

We theorize that radiation changes the mechanical properties of the coating [16] and its composition; the coating itself when submitted to radiation changes the internal stress distribution into the fiber behaving as a thermal treatment; this effect however saturates around 3MGy. These variations of temperature and strain coefficients induce an error on the two investigated parameters when the fibers are employed as sensors. This error is mostly related to the coating change when exposed to heating or to radiation [20]. Both release stress into the fiber and change the temperature and strain coefficients. We show that by performing pre-treatments we are able to reduce both these errors and improve sensor performances under extreme environments.

V. Conclusion

Our work explored three single mode optical fibers in order to evaluate their performances as distributed OFDR sensors in radiation environments. By performing temperature and strain calibration we investigate the stability of C_T and C_ε to γ irradiations up to 10MGy. Fiber coating radiation response affects the evolution of these coefficients thus introducing errors in strain or temperature distributed measurements. A pre-thermal treatment up to 80°*C* and/or a pre-irradiation up to 3MGy reduce the packaging linked error on C_T and C_ε variations from 5% to 0.5% improving the performances of fiber sensors for operation, in harsh environments. Future work will focus on the radiation and temperature effects on fibers with high temperature coating such as high-temperature acrylate, polyimide, Al, Au or Cu-coating as these specialty fibers are envisaged for operation in nuclear power plants.

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