TP-PHYSICS INTEGRATION
TPD – DIAGNOSTICS

TASK: TW4-TPDC-IRRCER
Irradiation effects in ceramics for heating and current drive, and diagnostic systems

***Deliverable:* In-situ measurement in the visible-UV range of the response of large-diameter core optical fibres to gamma irradiation**

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Optical fibers will play an important role in the future ITER and DEMO reactors as they will be incorporated into different assemblies to be used in plasma diagnostics, sensing, remote control and signal transmission over optical channels. [1] Optical links are needed for plasma diagnostics to pick-up the optical signal and to carry it to remote locations through a noisy electromagnetic environment, under high temperature, high gamma-ray dose rate and high neutron fluences. [2] Under irradiation optical fibers exhibit both a radiation-induced absorption (RIA) and radiation-induced luminescence (RIL) [3] – [7]. The first effect distorts the transmitted spectral to be evaluated, as in some spectral bands the attenuation becomes radiation dependent, while the second one deteriorates the signal-to-noise ratio, as an additional optical signal is superposed on the signal to be measured. Most of the investigations on this phenomenon were performed over the visible and near-IR part of the spectrum (above 400 nm and below 2000 nm). New techniques were developed to reduce the degradation of the optical transmission of optical fibers to be subjected to ionizing radiation. [8] – [10] As the UV spectral band (200 nm – 450 nm) of the optical spectrum is of great interest of plasma diagnostics optical fibers with an enhanced UV response were investigated under both gamma-ray and neutron flux irradiation. [11] – [12].

In investigating radiation effects on optical fibers (mainly in the UV range) one has to consider several aspects:

- colour centre appear in the 200 nm – 450 nm spectral range following exposure to UV radiation, after irradiation with ionizing radiation;
- some of the generated colour centres are stable while some others can disappear under different conditions (temperature rise, remove of the irradiation situation, exposure to optical radiation – photobleching);
- in some cases, the radiation induced increase of the optical absorption can be accompanied by a simultaneous optical radiation emission (radioluminescence);

- some colour centres are due either to the stress induced during fabrication or to the ingredients associated to the technology used.

Considering all these aspects we devised some experiments in order to observe:

- the dynamics of the colour centres;
- optical absorption recovery at room temperature;
- the photobleaching effect;
- the influence of the optical fibre core diameter on the irradiation induced absorption.

1. Experimental set-up

Our previous work was related to the evaluation of various types of optical fibers, from different manufacturers, in order to assess off-line their capability to resist transmission degradation under irradiation, and some time combined with temperature stress. In this report we focus our efforts on the on-line measurements of UV enhanced response optical fibers subjected to gamma-ray irradiation. In addition, some off-line investigations were performed in order to better assess the optical fiber behaviour under irradiation. A PC-controlled set-up to be used for on-line investigation of gamma radiation effects, at room temperature, was developed. The optical characteristics of large core diameter optical fibers were monitored in real time with a multi-channel optical fiber spectrometer. The mini spectrometer can perform spectral measurements over three bands (200 nm – 650 nm, 650 nm – 850 nm, 850 nm – 1080 nm, with a resolution of 1.5 nm over the first spectral interval and a resolution of 0.5 nm on the other two). The data acquisition integration time is programmable by the user and varies from 3 ms to 65 s. Spectral averaging and boxcar functions are available. The spectrometer input is coupled to different signal sources, depending on the type of investigations through an optical fiber multiplexer. The multiplexer can multiplex 8 channels with a reproducibility of 99 % and a switching time of 200 ms. Its common output can be switched to a reference position, when no signal enters the multiplexer. Each sample optical fiber is connected in an appropriate manner to the spectrometer and to the lamp through two 400 μm core diameter optical fiber probes. [13]

The multiplexer's operation as well as the data acquisition from the mini spectrometer is controlled by a PC. For these tasks we developed special virtual instruments (VIs) using the National Instruments LabVIEW graphical programming environment.

In the case of the radioluminecence determination, in order to accommodate the detection of the radioluminescence signal having a wide dynamic range, we developed a software module that evaluates the peak value of the emitted spectrum and modifies the integration time of the spectrometer in X 1; X 10 and X 100 steps. For each step the amplitude span of the detected signal can be as high as 3 500 counts. In this way, we are able to investigate emission signals over more than 5 decades. In this mode of operation, the user has to select only the type of fiber to be investigated, and the programmed automatically acquires spectra over the selected channel at programmed time intervals, and adjust the integration time so that the detected signal is located above a noise level and below the upper limit of 3 500 counts. After each measurement, all data are normalized to the scaling factor and are saved in Excel-like files. Each file includes in its name the time stamp (day/month/year/ minute/hour) for an easy correlation of data with external changes (i.e. increase of the dose rate, temperature rising, etc.). The user's interface displays the current integration time and the peak value of the luminescence signal for the acquisition under way. The virtual instrument runs continuously until an external stop command is issued by the operator. A text indicator displays a message indicating the status of the programmed (acquisition, saving, peak value computation, etc.)

For the case of the absorption measurements, another VI is used. The user can select the fiber type (from a library of existing fibers) and can enter also the optical fiber length. A temporal stamp is attached to the save data in this case, too. Information concerning the operating status of the instrument is displayed in the message window. By using the LabVIEW graph built-in capabilities, the operator can zoom on both X and Y-axes and can scroll through past data.

In the "absorption acquisition" mode of operation, the external optical fibre multiplexer is used to connect to the spectrometer input slit either the output from the deuterium lamp or the sample optical fibre to be evaluated as it is coupled to the light source. For the case the signal from the deuterium lamp is too strong, an attenuator, mounted on-line with the light source, is used to control the signal level. The spectral characteristic of the attenuator is almost flat; it decreases slightly below 300 nm. This fact does not affect the overall measurements of the optical fibres' spectral attenuation because the attenuator is coupled on-line with the deuterium source; hence its attenuation is rejected as a common mode signal.

The three signals (dark signal, deuterium source, and that propagating from the lamp through the fiber to be measured) are further utilized to compute the spectral optical absorption of the sample, according to the formula:

$$A_\lambda = -\log_{10}\left(\frac{S_\lambda - D_\lambda}{R_\lambda - D_\lambda}\right) X \frac{1}{l},$$

where, A_λ represents the spectral optical absorption (dB); S_λ – the spectral distribution of the signal measured by the spectrometer as the light is passing through the sample optical fiber; D_λ – the spectral distribution of dark signal measured by the spectrometer; R_λ – the spectral distribution of deuterium lamp output, measured by the spectrometer; l – the optical fiber sample length.

The operator can introduce also the optical fiber sample length, so that the attenuation in dB/m is calculated and displayed, for the case of an optical path with a uniform distributed attenuation.

For spectral attenuation measurements, because the sensitivity of the CCD detector is very poor in the UV region (200 nm – 450 nm), the acquisition is done over smaller spectral intervals (i.e. from 200 nm to 220 nm). In each case, an optimum integration time is used (parameter determined automatically by the software).

2. On-line measurements

For the in-situ investigations on optical properties of optical fibres subjected to gamma-ray irradiation we used the gamma-ray facility at the "Horia Hulubei" National Institute of R&D for Physics and Nuclear Engineering–IFIN-HH, in Bucharest.

The optical fibre sample (a 400 µm core diameter, black Tefzel jacket optical fibre) we measured was fixed on a specially designed mount in order to be able to fit the small irradiation volume to which we have access (a cylinder with a 10 cm diameter and about 20 cm height). In this mount, the fibre was bent several times, so that the length of irradiated optical fibre was 1.8 m, while its overall length was 2.71 m. In order to avoid the exposure to gamma radiation of the optical fibre probes used to connect the samples to the measuring set-up we kept the optical fibre sample ends out of the irradiation zone.

The optical fibre sample was in this case equipped with fixed SMA connectors. In order to obtain the best performances (the lowest insertion loses) the connectors were mounted at the Romanian subsidiary of one of the best known patch cost producers (the Diamond Company from Switzerland), where optical fibre's ends were also polished.

The radiation dose rate was ***0.33 kGy/h***. The irradiation was done at the room temperature.

Before the irradiation, the optical transmission in the UV spectral range was evaluated in the Laboratory, for the following components: the optical fibre sample, the optical fibre probes, and the optical attenuator. Some of the measurements were done both automatically and manually, for reference. We evaluated the optical transmission of two combinations of optical fibre probes:

- one 2 m long, 400 µm core diameter, solarization resistant optical fibre with plastic jacket and one 6 m long, 400 µm core diameter, solarization resistant optical fibre with metallic jacket;
- two 6 m long, µm core diameter, solarization resistant optical fibres with metallic jacket.

The initial transmission in the UV range of the optical fibre sample to be subjected to gamma irradiation was measured in the following situations (Figure 1):

- the optical fibre was kept on a straight line and connected directly to the optical fibre multiplexer;
- it was bent into the mechanical mount used during its irradiation;
- it was coupled to the optical fibre multiplexer by using two 6 m long optical fibres probes.

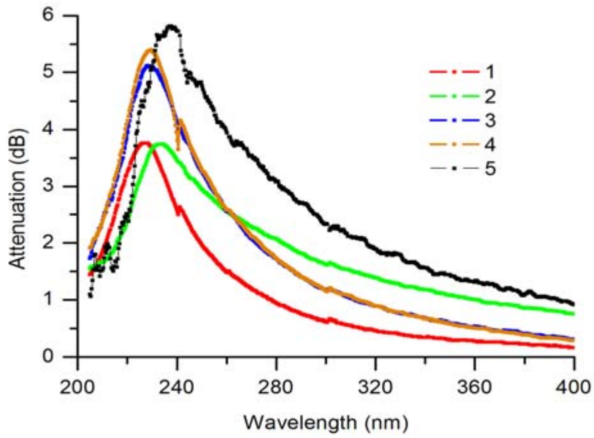

Figure 1. The absorption spectrum of the un-irradiated optical fibre sample and the optical fibre probes used in our experiment: 1- the optical absorption of the optical fibre probes before the gamma irradiation (2 fibres of 6 m length each); 2- the optical absorption of 2 optical fibre probes (one of 2 m and one of 6 m length); 3 – the optical absorption of the optical fibre sample of 2.71 m length; 4 – the same sample as that mentioned in case 3, this time the optical fibre sample was bent during the measurements; 5 – the optical absorption of the sample mounted between two probes of 2 m length each.

The characteristics in Figure 1 indicate the optical absorption existing in the UV spectral range for all the optical fibres used in this experiment, even before any irradiation. This initial absorption is one of the limits of the on-line measurements as it concerns the method's sensitivity. Curves 1 and 2 in Figure 1 indicate a slight change of the absorption peak as function of the optical fibre probes used. A small increase of the optical absorption appears to occur as the optical fibre sample is bent several times, with a bending radius at the limit of the allowed bending radius (curve 4 as compared to curve 3). By comparing curve 5 with curve 4 it is possible to evaluate the absorption added by mounting the sample between two probes of 2 m length each.

In addition, preliminary measurements on the optical transmission of the full set-up were done at the irradiation premises before the irradiation. The overall experiment for one optical fibre sample lasted several days because:

- the dose rate of the source is quite low;
- at the beginning of the investigation we perform irradiation only during daytime in order to be able to catch small radiation induced changes of the optical absorption in the sample. At each moment the sample was extracted from or introduced into the irradiation zone the absorption of the optical fibre sample was measured.

We have to underline that due to safety regulation the operation of the data acquisition system was not allowed during the nighttimes.

In the first day spent at the irradiation facilities the measurements were carried out at fixed intervals of about 20 min. In this way, we were able to track the build-up of the optical absorption when no saturation or other limitations (i.e. the limit of the spectrometer sensitivity) are present. In the second part of the experiment, as the optical transmission diminishes drastically, we increase the time interval between the two measurements. As the experiment advanced we left over night the sample in the irradiation zone, BUT without operating the electronic set-up. In this way, the total dose irradiation steps were increased. After the experiment we measured one more time all the optical fibres involved in data collection.

Figure 2 illustrates the increase of the optical absorption during the first hour of the experiment. After this time interval the fibre was ***removed from the irradiation zone*** and kept at room temperature (18 ^{O}C) for 18 hours until the next day. The recovery of the radiation induced optical absorption was measured (thermal annealing). A slight recovery at room temperature can be observed. The increase of the optical absorption as the sample was irradiated for 10 hours is presented in Figure 3.

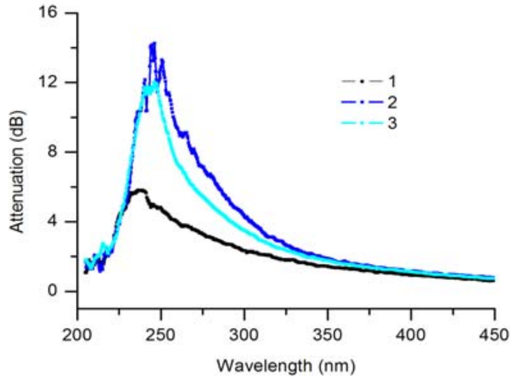

Figure 2. The radiation induced change in the optical absorption of the sample in the first hour of irradiation: 1 – the un-irradiated sample; 2 – at 0.33 kGy total irradiation dose; 3 – the optical transmission recovery after the sample was kept non-irradiated for about 18 hours.

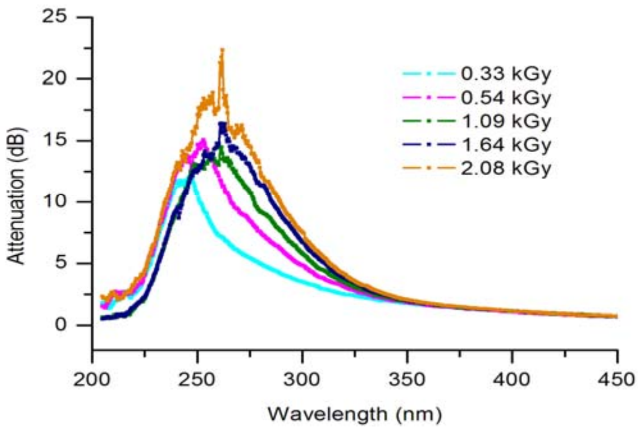

Figure 3. The dependence of the optical absorption on the total irradiation dose, for the first 10 hours of irradiation.

The changes induced by gamma-ray irradiation over a longer time interval are given in Figure 4, for total irradiation doses up to 12.2 kGy. A shift of the absorption peak towards longer wavelength as well as a broadening of the absorption band can be noticed, as the optical transmission decreases below 1 % and the sensitivity limit of the spectrometer is reached.

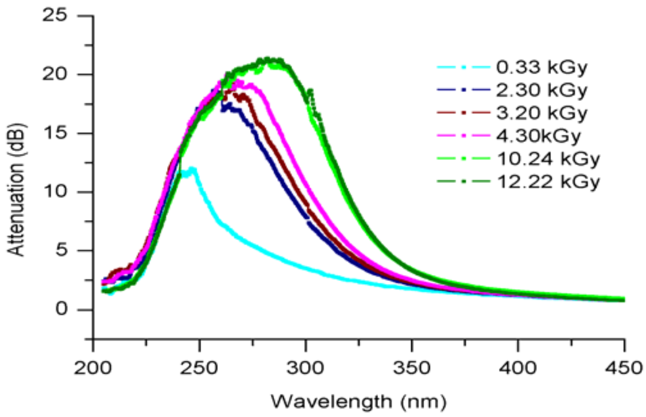

Figure 4. The dependence of the optical absorption on the total irradiation dose, for the first 3 days of irradiation.

From time to time (every three hours) we performed also a manual measurement of the optical absorption during the time the sample was subjected to gamma irradiation, in order to be able to compare on-line data with data collected off-line. In such situations, the optical fibre was exposed for a much longer duration to the optical radiation (for about one hour at a time, as compared to the automatic measurements when the exposure to UV radiation is for about 1/2 minute). This part of the experiment made possible the evaluation of the possible optical transmission recovery upon exposure to optical radiation. This photobleaching of the gamma irradiation induced defects was done ***during the gamma-ray irradiation***. In this case, a slight recovery of the optical absorption was observed under optical radiation exposure (Figure 5). The processes to which the sample was subjected are in this case are designated by the following notations:

- 0.76 kGy – total irradiation dose of 0.76 kGy;
- 1.19 kGy – total irradiation dose of 1.19 kGy and 40 min exposure to optical radiation;
- 3.64 kGy – total irradiation dose of 3.64 kGy;
- 3.97 kGy – total irradiation dose of 3.97 kGy and 40 min exposure to optical radiation;
- 10.8 kGy – total irradiation dose of 10.8 kGy;
- 11.23 kGy – total irradiation dose of 11.23 kGy and 40 min exposure to optical radiation.

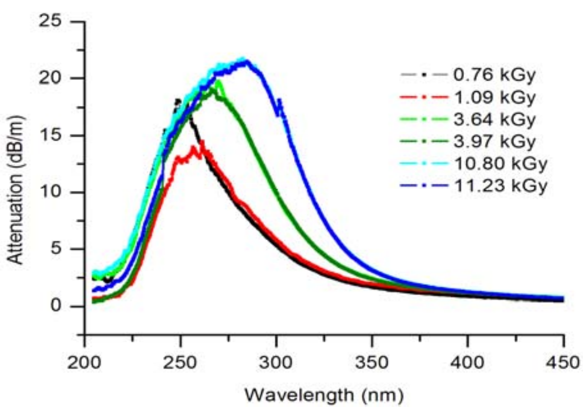

Figure 5. The effect of the optical irradiation of the sample during gamma-ray irradiation.

The curves in Figure 5 indicate a recovery of the optical transmission under exposure to optical radiation for lower total irradiation doses. At higher gamma-ray doses the optically induced bleaching is quite negligible.

From time to time we operated also the virtual instrument we designed from the acquisition of radioluminescence spectra. Because of the low dose rate we have, ***no*** emission spectra were recorded over the entire experiment.

At about 34.7 kGy total irradiation dose the optical fibre sample structure deteriorated drastically, as it crashed in several places. The degradation points were brought to evidence by coupling the fibre ends to a He-Ne laser. Unfortunately, the breakage of the sample affected other possible measurements on the irradiated fibre (i.e. its behaviour under temperature stress).

After the in-situ measurements we evaluated also in the Laboratory the transmission of the optical fibre probes used to couple the sample to our set-up. In spite of the fact that the probes were placed out the irradiation zone (the coupling between the probes and the sample was done at about 50 cm from the mechanical mount used to fix the sample during the irradiation) the optical fibre probes were themselves subjected to some amount of irradiation as proved by the change of their optical transmission (Figure 6).

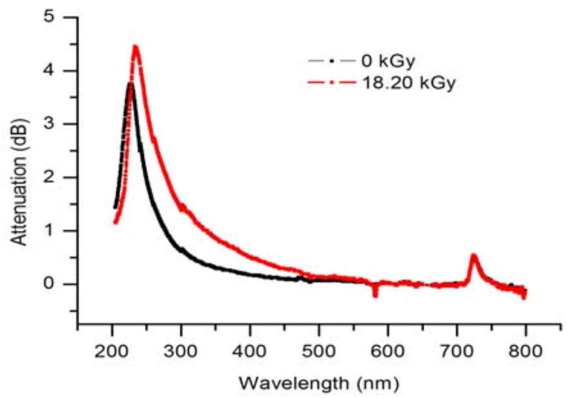

Figure 6. The optical absorption of the two optical fibers probes (each of 6 m length)

3. Off-line measurements

As we plan future on-line investigations on radiation induced effects in large core diameter optical fibres we performed, during the reporting period, some additional off-line measurements on gamma irradiated large diameter optical fibres from two manufacturers (in this report designated as OFS1 and OFS2), as the irradiation induced colour centre depend on the technology used to prepare the optical fibre. The main results are illustrated in Figures below. The investigations were carried out either for different products or for the same product with different core diameters.

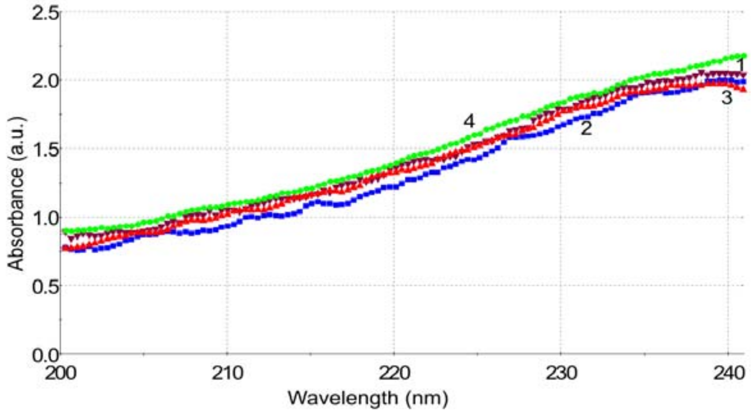

Figure 7. The gamma-ray induced optical absorption at the total irradiation dose of 10 kGy for: 1 – OFS1 (400 µm core diameter, black Tefzel jacket) ; 2 – OFS1 (400 µm core diameter, Polyimide jacket) ; 3 – OFS1 (400 µm core diameter, Tefzel jacket) ; 4 – OFS2 (400 µm core diameter, Tefzel jacket from a second manufacturer).

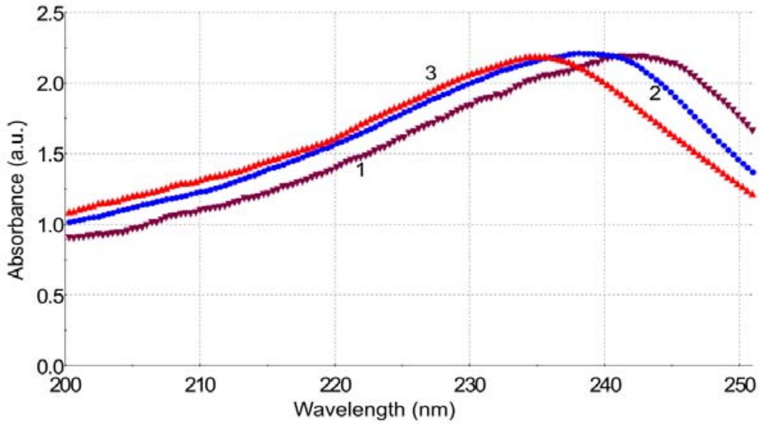

Figure 8. The gamma-ray induced optical absorption at the total irradiation dose of 10 kGy for: 1 – OFS2 (400 µm core diameter) ; 2 – OFS2 (600 µm core diameter) ; 3 – OFS2 (1000 µm core diameter).

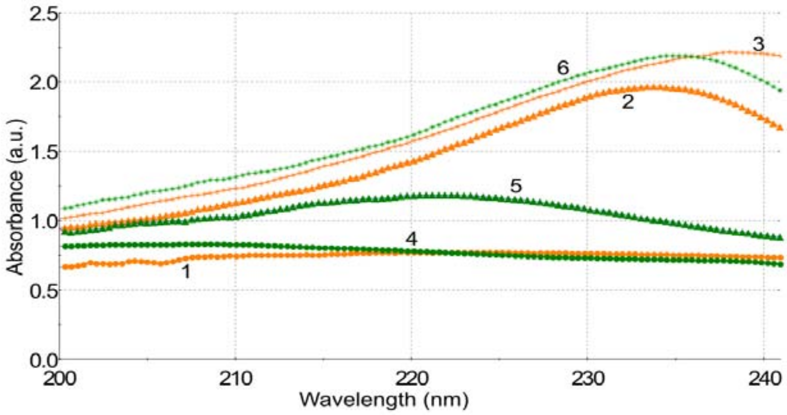

Figure 9. The gamma-ray induced optical absorption for: 1 – non-irradiated OFS2 (600 µm core diameter); 2 – OFS2 (600 µm core diameter) total irradiation dose of 3 kGy; 3 – OFS2 (600 µm core diameter) total irradiation dose of 13 kGy; 4 – non-irradiated OFS2 (1000 µm core diameter); 5 – OFS2 (1000 µm core diameter) total irradiation dose of 3 kGy; 6 – OFS2 (1000 µm core diameter) total irradiation dose of 13 kGy.

These investigations proved that OFS1 type fibers behave quite identically when subjected only to gamma irradiation (no temperature stress applied) and that all have a slightly reduced optical absorption as compared to OFS2. As the diameter of the optical fiber core increases the optical absorption peak moves to lower wavelengths, and has a slightly lower value as compared to smaller core diameter fibers.

Future work

Additional work has to be done in relation to in-situ:

- evaluation under gamma irradiation of solarization resistant optical fibres;
- electron beam irradiation of various optical fibres for the assessment of the radioluminescence effect, as the dose rate of the gamma-ray source we used is too small to have light emission, and electron beam irradiation can offer a high amount of energy transferred per volume unit;
- neutron irradiation of optical fibres with improved UV transmission;
- combined irradiation and temperature stress.

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