Accelerated ageing test bench for advanced ceramic slabs under extreme and controlled CST conditions

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Abstract

The behavior of ceramic materials exposed to high solar energy fluxes is of great interest for the study of the durability of materials, especially in Concentrated Solar Thermal (CST)technologies. A new accelerated ageing test bench has been developed at the SF40 Solar Furnace for the evaluation of advanced ceramic materials in operation solar conditions.

The description of this device, as well as the keys to its operation and testing of ceramic components under controlled and extreme CST conditions is shown in the present work.

Keywords: Accelerated solar ageing, durability, CST, solar furnace, focal point receivers, advanced ceramics

1. Introduction

The study of accelerated solar ageing of advanced ceramic materials that can be used as solar receivers in CST facilities is of great relevance for an industry that is set to replace fossil fuels in the global energy landscape.

Volumetric receiver technology has been developed since the early 1990s in various research and development projects (Avila, 2011). Due to their characteristics, ceramic materials are very attractive for use as volumetric absorbers in point focus solar thermal technologies. For the development of a new system and methodology to reproduce real test conditions, it is necessary to reproduce the same ageing mechanisms in accelerated ageing testing as in real CST conditions.

The use of point focus CST technologies is recommended in order to obtain the highest solar fluxes, being the solar furnaces and parabolic dishes the most suitable facilities to control the solar parameter in a small-scale solar test. Some previous test methods for solar furnaces are included in Table 1.

In recent years, different methods and test benches have been developed at Plataforma Solar de Almería for the accelerated ageing of metallic and ceramic materials, as well as reflectors, in solar furnaces. Thus, in projects such as Sfera III project, a test bench has been developed for tubular metal alloy receivers; in Raiselife project, a test bench for secondary reflectors in central receiver facilities, and in Nextower project, two test benches for the study and ageing of materials for volumetric absorbers, one of which is described in this work.

Among the ceramic materials, porous SiC is therefore a promising material to be used, which allows testing and evaluating ceramic samples under high solar energy fluxes, but the confidence in the reliability of innovative materials and components could still be checked and improved. Thus, in order to check its durability under extreme solar conditions, flat advanced slab based on SiC has been produced and a new accelerated ageing test bench (AATB) for advanced ceramic slabs subjected to high solar energy flux densities has been developed within the European NEXTOWER research project.

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Tab. 1: Different test methods for materials or components tested in solar furnaces (Cañadas, 2021).

Material or component tested	Project/ Receiver	Facility	Conditions	Variables measured	Reference
SIRCON Foam absorber made of SIRCON (Si_3N_4)	PLVCR-5	Solar furnace of Sandia (SNLA)	T average outlet air: 625°C T max outlet air: up to 1000°C Power: 5 kW P: 10 barFlux max.: 2 MW/m^2	Testing in solar conditions	(Pritzkow, W. 1991)
INCONEL with Pyromak 2500 layer	PROMES-CNRS	PROMES-CNRS SAAF	Samples: 1 mm Inconel (after spray-gun application of paint coating). Mean irradiance: 104 kW/m^2 - 173kW/m^2, 346 kW/m^2 Period: 10s,30s, Exposure time: 1000 s, 3000 s	Normal solar absorptance, thermal effusivity Thermal conductivity, thermal contact resistance between coating and substrate.	(Boubault A., et al. 2014)
Ceramic foams (SiC and ZrB_2) as high temperature volumetric solar absorber	OPTISOL project, SFERA project, and STAGE-STE	CNRS–PROMES 6 kW solar furnace. Kaleidoscope solar flux homogenizer	T_{out}: 833 to -998°C Mass flow rate: 1 g/s. α-SiC, Si-SiC, SiC, SiC + Al_2O_3, SiC + SiO2 + Al_2O_3, ZrB_2. SiC range of porosity (72–92%)	Calorimetry and fluxmetry	(Mey-Cloutier, S. et al. 2016)
Mullite	STAGE-STE. SFERA II H2CORK project	PSA-SF40	Tmax: average value of 1180 ± 35°C T differences ranging: - 200°C (700–900°C); - 400°C (700–1100°C) - 600°C (700–1300°C)	Mechanical properties: Typical strength, strain, microscopic techniques (SEM and optical microscopy).	(Oliveira, F.A.C., et al. 2019)

2. Materials and Methods

2.1. Materials

Among the most suitable ceramic materials as absorbers in point focus solar systems, porous SiC is one of the best candidates due to its thermal, optical and mechanical properties, as well as its chemical stability.

Porous SiC slabs, of 50x50x5 mm^3 have been produced by extrusion and partially sintered by LiqTech Ceramics using two granulometry of SiC powders and fired under argon atmosphere, at temperatures between 2100 and 2300ºC for 1.5 h, in a graphite furnace.

In order to demonstrate their durability, it is necessary to test these materials under real concentrated solar extreme and controlled thermal conditions, up to their working temperature. In this work, maximum temperatures of 800 to 1100ºC are studied and some of their optical properties.

2.2. Emittance test bench

Previously to accelerated ageing tests campaigns, the emittance at high temperature has been be estimated using a new method developed by CIEMAT. An adiabatic test bench has been developed, where the slabs are embedded in an alumina block (200×200mm^2, 100mm height) to achieve stationarity in thermodynamic variables. A group of first class type K thermocouples, 1.5mm diameter × 500mm long metallic sheath, allow measuring temperatures of alumina block and sample with an accuracy of σI =±0.004 T (375 °C≤T≤1000 °C). (Ballestrín et al., 2019), working under similar solar conditions than using the AATB at SF40. This procedure was based in Ballestrín et al. (2016)

2.3. Accelerated ageing test bench

Based on solar central receivers (SCR) technology, a new Accelerated Ageing Test Bench (AATB) has been designed and developed to be installed and tested at PSA-SF40 Solar Furnace for the evaluation of individual receiver ceramic components.

The test bench includes a support able to hold the samples. A porous support made of a material compatible with the SiC slabs has been chosen, as it allows a more homogeneous forced cooling of the slabs than if they were deposited on a continuous support.

Thus, the AATB consists of a 120x120x90 mm^3 SiC honeycomb module, inserted in a 130x130x93 mm^3 steel box, opened at its front side (Cañadas et al., 2021), developed to be tested at PSA-CIEMAT SF40 Solar Furnace (Rodriguez et al., 2016). As the durability tests of ceramic specimens are conducted in air, under solar central receiver conditions, the samples are directly exposed to concentrated solar radiation.

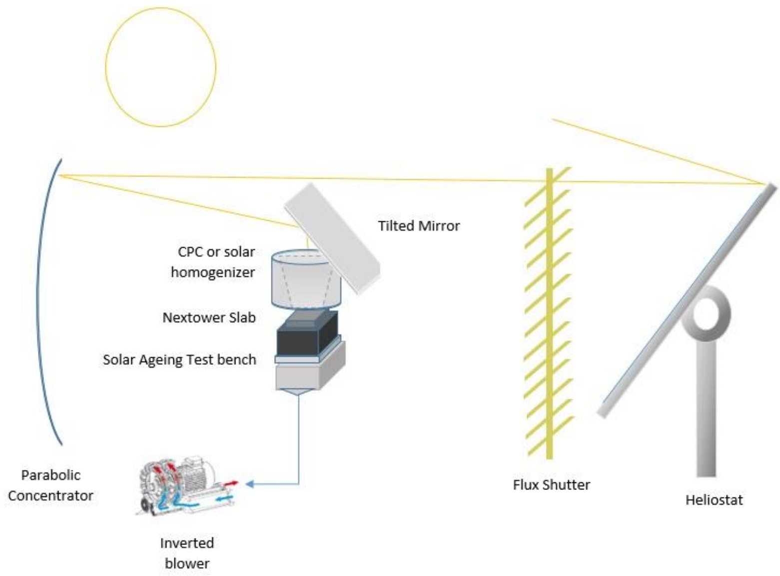

Fig. 1. Schematic draw of solar ageing test bench at PSA SF40 (CWA 17726, Cañadas et al. 2021).

A blind solar IR camera (Ballestrin, 2009) and a solar pyrometer (Ballestrin, 2010) are located in front of the samples in order to estimate the surface temperature, taking into account the emittance of the slabs at high temperature. Slabs are in contact with the front side of the honeycomb support. A solar homogenizer is placed in front of the samples to improve the solar flux on the ceramic samples (fig. 1). A flux shutter controls the power supply to the samples, and a double forced cooling system is implemented to complete the AATB and cool down the ceramic titles quickly. The forced cooling down system includes:

- A fast shutter closes instantaneously the flux on the samples (fig. 2).

- An inverted air blower, connected to the back side of the steel box, sucking the air and forcing to cool down the samples.

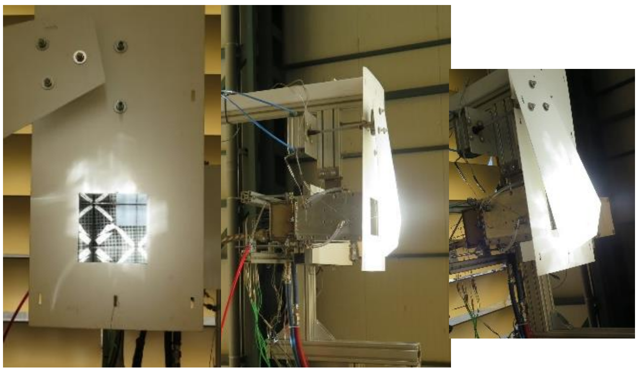

Fig. 2. a) Samples placed in solar focus with flux homogenizer, b) Fast shutter open, c) fast shutter closing under high solar flux conditions.

As the maximum temperature is reached, the cooling system starts, the forced cooling system is turned on to cool down the ceramic samples, and the flux shutter starts to closed. Depending of the desired cooling conditions, fast shutter is closed automatically, or depending of the thermal gradient, for controlling conditions. Please include acknowledgments here, before the references.

3. Accelerated solar ageing tests

The solar testing of advanced ceramics materials in the AATB, under high solar flux density (Figure 3), and correct operation and control of different SF40 parameters, allows to aged materials under extreme conditions as well as controlled CST conditions.

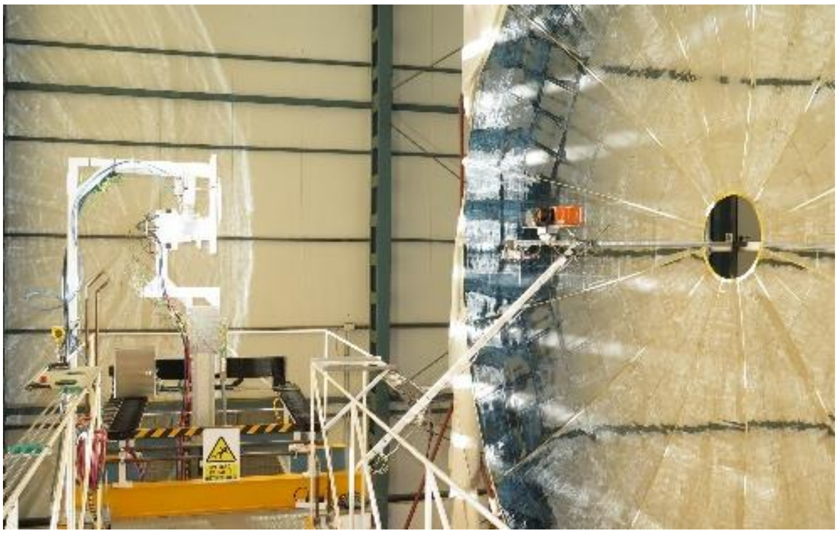

Figure 3. Accelerated ageing tests bench in solar operation at SF40.

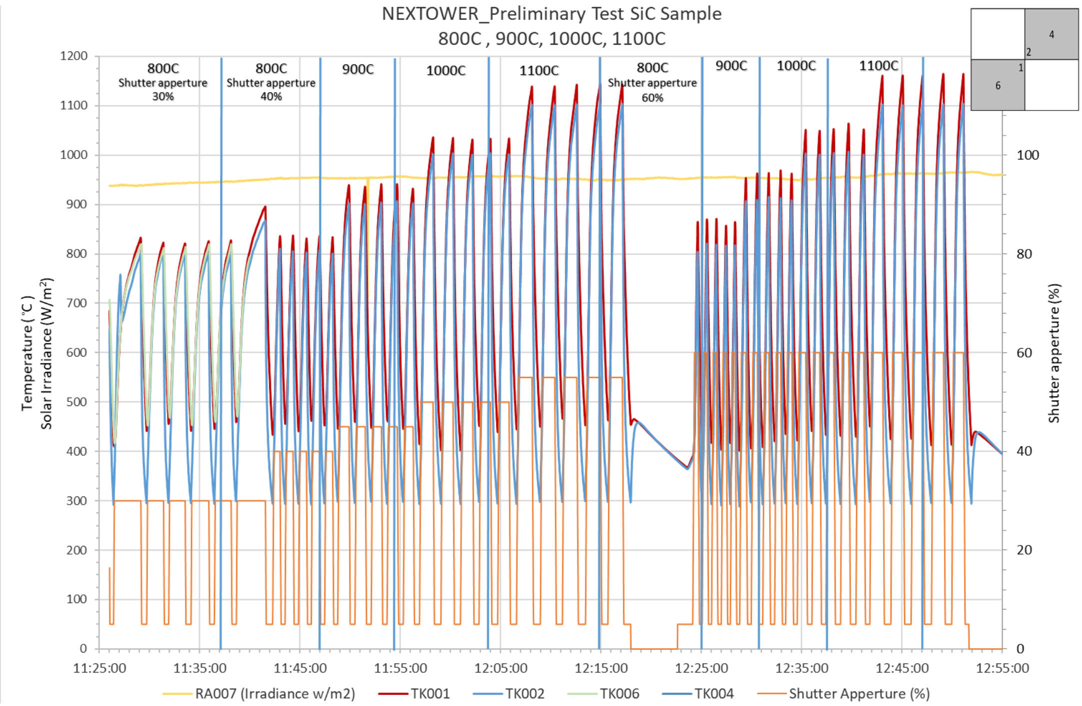

Figure 4. Preliminary test at temperatures up to 1150ºC

A preliminary test campaign was carried out to validate the test bench, and the behaviour of the materials under the solar accelerated ageing cycles (Figure 4). It shows a wide range of temperatures can be reached in accelerated conditions, controlling the maximum temperature and heating and cooling rates. Several K thermocouples measure the temperature on the back side of the samples. A solarblind IR camera and a solar pyrometer show the temperature of the exposed surface.

Two groups of ceramic slabs were tested at PSA-SF during the initial period. Group 1 was tested in the initial configuration, as a vertical solar test bench (fig. 5.a). As far as some samples cracked due to the fixing system, the slabs were changed to the horizontal plane (fig. 5.b), in order not to limit no one of their freedom grade. So Group 2 slabs were aged using an optimized horizontal solar test bench.

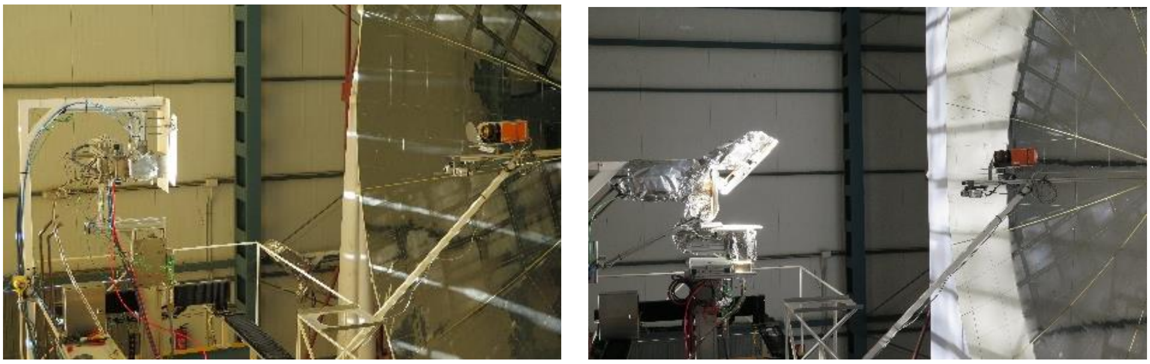

Figure 5. Comparative between a) vertical and b) horizontal plane test benches

Accelerated ageing tests are carried out by high frequency solar cycling on the ceramic tittles, as is showed in figure 6.

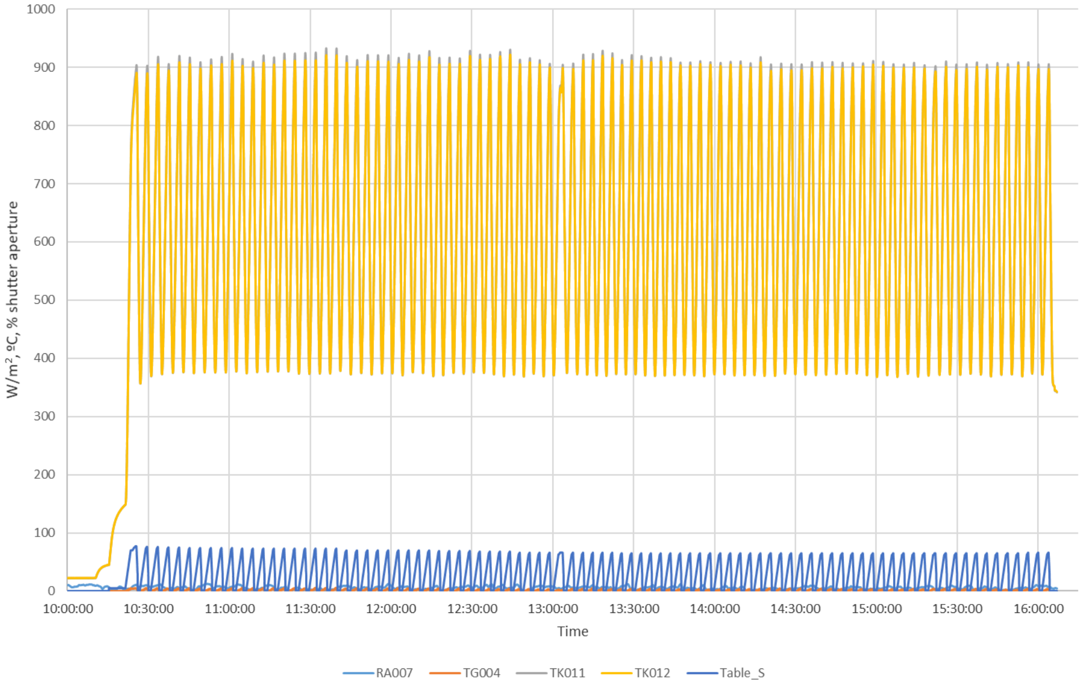

Fig. 6. Accelerated solar ageing test up to 900ºC

The solar testing of advanced ceramics materials in the AATB at SF40 Solar Furnace, under high solar flux density, controlling different operational parameters, allows to aged materials under extreme as well as controlled CST conditions. An experimental method to estimate the thermal gradient across the samples has been defined for the AATB under concentrated solar radiation. It includes two thermocouples, introduced in blind holes drilled in the samples, at different depths, in order to obtaining real thermal gradients across the sample. It is necessary to control the thermal gradient so as not to exceed the maximum allowed as it contributes to crack the slabs.

Cycles frequencies between 30 seconds per cycle up to more than 5 minutes per cycle have been studied in different groups of SiC samples. The control of heating and cooling rates and the inner thermal gradients is necessary in order to avoid the cracking of the slabs. For these porous SiC slabs, maximum thermal gradients around 70ºC/cm are allowed in order to aged them in safe conditions.

4. Results

Different accelerated ageing campaigns, from 500 up to 10,000 solar cycles was carried out at SF40 in order to achieve up to 25 years of ageing in ceramic samples using accelerated ageing under real conditions of concentrated solar radiation.

Preliminary optical analysis shows the oxidation of the ceramics materials after the solar ageing testing. The hemispherical absorptance was measured by a Perkin Elmer Lambda spectrophotometer located at the Advanced Optical Coatings Laboratory – OCTLAB at room temperature. Emittance was estimated up to 1200ºC. Figure 7 compares the optical analysis of new samples with samples aged for 10,000 solar cycles. As figure 7 shows, the emittance has increased after the solar ageing tests, for all the samples and all the temperatures.

Fig 8 shows the preliminary absorbance αAM1.5D results of three different slabs at room temperature. This preliminary values shows absorbance increases after the solar ageing tests, for all the samples compositions, being the samples 1,3 and 5 the exposed side, and 2, 4, 6, the back side. The absorptance, as well as the maximum temperature, is higher in the exposed side, due to inner thermal gradients reached in the SiC slabs during the accelerated solar ageing test.

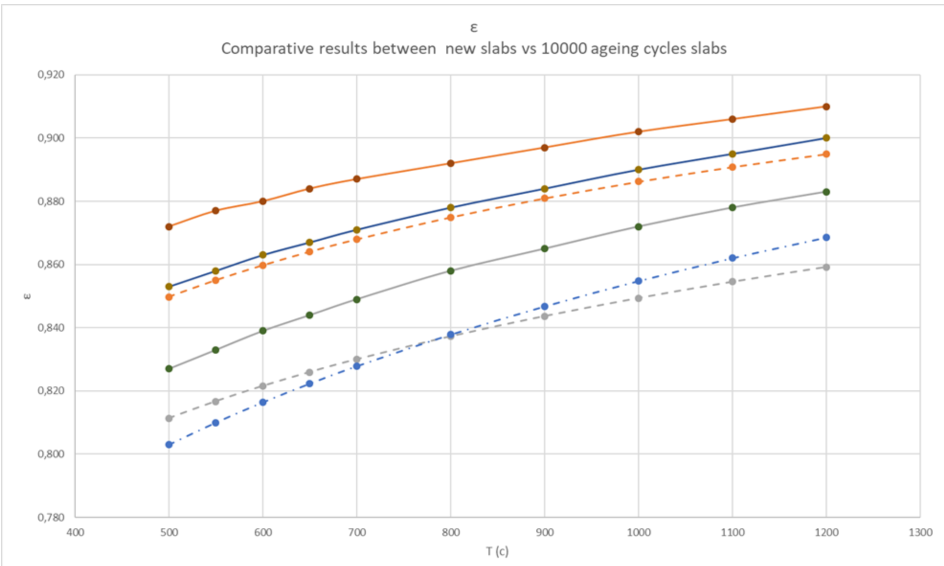

Fig 7. Comparative emittance results between different advanced slabs before solar ageing test, and after 10.000 ageing cycle. Discontinuous line (different composition new slabs); continuous line (aged slabs)

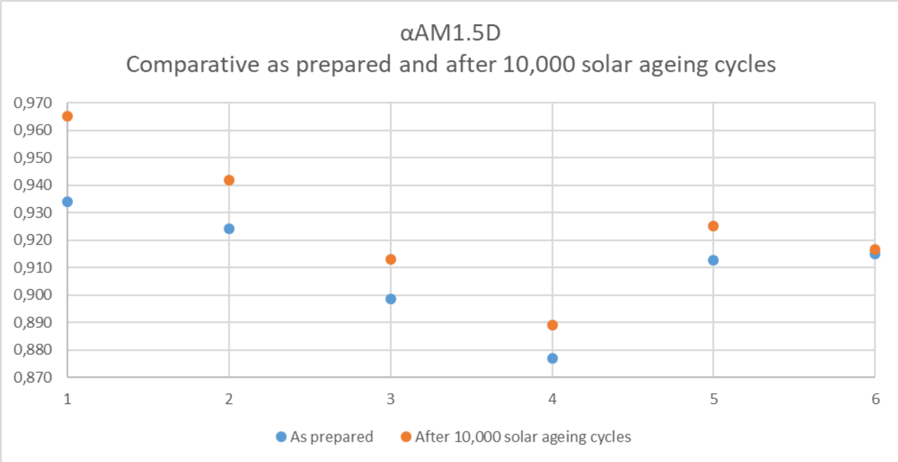

Fig. 8. αAM1.5D comparative as prepared (blue) and after 10,000 solar ageing cycles (orange)

5. Conclusions

Different ageing test campaigns have been developed during using the new AAATB, designed for the evaluation of individual plain receiver ceramic components. Experimental methods to measure the thermal gradient inside the samples and in the cups are carried out been developed, and control parameters have been improved in order to minimized the thermal gradient in slabs. Preliminary results show the emissivity increases at high temperatures. Some additional thermal and mechanical properties are described in Cañadas et al. 2021.

The results of their development and applications have been included as part of a CEN Workshop Agreement, CWA 17726 on "High temperature accelerated ageing of advanced ceramic specimens for solar receivers and other applications under concentrated solar radiation ", and their application continues in different projects such as CERAMITEC and HIDROFERR projects.

6. Acknowledgments

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