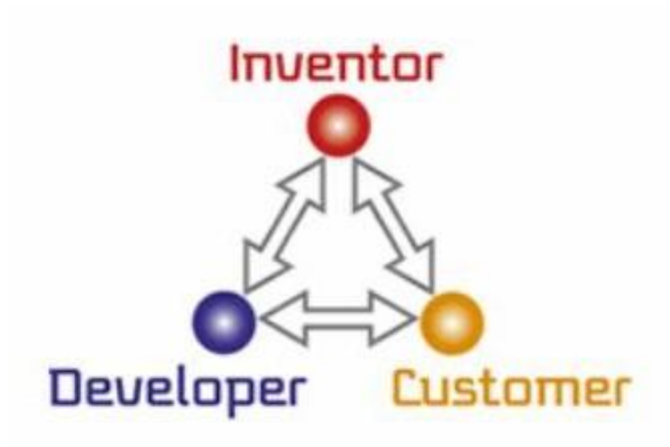
ESA contract 4000111843/14/NL/SC
ESA/ITI/Phase A

“ReWiG”
“A Resistive Wire Mesh TPS recession sensor”

1 September 2014 – 31 May 2015

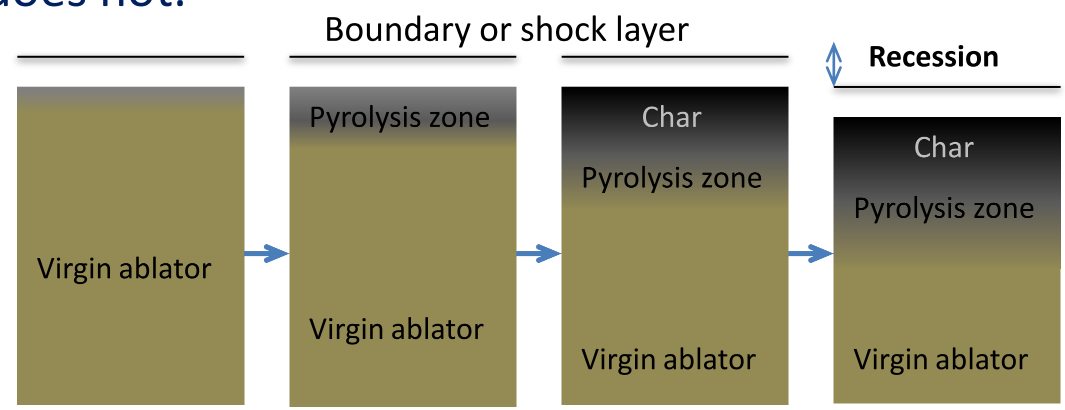


Dr George Vekinis
NCSR “Demokritos“, Greece

June 2015

Recession of Ablative TPS

All ablator TPS recede with time as the ablator is first pyrolysed and then converted to char which evaporates or erodes away. Recession also may result from shrinking due to the pyrolysis. While pyrolysis and evaporation consume energy, erosion does not.



Four stages of ablator heating (from left): start of heating, pyrolysis , start of charring and recession with further pyrolysis and charring

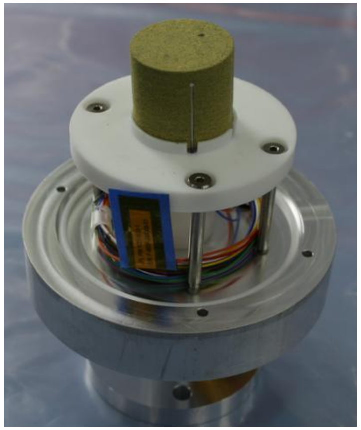
The Apollo 11 ablator heat shield displaying clearly appreciable and distributed recession

Why monitor TPS recession?

- The speed, extent and distribution of TPS recession determines the effective capability of the ablator to protect under specific conditions.
- The speed of recession, its extent and its distribution on the heat shield are critical parameters for designing, modelling and sizing the TPS.
- Ground plasma-jet tests give an indication, but live monitoring of the recession *in-situ* during atmospheric entry is the only way to confirm assumptions made during design, enabling the proper optimisation of the TPS.

Current TPS recession sensors

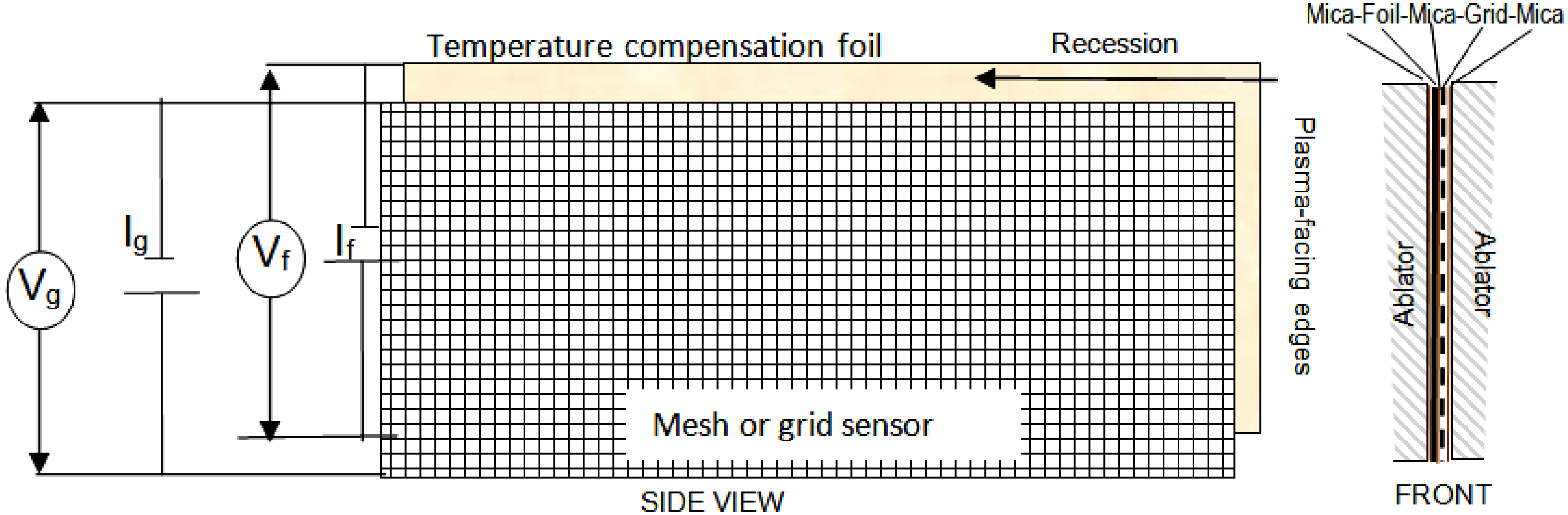
- At present only two types of operational sensors are found in open literature: ARAD and HEAT, developed by NASA.
- Made of an electrical conductor embedded in the TPS, they rely on the char to close an electrical circuit.
- They do not monitor the recession itself but the *temperature front* below the TPS surface.
- Their operation depends on assumptions made on the melting behaviour of the conductor and the reliability of the circuit continuity during pyrolysis and charring.
- Reported recession precision is "6mm using PICA calibration" (MEDLI plug (right) used on MSL)
- They are "unsatisfactory and unreliable" (statement by NASA official during IPPW12)



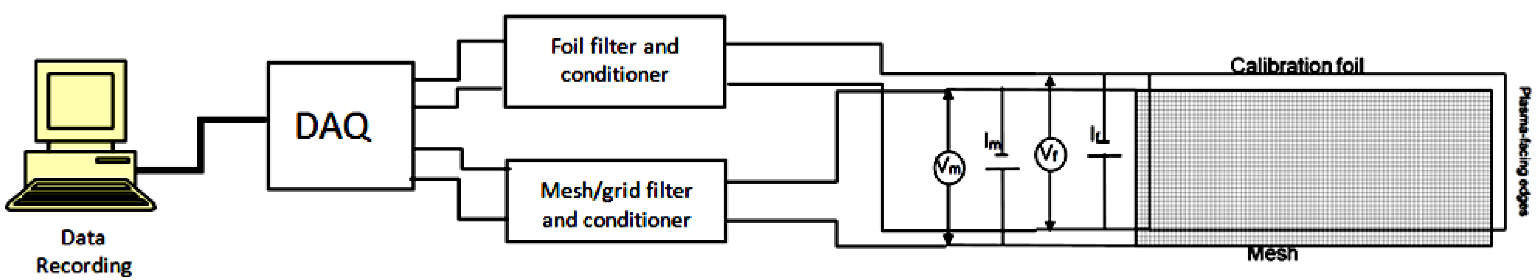
What should a TPS recession sensor *ideally* do?

- measure *directly* the recession
- ensure sensing (i.e. electrical) *continuity* at all times
- compensate for *temperature* variations
- be robust and reliable and be usable under extreme conditions without EM interference
- be usable for all types of ablative TPS
- be cost-effective and easy to manufacture
- be customisable for various heat flux levels
- not affect the performance of the TPS

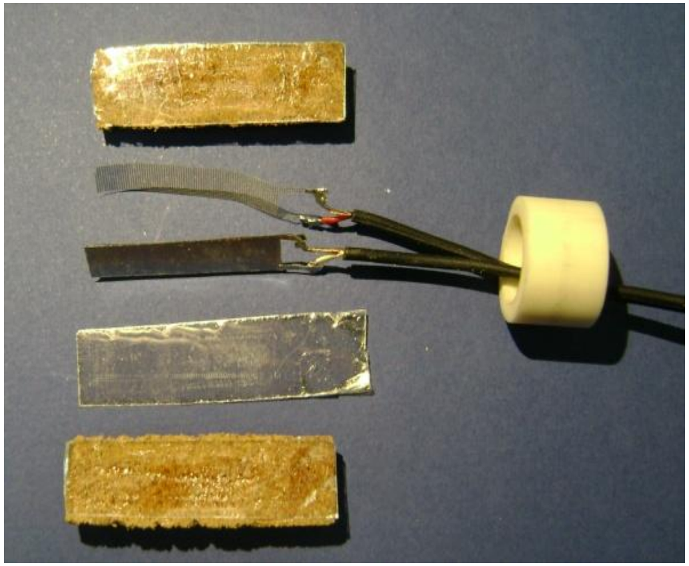
ReWiG: a new TPS recession sensor



Schematic of the ReWiG sensor. The plasma-facing edge is on the right. Both the grid and the foil are mounted flush with the TPS surface. The grid recedes which changes its resistance without opening the electrical circuit. The metallic foil is mounted parallel to the grid and provides temperature-compensation Insulation is by thin Mica sheets. The nett recession signal is given by $\Delta V = V_g - V_f$



ReWiG: a new TPS recession sensor



The ReWiG temperature-compensated sensor in a P50 ablator split plug, before assembly, left and assembled in a P50 body, right. The width of the sensor is 6-10mm and the total thickness less than 0.5mm. The length can vary according to needs, but longer sensors generally have low resolution at shallow recessions. In later configurations a conical plug is used. The actual sensor geometry is adjusted to improve linearity.

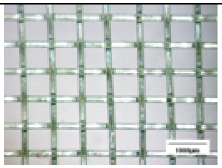
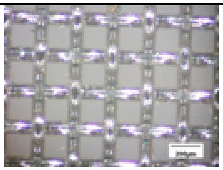
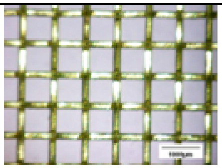
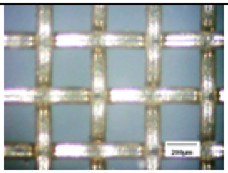
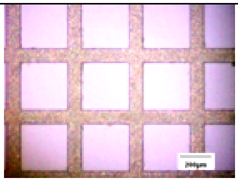
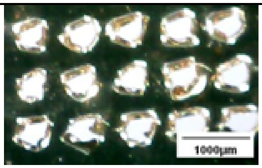
ReWiG (ITI/Phase A) Project Objectives

- Carry out a fresh documentary search of the publicly available reports on available TPS recession sensors (WP1)
- Carry out room temperature simulated recession (gradual cutting) tests on a number of sensor mesh and grid materials to ascertain geometric and material constraints and carry out a trade-off of materials and geometries (WP1)
- Carry out a series of simulated ablative recession tests using a high-temperature flame on specific sensors to check behavior and sensitivity of sensors, using cork or other appropriate material (WP2)
- Carry out 2 tests on P50 cork at a plasma-jet facility to ascertain the efficacy of the ReWiG concept under realistic conditions (WP2)
- Arrive at a decision on the "proof of concept" (TRL3) of the ReWiG sensor

Preliminary tests – RT cutting tests

- A range of materials and grids/meshes were originally screened for use as a ReWiG sensor. Testing was first carried out at RT by manually cutting the grid or mesh gradually and recording the signal.
- Meshes made of stainless steel (SS304), copper, brass of various sizes and grids of nickel and manganin were tested. The results showed that:
  - All wire meshes tested proved unreliable due to unreliable wire contacts
  - The Ni and manganin grids and the fine SS304 mesh displayed promising behaviour and were thus the subject of the final trade-off

Preliminary tests: screened meshes/grids

#	Mesh material	Source	Comments	Morphology
1	Stainless steel SS 304, woven wire, square 600µm openings, 100µm wires	Local manufacturer	Needs pressure from both sides to ensure good contact between wires otherwise signal fluctuates unacceptably	
2	SS304, woven wire, square 200µm openings, 60µm wires	HAVER & BOECKER OHG, Germany	Finer and tighter mesh, better wire electrical contact, but still needs pressure both sides for reliable electrical conduction	
3	Brass woven mesh, rectangular openings, 600µm, 100µm wires	Local supplier	Electrical contact not satisfactory unless pressure is applied on both sides and contact improved by a contact spray	
4	Cu woven mesh, rectangular openings, 250µm, 60 µm wires	Local supplier	Some contact problems. Needed contact spray and pressure to reduce poor contact fluctuations	
5	Nickel grid, made by deposition, 300µm square openings, 100µm wires, 40µm thickness.	Precision Forming, USA	No problems with electrical contacts. Gold and silver also available but Ni has higher melting point	
6	Manganin grid made from 15µm thick foil, irregularly shaped 500µm openings, 100-200µm contacts.	Goodfellow, UK	No problems with electrical contact. Holes made by pin impressions as square stamping resulted in tearing. Method gives regular mesh and can be used for any material in foil form.	

Trade-off

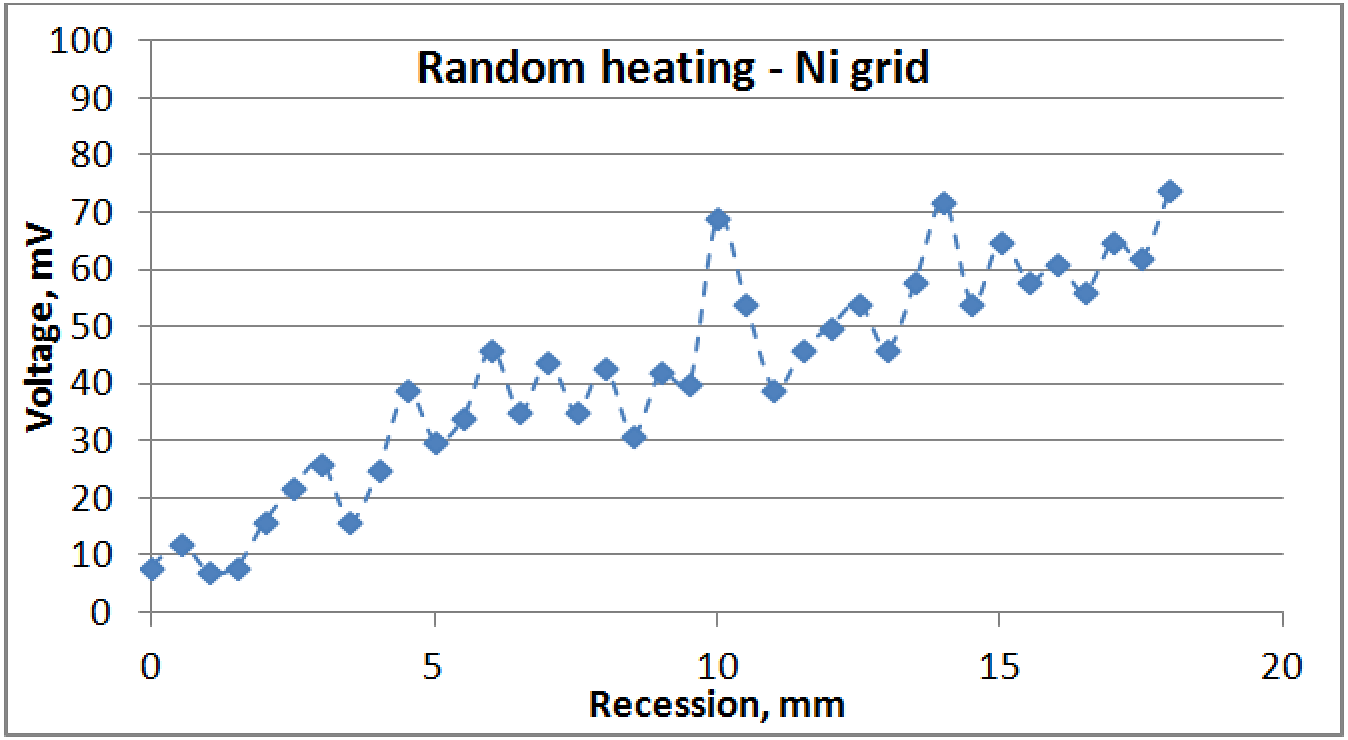
From the trade-off of the three short-listed materials, the Nickel grid made by precision deposition is clearly more promising

Characteristic \ Material	Nickel	Manganin	SS304
Forms available	Grid, various opening sizes and grid thicknesses	None	Wire mesh
Geometrical precision of grid	High	Depends on manufacturing	low
Melting point, °C, approx.	1455	960	1370
Solderability	Very good	Very good	low
Resistivity, Ωm	$7x10^{-8}$	4.8×10^{-7}	7×10^{-7}
Temperature Coefficient of resistance about RT, $°C^{-1}$	6×10^{-3}	2×10^{-6}	1×10^{-3}
Reactivity with carbon char	low	low	high
Commercial availability	yes	yes	yes
Trade-off score	*4*	*2*	*0*

Key: green = +1, blue = 0, red = -1

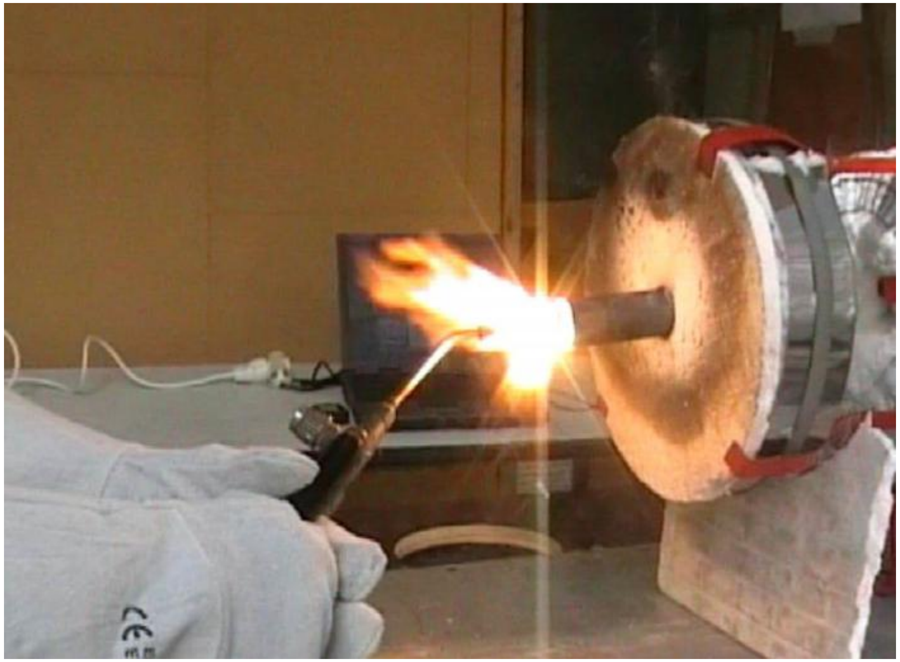
Preliminary tests – Heating effects

Random heating of the grid (as happens by random heat ingress during ablation) showed that the grid signal respond very sharply as shown in the figure. This was even more sharply seen in the flame tests and was the main reason that the decision was taken to include a foil in parallel which could be used to compensate for temperature fluctuations.



Flame recession tests

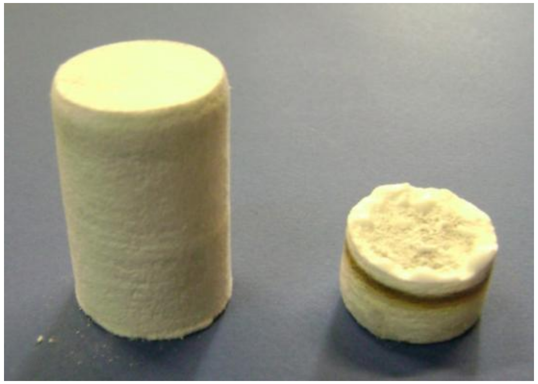
- Flame recession tests were carried out manually using an oxy-acetylene flame with a flame temperature over 2800°C.
- In practice the surface temperature of the two ablators used (see next slide) was measured at >>2200°C (max capability of pyrometer) and 2100°C respectively, reflecting their charring and melting/eroding temperature respectively.



A manual oxy-acetylene flame test. The specimen support is made of SiC.

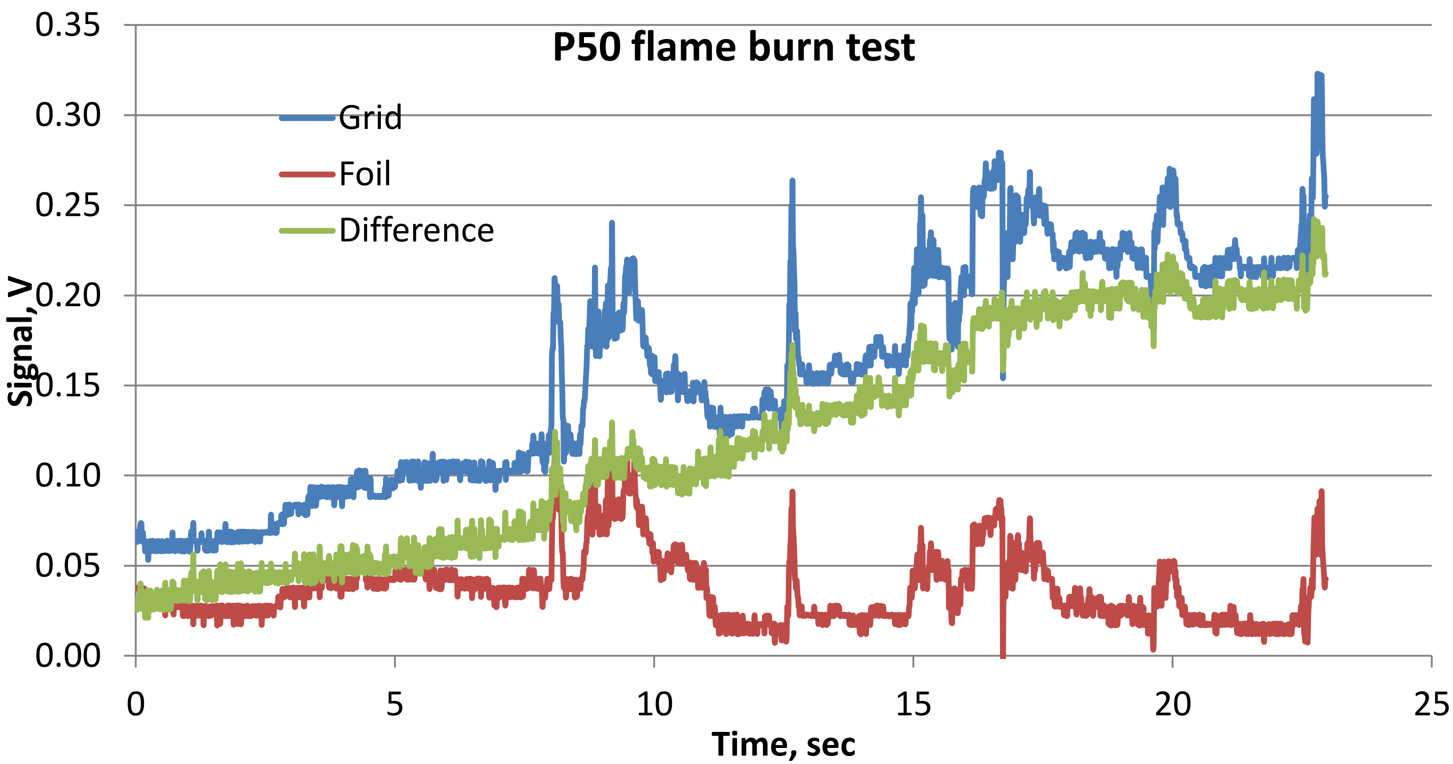
Flame recession tests

- The two materials used for the flame tests were P50 cork by Amorim, Portugal and Alumina-Silica fibreboard (AlSiFIB), both of which had similar thermodynamic properties but differed in their response to HT flame heating. While the P50 pyrolised and charred with appreciable swelling, the AlSiFIB melted and eroded
- The P50 cracks and deforms very substantially during HT flame heating with severe heat ingress making recession measurements very challenging. Most flame tests were inconclusive
- The AlSiFIB melts and erodes very uniformly and was thus used extensively as a simulant ablator for the purposes of the ReWiG development.



Irregular (left) and acceptable (centre) P50 recession - smooth AlSiFIB recession (right)

Flame recession tests using P50

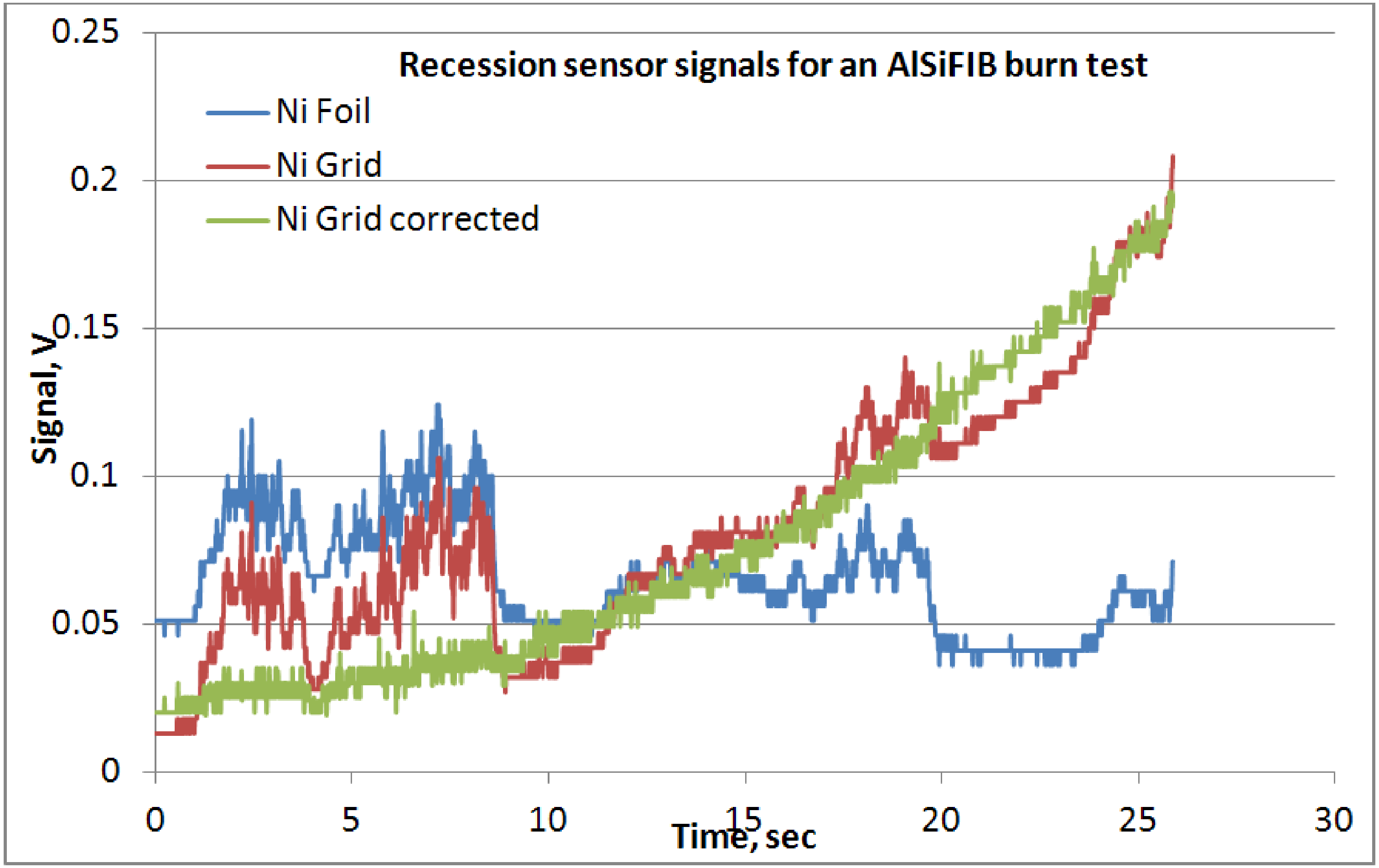


A satisfactory P50 flame burn test showing the raw data (red and blue lines) and the corrected sensor signal (green line) increasing with time. Recession occurred at a rate of about 0.8mm/sec and the sandwich sensor followed the recession front well. The fluctuations and spikes in the grid and foil signals are probably due to irregular heat ingress. Raw data (10ms data point interval) is shown artificially separated for clarity.

Flame recession tests using P50

Photos of Ni grid/foil sensors after satisfactory P50 burn tests. Sensor recession follows P50 recession well and sensor melting is concentrated to only about 1mm from the recessed surface together with localised mica sheet melting.

Flame recession tests using ALSiFIB – long sensor



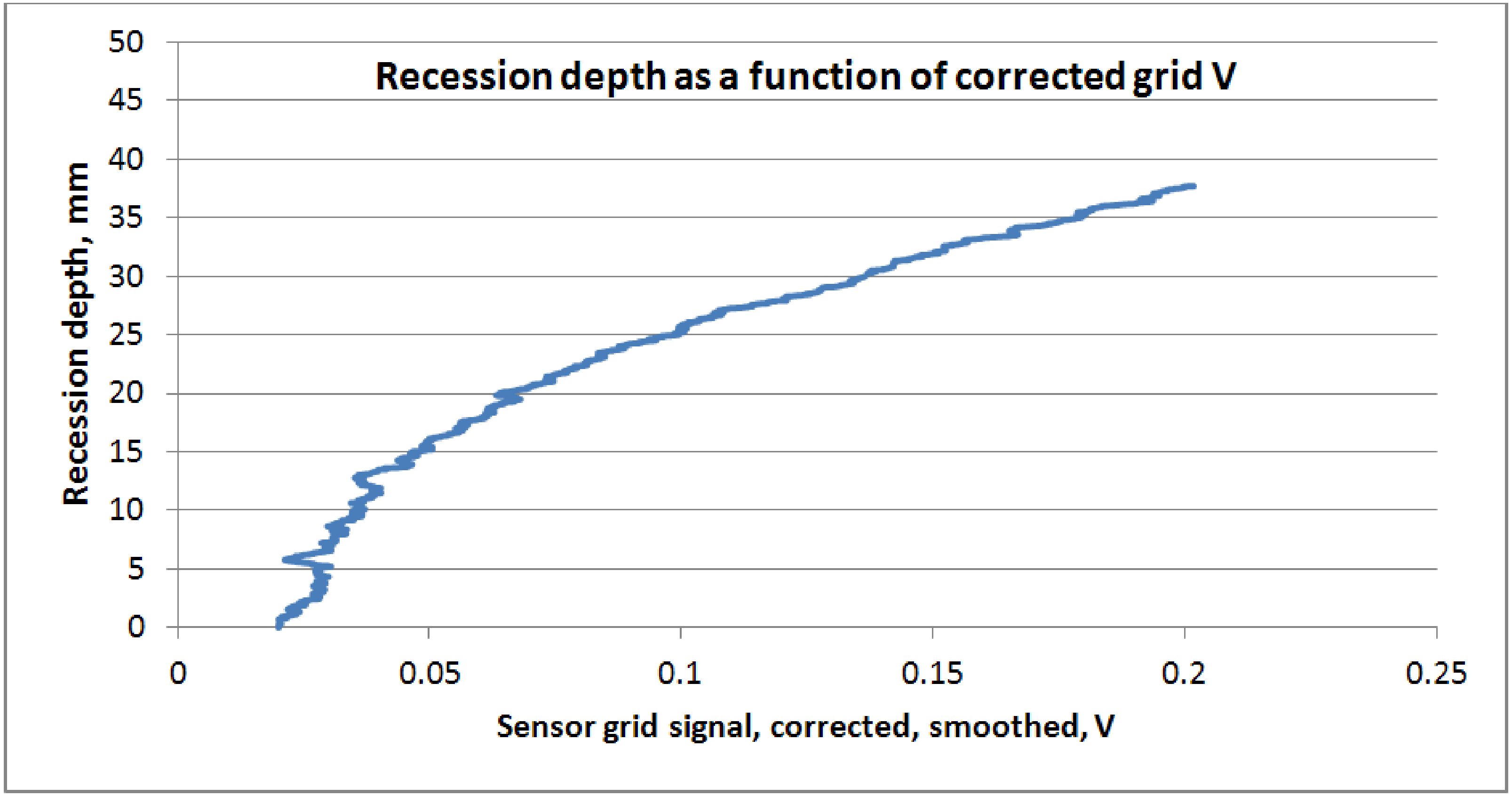
Raw data for an AlSiFIB recession test with a **long** Ni grid/foil sensor. The violent fluctuations at the start may be due to heating ingress which decreased once the surface melted and "filled and plugged" the gaps. Nevertheless, the corrected signal (difference between grid signal and foil signal) is clear.

Flame recession tests using ALSiFIB – long sensor



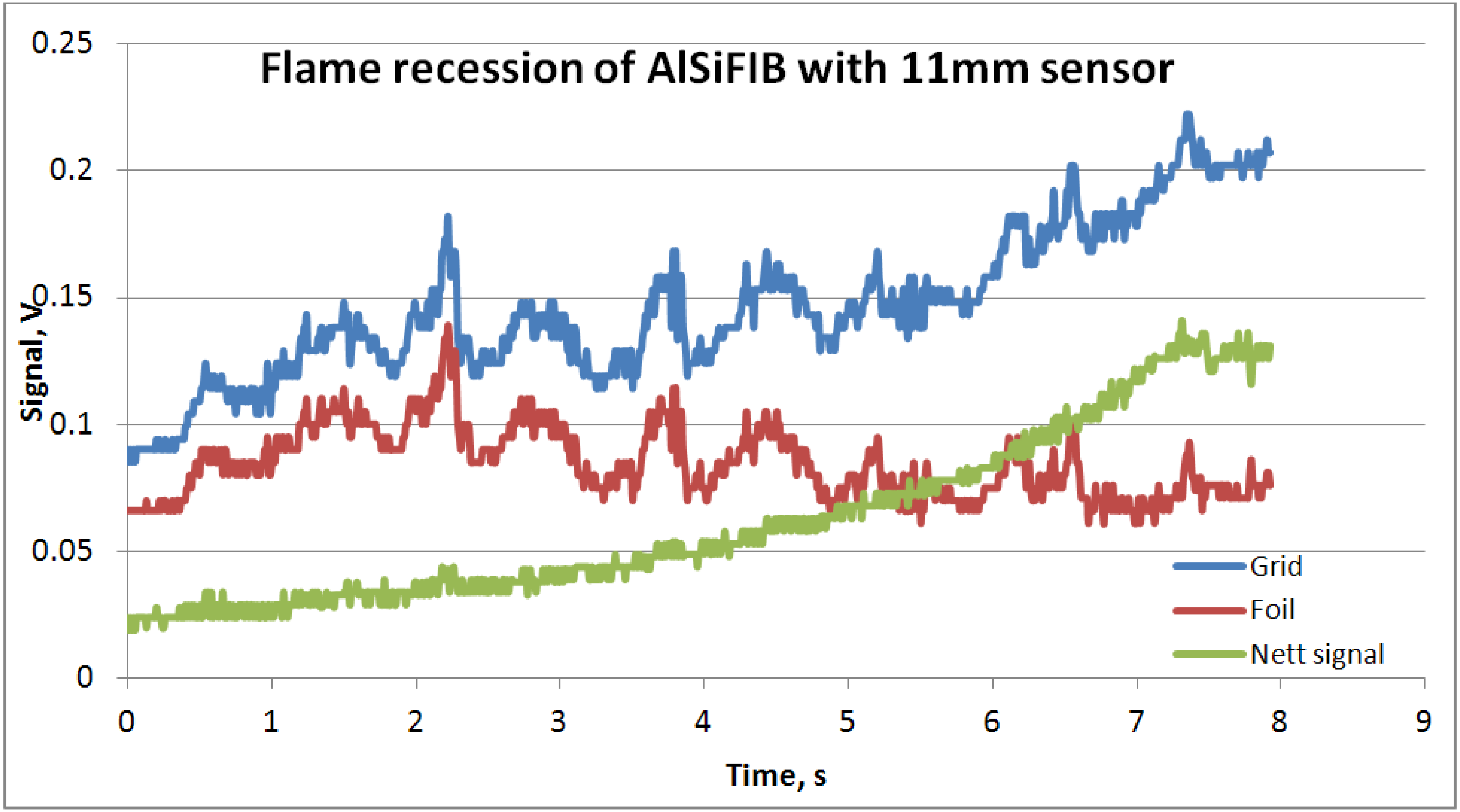
A Ni grid/foil sensor after a burn test with AlSiFIB (left). Recession of both sensor (including mica sheets) and AlSiFIB proceed in tandem well and the sensor is still in good condition after a recession of more than 40mm at a rate of about 1.4mm/sec.

Flame recession tests using ALSiFIB – long sensor



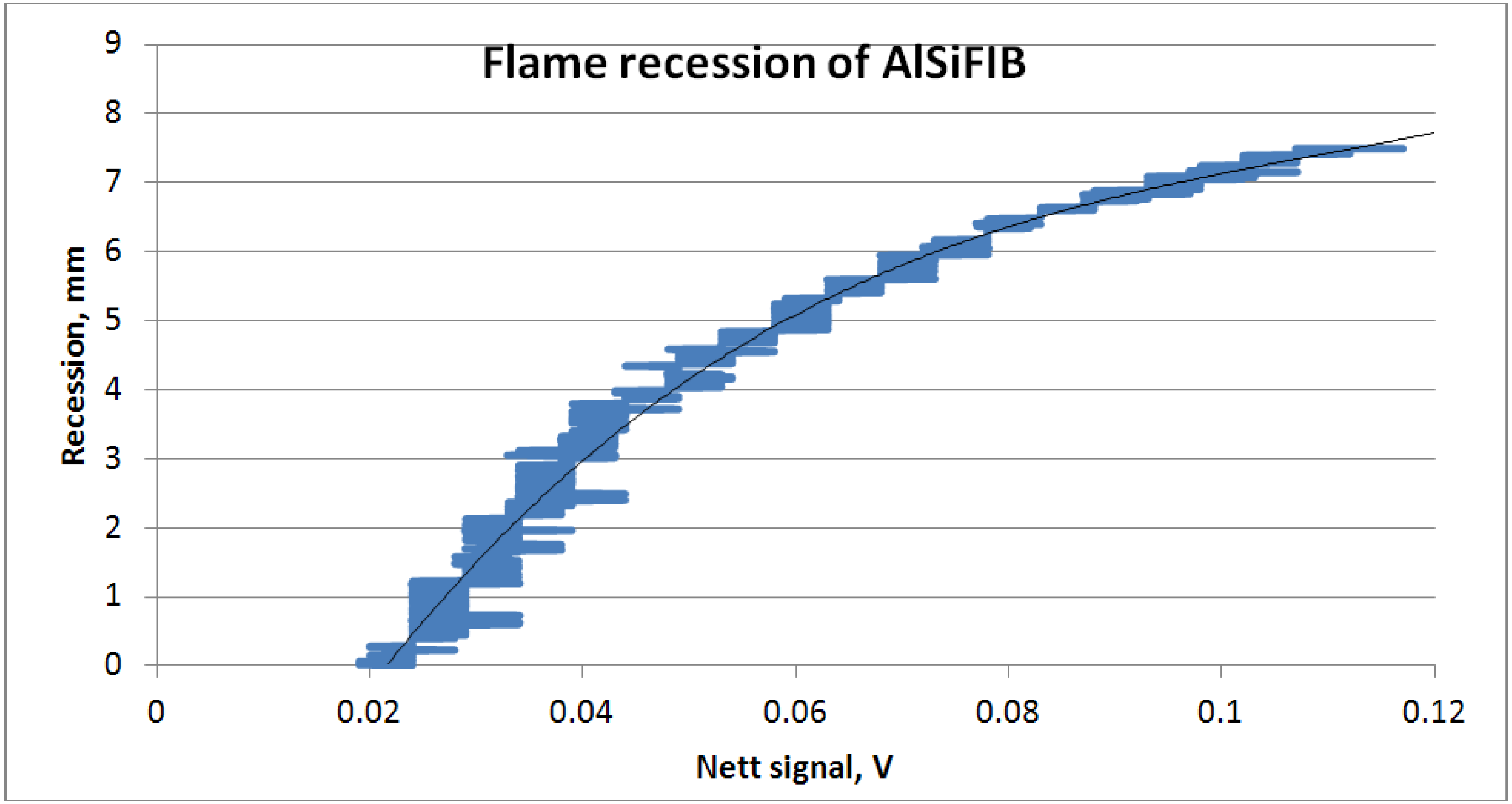
The ReWiG sensor "characteristic" for AlSiFIB recession for a **long** (50mm) sensor. The vertical error bars are estimated at ± 1mm and the horizontal ones at ± 2mV. The low resolution at low recession depths is due to the big length of the sensor. Short sensors give better resolution at low recessions.

Flame recession tests using ALSiFIB – short sensor



Raw signals from a short (11mm) Ni grid/foil sensor with wider plasma-facing edge in AlSiFIB. Random response to heating is evident but it is well compensated by the foil

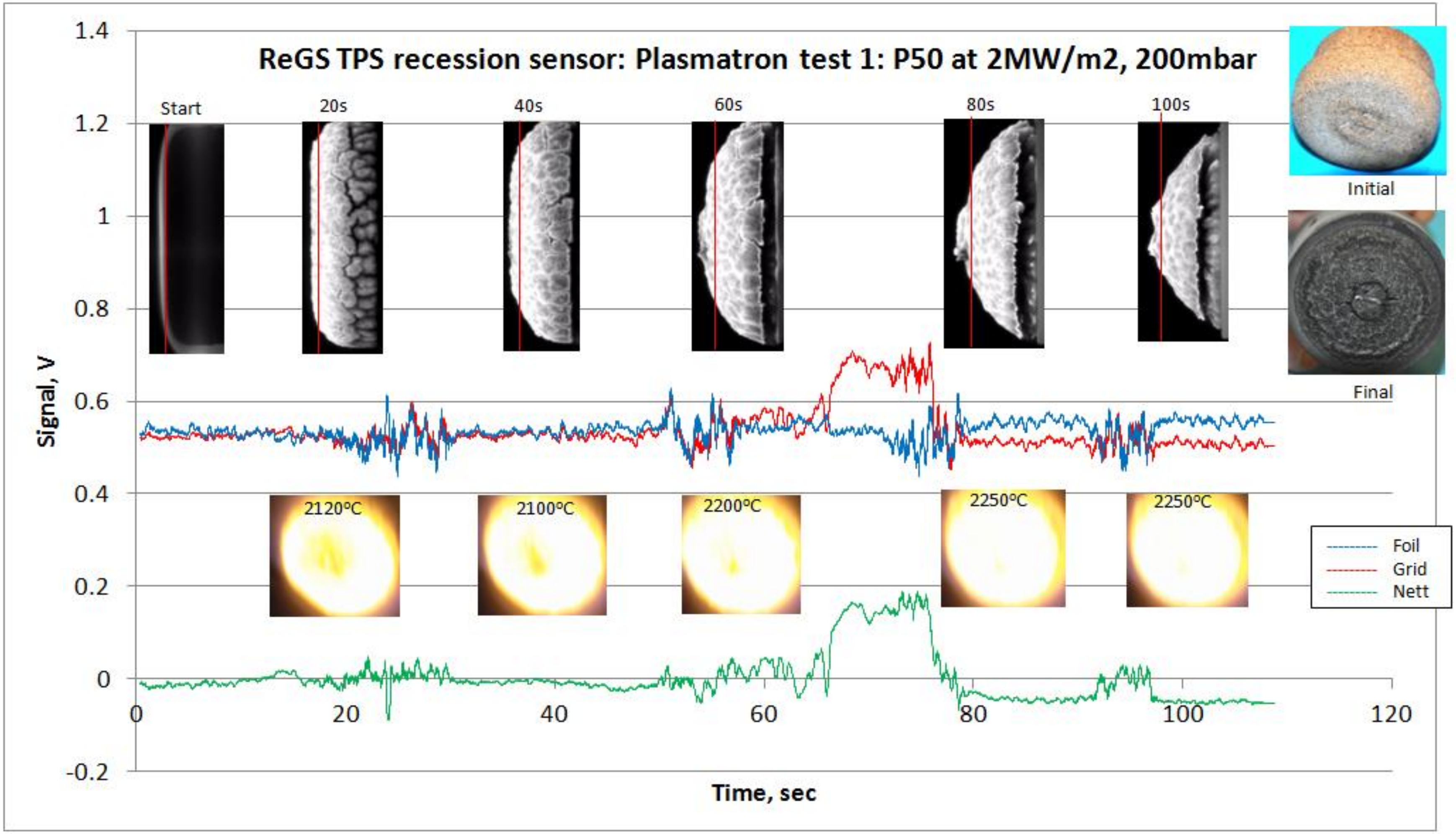
Flame recession tests using ALSiFIB – short sensor



The recession-signal characteristic for a Ni grid/foil sensor for an 11mm sensor. Recession resolution at low recession is about ±0.7mm which may improve by changing the geometry of the sensor.

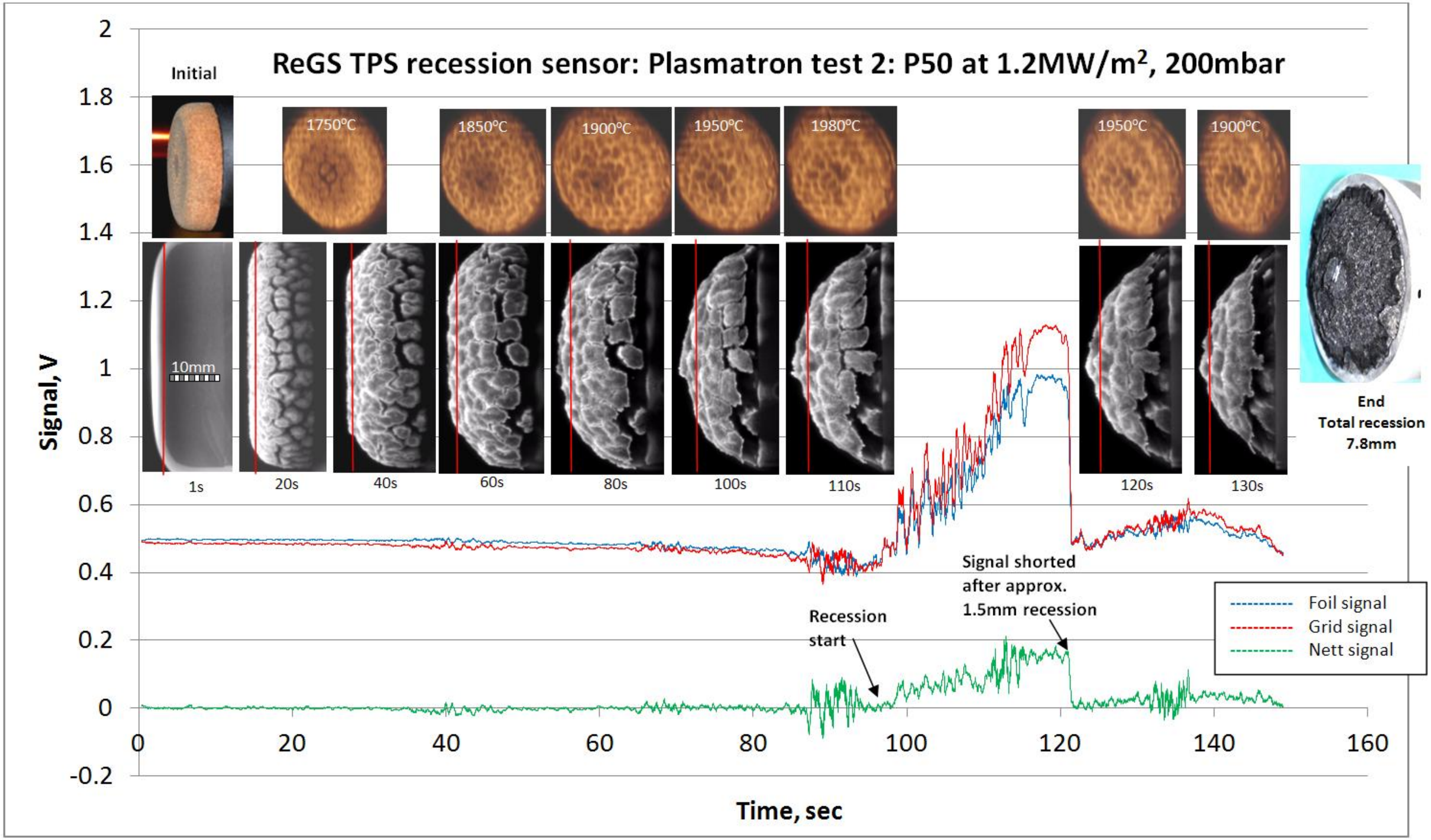
In general, the flame tests showed that the ReWiG sensor works in principle.

Plasma-jet test on P50: 2MW/m^2



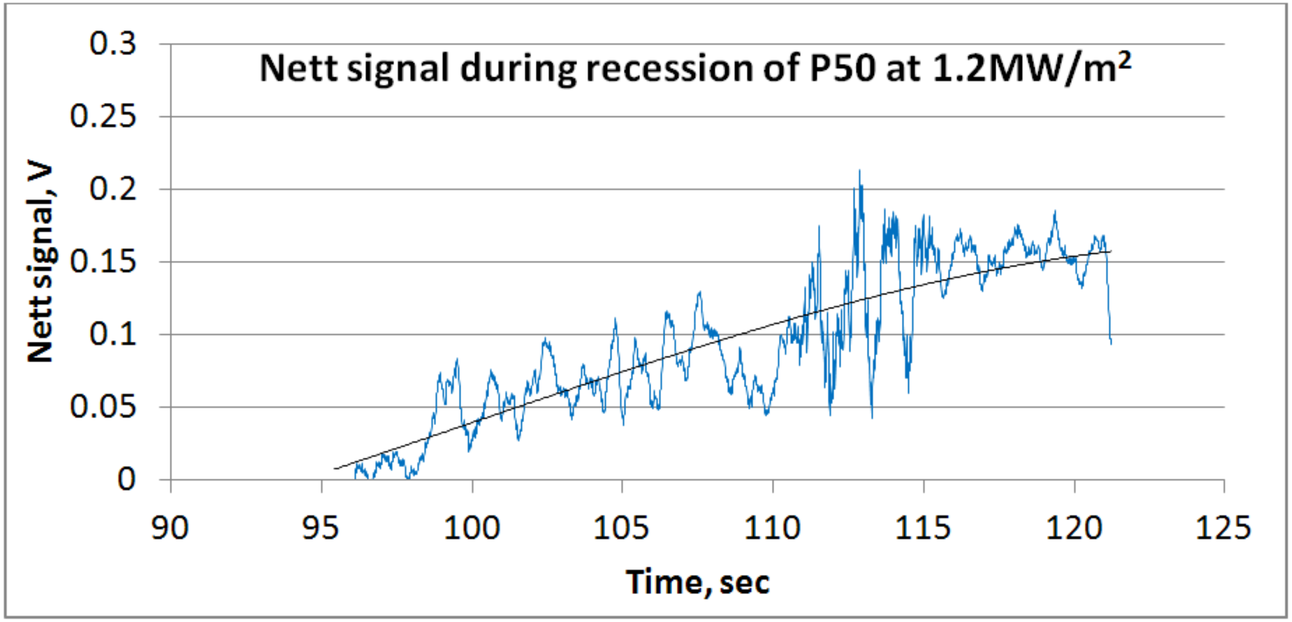
A constant-signal period (~65 sec) during swelling is followed by a signal from the grid but no signal from the foil. It seems that the foil wires were shorted first followed by those of the grid at about 75sec. Total recession was 1.8-2mm.
The test was inconclusive.

Plasma-jet test on P50: 1.2MW/m²



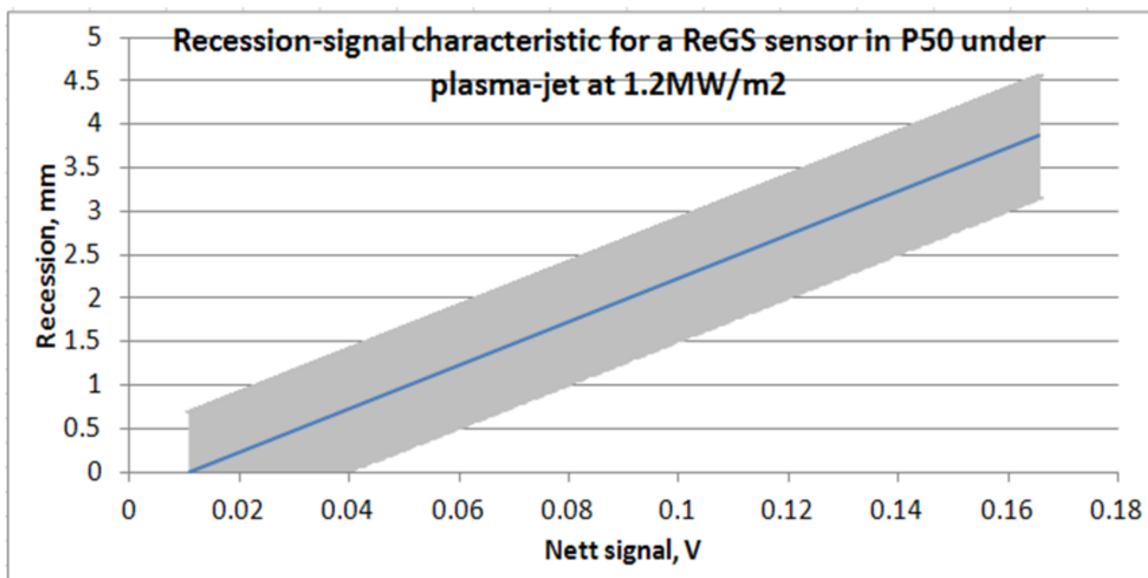
The 1.2MW/m2 test with a 27mm sensor. A constant-signal period during swelling is followed at 95sec by grid and foil signals. Total recession was measured to have been 7.8mm, of which 4mm was recorded.

Plasma-jet test on P50: 1.2MW/m²



The nett recorded signal covering 4mm of sensor recession before collapse

The averaged recession – signal characteristic of the 27mm sensor. Resolution is estimated at approximately ±0.8mm (higher at low recession depth)



CONCLUSIONS

- Burn recession tests of ablators using oxy-acetylene flame and plasma-jet show that the ReWiG sensor is able to provide a distinguishable signal as the recession proceeds
- The use of a grid/foil combination can offer reliable temperature compensation enabling better definition of the recession signal
- The results of the tests indicate that the concept of using a grid/foil combination as a TPS recession sensor is highly promising and, with further development, it can offer reliable *direct in-situ* measurement and monitoring of the recession of ablative TPS during atmospheric entry.

SUGGESTED STEPS GOING FORWARD* - TECHNICAL

- Optimise and calibrate correlation between sensor response and actual ablator recession
- Characterise and calibrate the effect of the grid and foil geometry and length as well as temperature on their signal to demonstrate their independence under various conditions.
- Characterise and calibrate the effect of grid/foil geometry (especially length) on the linearity of the nett signal especially at small recession depths.
- Improve data capturing resolution to at least 12bit, while retaining miniature size of the electronics and develop better EM noise filters to improve signal to noise ratio and suppress extraneous signals
- Develop an integrated grid/foil sensor by direct precision depositing of the grid and foil on either side of a thin insulating plate, to avoid manufacturing imprecision and increase resolution.
- Investigate the possibility of customising the sensor for various heat flux levels, by the use of materials of different melting points.

* Many of these have been included in the ReGS proposal submitted under ITI/Phase B – the remainder are planned to be added, if approved

SUGGESTED STEPS GOING FORWARD - TESTING

- Carry out further plasma-jet tests using other ablators which are not expected to swell during heating
- Extend testing to high-end ablators such as ASTERM at higher flux levels.
- Identify potential in-flight demonstration opportunities, e.g. cube-sats or one or more of the IRENA project suggested flight and ground demonstrators*

* At the latest workshop of the IRENA project (www.irena-project.eu) four (+ two reserve) flight and ground technology demonstrators were selected for analysis most of which will incorporate the ReWiG (ReGS) sensor

FINAL ROAD MAP FOR ReWig - TPS recession sensor: A00011472

	ReWiG	TRL	Funding	2013	2014	2015	2016	2017	2018	2019
1	Initial concept and preliminary tests	1	20000	Own funding						
2	Proof of Concept	3	50000		ITI/A					
3	Feasibility testing (plasma-jet testing of ASTERM etc)	5	150000			ITI/B				
4	Further testing in conjuction with capsule/shield design*	6	?					?		
5	Flight testing in a technology demonstrator*	8	?							?

* Owning to strong industrial interest for this sensor, the 4th and 5th stages of this road-map may be expanded to include non-space industrial RD, possibly with EC funding.

FINAL RD AIM for ReWiG

Develop a reliable TPS recession sensor for monitoring the thickness and recession rate of ablative TPS. This is important as it will allow to reduce the still significant uncertainties and related margins applied in the sizing of an ablative heatshield. Thereby this will allow to reduce the mass of the heatshield.

Overall Logic of the Roadmap

The results from ReWiG show strong promise as regards the eventual usage of a ReWiG sensor. This roadmap aims at TRL 7-8 after in-flight testing, perhaps as part of a technology demonstrator. From discussions with ESA (Dr Heiko Ritter) and Airbus D&S (which produces ASTERM) it appears that a simple, inexpensive recession sensor is useful and an important tool for the optimisation of the weight and sizing of TPS for re-entry missions. For this reason, once the feasibility testing is complete, the possibility to fly e.g. onboard of a cubesat (equipped with TPS for re-entry) or a small re-entry demonstrator capsule will be sought. In this regard, the IRENA project of the EC (www.irena-project.eu) has decided that such a recession sensor should be used in all its recommended atmospheric-entry demonstrators.

Description of the Next Activity

An ITI/Phase B proposal (ReGS: "A resistive grid ablative TPS recession sensor") has been submitted on 30 April 2015. The main objective is to continue the development of the ReWiG sensor, in light of the findings of the reWiG project. The main work packages are, briefly:

WP1: T0-M2: State of the Art and functional specifications (starting from results of ReWiG)

WP2: M3-M8: Further development of the ReGS sensor towards higher reliability, higher sensitivity at smaller recessions and customisability for a range of heat fluxes, temperatures and TPS materials (range of Tmelt of sensor material and optimisation of geometry)

WP3: M2-M5: Numerical modelling of the ReGS sensor for range of materials and conditions

WP4: M6-M12: Plasma-jet testing of the new ReGS sensors with various heat fluxes and materials - feasibility tests for various applications (Sample return, NEO return, etc)

WP5: M1-M12: Management

POTENTIAL FOR USE IN NON-SPACE SECTORS

- The ReWiG (ReGS) sensor has direct applicability in various non-space sectors, such as*:
  - The primary metal smelting (refining) sectors where monitoring of the thickness of the refractory lining of furnaces would be a very important energy-saving and maintenance aid
  - Heavy-vehicle brake and clutch pads where knowledge of the thickness of the remaining thickness would aid safety and performance
  - Any other sectors where direct monitoring of the thickness of a protective or other layer undergoing wear is not possible or easy, e.g. road tarmac, ice breakers' hull etc.

* As a result of a market analysis there appears to be a viable possibility for a spin-off company to industrially develop and market this sensor.

Many thanks to ESA for crucial support for this work