# Final Publishable JRP Summary for IND61 METROSION
# Metrology to enable high temperature erosion testing

## Overview

Erosion and wear can dramatically reduce the efficiency and life of high value components across a range of industrial sectors. Currently, assessment of the erosion resistance of materials and surface treatments is largely empirical, not standardised and hampered by a lack of traceable metrology. This project has developed measurement solutions to enable more accurate control and measurement of high temperature solid particle erosion (HTSPE) tests. In situ measurement methods have been developed and demonstrated to measure erosion rates at high temperature, increasing the speed in which tests can be conducted. By characterising the size, velocity and shape of the particles, generic modelling tools were created to model the erosion of materials without requiring experimental data. Understanding the wear of materials enables more reliable in-service life estimates and the development of new materials with better wear characteristics.

## Need for the project

Erosion and wear can reduce the efficiency and life of components in power, aerospace and material processing industries. Reduced efficiency in these industries impacts emissions of $CO_2$. For example, wear costs the power industry an estimated 200M€ a year in lost efficiency, forced outages and repair costs. Major improvements in the efficiency of power generating plant (7% to 10%) and aero-engines would be possible by the development of new materials that have improved resistance to high temperature particulate erosion.

For many years HTSPE testing has been limited to being able to rank materials comparatively under conditions which nominally replicate in-service conditions. Better models and understanding are required, through improved and more controlled, reproducible and representative tests. The measurement of damage, the temperature of the erosive particles and the supporting gas stream, the gas stream flow rates and the size and shape of erosive particles, all influence the erosion resistance of materials. The lack of control of these parameters has been identified as the cause of a lack of reproducibility in measurements (up to 100%) by an EPRI (Electric Power Research Institute) workshop. This project addresses these issues to establish a metrological based framework for high temperature erosion testing with traceability to National Standards.

## Scientific and technical objectives

The project had the following technical and scientific objectives:

- ***In situ* measurement of the volume of erosion through novel techniques**, using *in situ* sensors capable of measuring depth of damage to a resolution of 1 µm. This will enable on-line measurement of the erosion rate for the first time.
- ***In situ* measurement of the change in** mass of the samples. Measuring mass change at high temperature will greatly increase the speed in which the tests can be conducted, and removes the associated uncertainty of relocating the specimen in the gas stream. Reducing the test time also reduces the extent of oxidation of the sample thereby reducing another uncertainty.
- **Measurement of the gas flow and velocity of high temperature erodent particles and its distribution**. The volume of damage in erosion is highly dependent on the velocity of the erodent particles, so improved accuracy in the measurement of this parameter will significantly reduce the uncertainty in the evaluation of erosion and subsequent modelling.
- **High speed measurement of the temperature of high velocity erosive particles** and the supporting gas stream at temperatures up to 1000 °C. The mechanical properties of the particles, and hence their effect, are critically dependent on temperature, particularly temperature dependent properties such as modulus, hardness and the transition between ductile and brittle behaviour.



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Accurate measurement of temperature and velocity are therefore critical in the control and understanding test results.

- **Measurement of the gas stream flow rate and its distribution**. To be able to model the kinetic energy of particles hitting the surface it is important to know the impingement velocity of the particles. The gas stream has two velocity components a vertical and horizontal component. It is necessary to be able to measure the flow rate and component velocities to better understand the erosion mechanism. To achieve this computational physical modelling will be used and compared with the erosion performance of the samples.
- **Measurement and characterisation of the erosive particle size and shape, and consequentially their respective speeds**. These parameters dictate the detailed damage that takes place when particles impact the target material.
- **Determination of the influence of test parameters** such as the angle of incidence and the geometry of the test system on the repeatability and reproducibility of results. This will help industry to compare results from different sources and equipment.
- **Modelling of the high temperature erosion process to achieve a life prediction capability**. Developing a model based on fundamental physical principles, rather than test data, will reduce the reliance on empirical results, and allow more generic modelling approaches.

**Results**

*Measurement of erosion volume to a resolution of 1μm*
An *in situ* method for measuring the erosion scar has been developed and validated at room temperature. The desired resolution was achieved and comparison with commercial high resolution optical confocal microscope measurements of model and actual erosion scars has shown that the technique works well with less than 3 % variance. The *in situ* device has been incorporated in the NPL erosion apparatus. This provides a method of measuring the erosion scar at temperatures without unnecessary cool down and heat up delays during the test. This also means that there are no relocation errors in dismounting and remounting the sample between measurements. By providing a more accurate test methodology and the means to capture more data, the understanding of material performance and damage mechanisms is increased. This in turn can be used to accelerate the development and validation of new materials.

*Measurement of mass change*
An *in situ* design has been realised for mass measurement during erosion testing, which has the potential to reduce the test time from 5 days to 2 hours. It was demonstrated in a series of intercomparison tests that the erosion rates measured *in situ* compared very well with those measured conventionally. This provides confidence in the *in situ* mass measurement method, and has demonstrated that this novel approach is suitable and provides a significant reduction in the measurement time required for a HTSPE test.

*Measurement of the velocity of high temperature erodent particles and its distribution*
An *in situ* optical method for measuring the particle velocity during HTSPE testing has been developed. Integration of these sensors to existing test rigs is possible and provides, for the first time, full measurement of the particle velocity distribution as a function of particle size across the gas stream. These sensors have been used to measure the speed of the erodent powders which have been characterised using advanced 3D (X-ray Computed Tomography (XCT) and 2D (optical imaging) methods to measure the size and shape of the particles. Together these measurements have been used to develop particle velocity models and provide a parameter to index the relative erosivity of particles.

*Measurement of the temperature of high velocity erosive particles up to 1000°C*
Different thermocouples have different sensitivities and drift characteristics, so a review of contact thermometry has improved the understanding of these effects. A study of the thermal profile of high velocity erosive particle samples during the erosion test was also conducted. The objective has produced recommendations for the most appropriate thermocouples and immersion depths to be used to monitor different sample temperatures up to 1000ºC.

*Measurement of the gas stream flow rate and its distribution*
A series of multiphysics models have been developed to describe the gas flow velocity components through erosion rig nozzles. These have been validated using experimental pressure and gas flow data and used to optimise nozzle designs and to better understand the erosion mechanism.

*Measurement of the erosive particle size and shape, and their respective speeds*
The erosive particles to be used in erosion tests were characterised in terms of their shape and size, using a range of different measurement techniques (including optical microscopy and XCT). PTB developed a method to describe the shape of the particles using mathematical descriptors. This data was then used with the *in situ* velocity measurements to develop a velocity model which enables the distribution of particle velocities to be predicted and can be used in erosion models to provide more realistic predictions of damage accumulation using velocity distributions rather than a mean value. A measurement Good Practice Guide was produced describing the methods and can be downloaded from the project website (http://projects.npl.co.uk/metrosion/publications/).

*Determination of the influence of test parameters*
A series of HTSPE tests were conducted to allow the influence of variable test parameters to be determined. The influence of the standoff distance, the angle of incidence and ratio of the nozzle diameter to acceleration length were systematically compared for the first time. The results showed that at high temperatures (up to 650 °C) the erosion rate measured was relatively insensitive to these parameters, which is encouraging as it means that results from different apparatus are directly comparable, at least within the temperature range covered in this project. This was not the case at ambient temperatures however, and further work is needed to investigate the effects at lower temperatures.

*Modelling of the high temperature erosion process to achieve a life prediction capability*
A generic model of particle erosion was developed based on Newton approximation, which showed good agreement with observations and practical measurement of erosion damage from erosion tests. The generic model does not need commercial software to operate. In addition a Finite Element (FE) based model has been created to model particulate erosion. This FE based model (ERROW-Sim software tool) is able to apply single or multiple impacts to model the erosion damage on surfaces. A Measurement Good Practice Guide was produced on FE Erosion Modelling and is available from the publications area of the NPL website (www.npl.co.uk), although further work is needed to develop and fully validate these models.

**Actual and potential impact**
This project has provided a step change in the ability of industrial laboratories and research institutes to measure HTSPE through: the development of improved metrological test systems for HTSPE, better measurement of damage mechanisms and erosion, the development of in-situ and on-line measurement of mass and erosion rates, better control and measurement of test parameters such as temperature and erodent velocity, and the development of predictive modelling for the performance of materials subject to HTSPE. The project’s thermodelling techniques have also enabled room temperature data of mechanical properties to be extrapolated to give an indication of the high temperature wear resistance with great accuracy.

*Dissemination of results*
Within this project there have been 17 conference presentations and 9 publications aimed at disseminating the work to as wide a field as possible (e.g. Industry, academia, supply chain produces of materials and test methods). To assist in this, the project has held two industrial workshops, one in Germany and one in the UK, which were attended by academia and industry. To ensure longevity of the findings and to disseminate measurement good practice, many of the results have been incorporated into training material for BAM, CMI and Cranfield University. To further influence policy makers (e.g. the Civil Aviation Authority), government bodies and trade associations a series of articles and good practice guides have been written to promote best measurement practice for particulate erosion. Impact beyond the project will be realised through the use of a new International Measurement Standard for erosion which this project contributed to and has validated through the intercomparison work conducted.

Two good practice guides have been produced on using XCT to characterise powders and on the use of FE modelling to predict erosion behaviour. These are available from the project and NPL websites.

*Actual impact*

The project developed techniques for in-situ erosion measurements, at temperatures up to 900 °C, which have drastically reduced the time take to run erosion experiments. A UK based coatings company is using design approaches demonstrated in the manufacture of the NPL erosion rig and modifying in-house equipment to provide a more cost effective and robust testing solution to validate their coatings.

An SME, Pyro Optic in Denmark, now markets the particle velocity distribution measurement system developed by this project and has sales in academia and industry. This device is being applied to other measurement issues for example imaging droplet impact in water droplet erosion studies.

The project's ERROW-Sim software tool allows the pre-selection of materials according to its protective properties against erosion, thus reducing the necessity of full-scale erosion tests.

PTB has worked with Volume Graphics, a publisher of the software VG Studio Max, for visualisation of volume data; with metrology modules. This has led to improvements in the precision of the calculation of erosion parameters.

Throughout the course of the project the project team inputted and commented on a draft ASTM standard on Particulate Erosion. This was published and is now available as G76 – 13: Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets.

*Potential impact*

Industries which rely on or develop engineered surfaces for harsh environments or high value added applications, such as aerospace, energy, mining and oil and gas will benefit from this work. Improved measurement procedures and better understanding of uncertainties in test methods have increased confidence in the experimental data and enabled the development of accurate models. This will result in better life prediction of components, more in-service condition monitoring, planned maintenance and ultimately improved design of novel materials.

For example, reducing the erosion of the leading edge of turbine blades would result in improved efficiency and thus avoid, in the case of a large power plant (~800 MW), the emission of an extra 250,000 tonnes of $CO_2$ over the lifetime of the plant. Improved materials that can withstand HTSPE at higher temperatures and the option to use environmentally friendly biofuels will allow power generation to operate at higher temperatures and be more efficient.

**List of publications**


1. Metrology to Enable High Temperature Erosion Testing–A New European Initiative. In Advances in Materials Technology for Fossil Power Plants: Proceedings from the Seventh International Conference, October 22-25, 2013 Waikoloa, Hawaii, USA (p. 400). ASM International.
2. Solid Particle Erosion of TBCS: Jet Tester Modelling and Erosion Forecasts. In Developments in Strategic Materials and Computational Design V: A Collection of Papers Presented at the 38th International Conference on Advanced Ceramics and Composites January 27-31, 2014 Daytona Beach, Florida (pp. 139-150). John Wiley & Sons, Inc..
3. Influence of apparatus design and test method on the high temperature solid particle erosion of Nimonic 80a, Proceedings of the eighth International conference on Advances in Materials Technology for Fossil Power Plants, Portugal, 2016
4. Dreidimensionale Form- und Größencharaketrisierung von Erosionspartikeln mittels Röntgen-Computertomographie, Sensoren und Messsysteme 2016, ISBN 978-3-9816876-0-6
5. Testing the erosion parameters, https://issuu.com/euresearcher/docs/eur9_digital_mag

6. High temperature particulate erosion: Setting limits with confidence, http://www.adjacentgovernment.co.uk/research-science-innovation-news/high-temperature-particulate-erosion-setting-limits-confidence/28035/

7. Modelling particulate erosion, improving material performance, http://www.adjacentgovernment.co.uk/research-science-innovation-news/modelling-particulate-erosion-improving-material-performance/29246/

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