ADVANCED MAINTENANCE ADVISORY SURVEILLANCE SYSTEM (AMASS) FOR EQUIPMENT OPERATING IN HOSTILE ENVIRONMENTS

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ABSTRACT

The system was developed differently from the original concept in the work programme.
The overall objective of the AMASS project** was to develop an on-line surveillance system, to monitor the condition of boiler tubing in service and reduce the number of forced outages due to degradation by erosion, corrosion and overheating. The system should integrate the outputs of on-line and off-line techniques, together with tube life algorithms to give real time estimates of tube life probability. It was not foreseen that the sensors would have their own independent data collection systems. However, because the sensors developed did have their own on-line data collection systems, it was felt that effort in developing the Amass system would be more usefully directed at developing an off-line data storage and retrieval system. Consequently a novel topological data base was designed to be used with modular data processing tools.
This paper presents the planned project objectives and the results achieved.

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1. INTRODUCTION

Boiler tube failures are the major cause of forced outages in fossil power plants. The aggressive environment in fossil boilers is the main reason for the large number of failures, as the effects of stress, temperature, corrosion, erosion and vibration combine to produce degradation of tube steel. Overheating, corrosion and erosion, in combination, are responsible for half of all boiler tube failures.

The methodologies generally used to prevent boiler tube failures do not incorporate direct on-line monitoring of boiler tube deterioration but instead rely on off-line condition assessment, which can only be performed during infrequent inspection periods and historical operating data.

In the AMASS project, it was intended to improve the overall boiler tube failure prevention procedure, and thus reduce the number of forced outages, by developing and incorporating new on-line condition monitoring techniques with advanced off-line procedures in an integrated boiler surveillance system.

On-line techniques developed in the project include an erosion monitor based on the thin-layer activation technique, a corrosion monitor based on the electrical resistance method, and a metal temperature monitor based on the temperature change of the magnetic permeability of duplex stainless steel.

Off-line techniques developed include the determination of sites of highest erosion by cold-air velocity measurements, determination of tube defects and metal wastage by laser shearography, and determination of tube internal oxide thickness by ultrasonic measurements.

A schematic breakdown of the AMASS main Tasks is represented in Fig. 1.

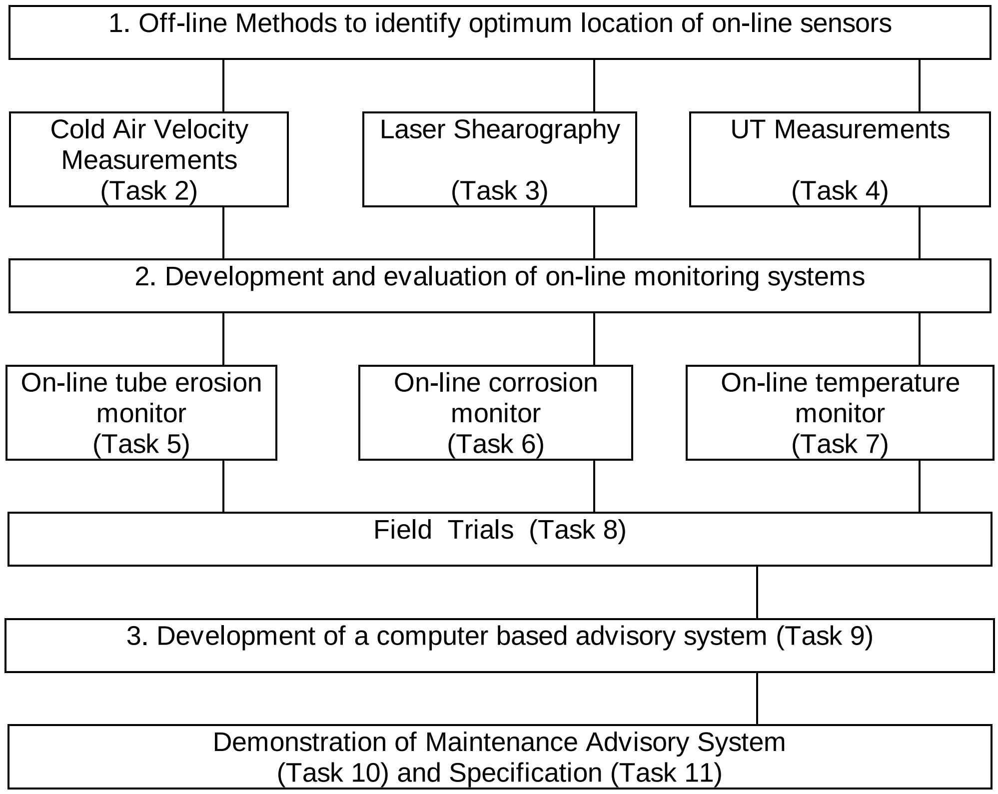

Fig. 1 - Schematic breakdown of the AMASS main research Tasks.

2. PLANNED OBJECTIVES AND RESULTS ACHIEVED

2.1. Determination of high erosion sites using Cold-Air Velocity (CAV) measurements

The objective was to use the Cold Air Velocity (CAV) technique to locate areas of high gas flow within a boiler and hence potential sites of erosion.

The basis of this technique is to identify regimes in the economiser-section of a coal-fired boiler in which the velocity of the draught caused by the boiler fans is greatest. During normal boiler operation, the tubes in these regions will receive the greatest bombardment by entrained ash particles. The air velocities are determined using a hand held anemometer whilst running the boiler fans.

The CAV technique was used with success. Gas velocity profiles inside a coal-fired boiler and thus areas of high erosion damage were determined. The high erosion was confirmed by means of tube thickness measurements.

As consequence of the CAV measurements, several modifications were made to improve the gas flow distribution. Baffles were installed and expansion joints were replaced by new ones with a different design.

Additionally to the original objective, the CAV measurements contributed significantly, together with others modifications made in the boiler, to improve the efficiency of the boiler, decreasing the flue gas temperature in the stack by 15ºC, giving an important economic and environmental benefit.

2.2. Location of corrosion and erosion damaged regions using laser shearography technique

Laser shearography is a non-destructive testing technique, which can reveal manufacture, and service induced defects. In this project, it was used to locate corrosion and erosion damage. The principle of the laser shearography technique is illustrated in Figure 2.

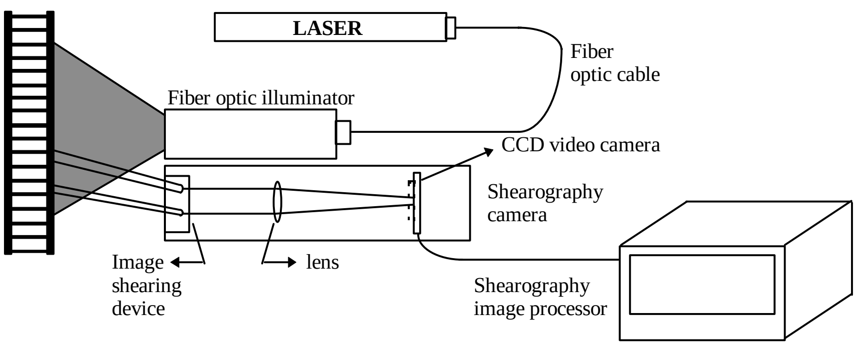

Fig. 2 - Principle of Laser shearography technique

The laser shearography technique was used successfully in the laboratory, being able to detect introduced defects simulating pitting, longitudinal cracks and thinned regions. Mock-ups, simulating boiler components, were manufactured from new and ex-service boiler tubes, containing internal and external simulated defects, characteristic of corrosion and erosion damage. Longitudinal cracks, simulating corrosion-fatigue phenomena, were also introduced.

After the laboratory evaluation, laser shearography was applied in Power Plant boilers. These field trials confirmed that laser shearography is applicable to the inspection of boiler tubes.

The initial objective of the project was to develop an optical system to inspect relatively large areas of tube banks. However, due to budget limitations, a small camera was used allowing the examination of a 20 x 20 cm area on a single "shot". By changing the optical system and camera attachment a larger area may be analysed. An area of 50 x 50 cm is currently the limit for pressure stressed tubular components due to the resolution of available CCD cameras. It seems a promising technique. Therefore, further development concerning the inspection of larger areas and better image resolution is necessary to make this technique industrially successful.

2.3. Determination of tubes with the highest temperature exposure by measuring tube internal oxide thickness

From ultrasonic signals it is possible to deduce the thickness of the internal (steam side) oxide in boiler tubes. The thickness of steam side oxide is a function of the temperature and time of exposure. Hence, knowing the operating hours of a boiler tube and measuring the tube internal oxide thickness, we can determine the operating temperature.

This technique was used successfully in the laboratory and in boilers at Carregado and Compostilla Power Plants. Measurements of the oxide thickness in boiler tubes were taken both metallographically and ultrasonically with good results (see Table 1).

Table 1 - Comparison of ultrasonic and metallographic measurements of steam side oxide thickness of various tube samples.

Tube reference	Ultrasonic measurement / µm (delay / ns)	Metallurgical oxide measurement / µm
ISQ 1C	730 (235)	706
ISQ 1D	650 (208)	650
ISQ 1E	610 (200)	571
ISQ 3D	690 (222)	687
ISQ 3E	290 (95)	539 (382)[1]
ENDESA1 7A	260 (88)	231
ENDESA1 10A	260 (83)	166
ENDESA2 3A	270 (90)	162
ENDESA2 5A	300 (93)	145
ENDESA2 6A	320 (93	267

[1] Cracked oxide, measurement in parentheses is the measurement to the crack.

The correlation coefficient obtained between UT and metallographic measurements was about 0,90 (see Figure3).

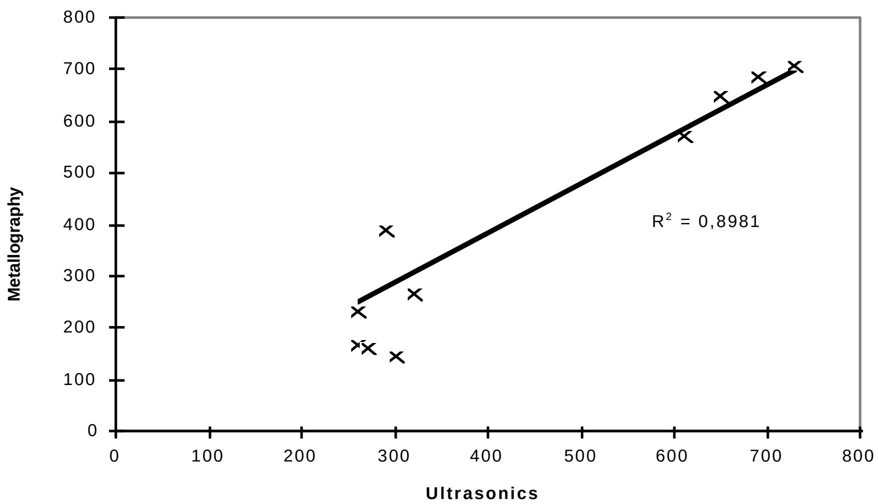

Fig. 3 - UT/Metallographic steam oxide data comparison

Additionally, an algorithm was developed to correlate tube internal oxide thickness to temperature based on operating hours, for three types of ferritic steel: 2 1/4 CrMo, 9 CrMo and 12 CrMo.

This algorithm makes the output of the technique vastly more useful in predicting tube life. It is therefore considered to be a very valuable product for life assessment in fossil-fired power generation plant.

2.4. Monitoring boiler tube erosion using Thin Layer Activation

The principle of the technique is that a small patch on the surface of a tube is activated with a radioactive isotope (very low dose) which can be detected through the boiler wall. When the implant is put into the boiler, the layer containing the radioactive isotope is progressively eroded, and the level of radiation is thus reduced. The reduction in the level of radiation detected can be converted into material loss data. The principle of the Thin Layer Activation (TLA) technique is illustrated in Figure 4.

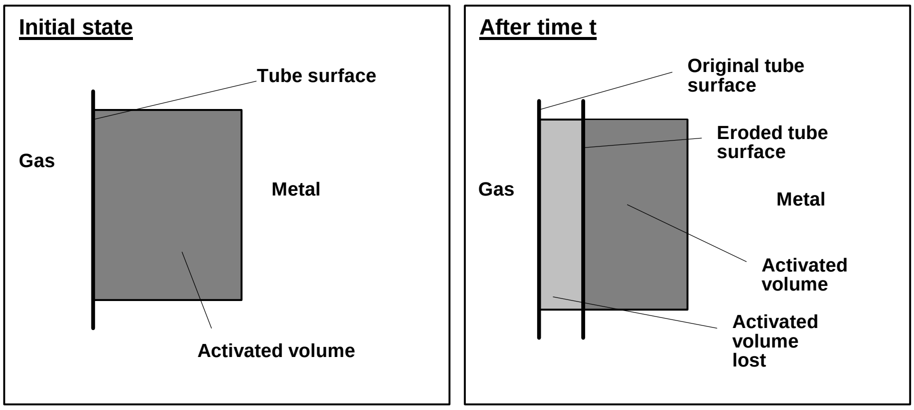

Fig. 4 - Principle of the Thin Layer Activation technique

This technique has been used in laboratory and pilot plant low temperature applications. The aim of this project was to transfer the technology to industrial high-temperature applications.

A laboratory evaluation of this technique was completed successfully. The viability of using the technique on boiler tube materials in a plant mock up, and the effect of diffusion of the activated species into the base material were determined in the laboratory.

Afterwards the TLA technique was applied in a coal-fired boiler at Compostilla Power Plant, with good results.

The results collected during the operation of the unit over seven weeks, with the data acquisition equipment installed in the unit control room, have shown that it is possible to establish erosion trends over long periods as shown in Figure 5.

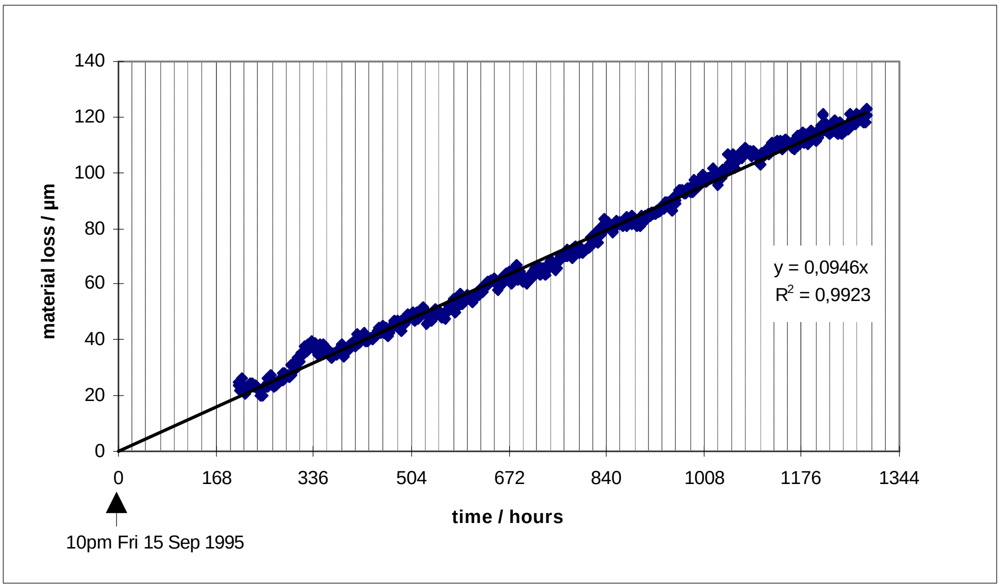

Fig. 5 - Erosion of economiser tube at Compostilla Power Station as measured by thin layer activation

However, to be used as an on-line monitor, the technique has some limitations.

-The activated tube must be within 1.3 meters of an accessible wall of the boiler.

-The relation between material loss and the source activity can only be identified when the scale falls off and consequently the technique can only be applied to monitor erosion.

-The high cost of the equipment and the necessity of a well trained operator.

Safety procedures for the use of TLA in laboratory and boilers were established and approved by the official authorities.

2.5. Monitoring boiler tube corrosion using electrical resistance probes

The objective was to develop and evaluate on-line electrical resistance corrosion probes to monitor the corrosion rate of boiler water wall tubes, through the membrane existing between the tubes.

The development of these corrosion probes required for more effort than originally foreseen. Several corrosion probes prototypes were constructed and tested in laboratory, but only one probe has achieved successful results.
This probe was installed and tested in an oil-fired boiler during three months.
The results of this testing were disappointing. The boiler furnace environment destroyed the front face of the probe, where the corrosion element was installed, and no data was collected by the acquisition system. Further developments and testing are required to improve the probe robustness to endure boiler furnace environments.

Additionally to the initial Work Programme a superheater corrosion probe was provided by a sponsorship agreement and tested in an oil fired boiler. In spite of some problems occurred during the tests, the probe was tested during 2000 hours and gave useful information. Some problems were found in the cooling system that is the critical aspect of the probe design.

Suitability of the prototype system and software has been demonstrated for on line application, although the cooling system should be designed for each specific case because the temperature distribution on the external surface of the probe depends on the local conditions of the boiler furnace.

2.6. Monitoring effective metal temperature in boiler tubes

The objective was to develop and evaluate a novel and relatively inexpensive metal temperature monitor (small studs of duplex stainless steel) based on the magnetic changes that occur on the ageing of duplex stainless steels. The basis of this technique is that the amount of ferrite in a duplex stainless steel, after ageing for long periods (in the order of 5000h) in the temperature range of 500-700ºC is characteristic of temperature exposure. The idea was developed by Lai at the city Polytechnic of Hong-Kong, who has given the device the name "Feroplug".

The ferrite content is determined by the magnetic permeability measurement using a magnetic ferrite gauge. The magnetic permeability of steel is proportional to the percentage of ferrite contents.

A magnetic ferrite gauge was obtained and evaluated to verify that whether it measures accurately the ferrite content of steels. Steel samples were assessed metallographically and the ferrite contents determined were compared with results obtained from the ferrite gauge. The results showed a very good correlation between the two methods of determination(see Table 2).

Table 2 - Correlation between ferrite contents measured metallographically and using the ferrite gauge

Sample reference	**Ferrite content / %**	
	by metallography	by ferrite gauge
ETG1	38.0	38.1
ETG2	42.0	38.6
EXS	46.6	43.8
EXT	45.0	45.0
EXV	43.4	42.8

The ferrite gauge is a very simple instrument to use. It is battery operated, very light weight and capable of storing up to 1000 readings. The readings, taken in situ, can be downloaded to a computer in standard windows software on IBM PC compatibles.

Four different alloys were selected for assessment of the ageing characteristics. The programme of testing involved the isothermal ageing of six specimens of each of four alloys at 400ºC, 450ºC, 500ºC, 550ºC, 600ºC, 650ºC and 700ºC, to over 4000 hours, with regular interruptions to make measurements of ferrite content. Investigation of the physical metallurgy of the ferrite decay process were also carried out by ERA in collaboration with the University of Zaragoza who has used X-ray diffraction to obtain a better understanding of the ageing curves. These alloys were also aged non-isothermally to determine their response under varying temperature conditions.

The temperature monitor (Feroplug) developed is a small capsule of duplex stainless steel that can be attached by welding, to the boiler tubes. The Feroplug was also tested in two Power Plant boilers.

From the analysis of the ageing results, the following conclusions can be appointed:

- Generally, changes are very slow at the lower temperatures (400ºC) and very rapid at the higher temperatures (700ºC).
- The ferrite contents of two alloys tend to level out at an "equilibrium" level for temperatures below 600ºC and the content of one alloy for temperatures above 600ºC. Therefore, the technique can be used for monitoring temperature in the 400-700ºC temperature range, but, this range cannot be covered by a single alloy.
- Any reduction in ferrite content is irreversible and, being a diffusion controlled process, it provides an effective temperature (it measures the average temperature over a long period of time).
- The initial objective, to develop a temperature monitor was not completely achieved. One steel type is not enough to cover the 600-700 ºC range. Two steel types are necessary.
- The accuracy of the technique is not as great as anticipated at the outset of the project. The accuracy is +15ºC, lower than the target accuracy of +5ºC. This is a limitation for the use of the technique in power plant boilers. The technique can be used to determine the relative temperature distributions in a boiler, but not an accurate temperature.

Figure 6 shows an example of the ageing behaviour of one the evaluated alloys.

Fig. 6 - Ageing behaviour of a commercial alloy evaluated for application as a temperature monitoring device.

Additionally to the initial work programme an algorithm was developed to determine the temperatures to which the "feroplug" has been exposed considering the ferrite content and duration of exposure.

To determine temperatures from " Feroplug" implants which have been exposed to a boiler environment it has been necessary to derive algorithms to describe the variation in ferrite content of the material with time and temperature of ageing, for each of the four alloys which have been characterised. These algorithms have been derived from the calibration data accumulated during the laboratory ageing experiments. In all cases the model has the same form.

2.7. Development of the advanced maintenance advisory system

The objective was to develop a computer based system to store and manage data from on-line (monitors) and off-line techniques, together with tube life algorithms to predict life of boiler tubes and issue maintenance advise. However, the system was developed differently from the original concept.

When the project was conceived it was intended that the computer system should collect data from the AMASS on-line sensors and it was not foreseen that the sensors would have their own, independent data collection systems. However, because the sensors developed did have their own on-line data collection systems, it was felt that effort in developing the Amass system would be more usefully directed at developing an off-line data storage and retrieval system. Consequently a novel topological data base was designed to be used with modular data processing tools.

Therefore, the AMASS system was designed as a computer based system developed to be PC compatible running Microsoft Windows 3.11/3.0 with DOS 6.2, to integrate the output of the on-line and off-line sensors with all available data and life prediction algorithms. A multilingual interface was foreseen to allow the user to choose the working language.

The system was divided in the following parts: Data input, Data storage and handling, Data analysis tools and Data output:

1 - Data input

Data from all AMASS on-line and off-line sensors can be stored. Other information may also be stored, such as plant information (pressures, temperatures, operating details, etc.), inspection data (metallographic, hardness, thickness, etc.) and materials data.

2 - Data storage and handling

Data can be stored in chronological order (time-stamped) with reference to the location of the components that have been measured.

A diagrammatic boiler display can be used to identify the boiler sub-components and associated data. Facilities were provided to access data using various keys, e.g.: site, time, component location, sensor-type, etc.

3 - Data analysis tools and output

Tools have been provided to analyse data from the AMASS sensors, Thin layer activation, Steam side oxide measurements and Feroplug. The output from these is metal loss data and temperature data. This output may be used in the tube life algorithm tool, which provides tube life information based on wall thinning rates and temperature of operation. The data input for this tool may alternatively come from conventional sources, such as thermocouples and ultrasonic wall thickness measurements. The tube life calculation will determine whether the final failure will be through creep, at higher temperatures, or plastic collapse, at lower temperatures, based on material data stored within the system.

The system contains the following extra facilities:

<u>User Definable Interface</u>

This allows the user to customise the system according to his needs. This has been achieved by making it possible to incorporate specific plant images and by allowing the user to set up highlight regions and hotspots and to create links between images, data, tools and location keys.

Location keys Mechanism

This mechanism allows data to be searched at different levels of resolution. The lowest level of resolution is the name of the plant while the highest level of resolution is the specific position on a tube in particular tube bank in the boiler of plant.

Ability to absorb standards

Nomenclatures used to describe locations within a plant vary considerably from operator to operator. Within the AMASS system it is possible for the user to adopt any form of nomenclature while the location key mechanism continues to maintain the relationship between the data components.

Registration and incorporation of user defined programs

The user can at any time include further programs for analysing or processing data written by the user or for the user by a third party.

Linking of menus to knew data when new tools are added

When new tools are registered or associated with data, menus are created for using those tools.

Dynamic Link Libraries (DLLs)

The DLLs are used to increase performance and flexibility.

Context handling system to ease user burden

A context handling mechanism has been designed to allow the user to define the Site name, Plant type, Coding system, Language, etc.

The "actual system" is a prototype and is not working properly due to the bugs still existing in the software. Further developments are necessary to achieve industrial and commercial interest in the maintenance of industrial boilers.
The system was extensively tested by the Amass partners, simulating its operation in conjunction with Power Plant technicians. These testing sessions allowed the evaluation of the system potentialities. The partners believe that the system is a promising software with interesting capacities for Power Plant applications.
ERA that has developed the system is committed in achieving a full workable prototype, correcting the bugs still existing in the software.
After solving these problems, ERA will present to the partners a proposal indicating the further development needs, in order to establish the route to commercialisation.

To produce a commercial system with a wide range of industrial application, to give tube life prediction and maintenance advice, further work is required and funding for this will be a major question.

3 – ACKNOWLEDGMENTS

We would like to thank the European Commission for making this project possible by funding it through the BRITE-EURAM programme and for collaborating during the entire project. We would like to thank also the partners as well as Carregado, Setubal and Compostilla Power Plants, for their collaboration.

4 – REFERENCES

This paper was prepared by EDP/PROET on behalf of AMASS project consortium. It is based on the work performed and results achieved by all partners.

The project consortium and role of partners was established as follows:

- EDP - Electricidade de Portugal, SA, Portugal: Mendes Martins, A. Batista, J. Enes

- Project co-ordinator
- Organisation and execution of field trials and final field demonstration of the system in an oil-fired boiler.
- Contribution to the development of the AMASS system and monitoring techniques.

- ERA Technology Ltd, United Kingdom - A. Tomkings, R. Townsend, B. Meadowcroft

- Responsible for the development and specification of the AMASS system.
- Development of three surveillance techniques (UT oxide thickness measurements, TLA monitoring and the temperature implant technique).
- Contribution to the development of corrosion monitors and to the specification and procurement of instrumentation and materials.

- ENDESA SA, Spain - E. Santos, J. Ribelles

- Organisation and execution of field trials and final field demonstration of the system in an coal-fired boiler.
- Leader in developing procedures for the Cold-Air-Velocity measurements.

- MAGUE/ABB, Portugal - E. Barata

- Lead role in the specification and procurement of materials, contribution to the design aspects of the corrosion probe and methods to reduce erosion damage.

- Responsible for the construction of boiler tubes mock-ups for trials of laser shearography and to the design of TLA implant and attachment devices.

- CORMON, United Kingdom – M. Greenway, B. Pike, B. Hemblade

- Responsible for the development, design and manufacture of the electrical resistance corrosion probe.

- University of Zaragoza, Spain - R. Rios

- Selection and characterisation of dual phase steels and determination of the temperature-magnetic permeability relationships for the selected materials.
- Determination of diffusivity characteristics of activated species and evaluation of diffusion effects for the TLA monitoring technique.

- ISQ, Portugal - J. Barata

- Responsible for the development and evaluation of the laser shearography technique, procurement of instruments and materials for its development and trials of this technique in a boiler.

- ENEL (Sponsor), Italy - S. Ghia

- Sponsor of the UT oxide thickness measurement, TLA and temperature monitoring techniques.
- Supply of a superheater corrosion probe to be tested in the field trials.