

HIGH-TEMPERATURE EROSION TESTING STANDARD AND ROUND ROBIN TESTING

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Abstract

Solid Particle Erosion (SPE) of hardware remains an ongoing concern with the operation of Steam Turbine power plants. SPE of both rotating and stationary components of turbines leads to loss of efficiency, higher cost of operation and maintenance of turbines. Ultra Supercritical (USC) and advanced USC programs underway in North America, Europe and Asia have created renewed interest in the understanding of the effects of SPE on the advanced alloys and high-temperature SPE testing. ASTM's G76 "*Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets*" defines a standard test method for conducting room temperature SPE erosion testing. The current G76 erosion test reference conditions are 90 degree particle impingement with 50 micron alumina on AISI 1020 steel at room temperature and a relatively low particle velocity of 30 m/s. The objective of the current Electric Power Research Institute (EPRI) sponsored program is to develop an elevated temperature SPE standard that will provide more appropriate reference conditions for SPE conditions encountered in current and next generation steam turbine applications. Currently such test standard is not available from any of the standards organizations. Various laboratories around the world have developed their own equipment and procedures to conduct their tests. This makes it difficult to compare these interlaboratory test results for the purpose of screening and selecting alloys and coatings for erosion mitigation. Organizations from the United States, United Kingdom, Canada, China, Germany, Italy and India have so far expressed interest in participating in an interlaboratory "Round Robin" test program to develop an elevated temperature erosion test standard. Initial test conditions and test matrix have been developed for this round robin test

program. Type 410 stainless steel substrate will be used at impingement angles of 30 and 90 degrees with 50 micron alumina erodent with particle velocity of 200 m/s (667 f/s) at room temperature and 600 C (1112 F). This paper will provide an overview of prior elevated temperature SPE testing, test capabilities of participating organizations and the status of the development of the new test standard.

Solid Particle Erosion in Fossil Power Plants

Solid particle erosion has been a pervasive generic problem in fossil power generation equipment. Exfoliation of oxide particles from the steam side surfaces of high-temperature steam path components in boilers and stem pipes lead to erosion of turbine blades, nozzles and control valves. Electric Power Research Institute (EPRI) conducted studies on the extent of this problem and costs associated with this on utility steam turbines^{1,2,3}. While thermal spray coatings have been effective at increasing the SPE resistance of the uncoated component, component erosion damage is still observed in service.⁴ Some examples of the effects of SPE on high-temperature steam turbine parts are shown in Figure 1.

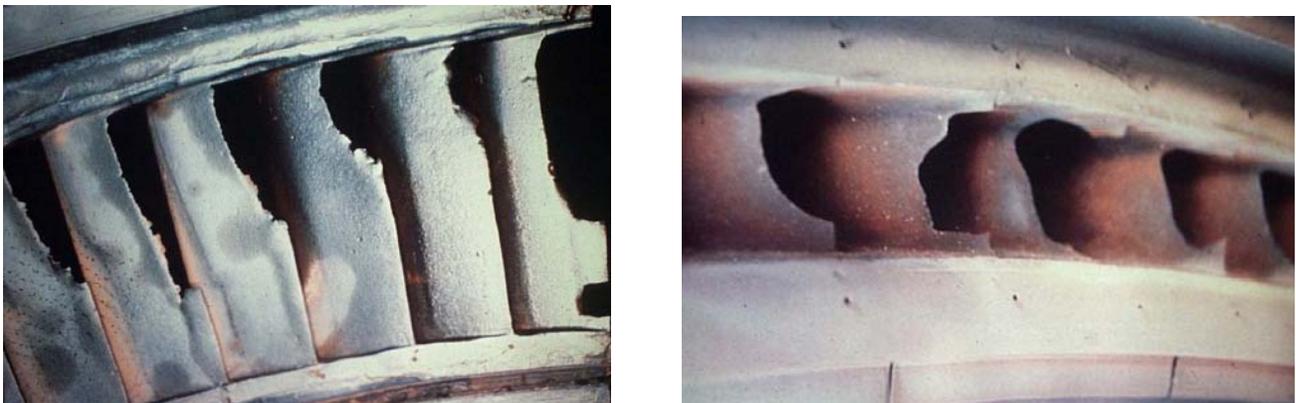


Figure 1. SPE Damage on High Pressure Steam Turbine Blades (courtesy of Encotech)

This SPE problem is expected to be more pronounced in USC turbines which operate at much higher temperatures and pressures. Several high-temperature steels and exotic alloys in combination with protective coatings are being developed and evaluated for the USC application, as covered by several papers in this conference. However, their erosion properties and resistance to SPE of these alloys under plant operating conditions have not been reported.

It is important to understand the SPE behavior of the alloys used in high-temperature application under various conditions in order to develop effective erosion mitigation options which may include coatings and other surface modification techniques. The variables which control the SPE behavior are the temperature, particle size, velocity impact angle, hardness of the particles as well as the substrates, morphology of the particles (sharp, blunt, angular etc). The particle size distribution found in a typical boiler scale of a fossil power plant is shown in Figure 2.⁵ The

composition of the scale is mainly magnetite (Fe_3O_4). The particle size distribution varies from about 5 microns to 100 microns. Depending on the volume fraction, velocity, angle of the particles, the erosion characteristics will vary.

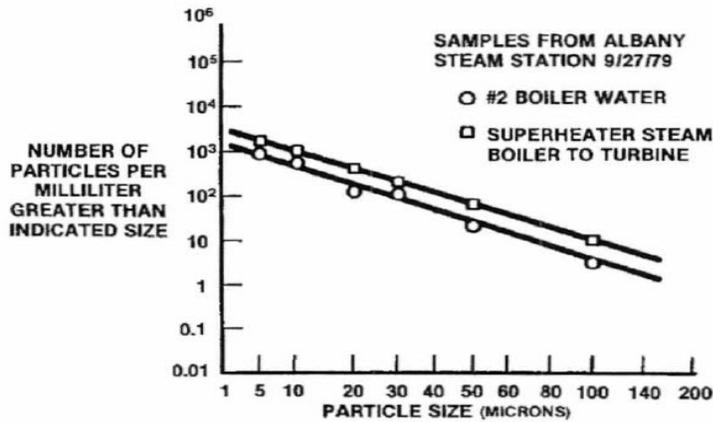


Figure 2. Particle size Distribution of Boiler Scale Recovered from Boiler Water and Superheater Steam Drains⁵

SPE in aero engines is also a problem for engines operating in dusty environment. Damage to the compressor blades as well as the hot section components reduce the efficiency and life of the engines resulting in costly change outs and repairs. The effect of SPE on an aero engine compressor blade is shown in Figure 3. Increasing the SPE resistance of aero engine compressor components with protective coating continues to be an active area of development.^{6,7}

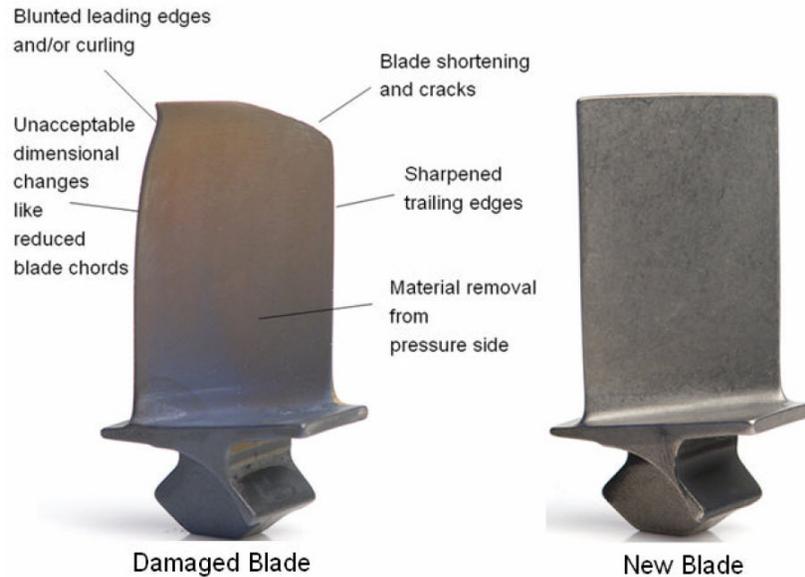


Figure 3 Comparison of an eroded compressor blade with a virgin blade⁸

A brief overview of the SPE behavior of some of the materials under different conditions is presented below.

Solid Particle Erosion Characteristics

The topic of solid particle erosion has been studied by numerous researchers over the years. Several good reviews of the particle erosion literature can be found in articles by Wright⁹, Finnie¹⁰, and Mathews.¹¹ One of the key concepts that has been identified is the difference in the erosion behavior of ductile materials such as metals and that of brittle materials such as most ceramics. With ductile materials the erosion response as a function of particle impact angle has been shown to approach zero at very low angles of attack, increases to a maximum as the angle of incidence is between 15-20 degrees and then drops to 1/2 to 1/3 of the maximum erosion rate as the particles impacting the surface approach 90 degrees. The erosion rate of brittle materials is at a maximum at 90 degrees with the rate decreasing continually to a negligible mass loss at very low angles of impact. This response reflects fracture induced mass loss where the extent of the erosion is dependent on the vertical component of the particle impact energy. This difference in ductile and brittle material behavior is plotted in Figure 4.

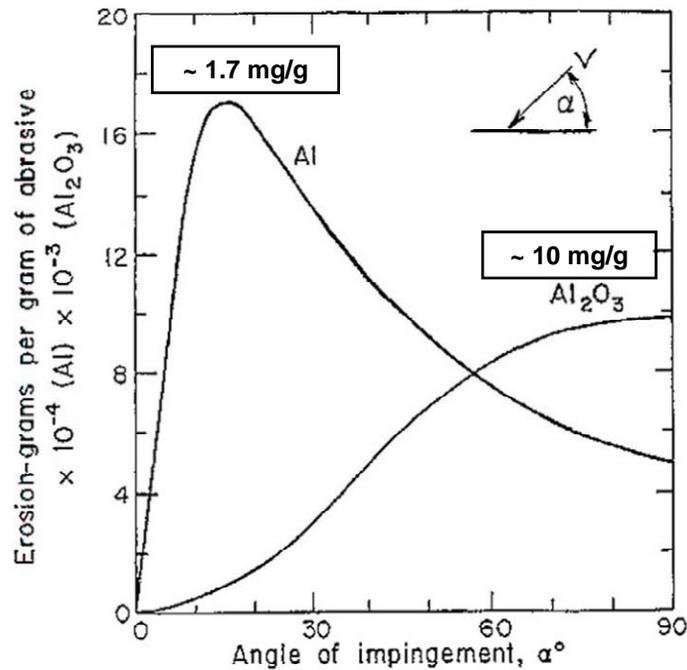


Figure 4. Erosion Behavior of Ductile and Brittle Materials¹⁰

In ductile erosion, the metal is indented by the particles impacting the surface and material is extruded around the indentation. At high angles the energy of the particle is dissipated through ductile deformation and is more resistant to erosive wear than at low angles where the metal indentation proceeds by a plowing or micromachining action. At high angles the material removal mechanism is thought to proceed by work hardening of the extruded material by repeated impacts, leading to local fatigue or fracture based loss of material. With brittle materials the particle impact generates brittle fracture within the near surface zone of the material, with cracks radiating outward and downward from the point of impact. These mechanisms are illustrated in Figure 5.

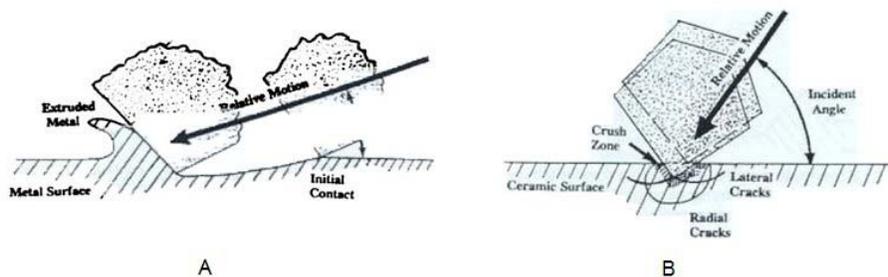


Figure 5. Particle Erosion Mechanisms. A) Plowing and Extrusion Mechanism for Ductile Materials B) Brittle material Erosion Proceeds through Lateral and Radial Cracking around the Crush Zone. (From D'Alessio 1994)¹²

EPRI Program Objectives and Approach

The main objective of this EPRI project is to promote and facilitate high-temperature solid particle erosion test standard development for application in steam turbines and land based & aero gas turbines engines. The technical approach to accomplish the objective is as follows:

1. Conduct a literature search and survey of high-temperature erosion test facilities and capabilities around the world
2. Define the various testing parameters and develop a test matrix for elevated temperature erosion testing
3. Conduct round robin tests and perform statistical analysis of the results
4. Develop a high-temperature solid particle erosion test standard which could be used by the international community to conduct SPE testing
5. Organize an international workshop on erosion

The standard testing method developed under this EPRI project will be used to develop an ASTM standard for high-temperature SPE testing. The various testing laboratories participating in the round robin program will provide critical input to develop this standard. The SPE test methods used for the evaluation and characterization of various alloys and coatings vary greatly among the various laboratories. Several test techniques and procedures are in use which are summarized below.

Erosion Test Methods

Several erosion test methods are used for the characterization of the erosion performance of turbine materials and coatings. In all cases a screening test is no substitute for field testing under actual turbine operating conditions. It is difficult to simulate engine conditions in laboratory testing. The goal of any of these screening tests is to have fidelity with the type of degradation observed in the field and to rank the relative erosion resistance of the materials and coatings consistent with that.

Among the key factors to take into consideration are the type of erodent (i.e. Alumina, Silica, Arizona Road Dust, Iron Chromite, Magnetite, etc.), particle size range (10 micron – 200 micron or larger), particle velocity (30 m/s to 215 m/s or higher) and angle of impingement (15 to 90 degrees). In reporting erosion test results it is important for these parameters to be specified. The ASTM G76 test method for conducting solid particle erosion via gas jets is often referenced for erosion test studies conducted at room temperature. It was developed for erosion characterization of structural materials and is not completely suited for conducting studies of turbine components or coatings. This has resulted in a number of different approaches being taken for testing these materials.

Initial room temperature screening is generally carried out with some form of a modified G76 test since it is the simplest to set up shown in Figure 6.

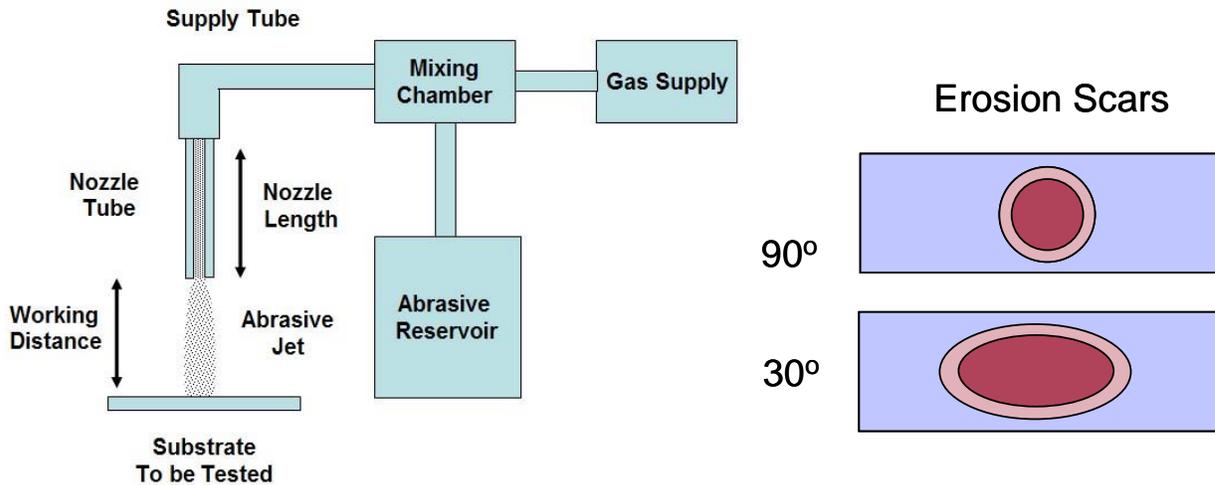


Figure 6. Schematic drawing of test system according to ASTM G-76 test standard for room temperature SPE testing and erosion scar geometry for two angles of impingement

Typically researchers will modify the test conditions to be more representative of field conditions and to be better at monitoring erosion of coatings especially those that are in the 10 - 20 micron thickness range for compressor airfoil applications.⁷ Typical modifications are use of silica, instead of alumina, to use higher particle velocities to better simulate turbine conditions, a larger diameter nozzle to increase the area tested and evaluating weight loss instead of volume loss. Erosion results are influenced by the hardness, friability and angularity of the particles. Silica provides results that are closer to conditions in the field than alumina does for aero engine applications.⁶ Several particle size ranges may be used depending on the SPE test objective.. The larger test area helps to screen for coating defects that might be present and to improve the resolution of the test. Erosion rates are usually defined as the number of grams of material or coating eroded per gram of erodent impacting the sample (mg/g) rather than as a volume loss (mm³/g) as specified in G76. For coatings it is difficult to establish a reliable density to calculate volume loss from the weight loss.

A critical feature in all erosion testing is the use of a witness coupon for comparison of erosion results taken at different times. Often it will be the substrate material being coated (e.g., Ti-6Al-4V, IN-718, 17-4 PH etc.) rather than 1020 steel called out in G76. This also provides some measure of erosion performance compared of the substrate to guide the development of any surface modifications needed. It is difficult to make comparisons erosion data generated in different labs since there are often differences in the actual practice of the test that lead to different erosion rates. Two keys areas of variation are the actual particle velocity and geometry factors with the amount of erodent hitting the coupon. In the case of particle velocity – it is difficult to measure accurately without specialized equipment (e.g., laser doppler velocimeter or

particle image velocimeter, etc). Some of the laboratories use double rotating disc method to determine the particle velocity.¹³ The particle velocity is also sometimes estimated based on an aerodynamic calculations of particle speed, but is less preferred than direct measurement. The second factor is the amount of erodent actually hitting the sample. At low angles this can be especially significant since the erosion “footprint” may be larger than the coupon being tested. When doing component testing, low angle results need to be carefully evaluated.

More sophisticated test methods with better instrumentation are used as part of a typical development path prior to an engine test. This often includes doing elevated temperature erosion testing of the coatings by the engine and coating manufacturers. Gas turbine compressor temperatures range from ambient at the inlet to a compressor discharge temperature of 600C (1112F) in some cases. This temperature is similar to steam temperatures encountered in the USC steam turbines. Thus, high-temperature erosion testing of materials and coatings for these applications is critical for screening, ranking and final selection of the most effective materials and coatings.

Under this EPRI program, a detailed survey of the high-temperature erosion testing capabilities around the world was conducted. All of the steam and gas turbine manufacturers, independent testing laboratories, universities, coating manufacturers and turbine repair companies were surveyed to gather information. The data collected include temperature limits, velocity, methods used to obtain high-velocities (compressed air jets vs. combustion tunnels), methods used in velocity measurements, types of erodents and sizes used.

Survey of Erosion Test Facilities

The following organizations have high-temperature erosion test facilities and provided details of their testing capabilities and accepted EPRI’s invitation to participate in the round-robin test program.

1. General Electric Company, Schenectady, USA (test facility at GE Global Research Ctr, Bangalore, India)
2. United Technologies Research Center , East Harford, USA
3. Air Force Materials Lab / University of Dayton Research Institute (UDRI), Dayton, USA
4. Cranfield University, Cranfield, UK
5. ERSE Spa, Milan, Italy
6. Technical University of Brandenburg at Cottbus, Brandenburg, Germany
7. Institute of Turbomachinery, Xi’an Jiaotong University, Xi’an, P.R. China

8. National Research Council (NRC), Ottawa, Canada

9. National Physical Lab (NPL), Middlesex, UK

All of these facilities except four are capable of conducting tests at high temperatures and high velocities using various erodents. UDRI, NRC, Technical University of Brandenburg and NPL do not have the high-temperature test capabilities but are in the process of installing such facilities and expect to participate in the round robin program in 2011. All of the labs are able to conduct tests at room temperature tests. Configurations of the test systems, their maximum velocity (at RT) and temperature capabilities from some of the test facilities are shown below in Figures 7 through 13. At elevated temperatures, higher than indicated velocities could be obtained.

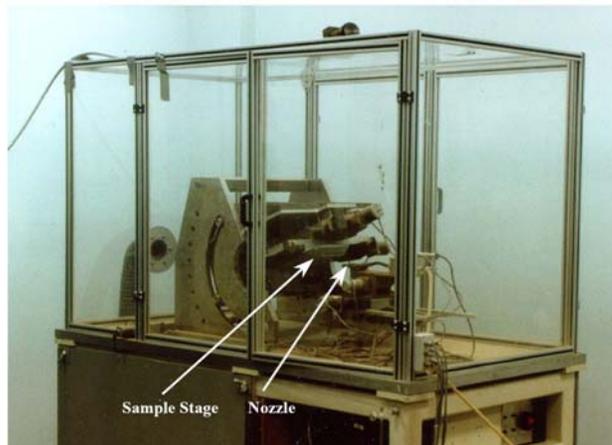


Figure 7. Test facility at AFML/UDRI (330 m/s; RT Only)

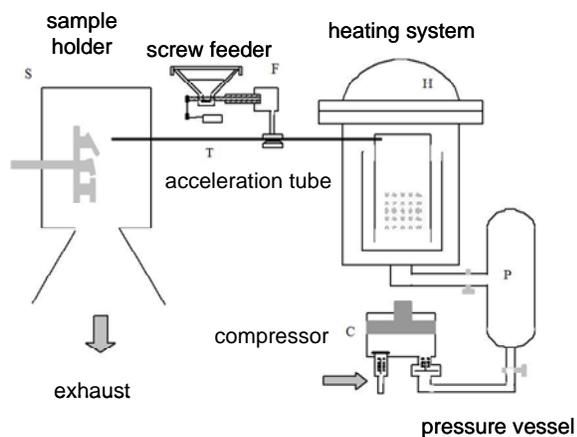


Figure 8. Test system schematic (left) and photo at Cranfield University (200 m/sec; 850C)

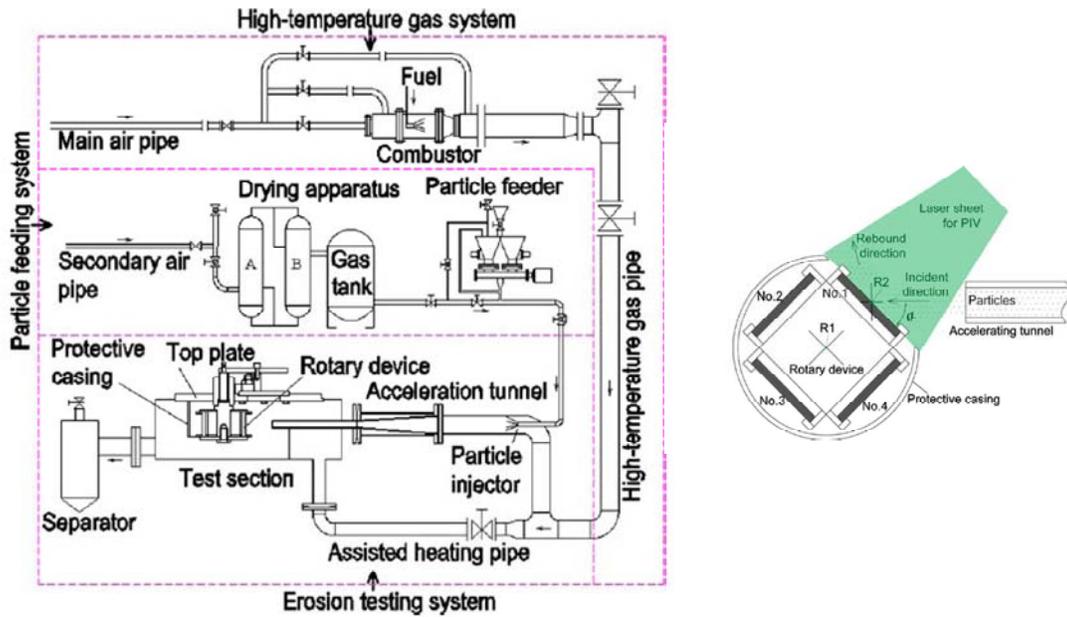


Figure 9. Schematics of the test system at Xi'an University (450 m/s; 650C)

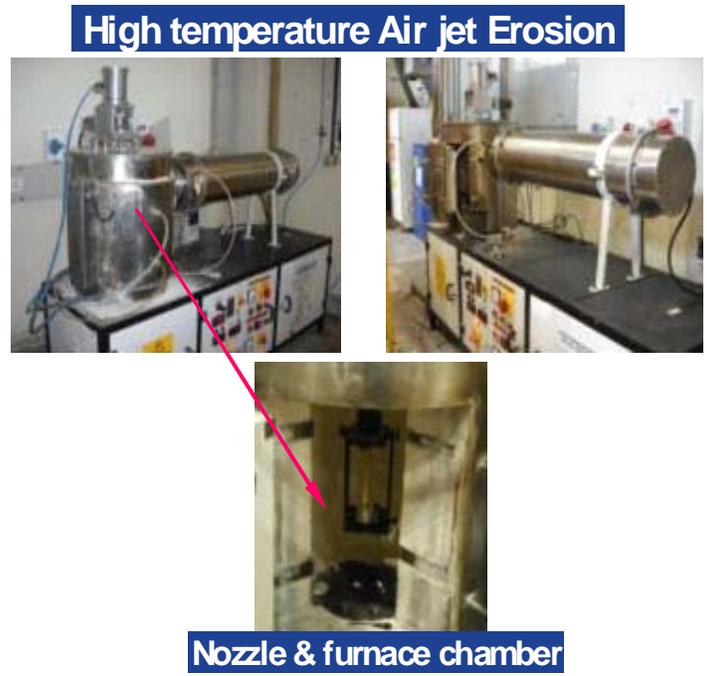


Figure 10. High-temperature erosion test rig at GE Global Research (305 m/s; 982C)



Figure 11. Test system at ERSE Spa. (200 m/s; 800C)



Figure 12. Test rig at NRC (300 m/s; 750C)

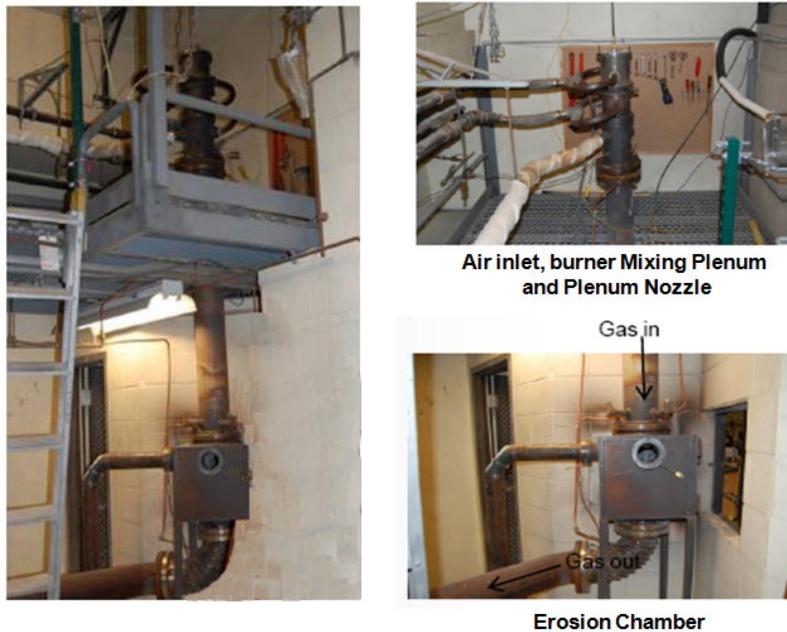


Figure 13. High-temperature erosion test rig at UTRC (265 m/s; 1260C)

As can be seen in these figures the architecture of the test systems and their capabilities are diverse. The nozzle, specimen design, mounting methods, stand off distances, erodent feeding, mixing, temperature control, etc., vary among these test facilities. Two of the test rigs employ combustion gases and the others use compressed air with external heat. Velocity measurements methods are also unique to each of these systems. The challenge is to conduct the round robin tests at similar conditions to compare and use these results in the development of the test standard which could be used by all the labs. Thus, a test matrix was designed such that all of the participating labs will be able to meet the testing requirements as presented below.

Round Robin Test Matrix

The material selection was based on the alloys used in high-temperature steam turbine application. Type 410 stainless steel or similar steels are used in the steam inlet regions of most of the turbines. The test coupons size is fixed at 75 mm x 25 mm x 4.5 mm which is suitable for all of the laboratories. Some of the labs need to make minor modification of their specimen fixture arrangements to accommodate this sample size. The test matrix is shown in Table 1.

Table 1. EPRI Test Matrix in comparison to ASTM G76 specification

EPRI ROUND ROBIN TESTS	ASTM G76 SPECIFICATION
200 m/s particle velocity	30m/s particle velocity

Adjust stand off distance to create 14 mm diameter erosion scar	10 mm stand off distance; results in relatively small erosion scar
1.5 - 9 mm (0.060 – 0.360”) Nozzle Diameter (dependent on lab)	1.5 mm (0.060”) Nozzle Diameter
50 μ Alumina erodent	50 μ Alumina erodent
410 Stainless Steel Substrates	1020 Steel Substrates
2 grams/minute powder feed	2 grams/minute powder feed
5 - 10 minute min. test intervals per sample	10 minute min. test time
RT & 600C Test Temperatures	Room Temperature Test Only
30 & 90 degree impingement angles	90 degree impingement angle
mg/gram of erodent to be reported	mm ³ /gram of erodent (<i>need to know substrate/coating density</i>)

The chemistry and mechanical properties of the Type 410 stainless steel coupons which have been procure are given below.

Table 2. Chemistry of Type 410 Stainless Steel Test Coupons

Grade 410 SS	Fe	Cr	Ni	Mn	Si	Ti	C	P	S	N
min.	bal	11.5	-	-	-	-	-	-	-	-
Coupon Lot	bal	12.1	0.13	0.31	0.49	0.13	0.014	0.021	0.002	0.0074
max.	bal	13.5	0.75	1	1	-	0.15	0.04	0.03	-

Dimensions: 25mm x 75 mm x 4.5 mm

Yield strength: 42.5 KSI

Tensile Strength: 64.5 KSI

Hardness: 74-76 RB

Surface Finish: < 0.2 microns Ra



Microstructure of the 410SS Coupons

The erodent selected was 50 μ alumina for this round robin test program. This powder lot was evaluated for particle size distribution and particle characteristics. It is highly desirable to keep the size distribution tightly around 50 μ . A single master lot of white alumina powder was procured from Japan and distributed to the test labs. The particle size distribution is shown in Figure 14.

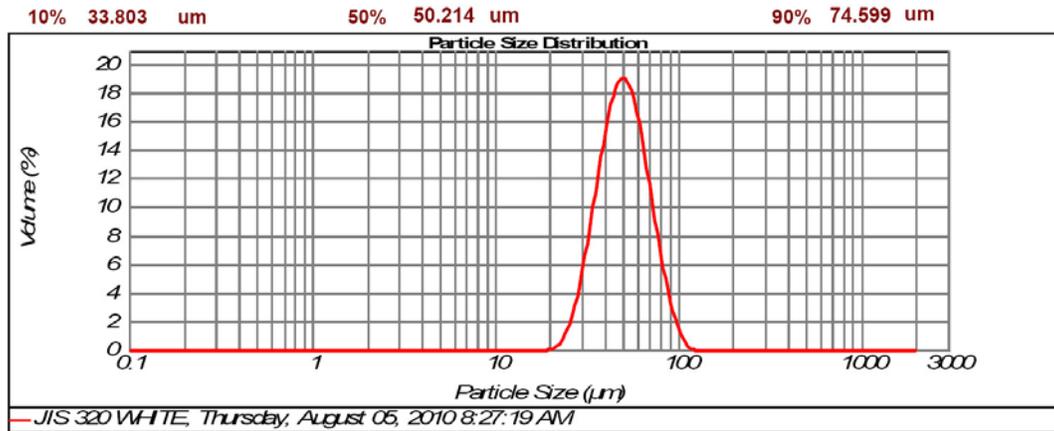


Figure 14. Alumina powder size distribution (JIS 6001-320) (D10 = 33.8 μ ; D50 = 50.3 μ ; D90 = 74.6 μ)

The powder was evaluated under scanning electron microscope (SEM), for the particle characteristic. A SEM photomicrograph of the powder is shown below.

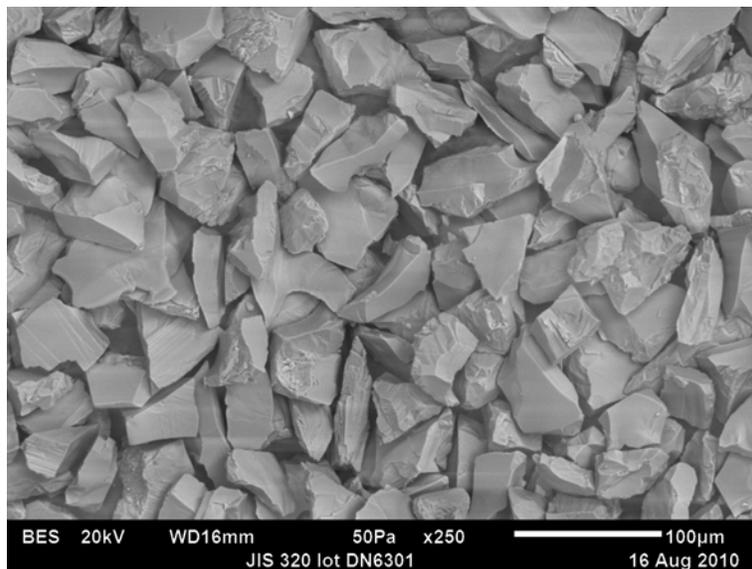


Figure 15. SEM Photomicrograph of the Alumina Powder

Two angles of incidence, 30 and 90 degrees, were selected for both the RT and 600C tests. Attempt will be made by all the laboratories to keep a constant dose (total amount of the erodent impacting the test coupon) by selecting a constant feed rate and the time intervals. Initial bench

mark tests at room temperature are planned at UDRI to assess the extent of weight loss based on these test conditions shown in Table 1. Based on these results, minor adjustments to the test parameters may be made, if necessary.

It is targeted to complete this round robin test program by the middle of 2011. Statistical analysis as required by the ASTM guidelines will be conducted on the data received from the labs. A draft ASTM specification is planned for submission to the G-02.10 committee by the end of 2011 with the aim of finalizing a standard test method document by 2012.

Summary

A literature search and survey of test facilities around the world with high-temperature erosion test capability have been completed. Total of nine laboratories have agreed to participate in this round robin test program. Three of the labs are installing high temperature capability at the time of this writing and expect to complete the installation by the first quarter of 2011. A test matrix has been developed for tests to be conducted at room temperature and at 600C (1112F). Type 410 stainless steel test coupons and a master standard 50 μ alumina powder have been procured and distributed to the participating laboratories. It is anticipated that all of the testing could be completed by the middle of 2011, a draft standard submitted to ASTM by the end of 2011 and final test standard by the end of 2012.

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