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HIGH-TEMPERATURE SOLID PARTICLE EROSION TESTING STANDARD FOR ADVANCED POWER PLANT MATERIALS AND COATINGS

V.P. "Swami" Swaminathan, *TurboMet International, 8026 Winter Park, San Antonio, TX 78250*

Jeffery S. Smith, *Material Processing Technology, LLC, 1965 Forest Park Road, Norton Shores,*
MI 49441

David W. Gandy, *Electric Power Research Institute*
P.O. Box 217097, Charlotte, NC 28221

Abstract

Solid Particle Erosion (SPE) of hardware remains an ongoing concern with the operation of Steam Turbine power plants as well as Land Based Gas Turbines. SPE of steam piping, rotating and stationary components in turbines leads to loss of efficiency, higher cost of operation and maintenance downtime and cost. 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 at high temperature. The Gas Turbine industry has also been conducting studies for improving the elevated temperature erosion resistance of compressor and hot section components and coatings. 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 but has many limitations that restrict its usefulness to evaluate alloys and coatings used in turbines.

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 parameters for SPE conditions encountered in current and next generation steam turbines, gas turbines as well as in the selection and qualification of alloys used in other steam path components. 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 elevated temperature (ET) SPE tests. This makes it difficult to compare these inter-laboratory test results for the purpose of screening and selecting alloys and coatings for erosion mitigation. Organizations from the United States, United Kingdom, China, Germany, Italy and India have been participating in the EPRI inter-laboratory "Round Robin" test program to develop a new ASTM ET erosion test standard. Standard test coupons from Type 410 stainless steel have been tested using a standard alumina erodent powder at specified test conditions at room temperature and 600C. Impingement angles of 30 and 90 degree were used. An international conference on solid particle and liquid droplet erosion was organized in 2012 to gather the world experts in erosion testing, modeling and application [1]. Valuable information was obtained at this conference which helped in the preparation of the first draft standard which has been

submitted to ASTM for balloting by the committee membership. This presentation will describe the program structure, test conditions used, test results and the development of the draft ASTM ET SPE test standard.

Key Words: Solid particle erosion; high-temperature; round-robin testing; ASTM Standard; steam turbines; gas turbines; particle velocity measurement

INTRODUCTION

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 [2,3,4]. While thermal spray coatings have been effective at increasing the SPE resistance of the uncoated component, component erosion damage is still observed in service.[5] Some examples of the effects of SPE on high-temperature steam turbine parts are shown in Figure 1.

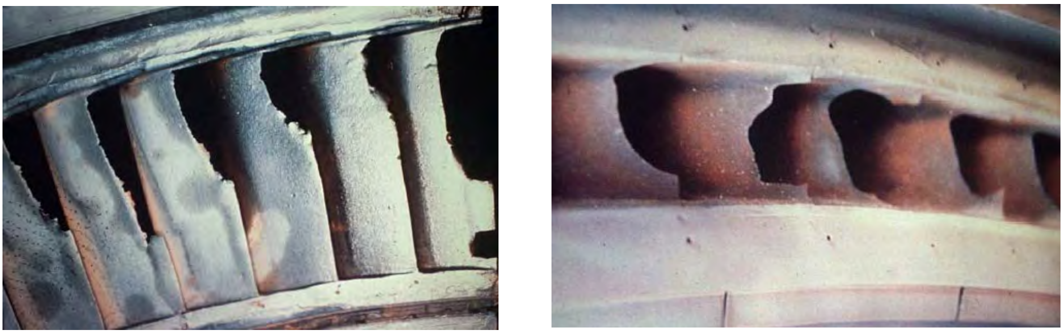


Figure 1. SPE Damage on High Pressure Steam Turbine Blades (courtesy of Encotech)

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. Several papers on this subject were presented at the EPRI conference in 2010[6]. 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 [7] 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.

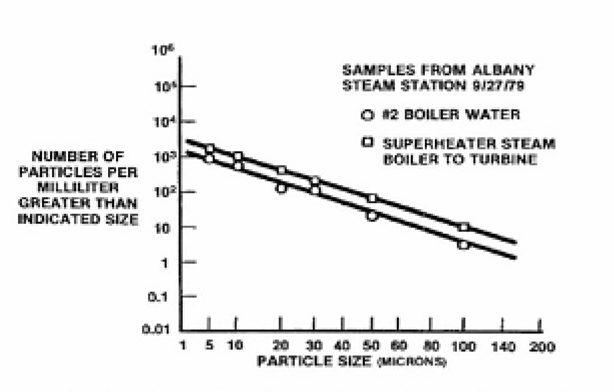


Figure 2. Particle size Distribution of Boiler Scale Recovered from Boiler Water and Superheater Steam Drains[7]

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.[8,9]

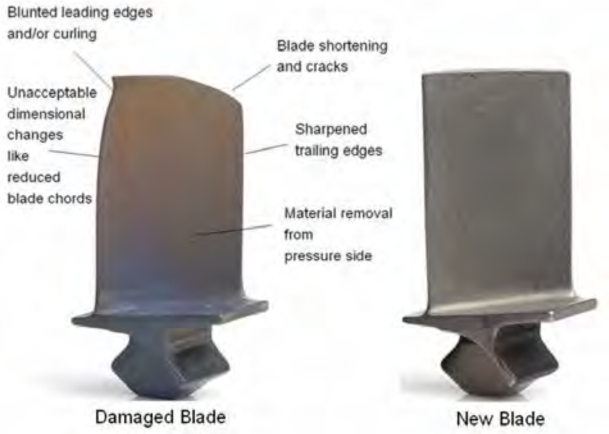


Figure 3 Comparison of compressor blade damaged by SPE (left) with a virgin blade (right) [10]

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 Wright [11], Finnie [12], and Mathews.[13] 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 show 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.

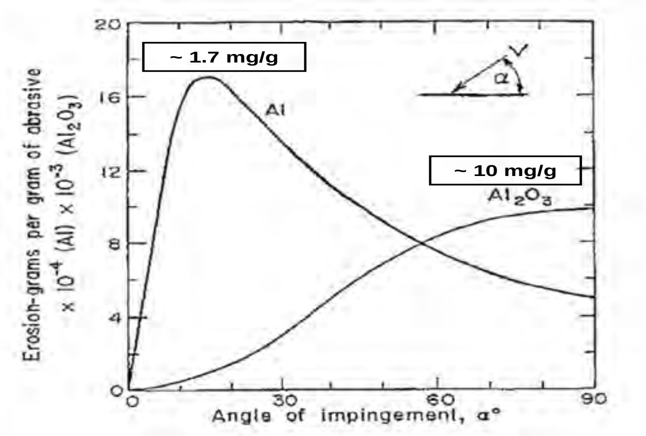


Figure 4. Erosion Behavior of Ductile (Al) and Brittle (Al_2O_3) Materials [12]

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 were 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.

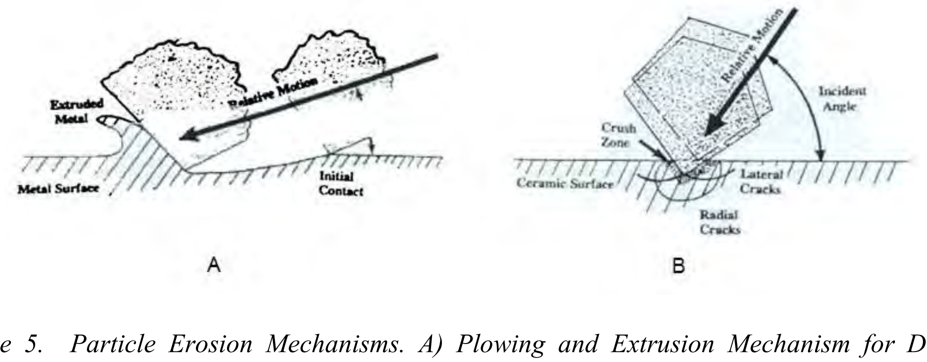


Figure 5. Particle Erosion Mechanisms. A) Plowing and Extrusion Mechanism for Ductile Materials B) Brittle material Erosion Proceeds through Lateral and Radial Cracking around the Crush Zone. (From D'Alessio 1994) [14]

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. Organize an international workshop on solid and liquid particle erosion
5. Develop a high-temperature solid particle erosion test standard which could be used by the international community to conduct SPE testing and compare the results on a common basis

The standard testing method or guideline developed under this EPRI project is used to develop an ASTM standard for high-temperature SPE testing. The SPE test methods used for the evaluation and characterization of various alloys and coatings vary greatly among the various laboratories. Several test equipments, techniques and procedures were used by the participating laboratories and provided results to develop this test standard.

Elevated Temperature Erosion Testing

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 erodent and sizes used. Details of the test equipment and methods used by the laboratories were presented in Reference [15].

In general this test method utilizes a repeated impact erosion approach involving a small nozzle delivering a stream of gas containing abrasive particles which impacts the surface of a test specimen. A standard set of test conditions for the elevated temperature testing were provided to the test labs. However, deviations from some of the standard conditions are permitted if described thoroughly. This allows for laboratory scale erosion measurements under a range of conditions. Test methods are described for preparing the specimens, conducting the erosion exposure, and reporting the results. Among the key variables 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 test to set up [16].

A schematic diagram of the elevated temperatures testing system used by the participating laboratories around the world is shown in Figure 6.

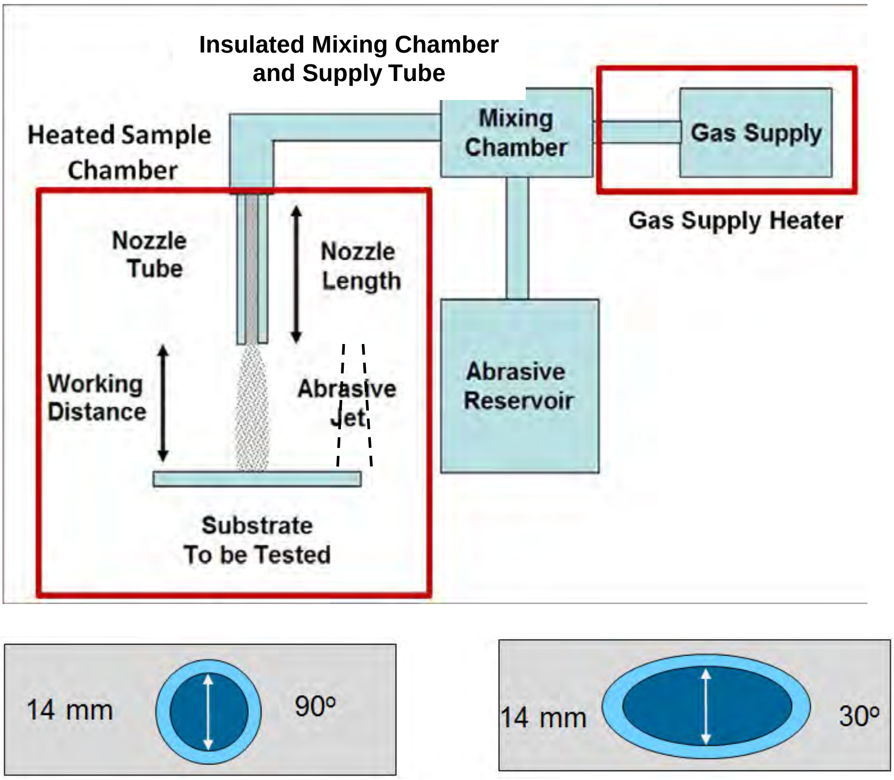


Figure 6. Schematic drawing of test system used for elevated temperature SPE testing and erosion scar geometry achieved for two angles of impingement (30 and 90 degrees) on Type 410 stainless steel test coupons

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 [9]. 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 (LDV) or particle image velocimeter (PIV) etc). Some of the laboratories use double rotating disc (DRD) method to determine the particle velocity [17]. Another 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.

The following organizations have high-temperature erosion test facilities and provided details of their testing capabilities and participated in the EPRI sponsored round-robin test program to develop the ASTM test standard..

- Air Force Materials Lab (AFML) / University of Dayton Research Institute (UDRI), Dayton, USA (room temp testing only and baseline data); LDV used for real-time velocity measurements
- General Electric Company, Schenectady, USA (test facility at GE Global Research Ctr, Bangalore, India) - room temperature and 600C tests; DRD for velocity measurements
- Cranfield University, Cranfield, UK – Room temperature and 600C tests; no direct velocity measurements but fluid dynamics principles used to compute particle stream velocity
- ERSE SpA, Milan, Italy – Room and 600C tests; DRD used to measure the velocity
- Institute of Turbomachinery, Xi'an Jiaotong University, Xi'an, P.R. China – Room and 600C tests; PIV used in real time for velocity measurements
- DUCOM, Bangalore, India – Room temp and 600C tests; DRD used for velocity measurements

Configurations and photos of the test systems, their maximum velocity (at RT) and temperature capabilities from these test facilities are shown below in Figures 7 through 12.

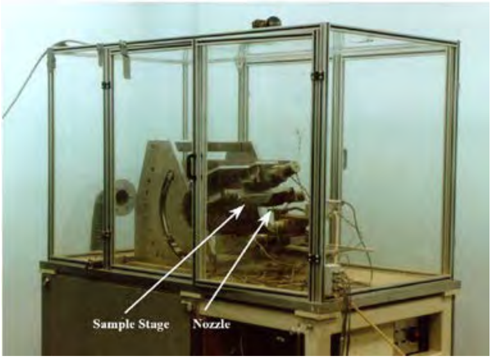


Figure 7. SPE Test facility at AFML/UDRI, Dayton, OH (330 m/s; RT Only)

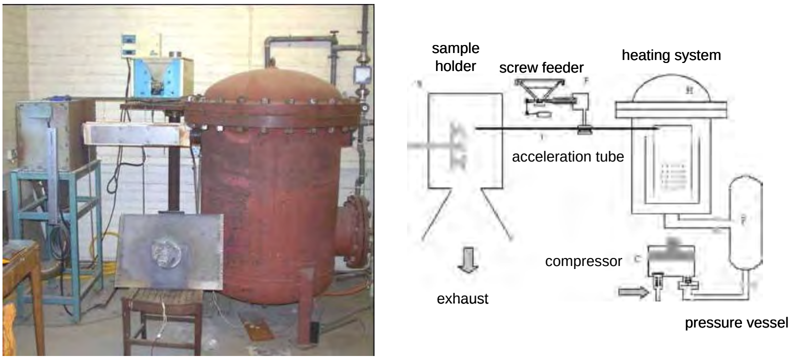


Figure 8. Test system schematic (left) and photo at Cranfield University, UK, (200 m/sec; 850C max.)

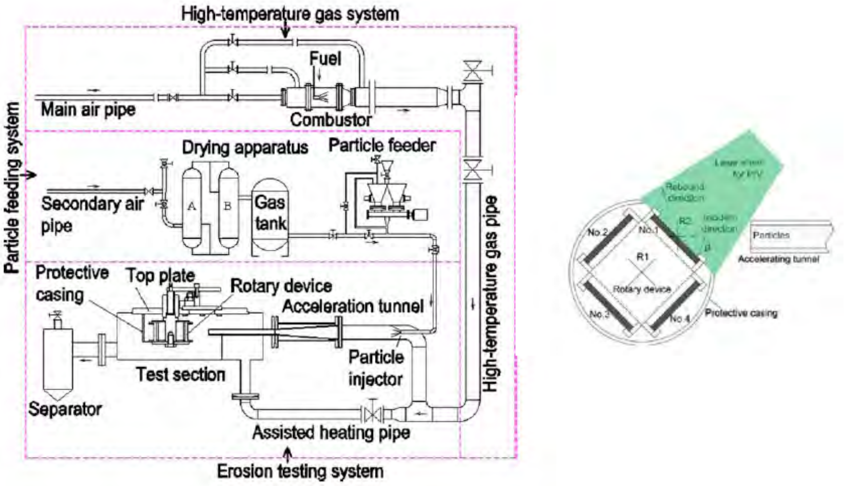


Figure 9. Schematics of the test system at the Turbomachinery Labs, Xi'an University, China (450 m/s; 650C)

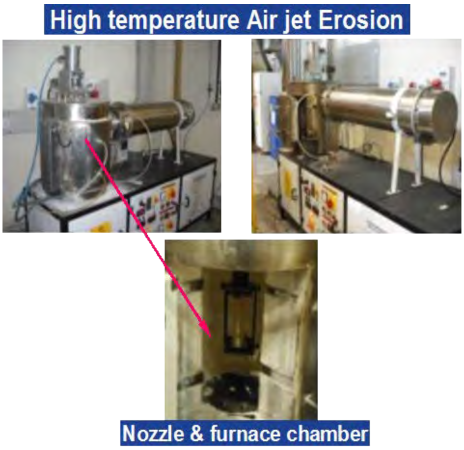


Figure 10. High-temperature erosion test rig at GE Global Research, Bangalore, India (305 m/s; 982C)

Figure 11. Test system at ERSE SpA, Mila, Italy, ***(200 m/s; 800C max.)***

Figure 12. Test system used at DUCOM, (200 m/s; 800C max.)

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.

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 erosion 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 Round Robin Test Matrix for room temp. and 600C in comparison to ASTM G76 specification

EPRI ROUND ROBIN TESTS (Room Temp. & 600C)	**ASTM G76 SPECIFICATION**
200 m/s particle velocity	30m/s particle velocity
Adjust nozzle to test coupon standoff 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 *(from a single batch)*	50 μ Alumina erodent *(multiple sources)*
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 (*need to know substrate/coating density to calculate weight loss*)

The chemistry and mechanical properties of the Type 410 stainless steel coupons used in this program 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	-

Microstructure of the 410SS Coupons

Dimensions: 25mm x 75 mm x 4.5 mm

Yield strength: 42.5 KSI

Tensile Strength: 64.5 KSI

Hardness: 74 - 76 R_b

Surface Finish: < 0.2 microns Ra

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. (JIS 6001-320: D10 = 33.8μ; D50 = 50.3μ; D90 = 74.6μ). Additional details on the particle size distribution are covered in Reference [18].

TEST RESULTS AND DISCUSSIONS

Room Temperature (24C) Data

Initial baseline tests were conducted at room temperature at AFML/UDRI labs. The erosion rate data obtained showed linear trend as shown in Fig. 14. This baseline data was used to compare the results from the other labs. Other feed rates up to 5 g/min were also used to evaluate the effect of feed rate on the erosion rare. No significant differences were obtained in the erosion rate expressed as mg/g. However, all of the tests in this program were conducted at a feed rate of 2 g/min.

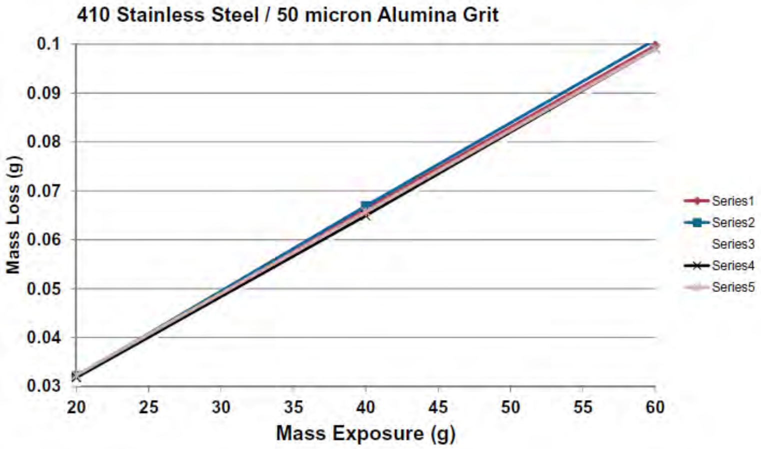
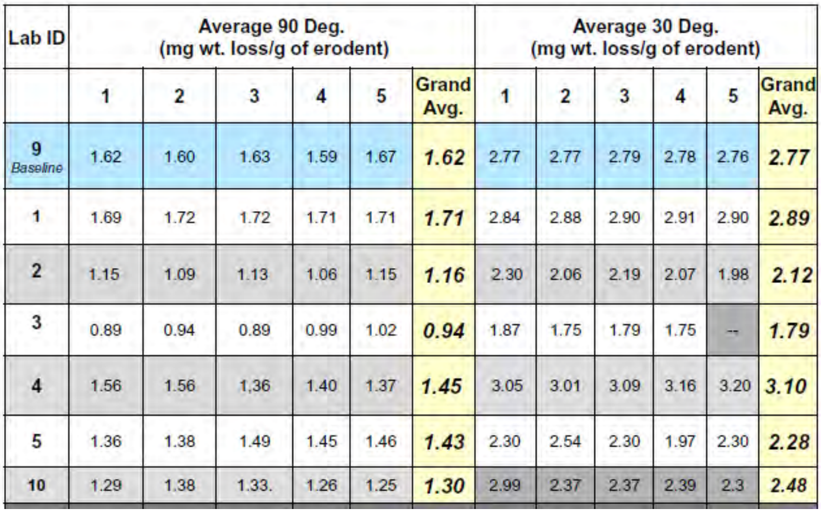


Figure 13. Tight clustering of baseline erosion test data on Type 410 Stainless Steel at Room Temperature (24 C), 200 m/s at 90 degrees with 50 micron alumina at 2 g/min feed rate

Table 3 summarizes the results of room temperature tests conducted by the various labs. Five readings were taken on each coupon at 20 g intervals. Thus a total dose of 100 g erodent was applied for each coupon. Five coupons were used for repeat tests and the average of the five reading from each coupon was reported along with the individual readings. Thus a total of 25 readings were obtained for each angle of incidence at a given temperature. The baseline data by Lab 9 with known measured velocity (by LDV) of 200 m/s was used to compare the results from the other labs. As mentioned previously, each of the labs used different methods to measure or to estimate the particle velocities. The reported velocities are 200m/s +/- 10m/s. However, it can be seen from this table that the results reported by Lab 3 are much lower than that of the other labs. This raised the question about the particle velocity measurement accuracy at these various labs. Additional tests by selected few laboratories were conducted at different velocities to understand the effect of velocity on the erosion rates and arrive at a common basis for cross comparison of the results among these labs.

Table 3. Results of the solid particle erosion tests conducted at room temperature by the laboratories at 90 and 30 degree impingement angles at 200m/s (Note: the lab ID numbers were assigned at random)



Lab ID	Average 90 Deg. (mg wt. loss/g of erodent)						Average 30 Deg. (mg wt. loss/g of erodent)					
	1	2	3	4	5	Grand Avg.	1	2	3	4	5	Grand Avg.
9 *Baseline*	1.62	1.60	1.63	1.59	1.67	***1.62***	2.77	2.77	2.79	2.78	2.76	***2.77***
1	1.69	1.72	1.72	1.71	1.71	***1.71***	2.84	2.88	2.90	2.91	2.90	***2.89***
2	1.15	1.09	1.13	1.06	1.15	***1.16***	2.30	2.06	2.19	2.07	1.98	***2.12***
3	0.89	0.94	0.89	0.99	1.02	***0.94***	1.87	1.75	1.79	1.75	--	***1.79***
4	1.56	1.56	1,36	1.40	1.37	***1.45***	3.05	3.01	3.09	3.16	3.20	***3.10***
5	1.36	1.38	1.49	1.45	1.46	***1.43***	2.30	2.54	2.30	1.97	2.30	***2.28***
10	1.29	1.38	1.33.	1.26	1.25	***1.30***	2.99	2.37	2.37	2.39	2.3	***2.48***

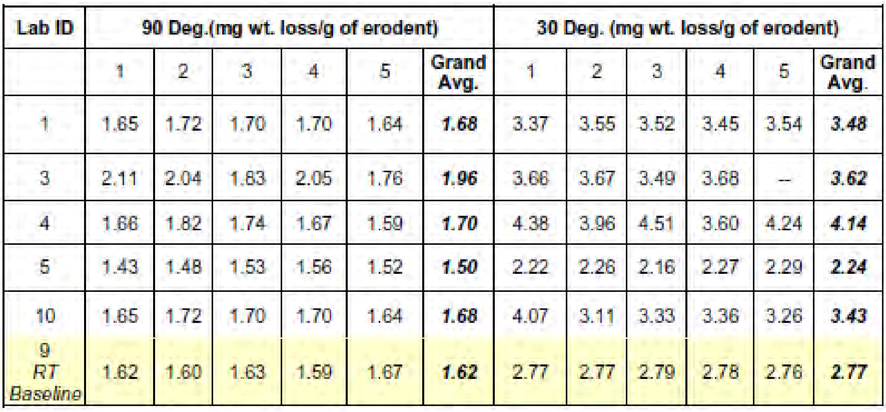
Since the Type 410 stainless steel is a ductile material, the erosion rates follow the trend similar to that shown in Fig.4 for ductile materials. The erosion rates at 30 degree impingement are higher by approximately a factor of 2x compared to the 90 degree data in Table 3.

Test Data at 600C

Out of the seven labs that conducted room temperature testing only five of the labs were able to conduct high-temperature tests at 600C at 200 m/s particle velocity due to equipment limitations. Labs 1 employed direct in-situ velocity measurements by PIV whereas three labs used DRD and the one of the labs estimated the velocity using fluid dynamics principles and prior calibration data. When DRD is used, the particle velocity is measured prior to the erosion tests on the coupons. Then the DRD is removed from the test chamber and the test coupon is positioned for the erosion tests. These velocity measurements are done at room temperature since DRD cannot be used in high temperature environments. The hopper which supplies the erodent powder is kept at room temperature. The particle stream is exposed to high temperature as it enters the career hot gas stream or the heated test chamber depending on the test system.

The results from the 600C tests from five labs are summarized in Table 4. For comparison, data from room temp from Lab 9 is also included in this table.

Table 4. Summary of results of erosion tests at 600C by five laboratories at 200 m/s along with the baseline room temperature data from Lab 9.



Lab ID	90 Deg.(mg wt. loss/g of erodent)						30 Deg. (mg wt. loss/g of erodent)					
	1	2	3	4	5	Grand Avg.	1	2	3	4	5	Grand Avg.
1	1.65	1.72	1.70	1.70	1.64	***1.68***	3.37	3.55	3.52	3.45	3.54	***3.48***
3	2.11	2.04	1.83	2.05	1.76	***1.96***	3.66	3.67	3.49	3.68	--	***3.62***
4	1.66	1.82	1.74	1.67	1.59	***1.70***	4.38	3.96	4.51	3.60	4.24	***4.14***
5	1.43	1.48	1.53	1.56	1.52	***1.50***	2.22	2.26	2.16	2.27	2.29	***2.24***
10	1.65	1.72	1.70	1.70	1.64	***1.68***	4.07	3.11	3.33	3.36	3.26	***3.43***
9 *RT* *Baseline*	1.62	1.60	1.63	1.59	1.67	***1.62***	2.77	2.77	2.79	2.78	2.76	***2.77***

The rests fall with an acceptable scatter band. The data at 90 impingement angle at both temperatures (RT and 600C) show very small difference. This infers that the erosion mechanism is similar at both temperatures. The 30 degree data at 600C show higher erosion rates with more scatter than the room temperature data. It should be noted that there was no noticeable oxidation on the Type 410 stainless steel test coupons at 600C. This is expected since the cumulative exposure time to high temperature is less than an hour for any given sample during these tests.

The interlaboratory study (ILS) group at ASTM International conducted a precision and bias study on all of the test data. Both the repeatability and reproducibility were determined for the data sets and they ascertained that all of the data are within acceptable limits. A detailed treatment and discussions will be presented in a research report prepared by ASTM in support of the proposed test standard.

Erosion Tests at Additional Velocities

Additional tests were conducted by two of the laboratories at velocities ranging from 60 m/s to 232 m/s at room temperature and 90 degree impact angle. The velocities were measured by different techniques at each of these labs using PIV, LDV or a DRD system. One of the labs conducted a series of tests at predetermined velocities. The test data summary and a plot are presented in Fig. 14.

“Known” velocity, erosion
data from Labs 1, 5, & 9

Impact speed (m/s)	Erosion rate (mg/g)	Lab
60	0.12	5
84	0.23	5
114	0.58	5
147	0.96	5
180	1.13	5
192	1.44	5
200	1.62	9
200	1.71	1
232	2.39	1

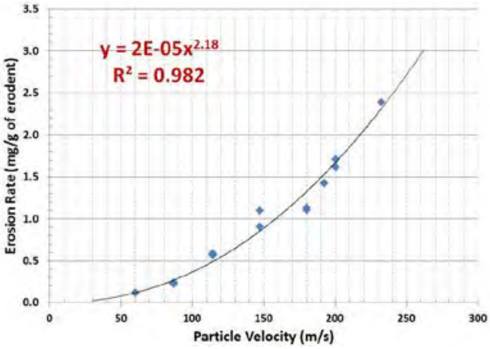


Figure 14. Summary of average erosion rate data and power-law plot at additional velocities at room temperature and 90 degree impact angle

The relationship of erosion rate (***E***) and impact velocity (*v*) is shown below in Equation 1.

$$E=kv^m \qquad \text{(Equation 1)}$$

where ***k*** is a constant and ***m*** is the velocity exponent.

The data falls in a tight scatter band and describes the erosion behavior very well in this velocity range. There does not appear to be a mechanism change in this velocity range. The pre exponential constant and the velocity exponent are included in the plot in Fig.14. The exponent value of 2.2 indicates the parabolic nature of the erosion behavior in this velocity range. This equation could be used to cross check the velocities from tests conducted by any other lab and could be considered as a ‘calibration curve.’ One of the participating labs conducted tests at additional velocities at 600C at 90 deg. and 30 deg. impact angles. Particle velocity was measured using a DRD apparatus. Figure 15 shows the summary plot of the data at 90 deg. The velocity exponent of 2.24 indicates, similar erosion mechanism at room temperature is also occurring at 600C.

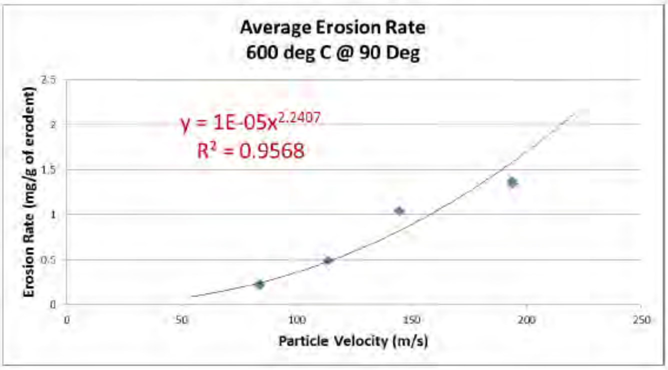


Figure 15. Power Law data fit for the erosion rate as a function of particle velocity at 600 C and 90 degree impingement angle

A summary plot of erosion test data obtained at 600C/30 deg. angle is shown in Fig. 16. Again, the velocity exponent is close to 2 which indicate the parabolic nature of the erosion phenomenon with velocity and the erosion mechanism seems to be independent of temperature under the testing conditions used in this program. Of course, the elative positions of the curves, i.e., the actual erosion rates, are determined by the pre-exponential constants.

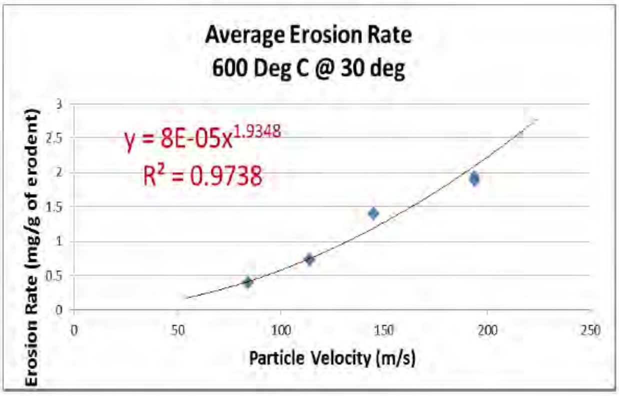


Figure 16. Power-law erosion rate plot at additional velocities at 600C and 30 degree impingement angle

Erosion Scar Analysis

Erosion scars formed on some of the randomly selected test coupons were analyzed using optical microscope and contact profilometry techniques. The diameter of the circular scar formed at 90 degree impingement angle, major and minor axes of the elliptical scar formed at 30 degrees and the maximum depth of the scar are important parameters. Scar analysis is more important when the erosion tests are conducted on coated samples. Volume and the depth of the coating removed are critical since the weight may vary depending on the composition of the coating. Also, breaching of the coating is undesirable to have valid data on the coatings. Typical surface profilometry of a scar for 90 degree impingement is shown in Fig. 17 and that for 30 deg. is shown in Fig. 18.

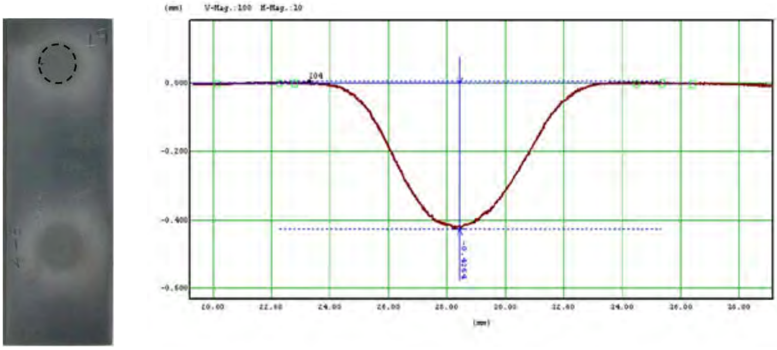


Figure 17. Contact profilometry data of RT test scar at 90 deg. impingement; 5mm nozzle dia,; 14 mm stand-off distance; 25 g dose; Scar diameter = 10mm; maximum depth = 0.42mm

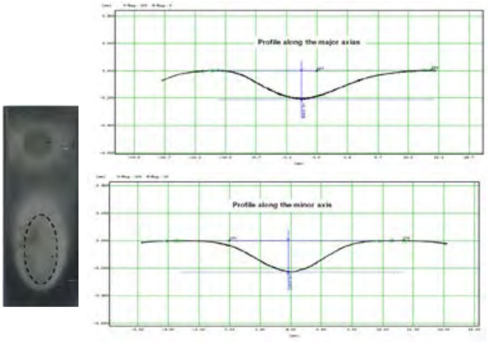
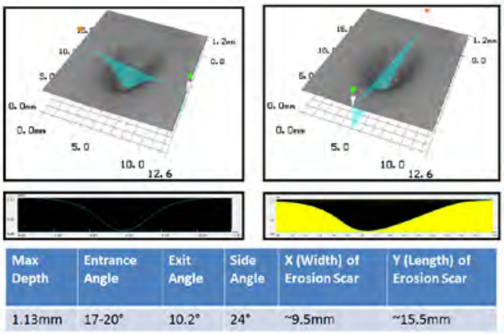


Figure 18. Contact profilometry of RT test scar at 30 deg; 5mm nozzle dia, 18 mm SOD; 50 g dose; major axis = 20 mm; minor axis = 11 mm; Maximum scar depth = 0.23mm



Max Depth	Entrance Angle	Exit Angle	Side Angle	X (Width) of Erosion Scar	Y (Length) of Erosion Scar
1.13mm	17-20°	10.2°	24°	~9.5mm	~15.5mm

Figure 19. Optical profilometry of erosion scar on test specimens eroded 30 degrees at room temperature. 2mm nozzle dia; 16 mm SOD; 100g dose.

Figure 19 shows the results obtained using an optical profilometry system on a scar of a specimen tested at room temperature at 30 degree impingement. The difference in the measured parameters between Fig. 18 and 19 are due to the differences in the nozzle diameter, SOD and the total dose applied. These results illustrate methods of scar analysis and the variability in the scar geometry due to test system set-up parameters and test conditions. Such scar analysis will help refine the test coupon set-up and standoff distance to obtain desirable scar sizes.

Summary

Currently high-temperature solid particle erosion testing is conducted by many organizations around the world using their own equipment and procedures developed ‘in-house’. This EPRI sponsored round-robin testing and ASTM test standard development program was directed at developing a high-temperature solid particle erosion test standard which will help the industry to perform such tests and compare the results on a common basis. Such common test method and data analysis procedure is essential to screen materials and coatings which may be selected for use in USC and other high-temperature steam power plants as well as gas turbine applications. This program was very successful in organizing an international conference on this critical subject to assemble many well known experts in the field of solid particle and liquid droplet erosion to share the current technology, ideas and information developed over many years. There was a consensus in this forum for the development of a common test standard which could be used by any organization to conduct these erosion tests. Many laboratories around the world voluntarily participated in a round robin test program to perform tests on standard coupons provided by EPRI. Type 410 stainless steel coupons from a single heat and 50 micron alumina powder from a single batch was distributed to these laboratories.

Tests were conducted at room temperature and at 600C at impingement angels of 90 and 30 degrees. The test results reported by these labs show good general agreement at these different test conditions. The erosion rates show a linear relationship with the applied erodent dose at all test conditions. However, noticeable difference was found in the initial reported erosion rate results from some of the labs for the same reported velocity. Additional tests were conducted at different known particle velocities by selected few labs. A power law with an exponent of 2 applies to the erosion rate as a function of particle velocity. Due to this power law nature of the erosion rate, it is highly critical to accurately measure the particle velocities. A master calibration curve relating the erosion rate and velocity is proposed. Rigorous statistical analysis of all the data conducted by the ASTM interlaboratory study group show good repeatability and reproducibility of the results. Limited erosion scar analysis was also conducted to provide some guidance on the use of two different methods. A draft test standard has been developed and submitted to the ASTM subcommittee G02-10 for balloting. At the time of this writing, first ballot has been completed. With further revisions and next balloting by the main committee, it is anticipated that the final test standard will be issued in early 2014.

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