9. Solid Particle Erosion of Turbine Blades
## Contents

1. Generals for Solid Particle Erosion  
2. Prediction of Particle Behaviors  
3. Erosion Mechanisms  
4. Erosion Parameters  
5. Solid Particle Erosion of Valves  
6. Solid Particle Erosion of Turbine Blades  
7. Reduction of Solid Particle Erosion  
8. Foreign Object Damage  

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HloPE
Surface Damage makes the structure and composition of materials quite different from their original ones. There is a number of other surface damage modes, such as extrusion, chip formation, tearing, brittle fracture, etc.

### No Material Loss
- Structural changes
- Plastic deformation
- Surface cracking

### Material Loss
- Wear
- Erosion

### Material Gain
- Fouling (deposits)
- Corrosion

#### Disadvantages of Surface Damage
- Material loss eventually consume the wear part.
- Material loss deteriorates the function.
- Material gain also deteriorates the function.
- Material loss makes surface roughness severer.

#### Results of Surface Damage
- Aerodynamic efficiency decrease.
- Cost for maintenance increase.
- Life expectancy decrease.
- Availability (reliability) decrease.
## Wear vs. Erosion

### WEAR

- **Definition:** damage to a surface that generally involves progressive loss of material and is due to relative motion between that surface and a contacting substance or substances.

- **Types:**
  - Abrasive wear – wear by the sliding of abrasive materials (particles) under the action of an externally applied force.
  - Polishing wear – damage caused by the interaction between two solids that produces a polished surface on at least one of the contacting surfaces by removing materials.
  - Impact wear – wear of solid surface due to repetitive exposure to dynamic contact by another solid body.

### EROSION

- **Definition:** the loss of material that results from repeated impacts of small, solid particles.

- **Types:**
  - Solid particle erosion
  - Water droplet erosion
  - Slurry erosion – loss of a material exposed to a high velocity stream of slurry (mixture of solid particles and liquids).
  - Cavitation erosion – damage caused by the repeated nucleation, growth and violent collapse of cavities, or bubbles, in a liquid.
Surface Damage

Abrasive Wear

Two Body Abrasive Wear

Three Body Abrasive Wear
Surface Damage

Polishing Wear

9. Solid Particle Erosion of Blades
Surface Damage

Slurry Erosion

Slurry erosion of a valve
Increase of seal area is mainly caused by both rubbing and SPE.

Bucket Tip Leakage: 35%

Packing Leakage: 10%

Nozzle Erosion: 10%

Nozzle Roughness: 10%

Nozzle Repair: 15%

Bucket Erosion: 5%

Bucket Roughness: 5%

Deposits: 0%
Problem Areas in Coal–Fired Power Plant

Source: EPRI CS-3344 pp.1-3

Fans (0.6%)  
Boiler tubes (4.2%)  
Fouling/slagging (2.8%)  
Pulverizers (0.6%)  
Pumps (1.7%)  
Condenser (3.8%)  
Turbine blades (2.7%)  
Generator (3.8%)  
Bearsings (2.0%)
In order to limit the concentration of solids in boiler water, some of the concentrated boiler water is discharged (blowdown) and replaced with feedwater having lower solids. The quantity of blowdown depends on both the amount of feedwater solids and the level of solids that can be tolerated in a particular boiler.
Solid Particle Erosion of Boiler Tubes

[ Numerical Prediction ]

[ Experimental Results ]
9. Solid Particle Erosion of Blades

Typical Turbine Location of Problems

- SPE of Valves
- SPE of Blades
- Bearing Rubbing
- Seal Rubbing
- Fouling
- Stress Corrosion Cracking
- WDE of LSB
- Rotor Bow due to rubbing in transient operation such as during startup
SCC; Stress Corrosion Cracking

Steam turbine expansion line and typical damage in wet region

- Caustic SCC
- NaOH, Oxides
- Pitting, SCC, Corrosion Fatigue
- Cl⁻, SO₄²⁻, CO₃²⁻, O₂, Acetate
- Drying on Hot Surfaces

- ~30% NaCl Solution
- 2% Salinity
- 4% Salinity
- 6% Salinity
- 8% Salinity
- 10% Salinity
- 12% Salinity

Enrichment Zone (Wilson Line)

- CO₂
- Erosion
- Acids, <pH
- WDE

Elastic-Plastic Stress Distribution

Plastic Strain Distribution

Straddle Mount Blade Root
Solid Particle Erosion of Blade

Steam Flow

Potential Flow Separation

Erosion on Pressure Side

Erosion on Suction Side

Nozzle

Bucket

Particle Trajectory
Solid Particle Erosion is the loss of material that results from repeated impacts of small, solid particles.
Solid Particle Erosion/Water Droplet Erosion occurred in feedwater heater vent lines. This elbow is just downstream of a restricted orifice. The eroded surface has a ripple shape.

Formation of ripple patterns on metals
- Degradation of surface finish – increase of profile loss
- Increase of discharge area – decrease of momentum of steam entering the buckets
- Increase of seal area – decrease of steam flow in the main steam path
- Change of discharge angle – different flow angle from design condition
- Thickened trailing edge – increase of nozzle wake and excitation forces
In some cases, SPE is a useful phenomenon, as in sandblasting and high-speed abrasive waterjet cutting, but it is a serious problem in many engineering systems, including steam and gas turbines.

SPE is to be expected whenever hard particles are entrained in a gas or liquid medium impinging on a solid at any significant velocity (greater than 1 m/s, or 3.3 ft/s).

Manifestations of SPE in service usually include thinning of components, a macroscopic scooping appearance following the gas/particle flow field, surface roughening (ranging from polishing to severe roughening, depending on particle size and velocity), lack of the directional grooving characteristic of abrasion, and, in some but not all cases, the formation of ripple patterns on metals.

Particles contained in liquid phase can be accelerated or decelerated, and their directions of motion can be changed by the fluid.
<table>
<thead>
<tr>
<th></th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Generals for Solid Particle Erosion</td>
</tr>
<tr>
<td>2</td>
<td>Prediction of Particle Behaviors</td>
</tr>
<tr>
<td>3</td>
<td>Erosion Mechanisms</td>
</tr>
<tr>
<td>4</td>
<td>Erosion Parameters</td>
</tr>
<tr>
<td>5</td>
<td>Solid Particle Erosion of Valves</td>
</tr>
<tr>
<td>6</td>
<td>Solid Particle Erosion of Turbine Blades</td>
</tr>
<tr>
<td>7</td>
<td>Reduction of Solid Particle Erosion</td>
</tr>
<tr>
<td>8</td>
<td>Foreign Object Damage</td>
</tr>
</tbody>
</table>
Two-Phase Flow

- Gas-particle flows are characterized by coupling between phases.

- For example, a spray issuing into a hot gas stream, exemplifies thermal coupling through heat transfer to the droplet, momentum coupling through aerodynamic responsible for droplet motion, and mass coupling through evaporation.

- Inclusion of these coupling mechanisms complicates the analysis of gas-particle flows.

- Another difference between the flow of a single phase and gas-particle flow lies in the mechanism of information transfer between the elements of the particulate phase.

- There is no analog for pressure in a particle cloud and no information transfer between particles.
Lagrangian vs. Eulerian Approaches

- Basically, there are two approaches commonly used to predict particulate two-phase flows; Lagrangian and Eulerian.

- The Lagrangian or ‘tracking’ approach treats the particles as discrete entities in a turbulent flow field and their trajectories are calculated by the balance of forces acting on the particles.

- The Eulerian or ‘two-fluid model’ treats the particle as cloud. Therefore, the cloud of particles is regarded as a continuum and the appropriated governing equation is necessary to estimate the motion of the particulate phase. Thus, two continuum equations are required for two phases.

- Eulerian approach can not be applied to the wall dominated flow because there is no appropriate wall boundary conditions.

- For this reason, the Lagrangian approach has been used in power engineering popularly.
Particle trajectory can be predicted by integrating the force balance on the particle.

This force balance equates the particle inertia with the forces acting on the particle.

\[
\frac{du_p}{dt} = F_D(u - u_p) + g_x \frac{\rho_p - \rho}{\rho_p} + F_x
\]

\[
\frac{dx}{dt} = u_p
\]

- \( F_D(u - u_p) \): Drag force per unit particle mass
- \( g_x \frac{\rho_p - \rho}{\rho_p} \): Gravity term
- \( F_x \): Other forces, such as virtual mass force and thermophoretic force

\[
F_D = \frac{18 \mu C_D}{\rho_p d_p^2} \frac{Re}{24}
\]

\[
Re = \frac{\rho d_p |u_p - u|}{\mu}
\]

\[
F_x = \frac{1}{2} \frac{\rho}{\rho_p} \frac{d}{dt}(u - u_p)
\]

\[
F_x = \left( \frac{\rho}{\rho_p} \right) u_p \frac{\partial u}{\partial x}
\]

\[
F_x = D_p \frac{1}{T} \frac{\partial T}{\partial x}
\]

Small particles suspended in a gas that has a temperature gradient experience a force in the direction opposite to that of the gradient.
Prediction of Particle Trajectories

\[ \frac{dx}{dt} = u_p \]

Typical Continuous Phase Control Volume

Mass Exchange
Heat Exchange
Momentum Exchange

Typical Particle Trajectory

(a) Reflect B.C.
\[ e_n = \frac{v_{2,n}}{v_{1,n}} \]
\[ e_t = \frac{v_{2,t}}{v_{1,t}} \]

(b) Escape B.C.

\[ e = \text{coefficient of restitution} \]
# Prediction of Particle Trajectories

<table>
<thead>
<tr>
<th>Uncoupled Calculations</th>
<th>Coupled Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Solve the continuous phase flow field.</td>
<td>1) Solve the continuous phase flow field (prior to introduction of the discrete phase).</td>
</tr>
<tr>
<td>2) Plot (and report) the particle trajectories for discrete phase injection of interest.</td>
<td>2) Introduce the discrete phase by calculating the particle trajectories for each discrete phase injection.</td>
</tr>
<tr>
<td></td>
<td>3) Recalculate the continuous phase flow, using the interphase exchange of momentum, heat, and mass determined during the previous particle calculation.</td>
</tr>
<tr>
<td></td>
<td>4) Recalculate the discrete phase trajectories in the modified continuous phase flow field.</td>
</tr>
<tr>
<td></td>
<td>5) Repeat the previous two steps until a converged solution is achieved in which both the continuous phase flow field and discrete phase particle trajectories are unchanged with each additional calculation.</td>
</tr>
</tbody>
</table>

This method is adequate when the discrete phase is present at a low mass and momentum loading, in which case the continuous phase is not impacted by the presence of the discrete phase.

The coupled calculation must be followed in order to include the important impact of the discrete phase on the continuous phase flow field. Therefore, this method is adequate when the discrete phase is present at a high mass and momentum loading.
Transport of Ash Particles

Stokes Number

\[ St = \frac{\tau_a}{\tau_c} \]

\[ \tau_a = \frac{\rho_p d_p^2}{18 \mu} \]

\[ \tau_c = \frac{L_c}{V_c} \]

\[ St = \frac{\rho_p d_p^2}{18 \mu} \cdot \frac{V_c}{L_c} \]

Stokes number
\( \rho_p \) = density of the particle
\( d_p \) = particle diameter
\( \mu \) = viscosity of the carrier fluid
\( V_c \) = characteristic velocity of fluid
\( L_c \) = characteristic length
\( \tau_a \) = particle aerodynamic response time
\( \tau_c \) = characteristic time of the fluid phase

\[ St = 0.25 \ (d_p = 5 \ \mu m) \]

\[ St = 1.74 \ (d_p = 13 \ \mu m) \]

[ Flow of Particulate Phase in Staggered Tube Banks ]
Inertial impaction is the most dominant mechanism in SPE.

Large particles ($d_p > 10 \, \mu m$) have sufficient inertia to cross the gas streamlines and collide with the blade surfaces.
1. Generals for Solid Particle Erosion
2. Prediction of Particle Behaviors
3. Erosion Mechanisms
4. Erosion Parameters
5. Solid Particle Erosion of Valves
6. Solid Particle Erosion of Turbine Blades
7. Reduction of Solid Particle Erosion
8. Foreign Object Damage
Finnie (1960) developed the first analytical model to predict erosion rates based on the assumption that the mechanism of erosion was cutting.

This model predicts that the erosion rate per individual angular particle is proportional to the kinetic energy of the particle and inversely proportional to the shear stress of the target metal.

This model is valid for erosion at oblique impact angles.

However, this model is not appropriate when particles are impacted normally to the surface.

\[ E = Cf(\beta) \frac{mV^n}{\sigma} \]

- \( C \): Constant
- \( f(\beta) \): function of impact angle
- \( m \): mass of erodent particles
- \( V \): impact velocity
- \( n \): power (2.2~2.8)
- \( \sigma \): minimum shear stress of target material
Tilly (1973) suggested that erosion of ductile materials occurs in two stages:

- the first stage is the production of indentation and possibly the removal of chips of metal when the impacting particle strikes the surface,
- and the second is the shattering of the particle into smaller fragments which move radially outward simultaneously.

This model can be applied to erosion with higher impact velocity.
Bellman and Levy (1981) investigated the erosion of ductile metal by small impacting particles for pulverized coal plants.

With the aid of a SEM, it was found that a combined forging-extrusion mechanism which produces highly stressed small platelets of target material, which are knocked off the surface by the impact of succeeding particles, is responsible for erosion at both low and high impact angles.
General Observations on Erosion of Ductile Metals

1. The erosion rate is a strong function of the particle shape.

2. The dimensionless erosion rate varies as \((\text{impact velocity})^n\) where \(n\) is usually in the range of 2.2 to 2.8 (mean value of 2.4).

3. A maximum erosion rate of ductile metals occurs at an impact angle of 15° to 30°.

4. Erosion rate is affected by particle size.

5. Erosion rate is proportional to particulate concentration (impact frequency).

6. The temperature of the target metal influences the erosion rate.

7. Mechanical properties of particles also influence the erosion rate.

8. Particle rotational speed influences the erosion rate.
**Erosion Model**

Developed for the Impaction of Solid Particles

\[ E = K \cdot C_p \cdot f(\beta) \cdot V^n \cdot g(d_p) \cdot h(T) \]

- **E**: Erosion rate
- **K**: Erosion constant (it includes physical property for both base metal and solid particles)
- **C_p**: Particulate concentration
- **f(\beta)**: Impact angle
- **V**: Impact velocity
- **g(d_p)**: Particle size
- **h(T)**: Target material temperature
The scale is formed in the boiler tubes as a result of continued operation at high temperatures, and is attached to the tubes.

However, as temperatures change within the tubes – particularly at start up and shutdown – scale will exfoliate and become free within the tubes themselves.

In addition, boiler tube internal deposits are resulted from poor boiler water treatment, as shown in the figure. These deposits, besides hindering heat transfer, allowed boiler water salts to concentrate, causing corrosion.
Formation of Scale

Temperature Effect on the Formation of Scale on Boiler Tubes

Without scale the average temperature of the tube wall is 400°C

With a layer of scale the average temperature of the tube wall is increased to 510°C
- The solid particles formed by exfoliation of the oxide film of boiler tubes are primarily composed of magnetite (Fe₃O₄).
- It has a density of 5.08 g/cm³ and is very hard (6.0 Mohs’ scale).
- The scale has sharp or jagged edges initially.
- 12Cr steel used as the common material for steam path parts can be considered ductile material.

[ Particle size distribution for boiler scale ]
There are two important factors in terms of impact velocity of particles. One is the threshold velocity. The other is velocity exponent.

Threshold velocity is a function of impacting particles, impact velocity, and target material.

Threshold velocity in steam turbines is about 700 fps (213 m/s). That is, SPE is occurred when the impacting velocity is greater than 213 m/s. Therefore, SPE is occurred in control stage and the first reheat stage in steam turbines.

The value of velocity is between 2.2 and 2.8 for ductile materials. The reason for this is still vague.
Erosion Parameters

1. Impact Velocity [2/3]

Graph showing the relationship between friction coefficient and Reynolds number of plate for different roughness conditions:

- **Transition**
- **Fully Roughened**
- **Hydraulic Smooth**

**Friction Coefficient vs. Reynolds Number of Plate**

- Values of $k_s/l$ in $\times 10^{-3}$
- $k_s = $ Sand-grain roughness height
- $l = $ Axial width of cascade

Legend:

- **LP**
- **IP**
- **HP**
The kinetic energy of an impacting particle is only partially used to create chips or lips in the target metal.

The remainder is dissipated as energy of the reflected particle, as well as heat and sometimes its fragmentation.

Physically, the energy loss on impaction is the difference between the kinetic energy of the impacting and reflected particle.

Researchers have measured the impaction and rebound velocities of steel spheres striking a carbon steel target at a 30° impact angle.

They showed that a plot of the energy loss versus impact velocity gives a straight line with a slope of 2.3.

This result gives a good example as to why the value of the velocity exponent is greater than 2, which is the value of velocity exponent of kinetic energy of the impacting particle.
Erosion Parameters

2. Impact Angle

A maximum erosion rate of ductile metals occurs at an impact angle of 15° to 30°.

SPE of ductile metals (from Hamed et al., 2006)
Erosion Parameters

3. Particle Size

- Erosion Rate, mg/g
- Average Particle Size, μm
- Quartz against H46 Steel
- 244 m/s of Impact Velocity
- 90° of Impact Angle
4. Particle Shape

- Angular particles are much more erosive than spherical ones.
- Boiler scales (magnetite, Fe$_3$O$_4$) have angular shapes.

![Diagram showing the impact of particles on material loss and erosion rate](image)
Erosion can occur when the hardness of erodent particles is substantially lower than that of target metal.

The erosion rate increases continuously with the hardness of erodent particles, but only up to a critical hardness of particles.

The magnitude of the critical hardness of the erodent particles is related to the hardness of the target metal.

The erosion rate reaches a constant value when the hardness of the erodent particles is sufficiently higher than that of target metal. However, this is not always true because particle shape can be changes as the hardness of the particles increases.
Erosion Parameters

6. Particle Concentration

- The erosion rate increases linearly up to a certain point as the particle concentration increases.
- Then, it decreases because of particle-particle interactions.
### 7. Temperature of Base Material

#### Erosion Parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>Erosion Rate $\times 10^{-4} \text{ g/g}$</th>
<th>$V_p$</th>
<th>$\beta$</th>
<th>$d_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1018</td>
<td>[Graph showing data points and lines]</td>
<td>30 m/s</td>
<td>30°</td>
<td></td>
</tr>
<tr>
<td>2.25Cr-1Mo Steel</td>
<td>[Graph showing data points and lines]</td>
<td></td>
<td>30°</td>
<td></td>
</tr>
<tr>
<td>5Cr-0.5Mo Steel</td>
<td>[Graph showing data points and lines]</td>
<td></td>
<td></td>
<td>240 µm, SiC Particles</td>
</tr>
</tbody>
</table>

- $V_p = 30 \text{ m/s}$
- $\beta = 30^\circ$
- $d_p = 240 \mu m$, SiC Particles
At high temperatures, oxide growth is fast and may increase the plasticity of the surface which contribute to protection from impacting particles.

On the other hand, a high erosion rate can occur under the combined effect of both erosion and high temperature corrosion (oxidation).

At high temperatures, it was found that plastic deformation and work hardening occur at below half the melting temperature, and the recovery process or annealing is greatly accelerated as the temperature rises.

Solid particle erosion (SPE) is a particular concern with supercritical units, due to the once-through operation of the boiler.

SPE is caused by deposits, such as magnetite, that have exfoliated from the boiler tube surfaces.

The worst erosion is associated with particle impingement on the high pressure control stage and the first reheat stage.

Early experience showed that supercritical units required nozzle and bucket repair/replacement about one and half times more frequently than subcritical units, and SPE was reported as the major cause of heat rate degradation in supercritical turbines.

Hard particle erosion is a visible, and often severe consequence of cycling, and is more noticeable in once-through supercritical units.
8. Base Metal Properties

Erosion Parameters

- Carbon Steel
- Chrome-moly cast steel
- 300 Series Stainless
- 400 Series Stainless
- Tool Steel
- Stellite 6, 6B, 12
- Nickel
- Inconel
- Inconel weld overlay
- EPRI Norem

Normalized Erosion Resistance

0.1 - 100
1. Generals for Solid Particle Erosion
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5. Solid Particle Erosion of Valves
6. Solid Particle Erosion of Turbine Blades
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8. Foreign Object Damage
9. Solid Particle Erosion of Blades
As scale leaves the boiler superheater section, the steam transports it through the valve system of the high pressure section.

The valve system contains stop valves those remain fully open at all loads. The stop valves are closed only on loss of load and an anticipated emergency overspeed condition.

The control valve controls the quantity of steam being admitted to the turbine in response to the demand for load.

A bypass valve, which is installed in one of the main stop valves, has been designed to be opened at startup against the initial steam pressure.

This bypass valve admits steam sufficient to start the unit rolling and overcome the initial friction forces preventing rotation.

This valve also provides sufficient steam to obtain a small load on a generator.

Therefore, this valve is a prime candidate for solid particle erosion, because it is subjected to the major portion of the initial charge of steam containing scale as it enters the unit.
One preferred method of initial startup when the scale concentration is high and loads are small is to admit steam through the complete admission arc.

This means that control valves operate in parallel rather than sequentially, giving a more even distribution of scale around the complete inlet annulus.
SPE on a Bypass Valve

Problem
• Erosion on the bypass valve and valve stem

Fix
• Replacement valve stem and bypass disc
• Angled valve cap
• Diamond tuff coating

The pattern of valve damage by solid particle erosion is dependent upon the valve geometry.
Improvement of SPE on a Bypass Valve

Velocity Vectors

Previous Shape

 Improved Shape
Improvement of SPE in Main Stop Valve

Particle Trajectories

Previous Shape

Improved Shape
Improvement of SPE in Main Stop Valve

Particle Trajectories

Present Shape

Improved Shape
Improvement of SPE in Main Stop Valve

CONVENTIONAL TYPE

MULTI-HOLE TYPE

BYPASS VALVE

VALVE CAP

VALVE

VALVE CAP

VALVE STEM

SKIRT STELLITE

VALVE SEAT

VALVE STEM

BYPASS VALVE CAP

BYPASS VALVE

Toshiba
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4. Erosion Parameters
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9. Solid Particle Erosion of Blades
Effects on Trailing Edge

Material loss from the trailing edge of the nozzle due to solid particle erosion affects the discharge area and angle. These will cause a significant performance degradation of steam turbine.
Solid particle erosion occurs in both control stage and first reheat stage of steam turbines.

The erodent of solid particle erosion in steam turbines is iron oxide, which is formed and exfoliated from the inner surfaces of the boiler tubes.

Severe SPE damage may be found after time periods as short as 3 years, and time periods can be as shorter as 1 years in very severe cases.

SPE of turbine blades produces utility problems, such as

- Loss of sustained efficiency
- Potential cause of forced outage
- Extended maintenance outages
- Shorten inspection intervals
- Increased maintenance cost
Solid particle erosion of steam path surfaces is a major concern in steam turbines.

This is mainly due to the formation of iron oxide scale (magnetite) on the inside of boiler tubes.

Solid particles with high hardness coming from boiler will flow into the high pressure stage of steam turbine.

Large particles have sufficient inertia to cross the gas streamlines and collide with the blade surfaces.

These particles can erode the trailing edges of nozzle and leading/trailing edges of buckets.

This profile damage is the main cause of performance degradation because nozzle wake and excitation forces are increased and the flow angle entering bucket is different from design conditions.

The base material is generally protected by plasma/detonation sprayed and thermo-chemically formed diffusion coatings.
The erosion pattern occurred in the control stage is quite different from that occurred in first reheat stage. This is because particle velocities in the nozzle path are different from each other. This velocity is higher than erosion threshold velocity in control stage, however, this is not true in first reheat stage.
SPE on Control Stage Nozzles

Control Stage Particle Velocities along Stationary Blades

Impact Velocity (FPS)

100% LOAD

(PARTIAL ARC) 30% LOAD

10% LOAD

V_{STEAM} PARTICLE SIZE

V_{STEAM} PARTICLE SIZE

V_{STEAM} PARTICLE SIZE
A turbine having four control valves and operated with partial arc admission experiences sonic velocity under certain conditions.

At the first valve point (25% load), the pressure ratio across the first stage is about 4 to 1. At the second valve point (50% load) the pressure ratio is about 2 to 1. Both conditions produce sonic velocity in the first stage stationary blades.

In addition, the high throttle pressure accelerates the solid particles above the erosion threshold velocity (about 700 fps). These high velocity particles erode the pressure side of the first stage nozzle.

At full load, the smaller particles (10 microns) are accelerated close to the threshold velocity (about 700 fps).

However, at 30% load the smaller particles are accelerated to velocities higher than threshold velocity because of higher steam velocity.

Therefore, solid particle erosion is generally confined to the first two arcs of a four valve unit.

However, if this turbine is operated with throttling or sliding pressure control the particle velocity at 10% load are smaller than at full load and solid particle erosion damage does not occur.
In the first IP turbine stage the steam velocity and pressure level are lower than in the control stage.

The solid particles are not accelerated above the threshold velocity and no erosion occurs on the pressure side.

Instead, the solid particles moving at considerably less than steam speed impinge on the suction side of leading edge of the rotating blades.

They bounce back and cause erosion on the suction side of trailing edge of the stationary blades.
Velocity Triangles of Particles & Particle Trajectories

a: large particles having large St.
b: small particles having small St.

$U \quad C_a \quad W_a \quad C_b \quad W_b \quad U \quad W$
SPE on the First Reheat Stage Nozzles

Particle Impact Velocity

$V_p$: Impact Velocity
Large particles are rebounded between the nozzle and bucket and migrated out towards bucket tip section.
SPE on the First Reheat Stage Nozzles

Particle Behaviors in the First Reheat Stage

Low load, large particles

High load, small particles
Particle Behaviors in First Reheat Stage

Particle trajectories (Low load, small particles)

Particle trajectories (High load, large particles)
SPE on Nozzle

Vane partition erosion

Vane
The solid particle erosion on the control stage bucket is occurred on the suction side of leading edge and pressure side of trailing edge.

The eroded leading edge introduces an off-angle loss.

The erosion on the pressure side of trailing edge of the buckets has a small effect on stage efficiency.

However, severe erosion can cause mechanical failure.
9. Solid Particle Erosion of Blades

SPE on Control Stage Buckets

![Graph showing the relationship between Relative Blade Efficiency and Angle Deviation from Design Value, deg.]

- Relative Blade Efficiency vs. Angle Deviation from Design Value, deg.
- Initial Leading Edge
- Eroded Leading Edge
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Reduction of Solid Particle Erosion

SPE solutions include

1. minimizing of scale formation by using austenitic steels or chromizing treatments,
2. particle removal with cyclones or screens,
3. redesign of turbine configurations,
4. and application of plasma-sprayed or diffusion coatings to blades.
1. Particulate Reduction

Chromizing of Tubes

- It is clear that the most logical solution is the elimination of the source of the solid particles themselves.
- When the chrome is penetrated and diffused onto the surface of steel, Fe-Cr layer, which has higher hardness and greater erosion resistance, is formed.
- Chromizing is used on new boilers and for replacement sections of existing units.
- The cost is about two million dollars but may be cost effective since serious solid particle erosion problems cost about four million dollars per year.
- It was observed from the experimental and field service results that chromizing may provide a permanent solution to SPE in turbines.

Chemical Cleaning

- Chemical cleaning can be employed to reduce the concentration of particulate temporary and must be repeated about every five years.
2. Removal of Particles

Stop Valve Inertia Separator

Collection pipe (This pipe is emptied during outages)
2. Removal of Particles

Inertia Separator Installed In the Inlet of Hot Reheat Steam Pipe

From Reheater

Solid Particles

Hot Reheat Steam Pipe

Deswirler

Collection Pipe

Steam to IP Turbine
3. Modification of Turbine Design

3.1 Modification of Control Stage Nozzle

Design Modification using Erosion Parameters

Ductile Materials

Brittle Materials

Coating or Cladding

Impact Angle, $\beta$

Erosion Rate

Initial Design

Design Modification
3. Modification of Turbine Design

3.1 Modification of Control Stage Nozzle

Before modification
(after 18 months of operation)

After modification
(after 3 years of operation)
3. Modification of Turbine Design

3.1 Modification of Control Stage Nozzle

![Graph showing heat rate loss over years for original and modified designs](image)

- Original Design
- Modified Design (New Profile with Diffusion Coating)

Heat rate loss (%) vs. Year

- Year: 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20
- Heat rate loss: 0, 0.1, 0.2, 0.3, 0.4, 0.5
### 3. Modification of Turbine Design

#### 3.2 Increase of Axial Clearance Between Nozzle and Bucket (First Reheat Stage)

- This method can be applied in the first stage of IP turbine.
- The nozzle erosion which is caused by the particle rebounding phenomena may be significantly reduced by substantially increasing the axial clearance between the nozzles and buckets.
- The increased clearance provides more time for the steam to redirect the particles back toward the buckets after a impact with the bucket leading edge.

![Diagram showing before and after modification of axial clearance.](image)
3. Modification of Turbine Design

3.2 Increase of Axial Clearance Between Nozzle and Bucket (First Reheat Stage)

![Graph showing the impact of different modifications on loss over time.]

- **Original Design**
- **Increased Axial Clearance**
- **Plasma Spray Coating**
- **Increased Axial Clearance, Increased Scale Factor, and Plasma Spray Coating**

The graph illustrates the loss (Btu/kWh) over years for different modifications. The y-axis represents loss in Btu/kWh, and the x-axis represents years.

- **Loss (Btu/kWh)**: The graph shows a significant reduction in loss over time with the implementation of certain modifications.

**Legend**:
- Original Design: The baseline without any modifications.
- Increased Axial Clearance: Shows a moderate reduction in loss.
- Plasma Spray Coating: Indicates a substantial improvement in loss reduction.
- Increased Axial Clearance, Increased Scale Factor, and Plasma Spray Coating: The best-case scenario showing the least loss over time.
4. Blade Coating

4.1 Plasma Spray Coating

- One of the effective methods to prevent solid particle erosion is to increase surface hardness of blades.
- Plasma spray coating has been applied successfully to increase hardness of blades.
- The erosion resistant coating has been employed as the primary means of protecting solid particle erosion occurred in steam turbines.
- The plasma spray coatings are as much as 12 mils thick and have a layered structure because of the multipass application procedure.
- Chromium carbide plasma spray coating has about twenty times the erosion resistance of the uncoated 12Cr base metal.
4. Blade Coating

4.1 Plasma Spray Coating
A coating process used to change the surface composition of a metallic material with (1) another metal or alloy employing heat or (2) exposure to a gaseous or liquid metal to effect diffusion into the basis metal.
This process involves the exposure of the part to be coated to a pack cementation process to introduce the coating and subsequent heat treatment to restore the mechanical properties.

The diffusion coating has about thirty times the erosion resistance of the uncoated 12Cr base metal.

The thickness of coating layer produced by diffusion coating is only two mils and this is much thinner than that by plasma spray coating.
4. Blade Coating

4.3 Cladding and Welding of Stellite

PTA stellite cladding

Silver brazing (conventional technique)

After welding  Completed product  Completed product
Craters produced at the leading edge surface by smaller debris

Craters produced at the leading edge surface by larger debris
FOD

Blade failure in a control stage

Large impact craters on a rotating blade inlet edge

A missing of cover band segment from LP turbine
Generals for FOD

- There are many instances when the blades are damaged by impact with solid objects that have been generated within, or gained access to the steam path.

- The large objects, such as broken blades, can affect the dynamic balance of the unit, introduce dangerous level of rotor vibration, and be a cause of forced shutdown of the unit.

- When smaller blades fail, they may not affect balance, and there is no indication such a failure has occurred. Therefore, this kind of failure is not detected until the unit is opened for maintenance outage.

- In many cases, larger pieces carried into the condenser will cut or severely damage tubes. This will cause other problems, such as ingress of cooling water, which will produce other chemical problems in the turbine.

- Surface roughening associated with the craters produced by FOD is one of the main causes of performance degradation.
Sources of the Impacting Objects

1) **Mechanical failure of some portion of steam path**
   - Blades, cover band, tie wire
   - Of the various sources of steam path debris, the generation of a debris from steam path themselves is the most common and most likely to cause the most severe FOD in terms of requiring component replacement.
   - The debris produced initially can be a source of sequential damage that may be greater than the damage initially occurred.
   - The debris produced initially may be lodged in the stationary parts, such as casing, diaphragm, stationary blade row, extraction lines.
   - The debris produced initially can be broken into smaller pieces and distributed throughout the steam path.

2) **Debris carried into the unit from the boiler**
   - The boiler is a major source of small particles, such as weld bead and weld spatter.
   - The screens mounted around the valve inlet capture larger beads but smaller beads pass through the screen and impact the steam path.
   - The smaller particles can be removed by the use of fine mesh screens for short period, after initial start up and after return from repairs. There is an additional pressure drop associated with the use of fine mesh screen, but the removal of weld bead is important. The fine mesh screen should be used for only about six to eight weeks.

3) **Parts left in the unit during an outage**
   - Metallic pieces and/or dropped into a unit during an outage can be major sources of FOD.
Screen installed around the valves, and captured metallic debris those are too large to enter the steam path
질의 및 응답