ANALYZING THE POTENTIAL FOR EROSION IN A SUPERCRITICAL CO_2 TURBINE NOZZLE WITH LARGE EDDY SIMULATION

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ASME Turbomachinery Technical Conference
June 17-21 2019, Phoenix, AZ, USA
Paper number: GT2019-91791

Why sCO_2 power cycles?

Higher Efficiency

- High working fluid temperatures
- Recompression near liquid densities
- High heat recuperation

Lower Capital Cost

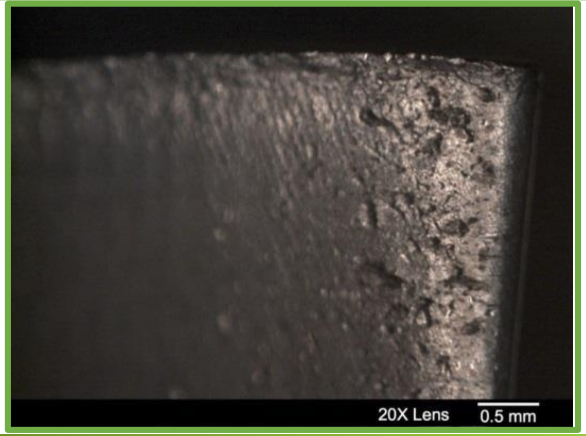
- Compact turbo machinery
- Simple configurations

Lower Environmental Impact

- Zero emissions
- Dry cooling
- Water production

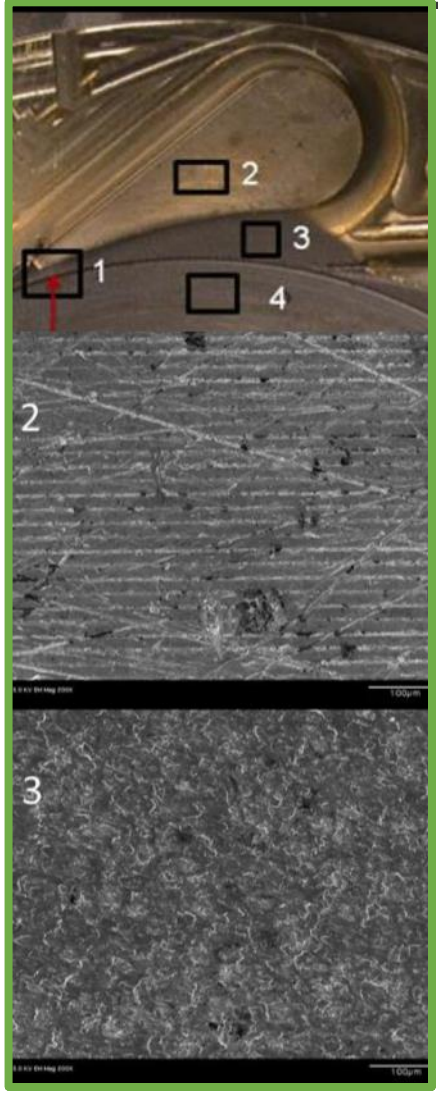
Erosion of sCO_2 Power Cycle components

Problem: Severe erosion of turbine blades and vanes has been observed in the sCO_2 cycle test loops in Sandia National Lab and Bettis Lab.



<u>Sandia Findings</u>

- Particle impingement on flow surfaces
- Particles in the loop:
  - Stainless steel
  - SiO_2
  - Al_2O_3



D. Fleming et al. (2014), Sandia Report, SAND2014-15546
M. Walker et al. (2016), Sandia Report SAND2016-9774
A. Kruizenga et al. (2017), Sandia Report, SAND2017-8300R

Root cause of damage?

- **Solid particle impacts?**
- Shear/press fluctuations?
- Phase change?

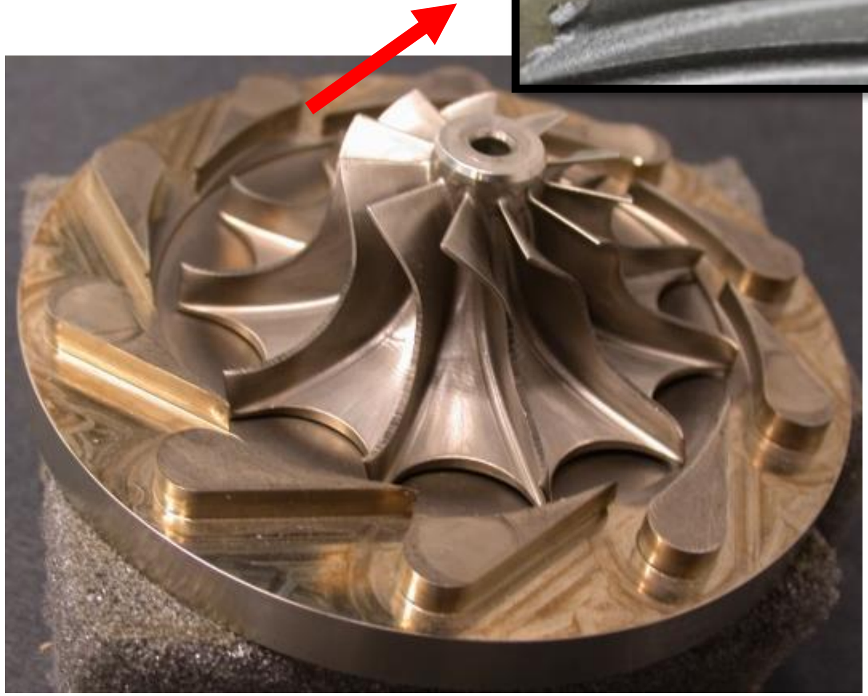
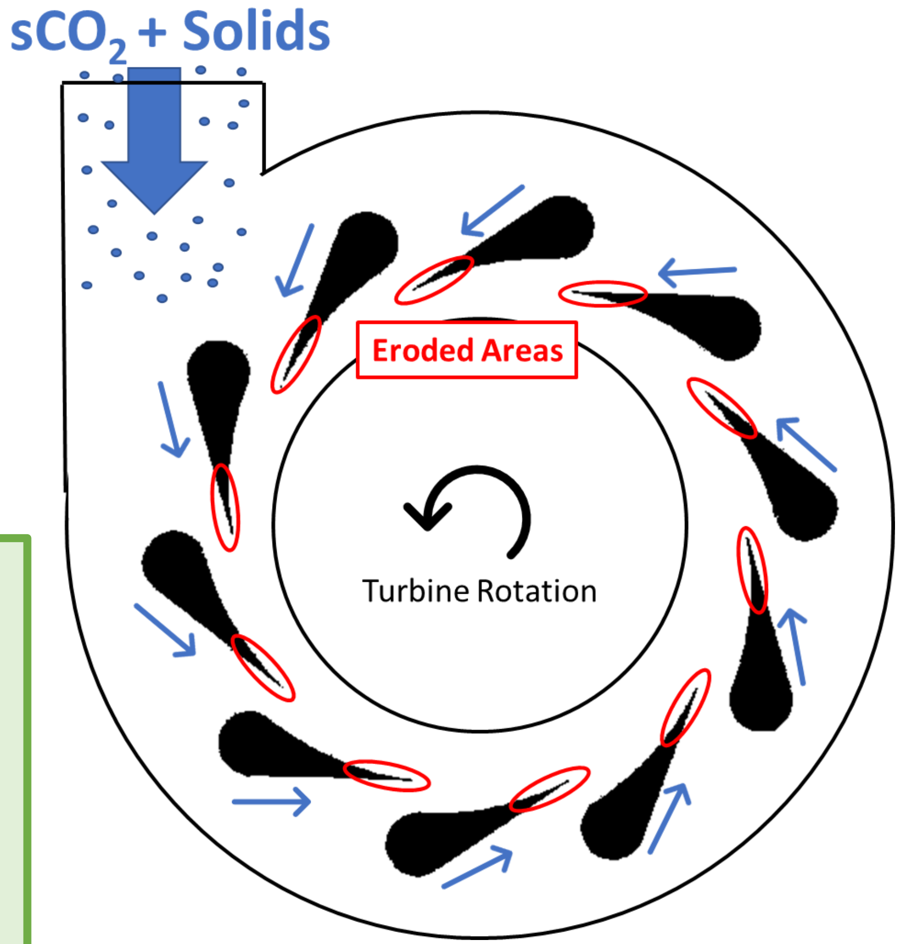


Image: Sandia turbine assembly. Inset shows damage to nozzle after operation with sCO_2 [1].



This Talk: Potential of entrained oxide particles to erode radial turbine nozzle.

- LES + Particle Tracking
- SNL nozzle geometry
- Semi-empirical erosion model
- Scaling to operating conditions

[1] D. Fleming, A. Kruizenga, *Identified Corrosion and Erosion Mechanisms in SCO2 Brayton Cycles*, Sandia Report SAND2014-15546, 2014.

Methodology: LES + Lagrangian particle tracking

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Fluid phase (sCO_2)

- Spatially filtered, incompressible N-S for Large Eddy Simulation

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0$$

$$\frac{\partial \bar{u}_j}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial q_{ij}}{\partial x_j}$$

- Dynamic Smagorinsky closure for sub-grid scale stresses

Key Assumptions

- Incompressible, low Mach number (for now)
- Constant properties (density, viscosity)
- One-way coupling of particles to flow (dilute assumption)

Solid phase (porous oxide particles)

- Large Eddy Simulation (LES) for turbulence
- Particle tracking/collision prediction

$$\frac{d}{dt}(\boldsymbol{x}_p) = \boldsymbol{u}_p \quad (6)$$

$$\frac{d}{dt}(\boldsymbol{u}_p) = -\frac{1}{\rho_p}\nabla \bar{P} + \frac{f(Re_p)}{\tau_p}(\bar{\boldsymbol{u}} - \boldsymbol{u}_p) \quad (7)$$

Numerical Solution

- Second order, co-located finite volume discretization for arbitrary, unstructured grids[1]
- Fractional step, pressure projection time advancement
- Fully parallelized, capable of variable density (future work)
- Validation for particle laden flows in complex geometries[2,3]

[1] Mahesh, K., Constantinescu, G., Moin, P., 2004. A numerical method for large-eddy simulation in complex geometries. J. Comp. Phys. 197, 215-240.
[2] Apte, S.V., Mahesh, K., Moin, P., Oefelein, J.C., 2003. Large-eddy simulation of swirling particle-laden flows in a coaxial-jet combustor. Int. J. Mult. Flow 29, 1311-1331.
[3] Shams, E., Finn, J., Apte, S., 2011. A numerical scheme for Euler–Lagrange simulation of bubbly flows in complex systems. Int. J. for Num. Methods in Fluids 67, 1865.

Operating conditions

Assumed Operating Conditions (125kWe SNL test facility)

- Nozzle chord length $L \approx 2.5cm$, height $h \approx 0.4cm$
- Flow rates in the neighborhood of $\dot{V} = 600GPM$
  - Velocity at nozzle tip, $u_{bulk} = 45m/s$
- Turbine inlet conditions : $T = 550^o C, P = 29.11MPa$
  - $\rho = 177\frac{kg}{m^3}, \mu = 39 \times 10^{-6} Pa \cdot s$
- Reynolds number: $Re_c = \frac{\rho \cdot u_{bulk} \cdot L}{\mu} \approx 5 \times 10^6$

Table: Simulation parameters

	sCO_2		Particles
ρ_f	$177\ kg \cdot m^{-3}$	ρ_p	$2500\ kg \cdot m^{-3}$
μ	$39 \times 10^{-6} Pa \cdot s$	d_p	$30\mu m$
θ	20^o	St_+	89
U_{in}	$8.37m \cdot s^{-1}$	St_b	0.08
u_{bulk}	$4.67\ m \cdot s^{-1}$		
Re	529,865	$\langle\langle \varepsilon \rangle\rangle$	10^{-3}
dt_f	$2.5 \times 10^{-8} s$	dt_p	$2.5 \times 10^{-8} s$

Simulation conditions

- Order of magnitude reduction in Re_c to accommodate LES, without wall model.
- Solid particles: Spalled porous oxide scales
  - $\rho_p = 2500\ kg/m^3, d_p = 30\mu m$
- Stokes Numbers (measure of particle inertia)

$$St_p = \frac{\tau_p}{\tau_k} = 89, \qquad St_b = \frac{u_{bulk} \cdot \tau_p}{R_c} = 0.08.$$

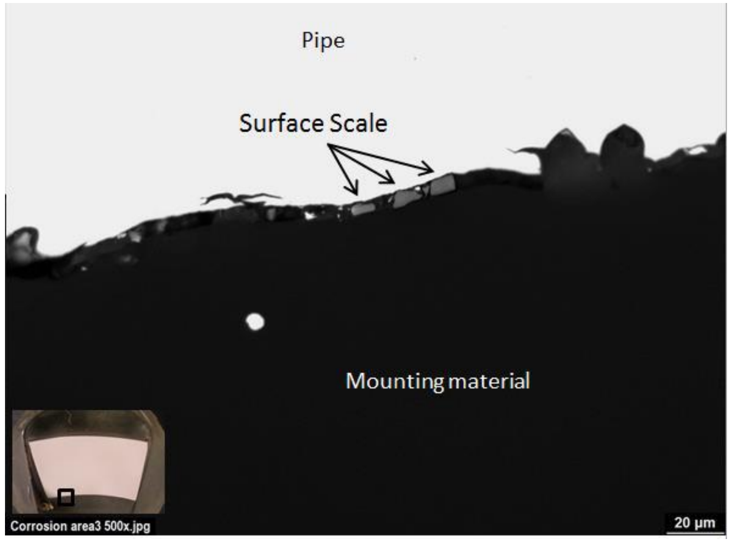
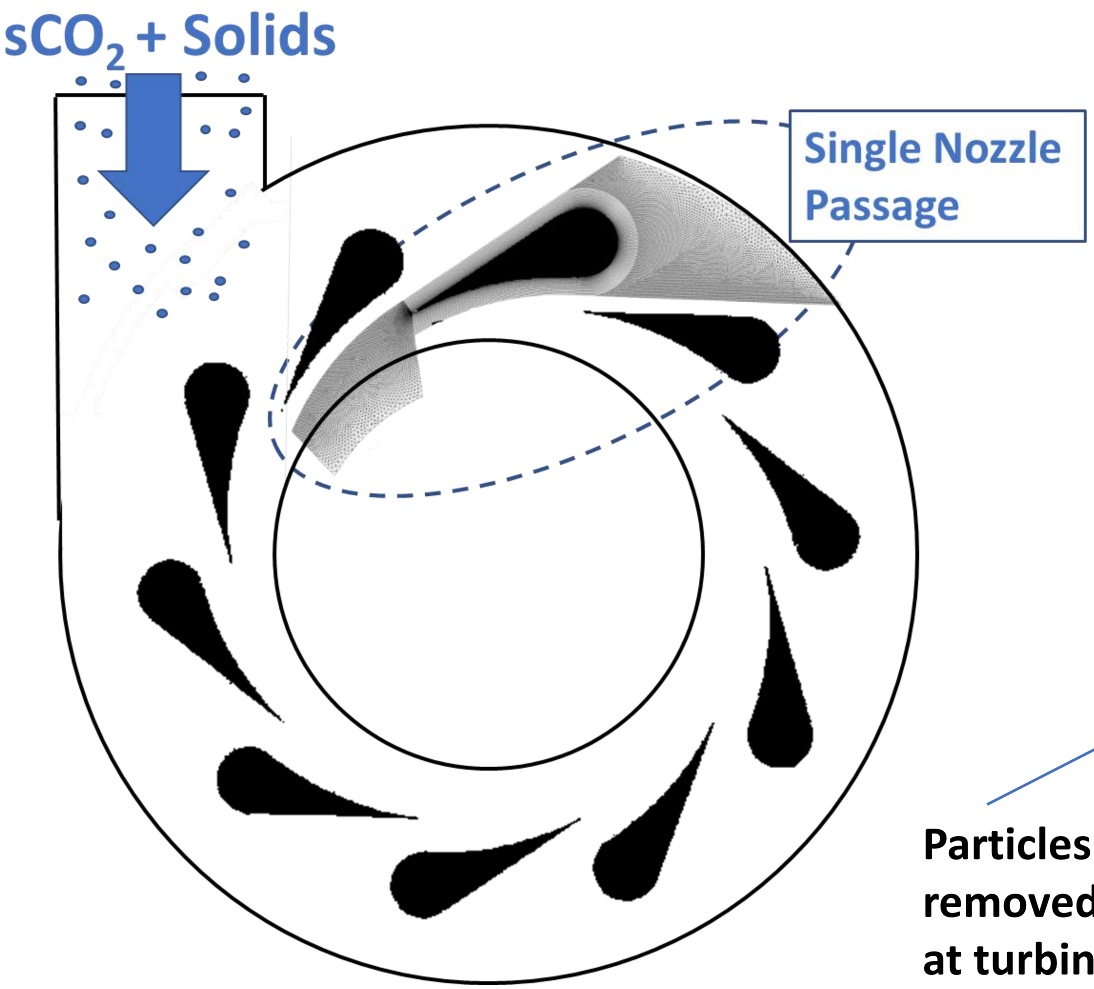


FIG: Evidence of intergranular corrosion and surface scale on sCO2 flow loop piping [1]

[1] D. Fleming, A. Kruizenga, *Identified Corrosion and Erosion Mechanisms in SCO2 Brayton Cycles*, Sandia Report SAND2014-15546, 2014.

Simulation Setup: Domain, Mesh, and B.C's



Particles removed at turbine tip radius

A-Priori grid spacing:

$\Delta_n^+ \approx 1, \Delta_s^+ \approx 20, \Delta_z^+ \approx 50,$

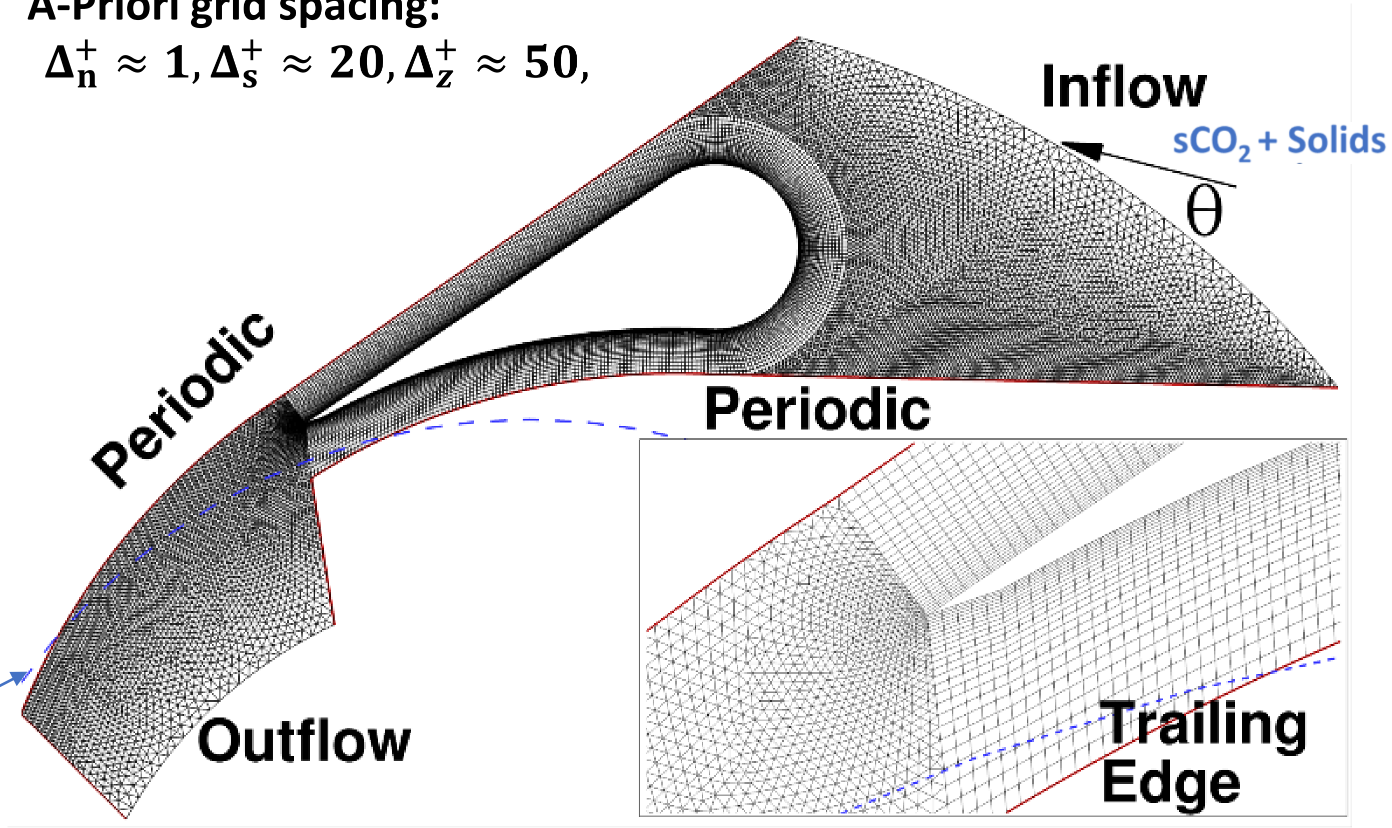


FIG: Single nozzle passage showing periodic approximation and unstructured, body fitted grid.

Turbulent inflow conditions

- Synthetic eddy method (Jarrin et al, 2006) used to specify homogeneous velocity fluctuations on top of mean flow:

$$\overline{u_i} = \langle u_i \rangle + a_{ij} u_i'$$

$$u_j'(x,t) = \sum_{i=1}^{N} \epsilon_{ij} g(x - x_i)$$

$$a_{ij} = \begin{pmatrix} \sqrt{R_{11}} & 0 & 0 \\ R_{21}/a_{11} & \sqrt{R_{22} - a_{21}^2} & 0 \\ R_{31}/a_{11} & \left(R_{32} - \frac{a_{21}a_{31}}{a_{22}}\right) & \sqrt{R_{33} - a_{31}^2 - a_{32}^2} \end{pmatrix}$$

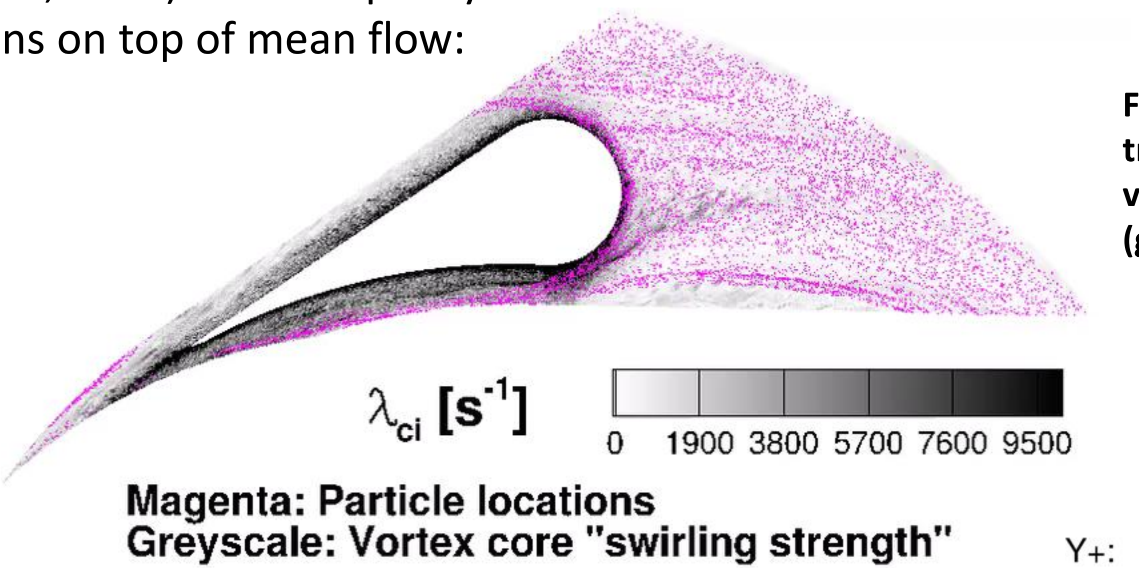


FIG: Simulated particle trajectories (magenta) and vortex swirling strength (greyscale) on center plane

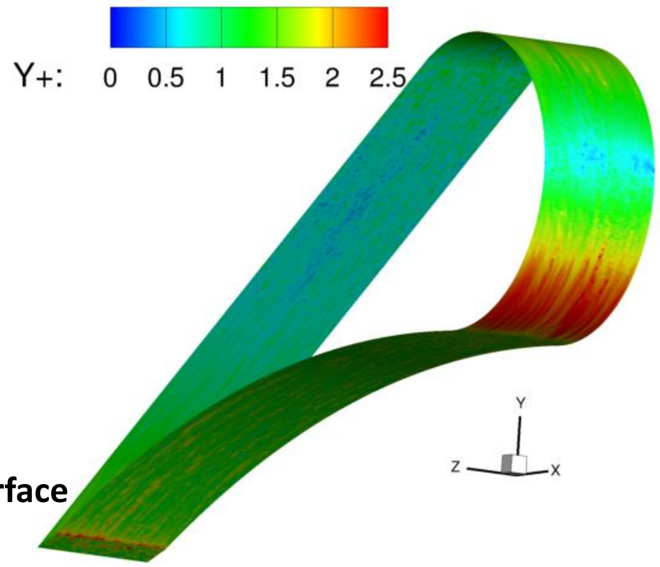
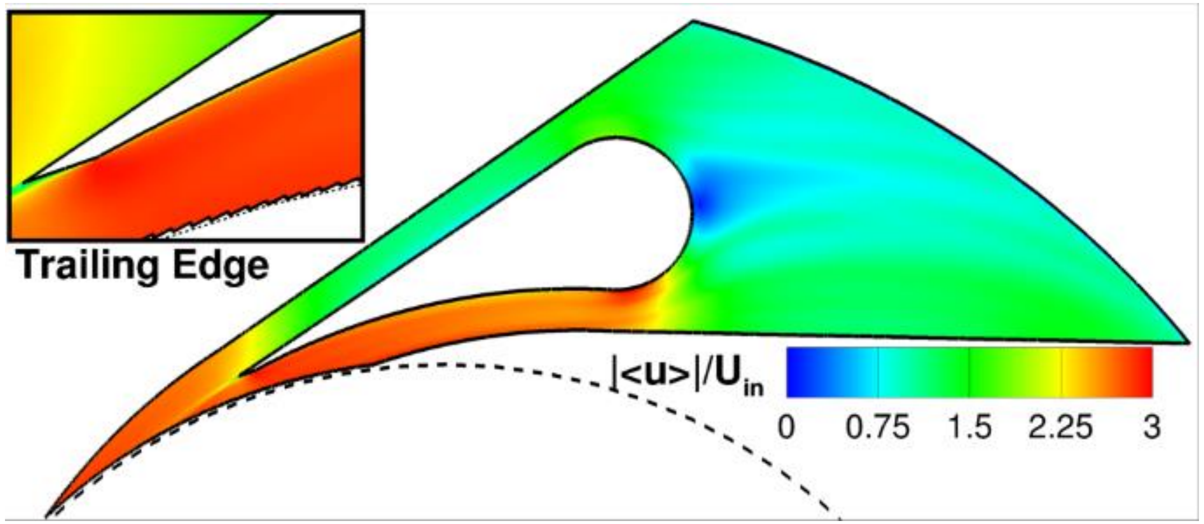
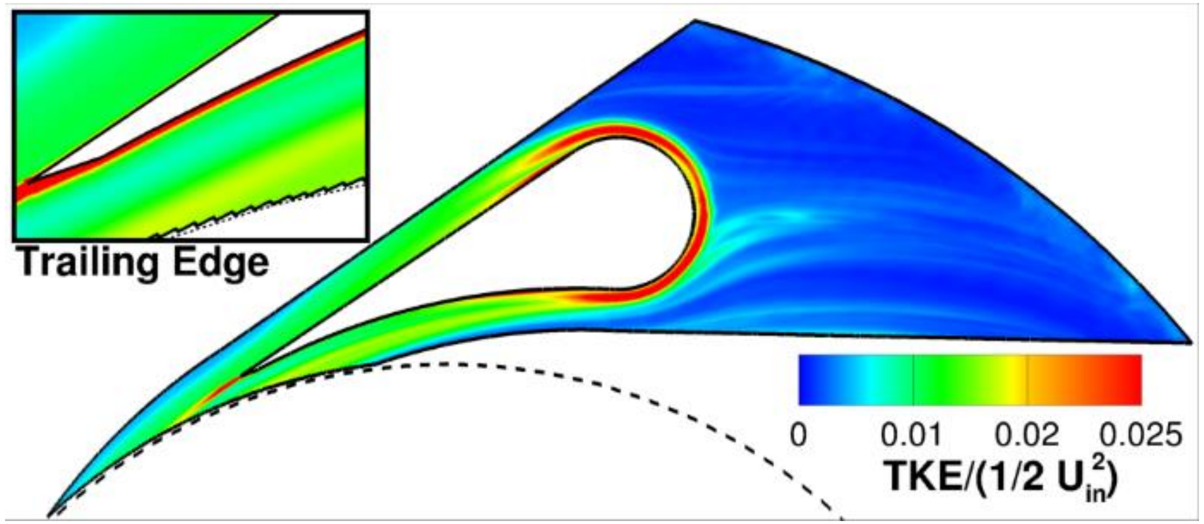


FIG: Y+ on the nozzle surface

[1] Jarrin, N., et al., International Journal of Heat and Fluid Flow, 2006. **27**(4): p. 585-593.

Results: Time averaged flow





Acceleration through the passage:

- Trailing edge velocity ~3x greater than leading edge
- Increasing TKE along pressure-side of passage

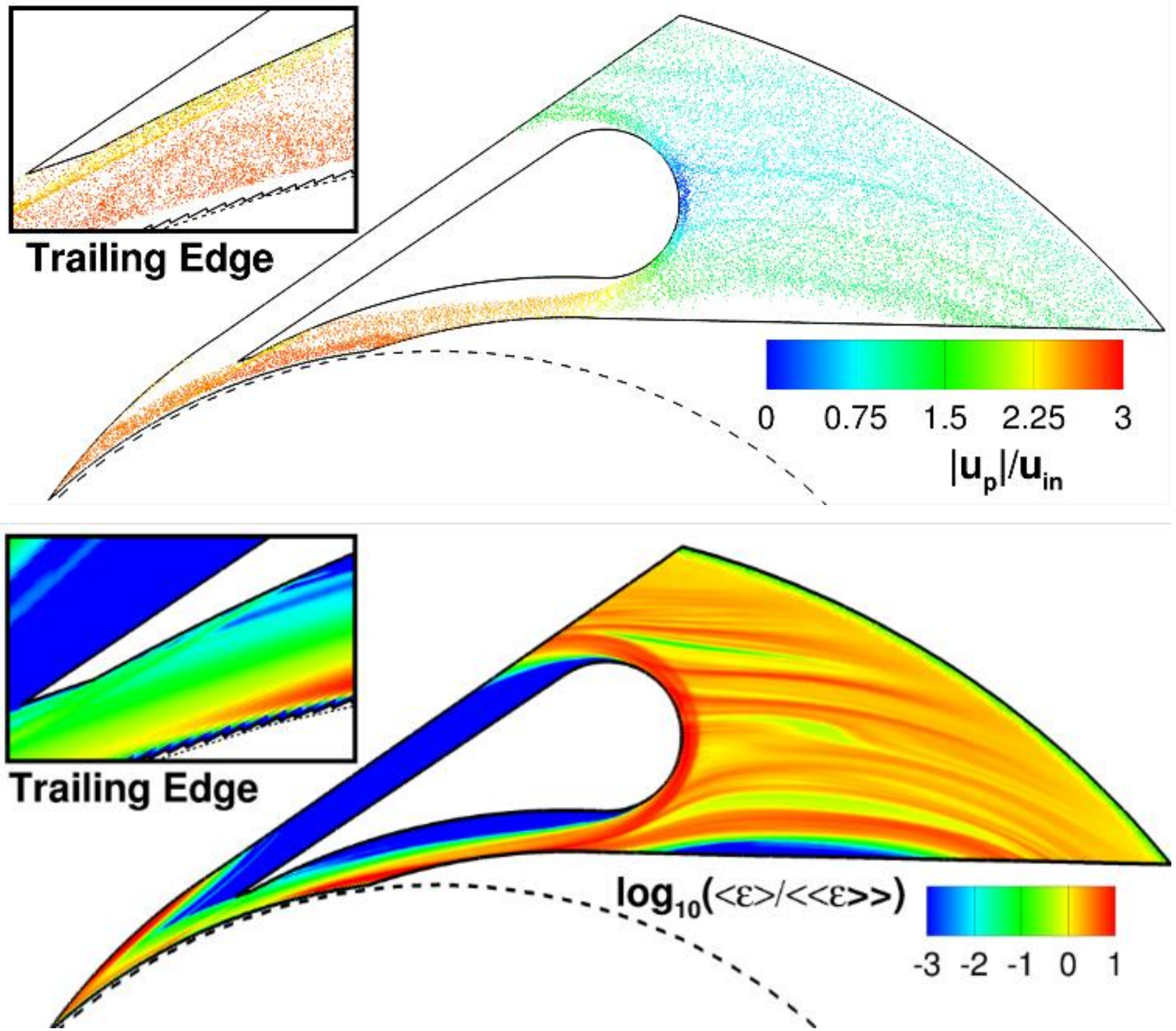
Particle dispersion

Increased slip velocities

High velocity impacts

FIG: Time averaged flow velocity magnitude (top), and Turbulent Kinetic Energy (bottom).

Results: Solid particle trajectories



High Stokes number particles *NOT* evenly distributed

- Stagnation at leading edge, separation around mid span
- Acceleration through the passage
- Particles 10x more concentrated in passage than upstream
- Small amount of high vel. particles approaching trailing edge

FIG: Snapshot of particle distribution, colored by velocity (top), and time averaged particle concentration field (bottom).

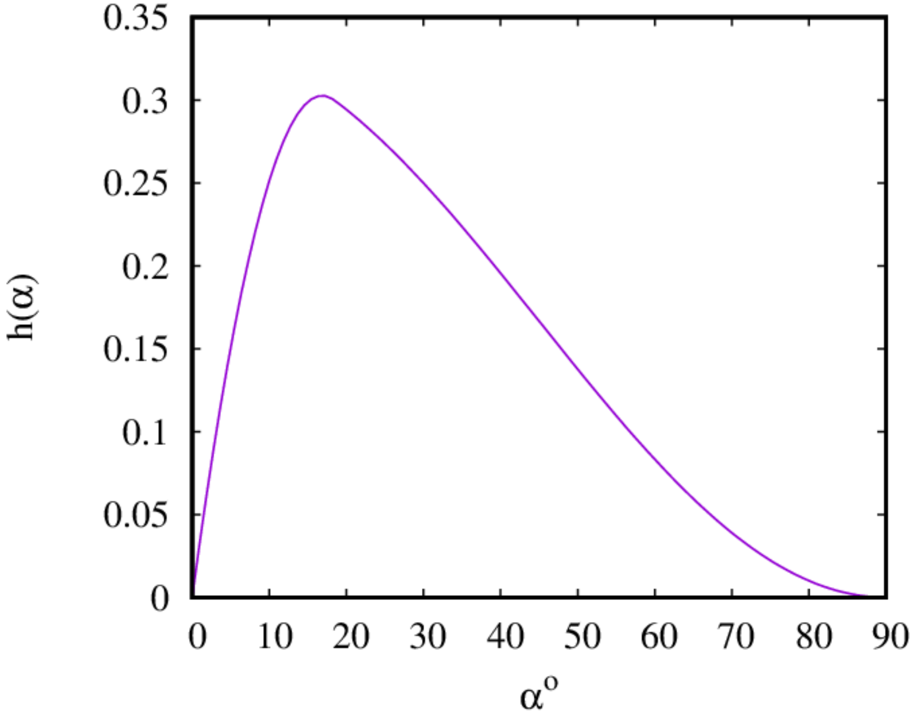
Erosion model

- Oxide scale collisions with nozzle
  - Specular reflections
  - Constant coefficient of restitution, $e = 0.8$
- Erosion rate calculated from collisions using a Finnie model [Finnie,1960]
- Erosion calculated over several flow through times, normalized by local maximum.

$$E \propto m_p |\boldsymbol{u_p}|^2 g(\alpha)\,.$$

$$h(\alpha) = \begin{cases} \frac{1}{3}\cos^2(\alpha) & \text{for } \tan(\alpha) \le \frac{1}{3} \\ \sin(2\alpha) - 3\sin^2(\alpha) & \text{for } \tan(\alpha) > \frac{1}{3} \end{cases}$$

Impact angle function, $h(\alpha)$



Finnie, I., *Erosion of surfaces by solid particles.* Wear (Amsterdam, Netherlands), 1960. **3**(2): p. 87-103.

Results: Erosion Magnitudes

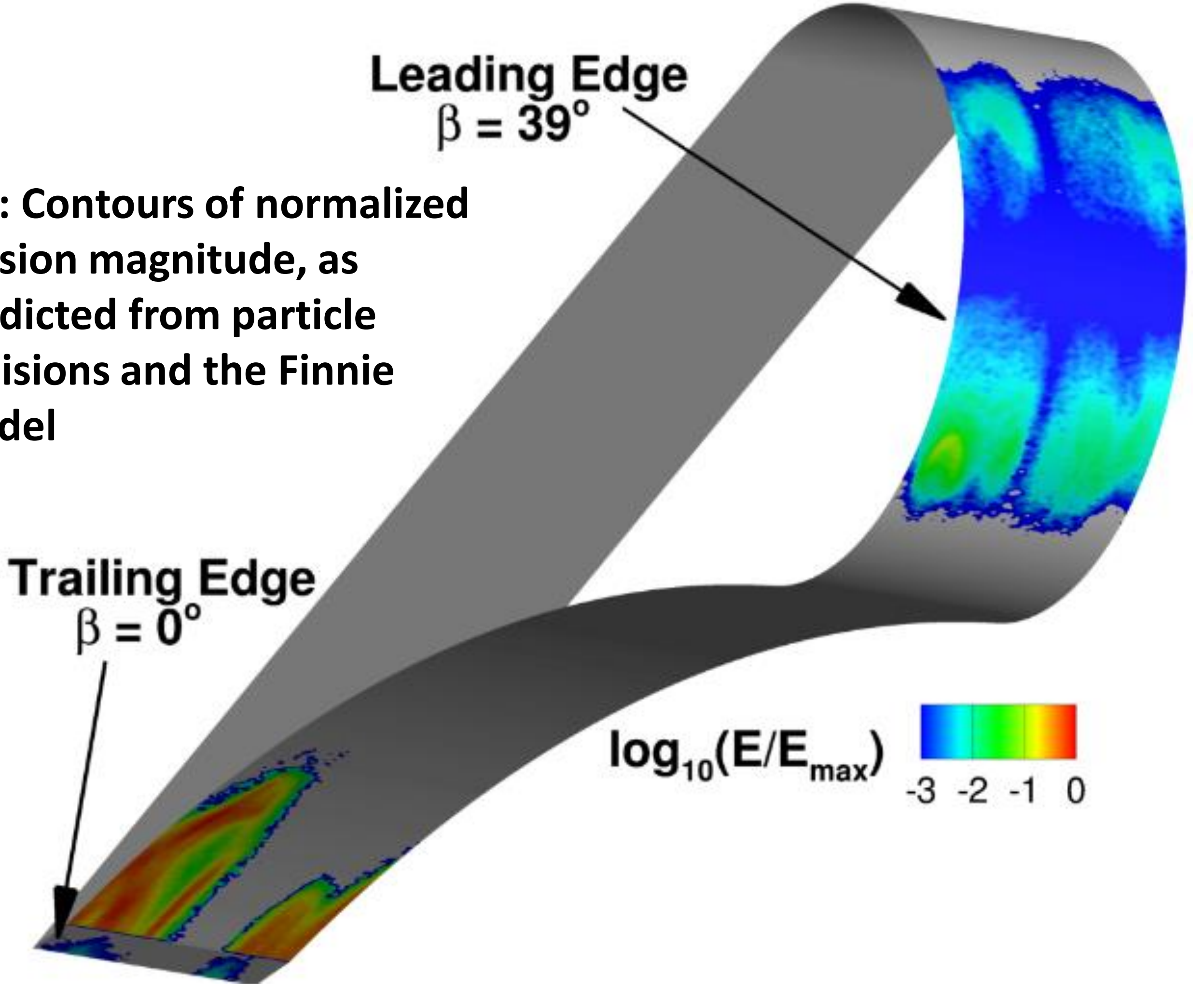
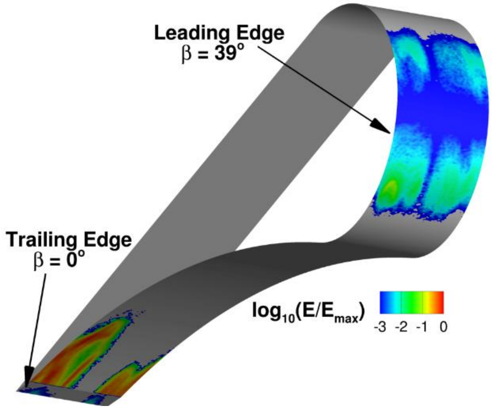


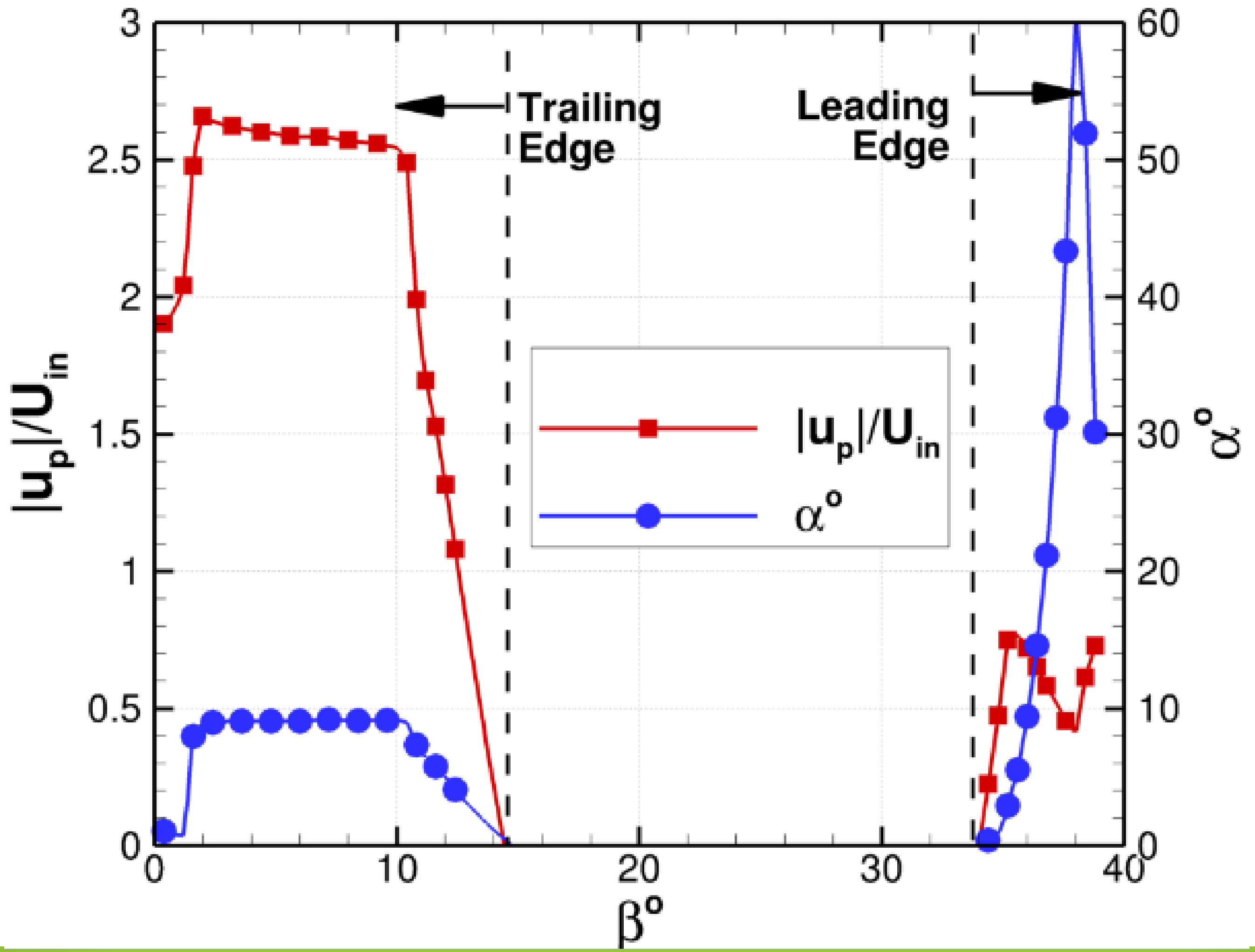
FIG: Contours of normalized erosion magnitude, as predicted from particle collisions and the Finnie model

- No particle collisions over much of surface
- Trailing edge erosion roughly 2 orders of magnitude larger than leading edge
- Consistent with location of damage observed at SNL

FIG: Eroded nozzle at SNL

Results: Impact statistics





Leading Edge:

- Low impact velocities near stagnation point
- Wider distribution of oblique impact angles

Trailing Edge:

- High velocities
- Consistently low impact angles

Implications for operational Re.

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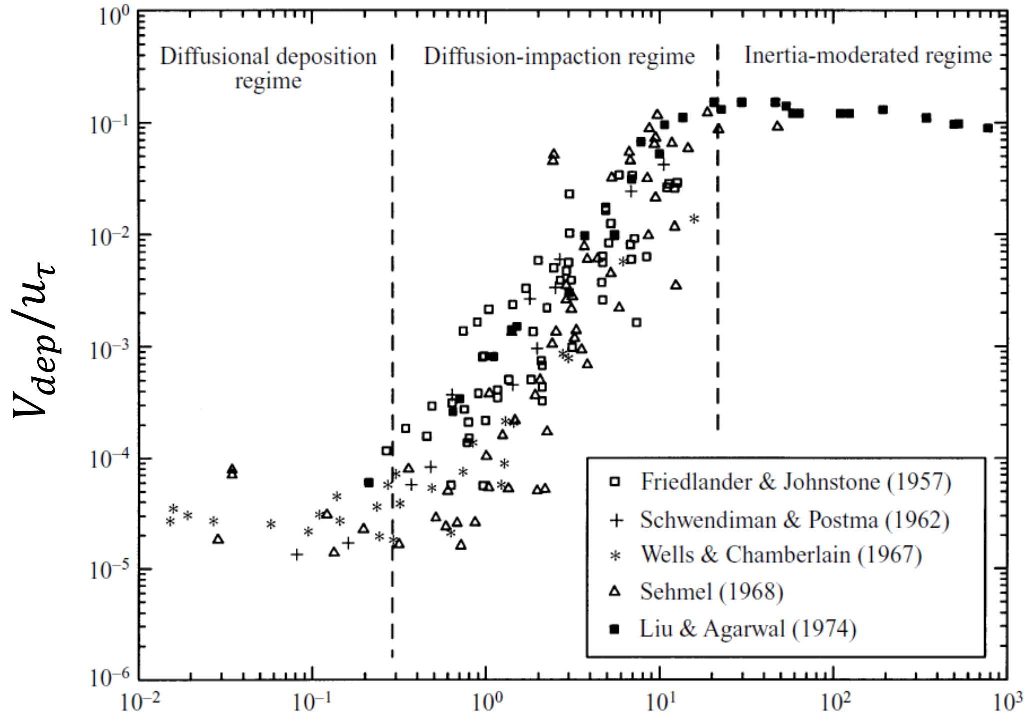
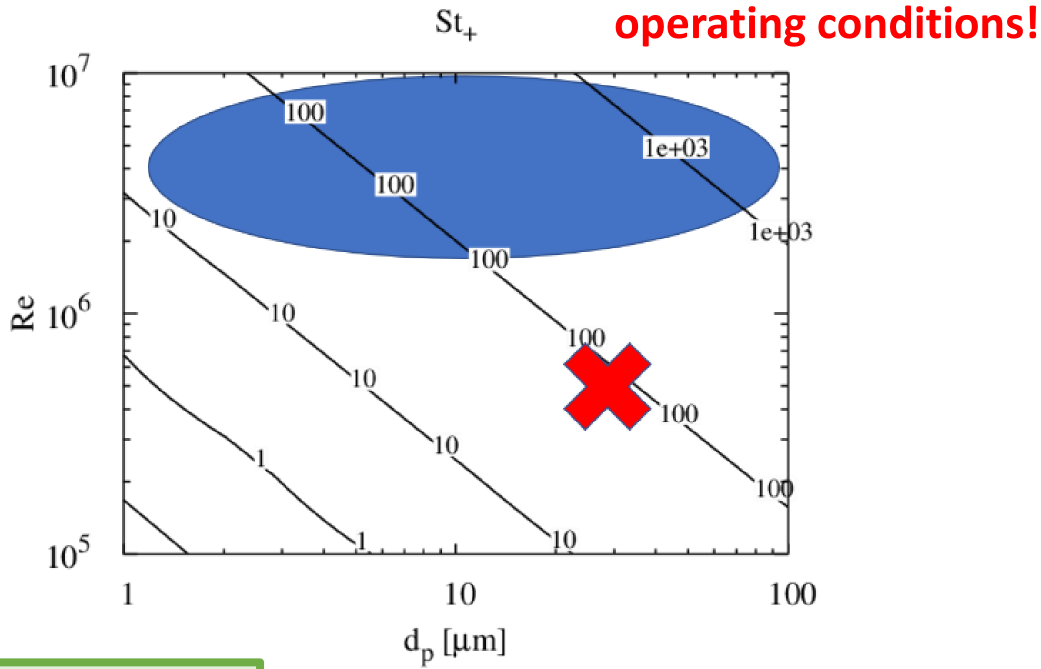
Particle Deposition velocity depends primarily on Stokes number[1]



$$St_p = \frac{\tau_p}{\tau_k}$$

In our system, St_p scales with d_p and Re_c

$St_p = \mathcal{O}(10^3)$ for operating conditions!



May need to filter very small particles from flow loop to avoid damaging impacts!

[1J. J. Young and A. Leeming, *A theory of particle deposition in turbulent pipe flow,* Journal of Fluid Mechanics, Vol 340, pp 129-159, 1997.

Conclusions

- Potential for **solid particle erosion** in sCO_2 turbine nozzle has been investigated
  - Spalled oxide scales entrained in closed flow loop
  - High velocity impacts cause damage to certain components
- **Approach:** Large eddy simulation with Lagrangian particle tracking
  - Periodic domain consisting of 1 nozzle passage
  - Synthetic turbulence specified upstream
- Uniformly distributed particles become **highly concentrated** as they traverse the passage
- **High velocity, oblique impacts** near trailing edge lead to relatively large erosion potential in region that was damaged at SNL

- **Ongoing effort**: More simulations to understand dependence on St_p

Acknowledgments

- **Supercomputing:** Simulations performed on NETL's Joule.
- **Sandia National Laboratory:** James Pasch & Darryn Fleming provided nozzle geometry.
- ***DOE*:** This work was performed in support of the US Department of Energy's Fossil Energy Crosscutting Technology Research Program. The Research was executed through the NETL Research and Innovation Center's Advance Alloy Development Field Work Proposal. Research performed by Leidos Research Support Team staff and was conducted under the RSS contract 89243318CFE000003.

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Extra Slides

Animation at lower Reynolds Number, Re=18,000