

# Experimental Investigation of Shrouding on Meshed Spur Gear Windage Power Loss



**Irebert Delgado (NASA) and Michael Hurrell (HX5 Sierra)**

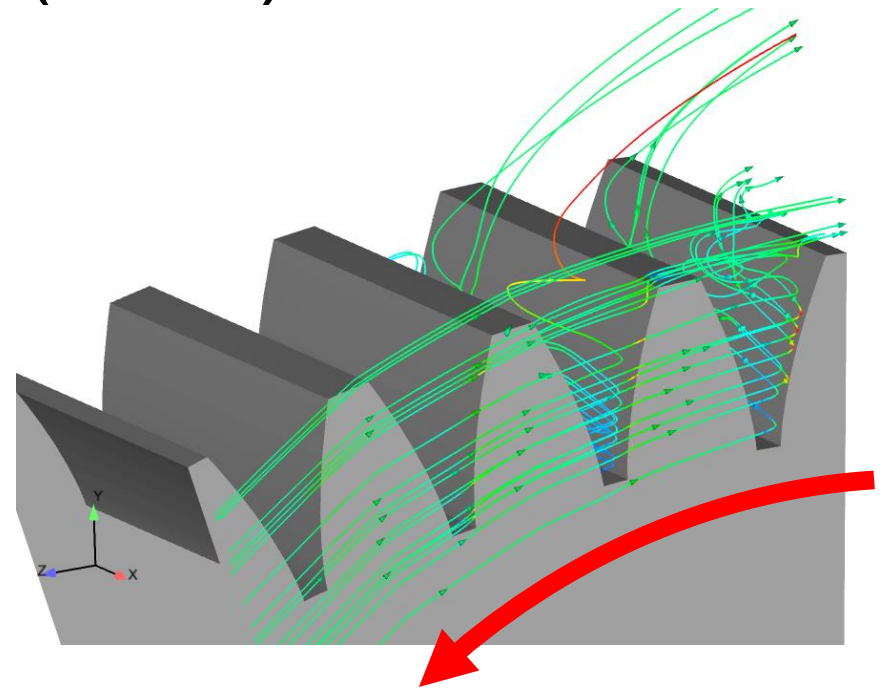
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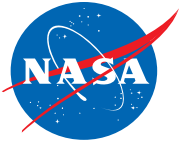


# Windage power loss (WPL)

- Drag on gear tooth in transmitting load.
- Viscous drag on gear faces
- Air/Oil impingement on tooth surface
- Generally occurs at greater than 10,000 ft./min.
- Gearbox efficiency losses
- Reduced rotorcraft performance (i.e. payload, range)

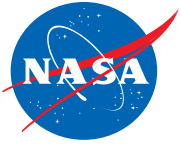


Ref:  
Hill, Matthew J., et al. "CFD analysis of gear windage losses: Validation and parametric aerodynamic studies." *Journal of Fluids Engineering* 133.3 (2011): 031103.



# Selected Spur Gear WPL Work

- (1984) Dawson: “Windage Loss in Larger High-Speed Gears”
  - single spur gears, air
  - reduction in WPL with shrouding
  - air flow patterns revealed through smoke experiment
- (1998) Lord: “An Experimental Investigation of Geometric and Oil Flow Effects on Gear Windage and Meshing Losses”
  - single and meshed spur gears, shrouding, air/oil
  - controlled lab experiments
  - decrease in WPL with increasing oil temp., increase in WPL with increasing oil flow
- (2011) Combined Analysis & Experimental Validation
  - single spur gear analyses, single phase, shrouding
  - Hill: “CFD Analysis of Gear Windage Losses....”
  - Handschuh: “Initial Expts. of High-Speed Drive Sys. Windage Losses”



# Focus of this work

- Obtain baseline WPL experiments on meshed spur gears
  - Re-validate use of NASA rig
  - Provide a consistent experimental procedure for robust data
- Compare with literature
  - Single vs Meshed
  - Unshrouded vs Shrouded
- Identify WPL trends, if any
- Outline additional research

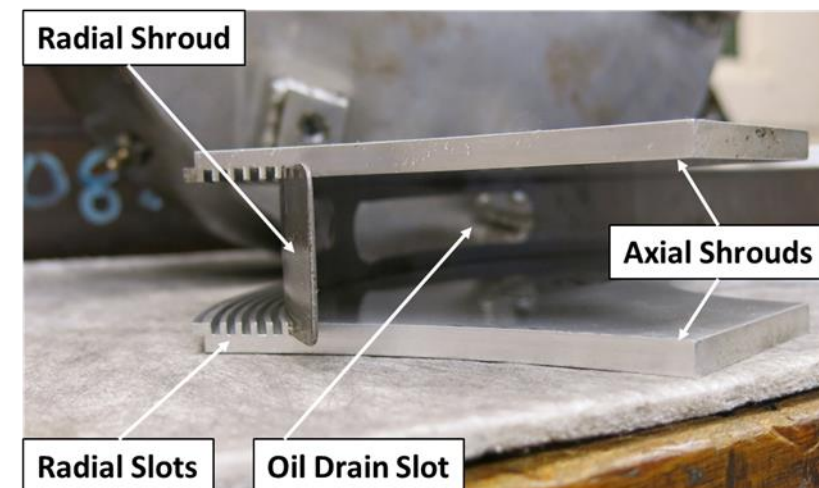
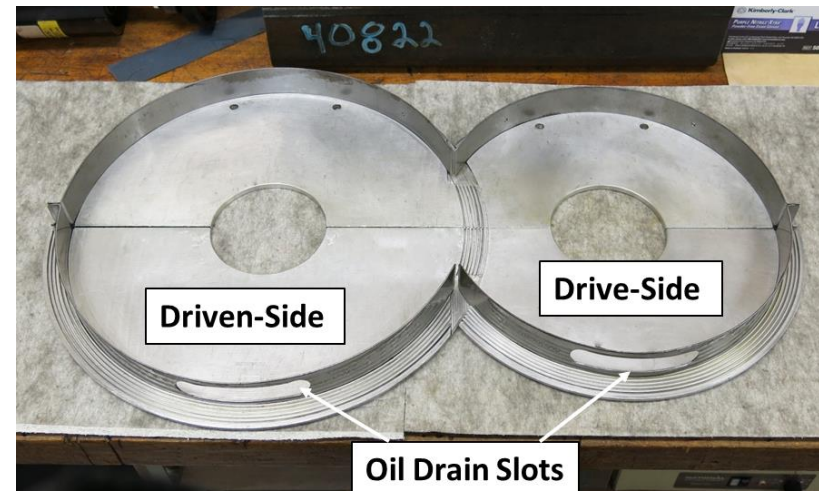
# Gear Information

Gear Parameter	Drive-side	Driven-side
Number of teeth	44	52
Pitch / module, 1/in. (mm)	4 (6.35)	
Face Width in. (mm)	1.12 (28.4)	1.12 (28.4)
Pitch Diameter, in. (mm)	11.0 (279.4)	13.0 (330.2)
Pressure Angle, deg.	25	
Outside Diameter, in. (mm)	11.49 (291.85)	13.49 (342.65)
Material	Steel-SAE 5150H	

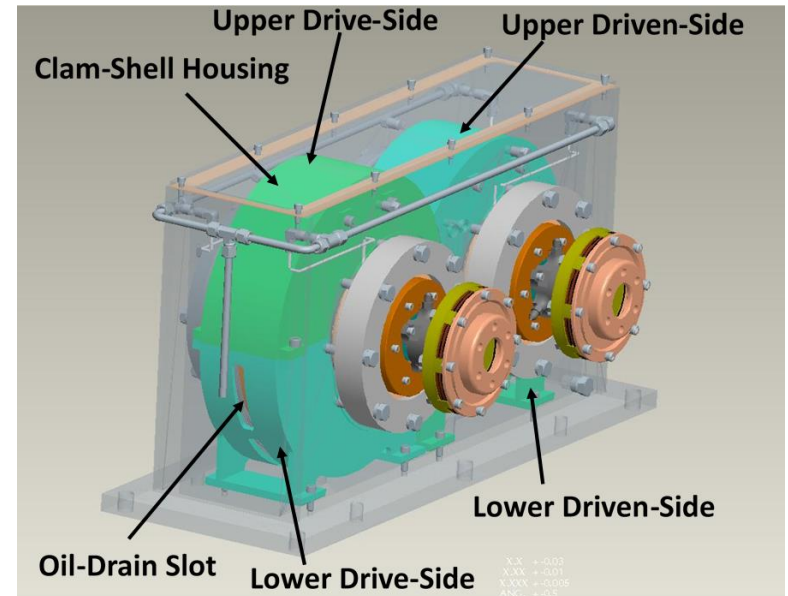
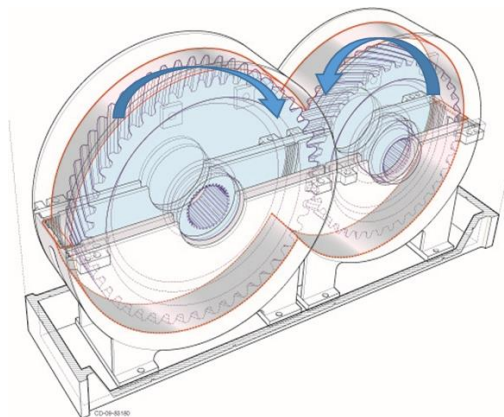


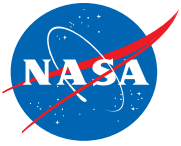
# Shroud Information

Shroud Config.	Axial Clearance	Radial Clearance	
	Per side [inches]	Drive-side [inches]	Driven-side [inches]
(U) Unshrouded w/o clam-shell housing	2.25	2.5	1.0
(CS) Unshrouded w/ clam-shell housing	1.5	0.82	0.82
(C1) shrouded	0.039	0.039	0.039



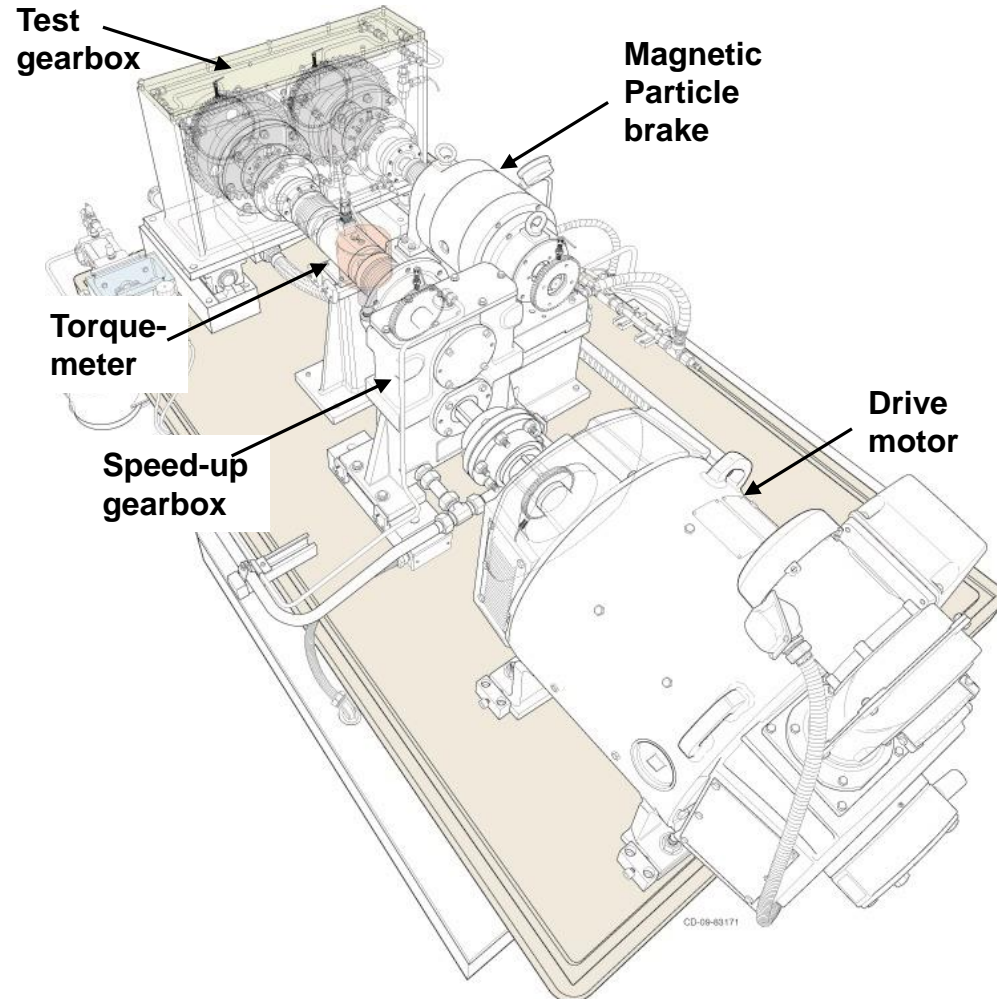
# Continued - Shrouding



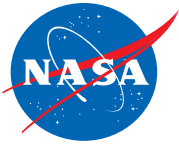


# NASA WPL Test Rig

- dc motor: (112 kW (150 hp))
- speed-up gearbox: 5.17:1 ratio
- Eddy-Current Dyno: 100 N-m at 2865 rpm
- torque-meter: 2,000 in-lbs
- Into-mesh lubrication
- Measurements
  - shaft speed
  - gear fling-off temperature
  - gear mesh oil flow
  - oil inlet/exit temperature

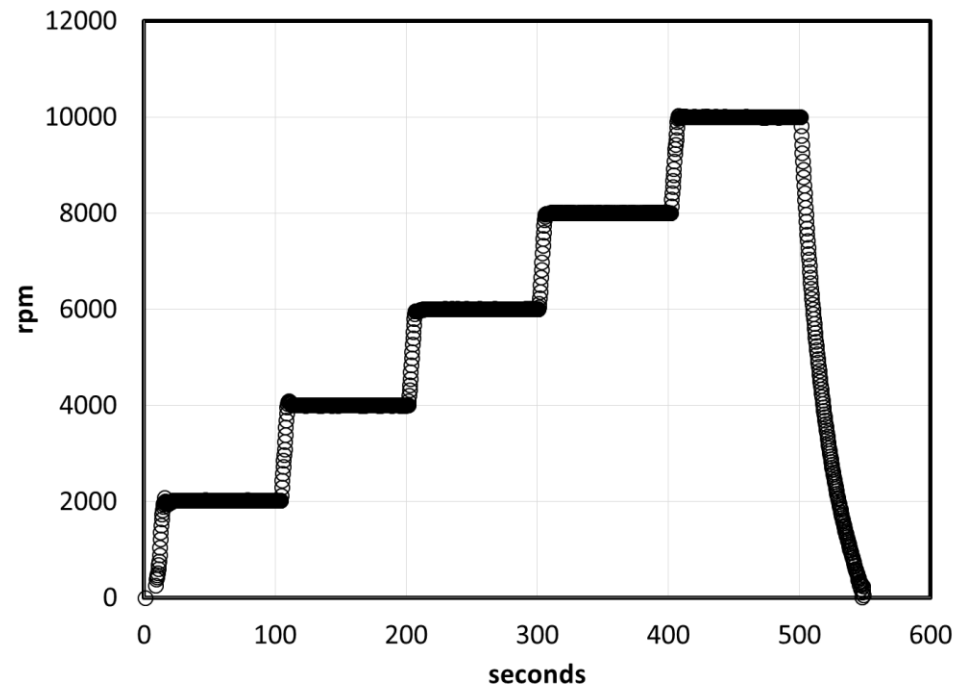


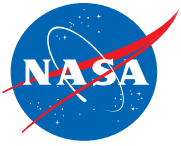




# Typical WPL Test

- 10,000 rpm in 2000 rpm increments every 100 seconds
- Spin-down at 10,000 rpm (i.e. disengage drive motor, clutches, dynamometer)
- Record speed vs time
- Repeat 2x for 3 cycles total.





# Windage Power Loss Calculation

- Total Power Loss = Gear Mesh Loss + Driveline Losses + Windage Losses

- $\tau = I \times \alpha$

Equivalent inertia for meshed spur gear system

Deceleration ( $\alpha$ ) calculated from velocity vs. time data

- $$P(\text{hp}) = \frac{T \text{ ft} \cdot \text{lbf} \times N \text{ rpm}}{5252}$$

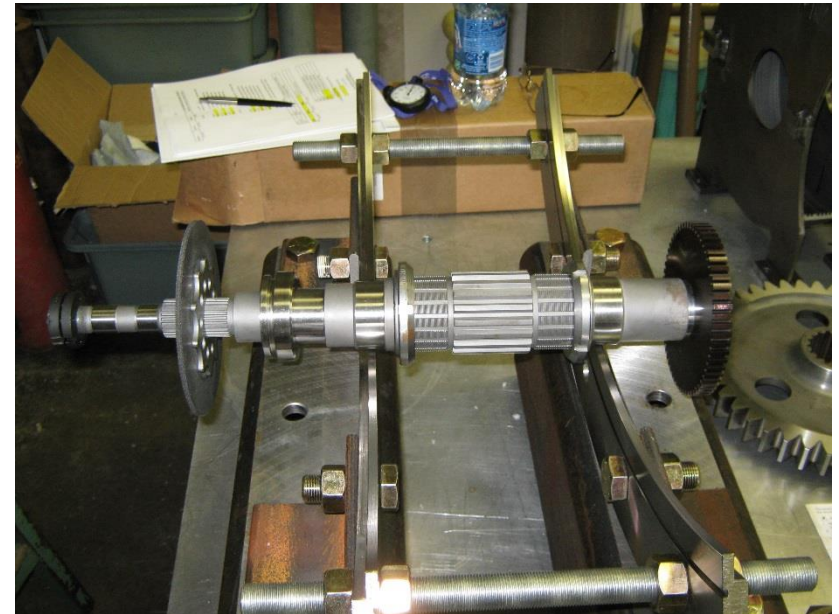
- Subtract Gear Mesh Losses (Ref: Anderson, Loewenthal)  
Minimal
- Subtract Tare (Driveline) Losses

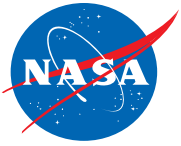
# Tare (Driveline) Loss Calculation

- Determine inertia of shaft components minus test gear
  - Use curved rail methodology (Ref: Genta)
- Conduct shaft only wind-down tests
  - Velocity vs. Time curves
- Calculate power loss

$$\tau = I \times \alpha$$

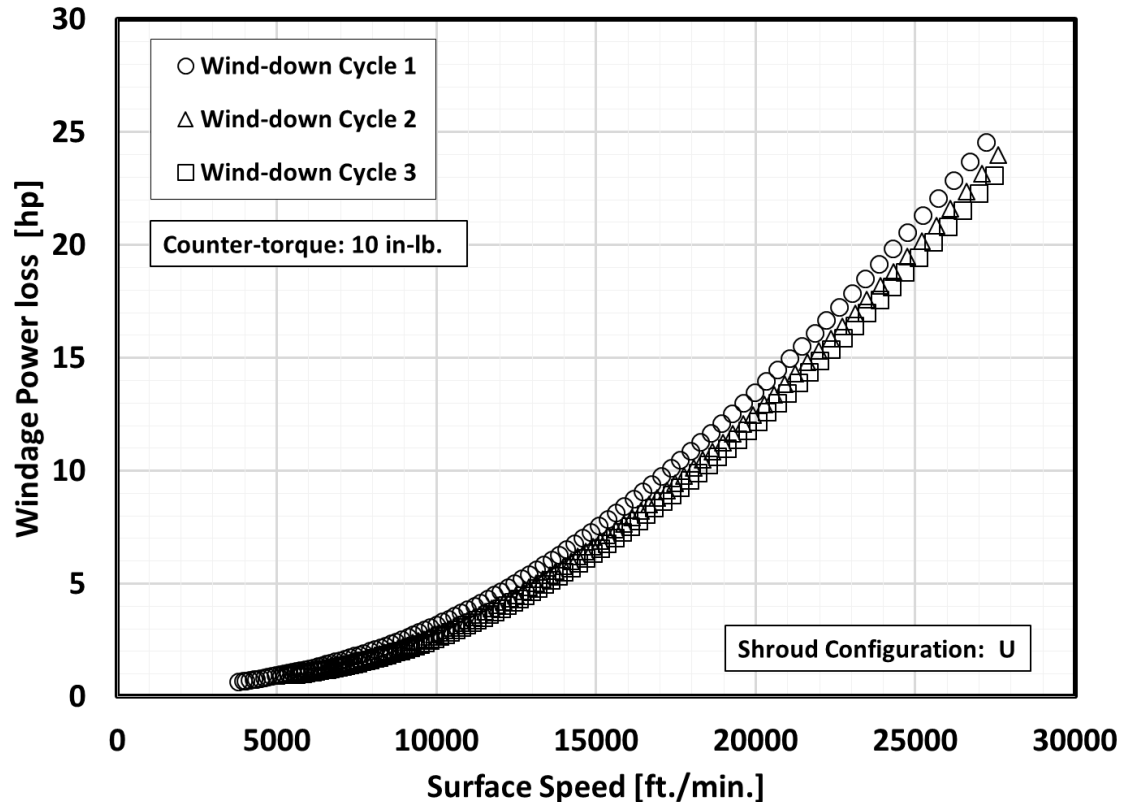
$$P(\text{hp}) = \frac{T \text{ ft} \cdot \text{ lbf} \times N \text{ rpm}}{5252}$$





# WPL Variation – Cycle 1 to Cycle 3

- Unshrouded (U) configuration
- Slight decrease in WPL with increasing cycles



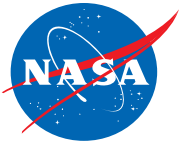


# Gear fling off & oil inlet temps. U vs. CS vs. C1 configs.

Configuration →	U Run 1	CS Run 1	C1 Run 1	C1 Run 2	C1 Run 3
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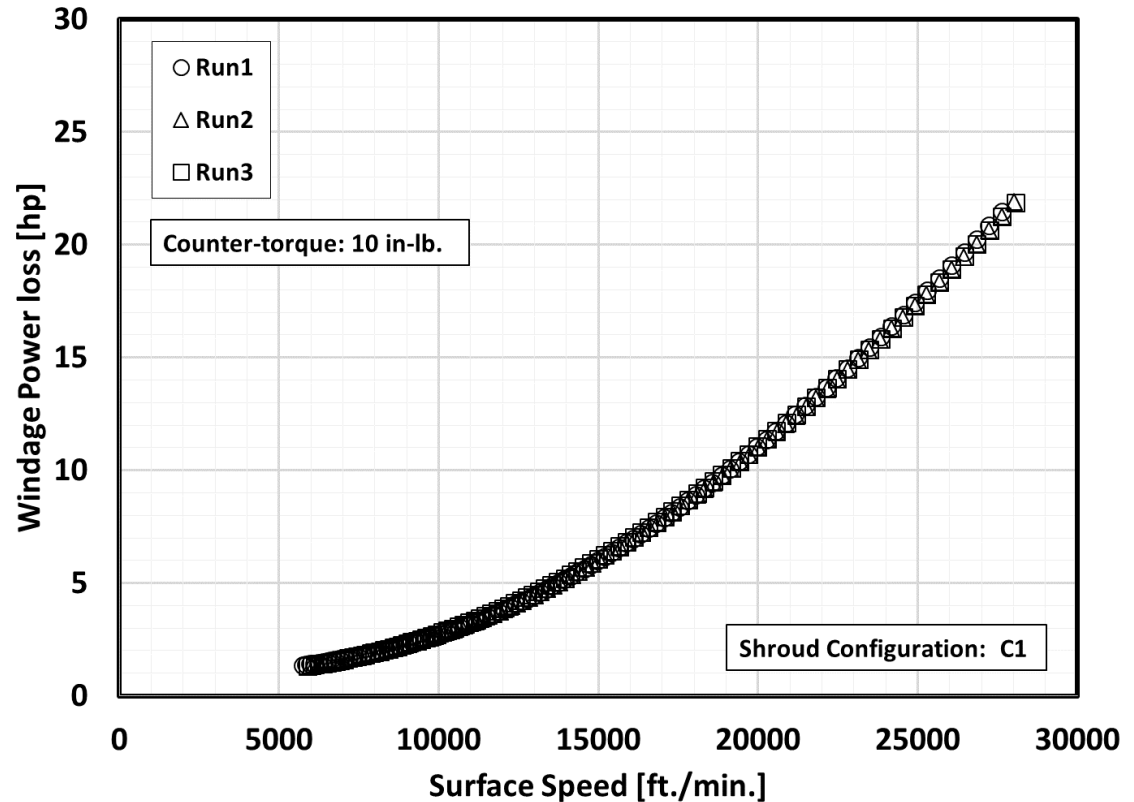
Wind-down Cycle	instantaneous gear fling-off temperature [°F]				
1	165	171	192	191	194
2	184	187	208	206	210
3	196	199	218	219	222

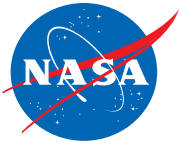
	oil inlet temperature [°F]				
start of wind-down cycle 1	86	86	92	91	95
end of wind-down cycle 3	101	104	108	106	109



# WPL Variation – Run 1 to Run 3

- Test data on 3 consecutive days
- Little variation in WPL for 3<sup>rd</sup> cycle



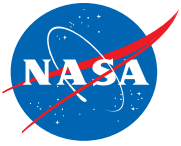


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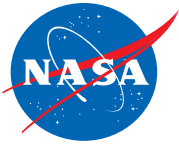
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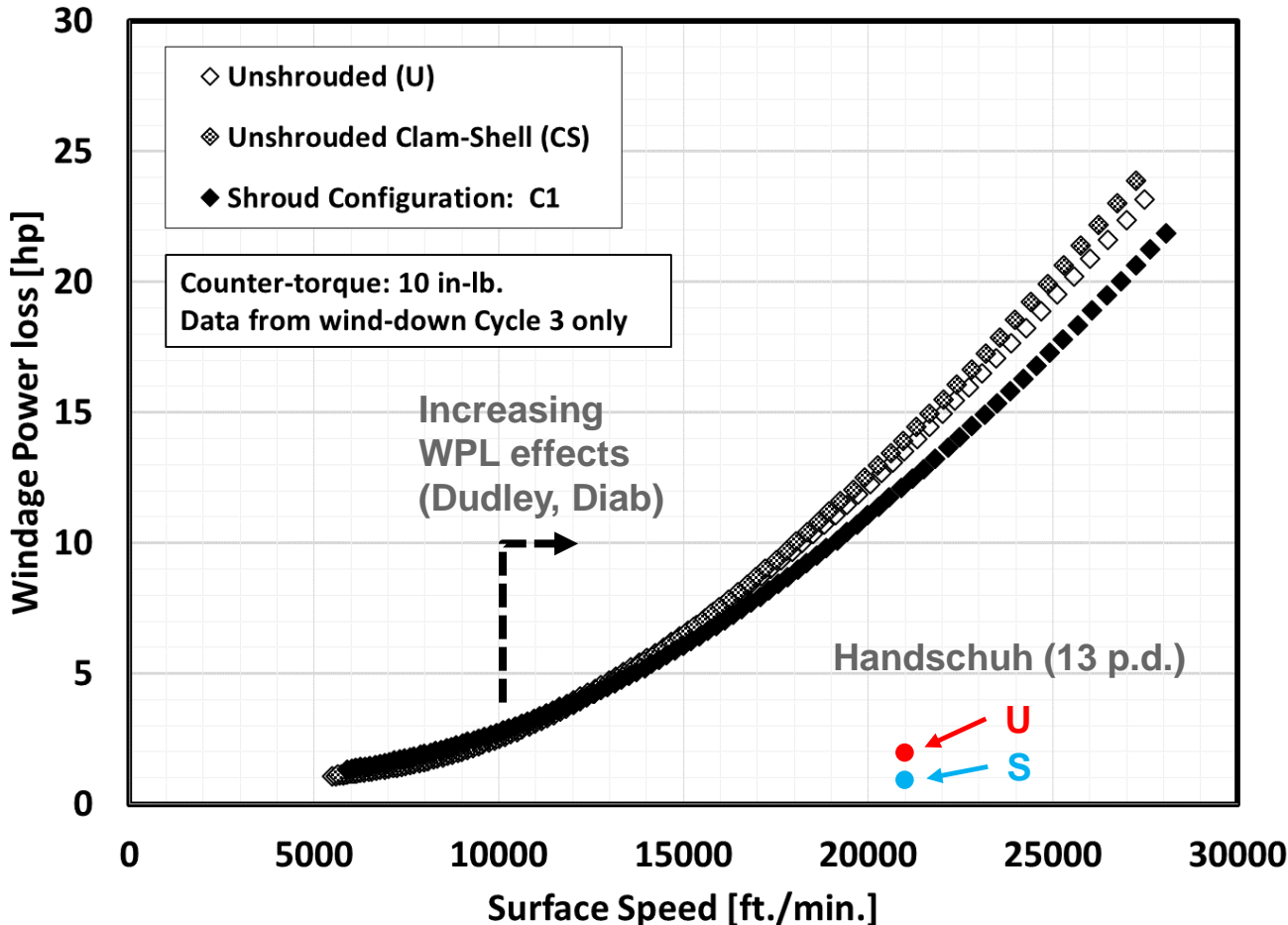
# Gear mesh oil flows U vs. CS vs. C1 configs.

<b>Configuration →</b>	<b>U</b>	<b>CS</b>	<b>C1</b>		
<b>Run →</b>	Run 1	Run 1	Run 1	Run 2	Run 3
	[GPM]				
<b>Cycle 1</b>	0.65	0.68	X	X	0.74
<b>Cycle 2</b>	0.69	0.78	X	X	0.81
<b>Cycle 3</b>	0.75	0.94	0.89	0.87	0.91

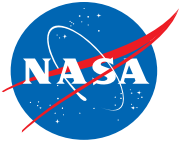




# WPL - U vs. CS vs. C1 configs.

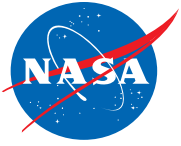


- 15,000 ft/min
  - No shroud benefit below
  - CS oil drain slots negatively affect WPL above
- Ref. Hill: slotting
- C1 vs U
  - 10% reduction in WPL @ 25,000 ft/min
  - Increasing shroud benefit above 15,000 ft/min
- Handschuh 13 p.d.
  - 7x difference (U)
  - 12X diff. (S)



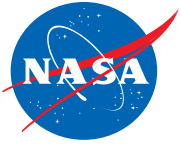
# WPL: Oil Flow vs Oil Temperature

- Sensitivity of oil flow rate and oil temp. w.r.t. WPL?
- Reported: Increased oil flow rate *increases* WPL (Ref. Lord)
- Reported: Increased oil temp. decreases oil viscosity, *decreasing* WPL (Ref. Lord)
- Need to separate effects in a future study



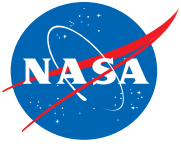
# Summary Points

- Demonstrated experimental repeatability.
- Observed: Increased shrouding effectiveness above 15,000 ft./min.
  - Windage power loss more pronounced above 10,000 ft./min.
- Observed: C1 shrouding results in 10% drop in windage power loss at 25,000 ft./min. compared to U configuration
  - C1 drain holes offset WPL reduction at 25,000 ft./min.
  - In general: oil drain holes may offset gains in shrouding.
- 7x increase in WPL
  - Comparison to Literature: unshrouded single vs. unshrouded meshed
- 12x increase in WPL
  - Comparison to Literature: shrouded single vs shrouded meshed



# Follow-up Studies

- Sensitivity of windage power loss on oil temperature and oil flow
- Axial vs. Radial shroud effectiveness
- Oil drain slot size, #, location vs. shrouding effectiveness
- Shroud effectiveness at higher surface speeds.
- Sources for more than doubling of windage power loss comparing single versus meshed spur gear in both unshrouded and shrouded configurations.



# Acknowledgements

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- Sig Lauge

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