JTC Engineering Investigation

Ring thrust bearing slips behind idler shaft during installation of FPIG

By: Jessica Nicholson

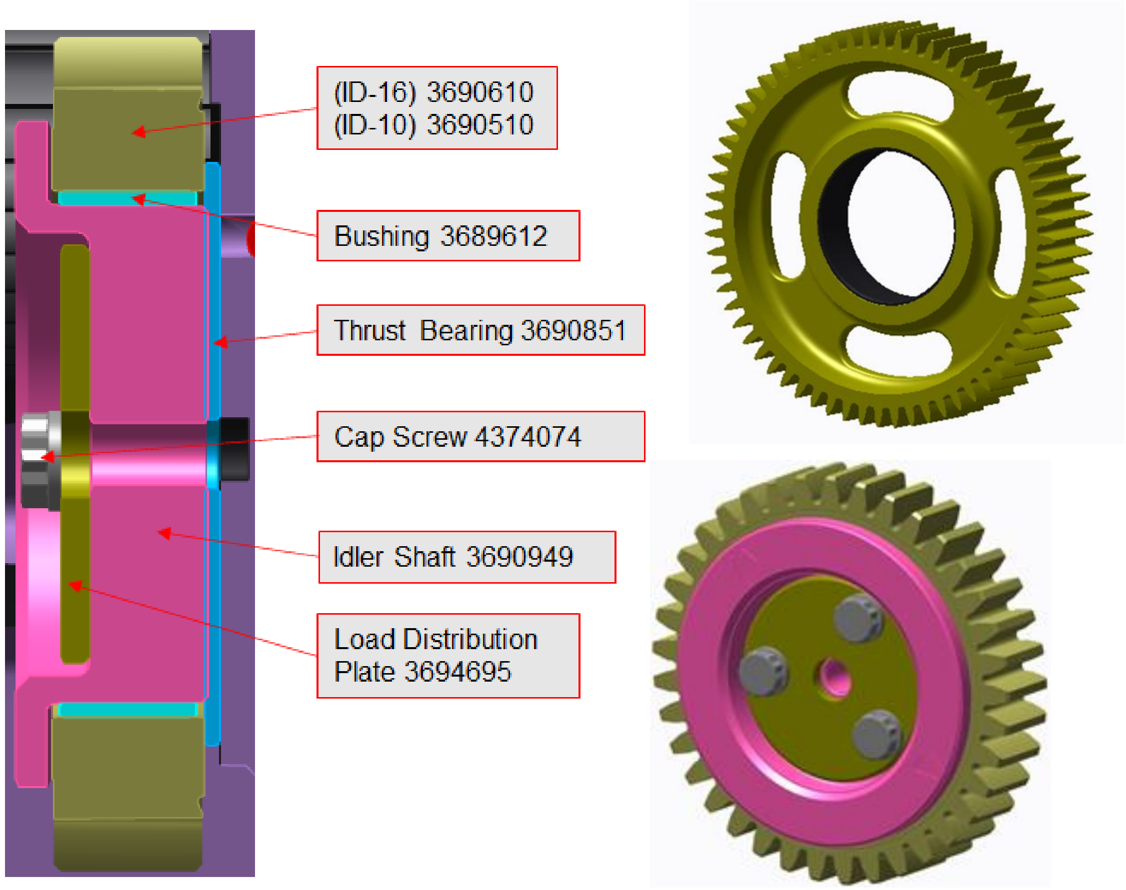
Date Opened: 6/7/2021

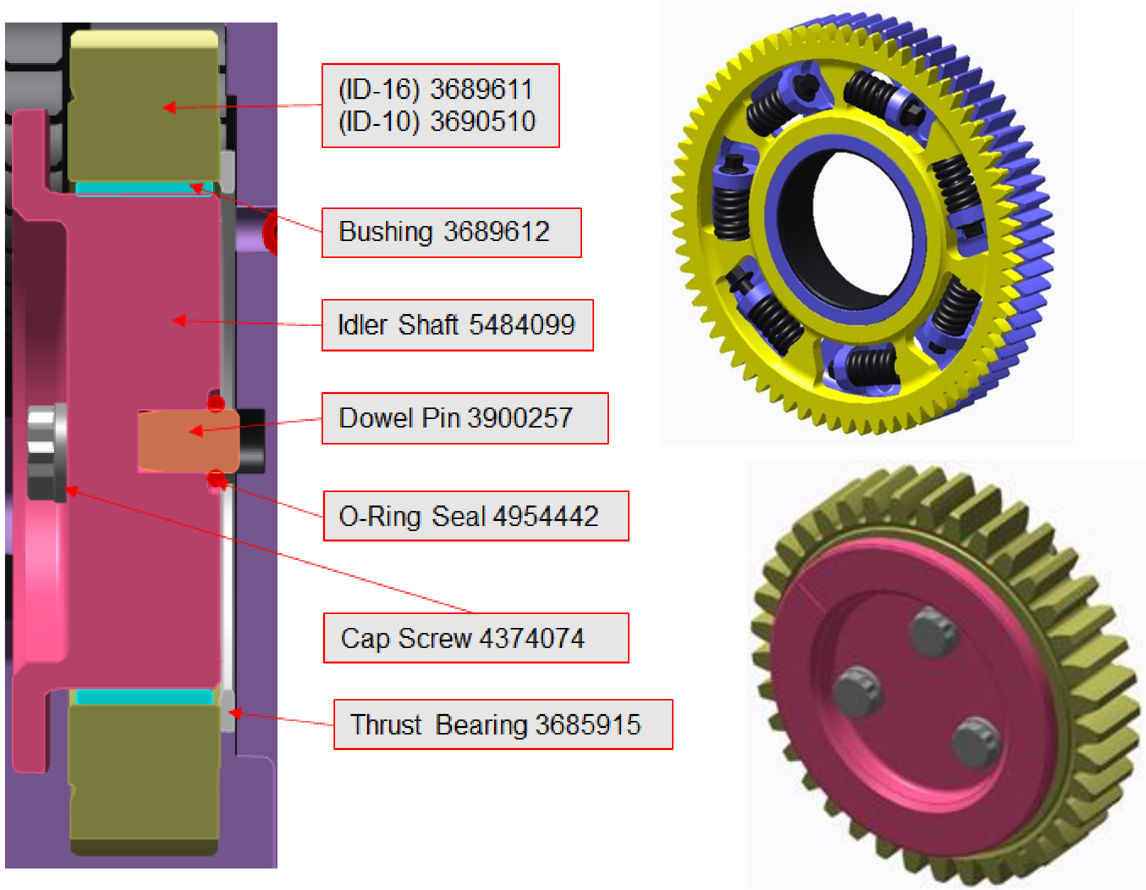
Date Closed: ____

System Background

= Censored for confidentiality

Adjustable vs Fixed Fuel Pump Idler Gear





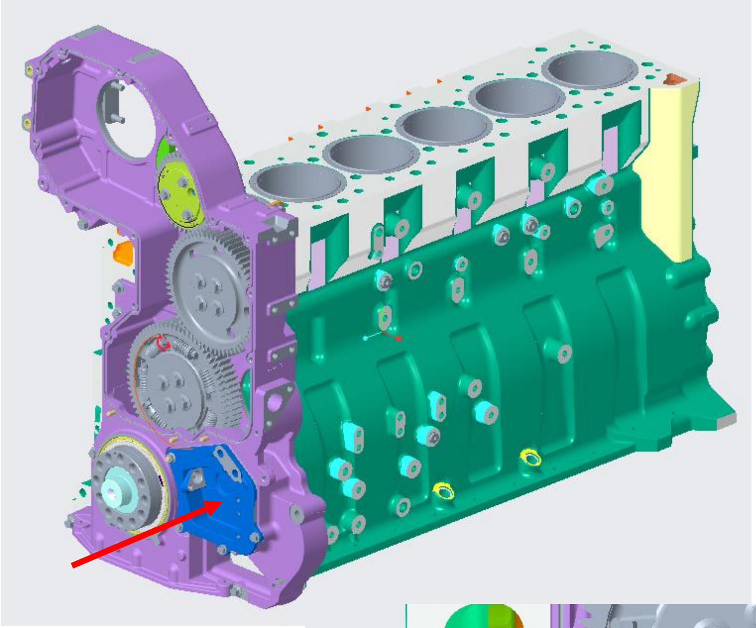
Adjustable: Plate thrust bearing

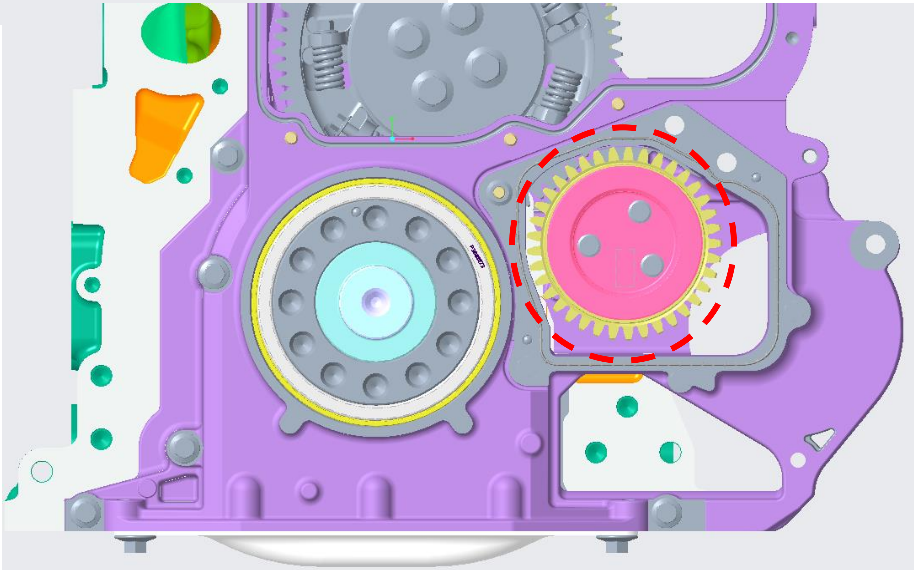
- Solid driving gear
- Distribution plate to adjust

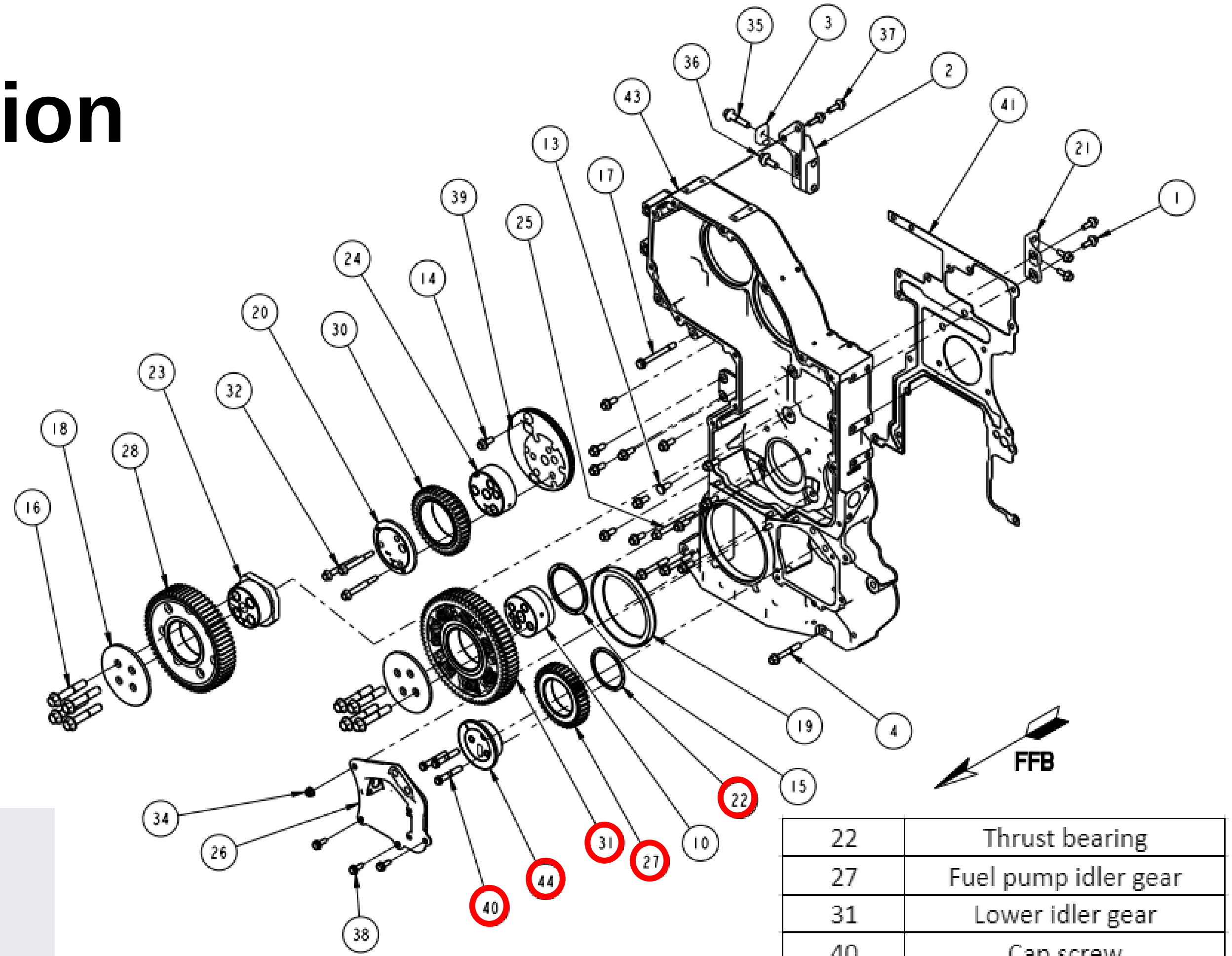
Fixed: Ring thrust bearing

- Scissor driving gear
- No adjustment for lash

Fuel Pump Idler Gear Location



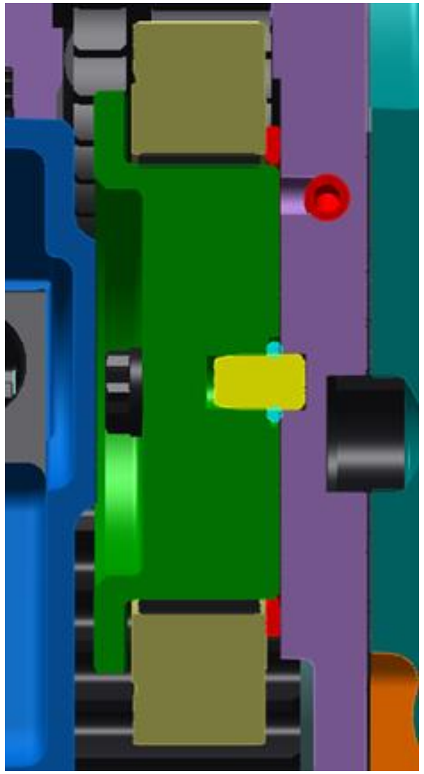




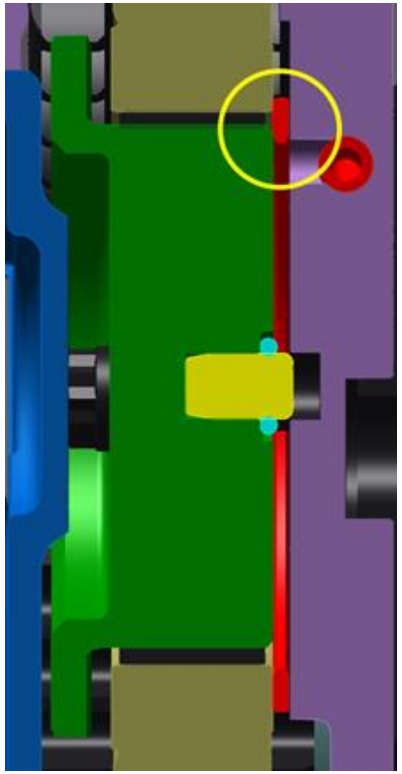
Assembly: bb1945

22	Thrust bearing
27	Fuel pump idler gear
31	Lower idler gear
40	Cap screw
44	Idler shaft

Failing Component and Effects



Correct Design
(section view)



Failed Design
(section view)

- **Fixed system fails**
- Thrust bearing slips behind FPIG idler shaft
- Slip occurs during installation

- Issue often goes unnoticed
  - Ring is thin
  - Changes in idler shaft position are difficult to visually identify
  - Ring is obscured by gear and idler shaft once installed
- Effects of failure
  - Idler shaft not fully connected by dowel pin, can misalign or detach
  - Efficiency loss and excess radial load occur
  - Gears fall out of mesh, short-term engine failure

Claims Research

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Purpose and Assumptions

- Failure codes: BKTB, BKIF, BKIS
- Conduct claims research for these failure codes in two systems
  - ISX3 – High performance, fixed system with ring thrust bearing
  - ISX1 – High efficiency, adjustable system with plate thrust bearing
- Only ISX3 can experience slipped ring failure, compare results to ISX1
- Full system failures due to slipped ring may not generate claims
  - Failed engine deemed not repairable, replaced
    - Failure mode never investigated
  - Slipped thrust bearing ring not discovered as the failure mode
    - Ring is thin and difficult to identify if slipped
    - Slipped ring causes entire gear train to stall, no clear source of failure

❿ Some rings may be identified as the failure mode and generate a claim

Search Criteria and ISX3 Initial Results

- Claims search criteria to identify thrust bearing failures
  - Two engine name searches: **ISX3 and ISX1**
  - Heavy duty engine group, 15 Liter, JEP, all regions
  - Build month range: 01/2007 to 07/2021
  - Failure codes: BKTB, BKIF, BKIS
- ❿ Plots all failures of ring (ISX3) or plate (ISX1) thrust bearings, idler gear, and idler shaft among build volume
- Slipped ring can cause multiple failure modes in the ISX3 system
- MAB plots show all failures of the idler gear, idler shaft, and ring thrust bearing, regardless of failure mode

ISX3 – RPH and CPE Plots

[redacted]

- Build volume: 113,866, Claims: [redacted], Average RPH = [redacted]
  - BKTB: [redacted], BKIF: [redacted], BKIS: [redacted]
- Average replacement cost = $2,864.12, Average CPE = $7.67

ISX3 – Claims Research Results

- Table 1 in Appendix separates claims by failure mode
  - All failure modes are potentially caused by slipped ring
  - All these claims must therefore be considered in evaluating potential failure rate due to slipped ring, and in comparison to ISX1 claims research
- ISX3 plots, average RPH, cost per claim, and CPE remain unchanged
- Highest failure rate trends
  - By configuration, D103011BX03 – [redacted] out of 23161 (RPH = [redacted])
  - By location, Australia – [redacted] out of 23886 (RPH = [redacted])
- Other locations and configurations have below average RPH

ISX1 Comparison

- ISX1 models have a plate thrust bearing rather than the ring
- Compare RPH and CPE of ISX1 claims data vs ISX3 for all 3 failure codes and corresponding failure modes
  - If slipped ring problem is solved, ISX3 systems should have similar failure rates to ISX1 since ISX1 cannot experience this failure mode
- Plate thrust bearing system (ISX1) experiences a significantly lower failure rate and CPE than ring thrust bearing system (ISX3)

ISX1 Comparison – RPH and CPE Plots

[redacted]

- Build volume: 468,391, Claims: [redacted], Average RPH = [redacted]
  - BKTB: [redacted], BKIF: [redacted], BKIS: [redacted]
- Average replacement cost = $10,240.43, Average CPE = $4.37

Claims Research Results

- According to claims research, solving this slipped ring issue can:
  - Reduce average RPH for recorded idler gear, idler shaft, and thrust bearing failures of ISX3 systems by up to 0.268
  - Eliminate an average of $2,864.12 in cost per prevented claim
  - Reduce average CPE from these ISX3 failures by up to $7.67
- ISX1 system has a lower rate and cost of failure than ISX3
  - CPE difference between ISX3 and ISX1 = 7.67 - 4.37 = **$3.30**
  - All ISX3 thrust rings will be replaced by the plate thrust bearing
    - ISX3 systems will experience a similar failure rate to ISX1 systems
  - This causes an expected $3.30 CPE reduction in ISX3 engines

➓ Compare predicted CPE reduction to cost of implementation

Proposed Solution and Redesign

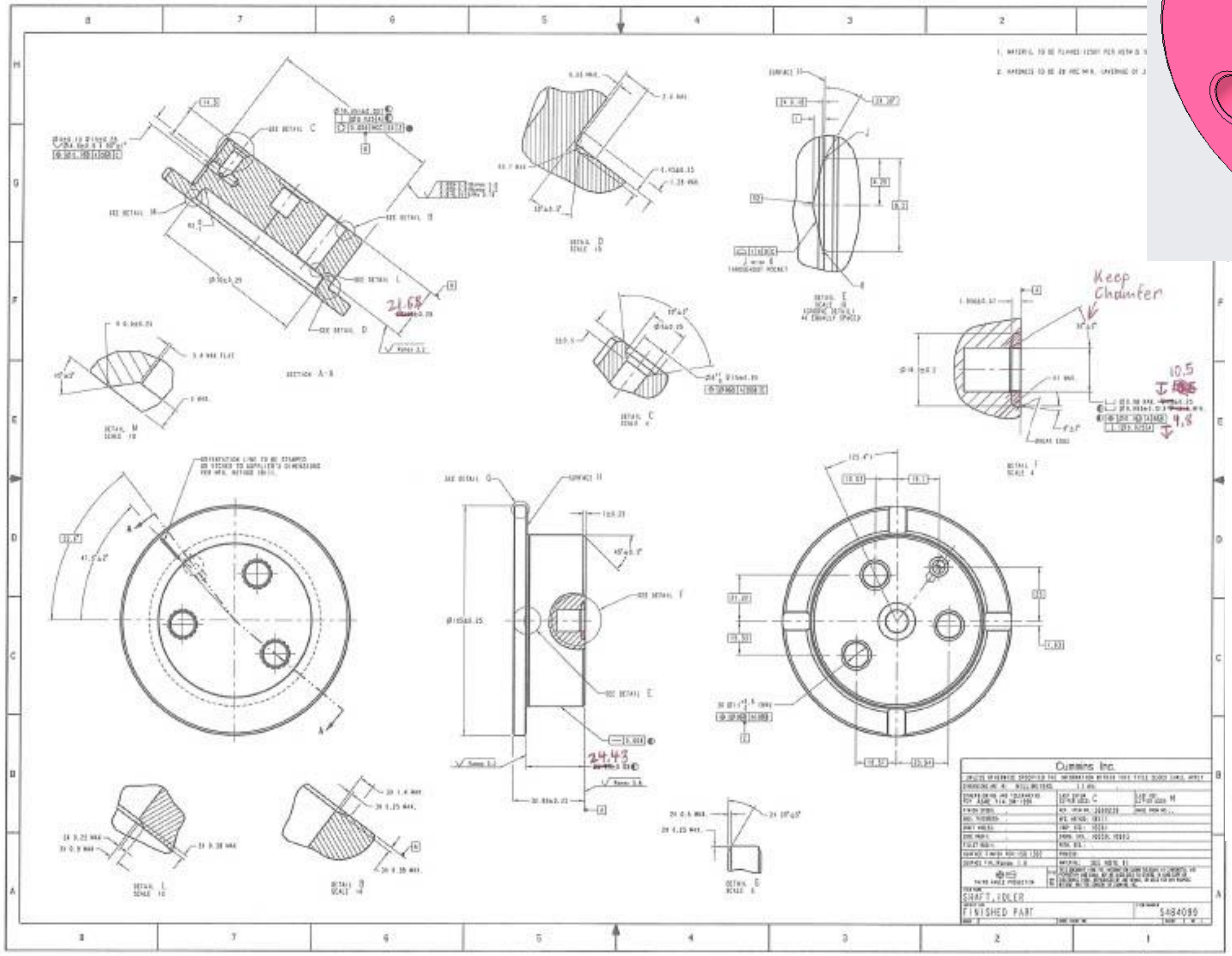
Solution and Justification

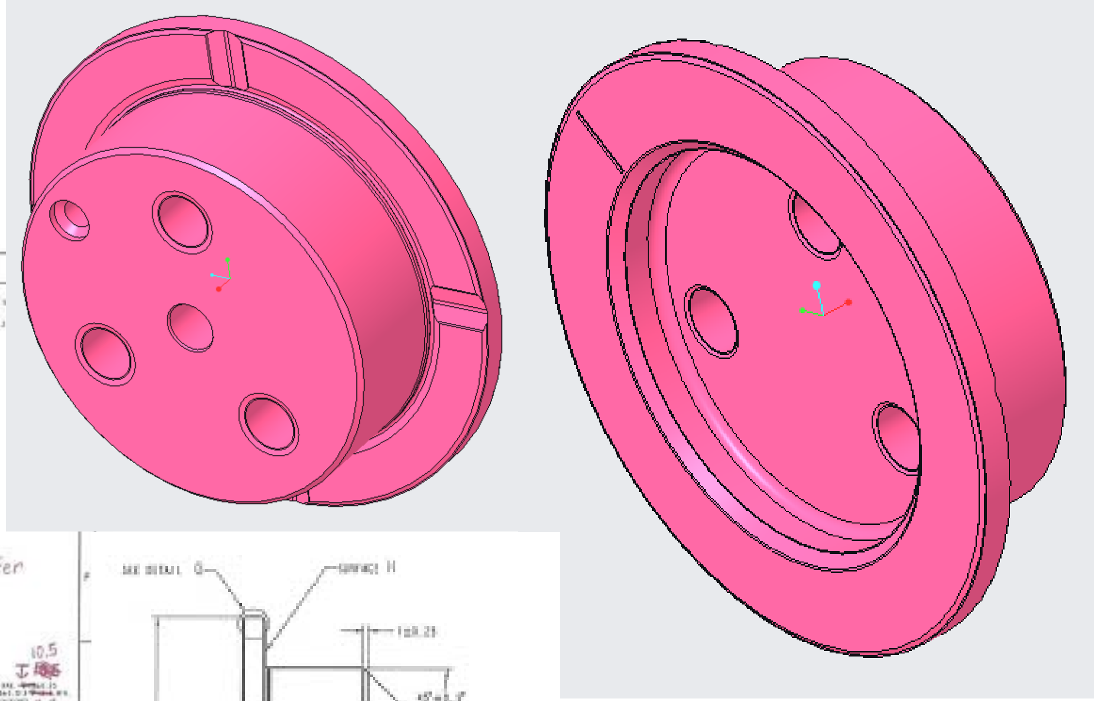
- Prevent the ring thrust bearing from slipping during installation
- **Design a plate thrust bearing for the fixed system** to replace the ring
- Opportunity to commonize the thrust bearing for both the fixed and adjustable systems; new plate design that works for both systems
- Must redesign components of fixed system to accommodate plate
  - Both systems perform the same function, are similarly assembled
  - Adjustable system does not experience the same failure mode
    - Plate thrust bearing bolted into the housing with the idler shaft
    - Cannot slip out of place or misalign the idler shaft
  - Plate thrust bearing advantages
    - Cheaper by part than the ring thrust bearing (long-term savings)
    - Proven reliable, lower failure rate shown by ISX1 claims data

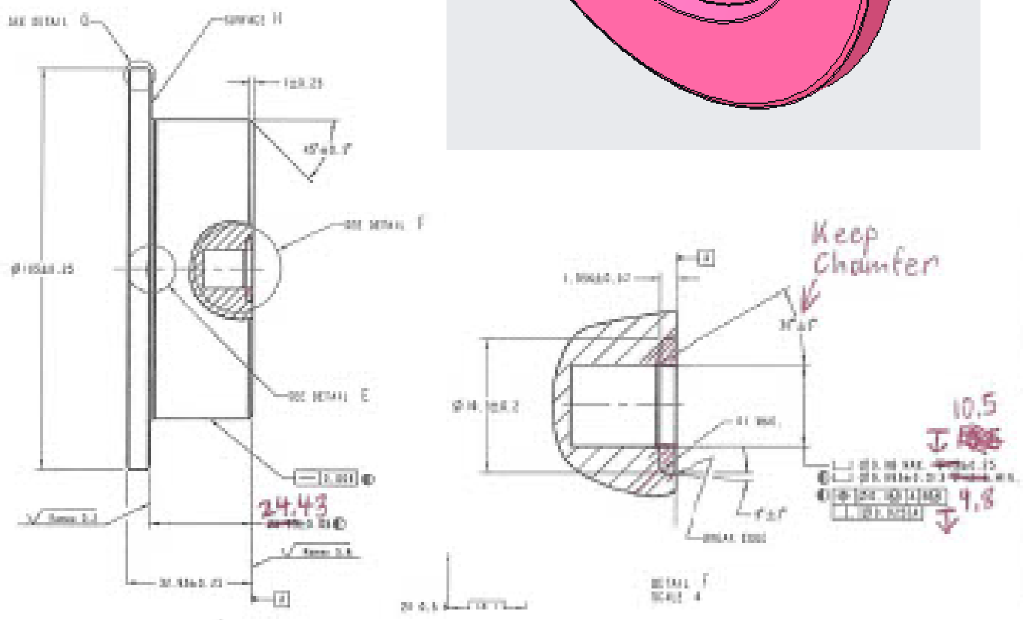
Redesign Process

- Key design differences between systems
  - Idler shaft cap screw holes in different positions relating to the centerline
  - Idler shaft cap screw hole diameters are larger for the adjustable design
  - Adjustable design idler shaft is 2.3 mm narrower for plate thrust bearing
  - Adjustable design idler shaft has larger counterbore for stabilizing plate
- Fixed idler shaft redesign
  - Reduced the width of the thinner section of the idler shaft by 2.5 mm to accommodate a plate thrust bearing rather than a ring
  - Reduced the depth of the dowel pin hole by 2.5 mm to account for the additional space taken by the plate thrust bearing
  - Removed the obsolete O-ring seal and filled in the space within the idler shaft that it occupied

Redesign Process

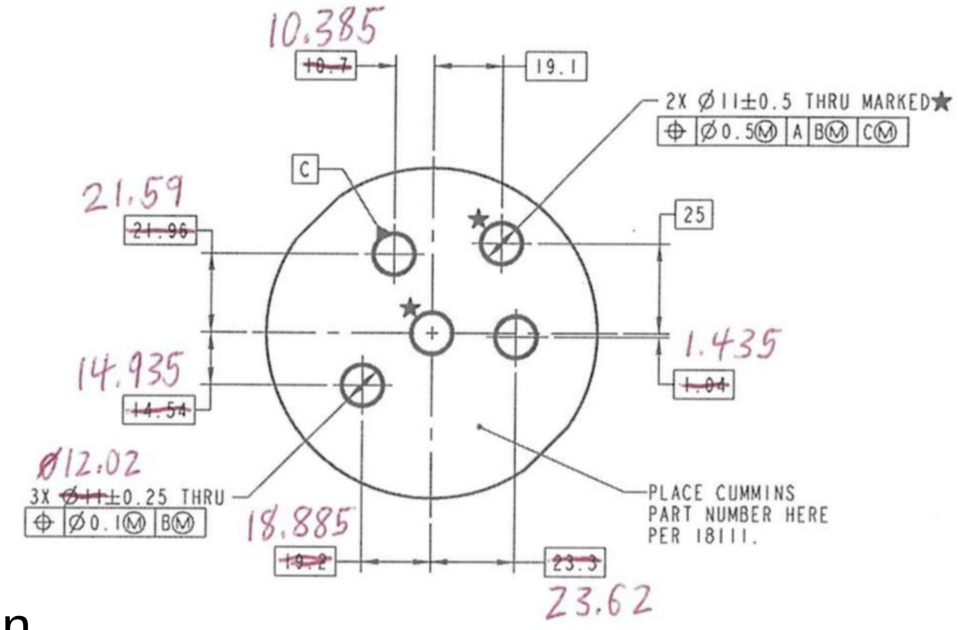


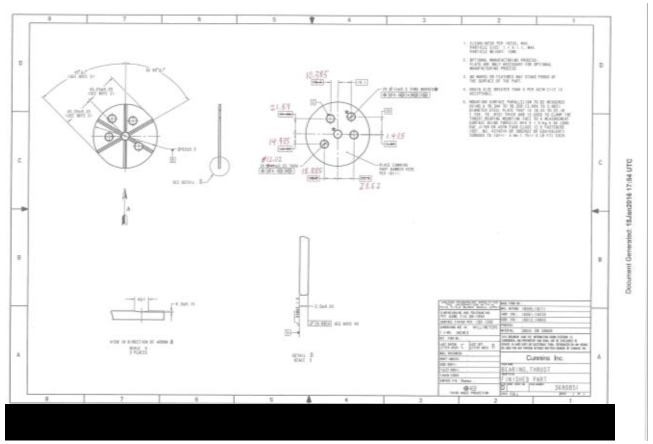


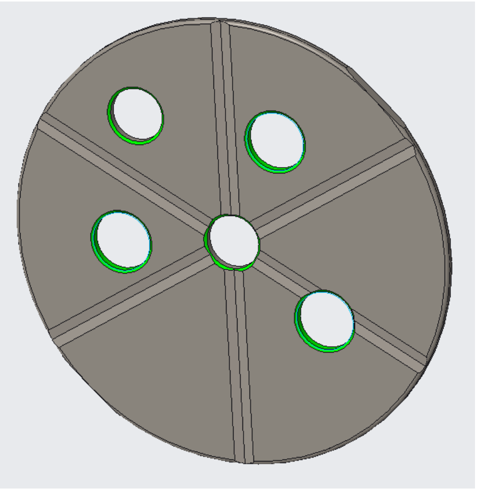


Redesign Process

- Commonized plate thrust bearing
  - Eliminated the ring design
  - Modified original part 3690851
    - Fit to the Idler shaft for the non-adjustable design
  - Moved cap screw hole positions
    - Accommodate difference in hole positions for both idler shafts
  - Changed hole diameters to 12.02 mm
    - Each hole fits the corresponding screw position of both idler shafts







Design Validation

FMEA

Part	Process Step / Functional Requirements	Potential Failure Mode	Potential Effect(s) of Failure	SEV	CLASS	Potential Cause(s) / Mechanism(s) of Failure	Current Process Controls (Prevention)	OCCUR	Current Process Controls (Detection)	DETEC	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
														Actions Taken & Effective Date	SEV	OCC	DET	RPN
Commonized Plate Thrust Bearing	Provides a surface for the idler gear to turn against	The plate can shift position in both designs during installation and it can shift position in the adjustable design during adjustment since screw hole diameters are larger than cap screw diameters (Slight shift)	Uneven, and potentially excessive, wear due to friction on the edges of the plate when used in misaligned state, causing slight change in idler gear position	3		Misalignment of the thrust bearing during installation, part sizing, larger screw holes due to commonized design	DVA tolerance stackup	8	None	9	216	Complete DVA, fit test new design, perform operation test if necessary	6/18/2021	DVA Completed: 6/15/21	3	8	9	216
	Separates gear from gear housing	The plate can shift position in both designs during installation and it can shift position in the adjustable design during adjustment since screw hole diameters are larger than cap screw diameters (Major shift)	Clearance at a point where the gear is no longer in contact with the thrust bearing, causing oil leakage and loss of hydrodynamic oil film	8		Loss of enough preload to cause the cap screw to angularly shift	DVA tolerance stackup	2	Engine audit test	4	64	Perform engine audit / oil leak test for new design	Set target date after prototype creation		8	2	4	64
	Resists slipping of components due to radial load	Idler shaft and/or thrust bearing slip out of place, causing fretting wear	Loss of preload, idler gear falls out of alignment with the rest of the gear train, causing system failure	8		Excessive radial load from driving gear, lack of adequate preload on cap screws due to assembly error or eventual corrosion	ALD, lower idler gear and idler gear positioned appropriately	3	Resultant torque verification	2	48	None	N/A		8	3	2	48
Non-Adjustable Idler Shaft	Holds the gear in place, prevents it from moving laterally	Slips out of place due to radial load from driving gear or inadequate preload	Loss of preload, idler gear falls out of alignment with the rest of the gear train, causing system failure	8		Excessive radial load from driving gear, lack of adequate preload on cap screws due to assembly error or eventual corrosion	ALD, lower idler gear and idler gear positioned appropriately	3	Resultant torque verification	2	48	None	N/A		8	3	2	48
	Feeds oil to the bushing of the idler gear	Oil does not cover full width of bushing during operation	Inadequate oil feed bushing failure, leading to excess friction in the system and loss of efficiency	8		The position of the oil output in this idler shaft is shifted 2.5 mm towards the front in relation to the original design. Insufficient hydrodynamic film pressure	Adjustable idler gear design precedent	1	None	3	24	Redesign new idler shaft if oil coverage is insufficient	N/A		8	1	3	24

Design Validation Plan

#	DFMEA	Identified Risk	Validation Tasks	Pass/Fail Criteria	
1	Commonized Plate Thrust Bearing	Experiences a slight position shift and becomes misaligned. This can happen in both designs during installation or in the adjustable design during adjustment, and it leads to uneven / excessive wear due to friction on the edges of the plate.	Complete DVA, calculate worst-case friction wear, fit test the commonized thrust bearing on both designs, and perform an engine endurance test if misalignments are unavoidable	Thrust bearing must be axially aligned with the idler shaft at the oil input and center holes within 2.5 mm	* = risk too low to justify testing and/or similar designs dont fail
2		Experiences a major position shift and loses some contact with the idler gear. This can happen in both designs if the cap screws lose enough preload to angularly shift, and it leads to excess friction wear with a loss of hydrodynamic oil film.	Use DVA results to ensure idler gear will not lose contact with thrust bearing, perform engine audit test for oil leak	No oil leak detected	
3		Components slip due to excessive radial load and/or inadequate preload during installation or due to corrosion	None	Thrust bearing, idler shaft, and gear housing must be axially aligned at the oil input and center holes within 2.5 mm	*
4	Non-Adjustable Idler Shaft	Slips out of place due to excessive radial load and/or inadequate preload	None	Thrust bearing, idler shaft, and gear housing must be axially aligned at the oil input and center holes within 2.5 mm	*
5		Oil does not cover full width of bushing during operation, leading to high levels of friction, loss of efficiency, and failure	Compare oil output and bushing coverage of current system and revised system	Comparable amounts of oil coverage and oil loss	*

Fit Test – Thrust Bearing 3D Print

- Adjustable design

Figure 1: Aligned Fit

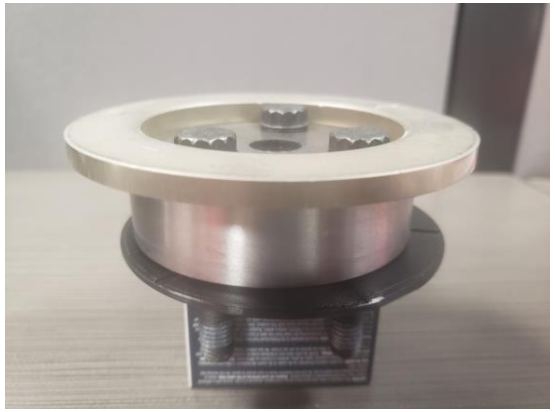


Figure 2: Max Misalignment (side view)

Figure 3: Max Misalignment (bottom view)

- Fixed design

Figure 4: Aligned Fit

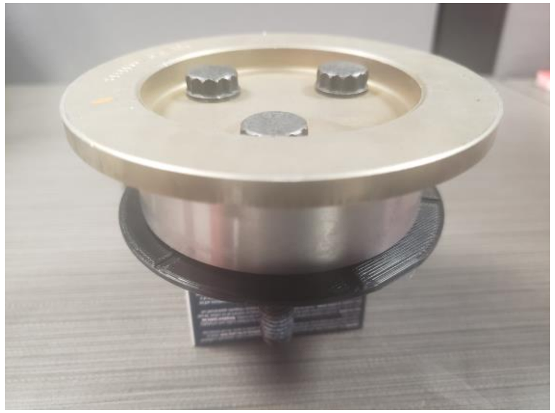


Figure 5: Max Misalignment (side view)

Figure 6: Max Misalignment (bottom view)

DVA Tolerance Analysis – Thrust Bearing / Idler Shaft

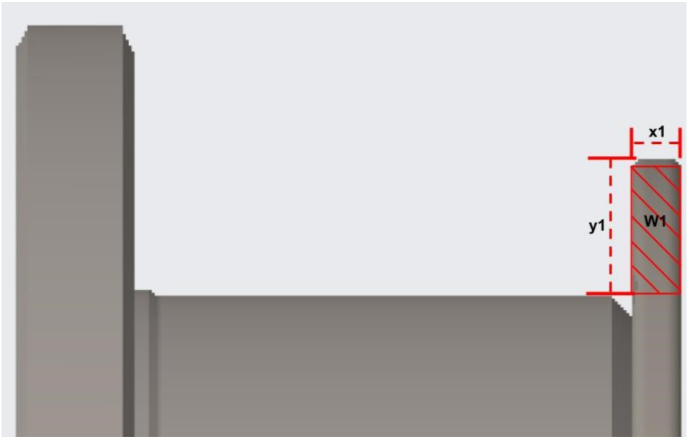
- Larger cap screw holes in commonized thrust bearing
  - More slop in both systems
  - Center axes can become more offset during installation
- Center axes of idler shaft and thrust bearing must align
- Misalignment may lead to long-term issues
- Measured the edge in this figure assuming greatest possible offset / misalignment
  - Fixed system
  - Adjustable system
  - Adjustable system with original thrust bearing, for comparison

DVA Tolerance Analysis Results

- Full table of results in Appendix
- DVA measurements of each system at critical edge:
  - Each aligned system: 6.07 mm +- 0.1901
  - Narrow edge of the fixed system, misaligned: 5.07 mm +- 0.4404
  - Narrow edge of the adjustable system, misaligned: 2.94 mm +- 0.4185
  - Narrow edge of the original adjustable system, misaligned: 3.96 mm +- 0.4185
- Magnitude of misalignment must not allow thrust bearing to lose contact with the idler gear as the bushing would be exposed and leak oil
- Additional calculation using worst-case thrust bearing misalignment
  - Added clearance between gear + bushing inner diameter and idler shaft
  - Max distance from thrust bearing edge to inner gear edge: **0.958 mm +- 0.4241**

➓ **No significant risk** of failure due to leakage from misalignment

Friction Wear in Misaligned State



- Idler gear contacts thrust bearing during operation
- Large enough misalignment may create uneven friction wear
- Maximum misalignment measured by DVA tolerance analysis
- Friction wear formula: $W = KFVT = xy$, $W_1 = W_2$, $x_1y_1 = x_2y_2$
  - W = Volumetric wear, T = Elapsed time
  - K = Wear factor constant, same on both sides, same material
  - F = Normal force of the idler gear acting on the thrust bearing
  - V = Rotational velocity of idler gear against thrust bearing
  - x = Rate of wear, loss of material
  - When $y_1 < y_2$, $x_1 > x_2$ and $x_1 = ax_2$ (a = constant)

System Type and Configuration	Narrowest edge (y1) [mm]	Widest edge (y2) [mm]	a (y2/y1)	
All systems, aligned	6.07	6.07	1.000	x1 = x2
Fixed, maximum misalignment	5.07	7.08	1.396	x1 = 1.396 x2
Adjustable, maximum misalignment	2.94	9.2	3.129	x1 = 3.129 x2
Original adjustable system, maximum misalignment	3.96	8.18	2.066	x1 = 2.066 x2

Friction Wear in Misaligned State

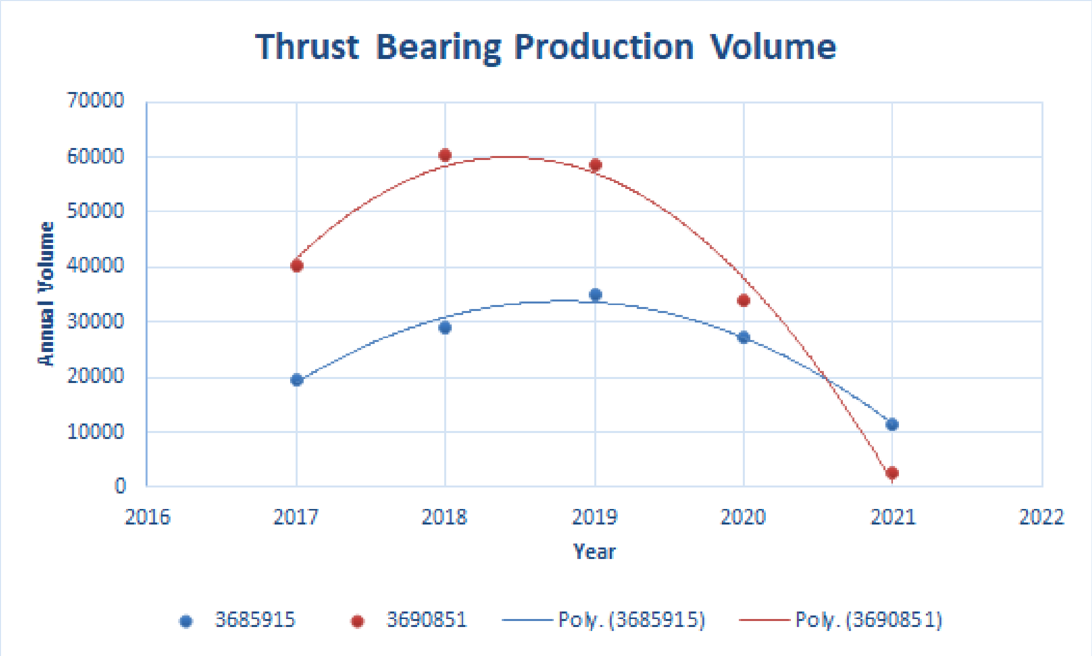
- System assumptions:
  - Normal force from idler gear remains constant on both sides
  - Material is constant in the thrust bearing
  - Rotational velocity from the idler gear is the same on all sides
- Theoretically, the narrowest edge of each system experiences *"a"* times as much wear as the widest edge of the system
- In practice, however, W1 is not always equal to W2
- The level of **wear on surface remains even** regardless of misalignment
  1. Wear due to friction starts to become greater on narrow edge of the thrust plate
  2. Normal force on the narrow edge becomes lower than that on the wider edge
  3. This lessens the rate of wear on the narrow side compared to the wider side
  4. Total wear due to friction on each edge evens out regardless of misalignment

Cost Justification

Production Volume Trends

- Proportion of plate to ring thrust bearings used per year is changing
- Quantity of plate thrust bearings (3690851) is decreasing in relation to ring thrust bearings (3685915)
  - Cannot use average yearly volume to conduct cost savings analysis
- Use a recent volume to predict future volumes needed in cost savings analysis
  - Quarter 2 in 2021 multiplied by 4 for both thrust bearings

Annual Volume by Year - Thrust Bearings			
Count of SERIAL_NO	Column L		
Row Labels	3685915	3690851	Grand Total
⊞ 2017	19693	40249	59942
⊞ 2018	29120	60480	89600
⊞ 2019	34964	58516	93480
⊞ 2020	27233	33997	61230
⊟ 2021	11357	2724	14081
⊞ Qtr1	4282	1127	5409
⊞ Qtr2	3398	1014	4412
⊞ Qtr3	3677	583	4260
Grand Total	122367	195966	318333



Current Production Cost

- Production cost and volume of current components
  - Plate thrust bearing
    - Current annual volume = 4,056
    - Cost per thrust bearing = [redacted] Total cost = $4,137.12
  - Ring thrust bearing
    - Current annual volume = 13,592
    - Cost per thrust bearing = [redacted] Total cost = $27,863.60
  - Non-adjustable idler shaft
    - Current annual volume = 13,592
    - Cost per idler shaft = [redacted] Total cost = $125,880.95

- Total annual cost = $157,881.67

Supplier Production Quotes

- New production volume needed for redesigned plate thrust bearing
  - Plate thrust bearing will replace all ring thrust bearings
  - New production volume is sum of demand for both thrust bearings = **17,648**
- Production cost and volume of redesigned components, from suppliers
  - Plate thrust bearing
    - Projected annual volume = 17,648 Total cost = $21,354.08
    - Quoted cost per thrust bearing = [redacted] Cost savings = $10,646.64
  - Non-adjustable idler shaft
    - Projected annual volume = 13,592 Total cost = $125,834.74
    - Quoted cost per idler shaft = [redacted] Cost savings = $46.21

- Total annual cost = $147,188.82 Annual cost savings = $10,692.85

Fixed Costs, Claims Savings, and Break-Even Point

- Fixed costs and production lead-time
  - Thrust bearing tooling modification cost = [redacted], lead time 10 weeks
  - Idler shaft tooling modification cost = [redacted], lead time 8 weeks
- Break-even point = 1.68 years
  - Considering annual production savings vs all fixed costs
- Claims cost comparison
  - Predicted reduction in ISX3 CPE with design change = $3.30
  - ISX3 average annual production volume = 8,133
  - Projected annual claims cost reduction / savings = $26,838.90
- This redesign creates a cost reduction in both production and warranty costs
- Total annual savings = **$37,531.75**, Actual break-even point = 0.48 years
  - Considering annual production savings **and projected claims reduction**

My Recommendation

Next Steps / Recommendation

- Prototypes and remaining validation tasks
  - Thrust bearing prototypes have arrived, follow up for idler shaft prototypes
  - Once idler shafts arrive, assemble to a Rottweiler engine and conduct a long-term operation test to ensure that the new components cause no failures
    - Referenced in validation plan
    - Piggyback test would be appropriate
    - Monitor for oil leakage and markings on bushing or idler shaft after test
- Implementation in production
  - Create CR from CTR #4126105, direct obsolete / supercede with new part #s
  - Have drafting create new prints and a DQR for both new part numbers
- Monitor ISX3 system claims after implementation to ensure reduction in failures


Cummins

Appendix

ISX3 – Claims per Failure Mode and Potential Cause

Table 1

Failure Code	Part Failed	Failure Mode	Failure Description	Number of Cases	Potentially caused by slipped thrust ring?
BKTB	Thrust Bearing	BR	Broken, cracked	[redacted]	Yes
		BE	Bent, distorted	0	N/A
		ER	Eroded, pitted, flaked, debonded, fretted	[redacted]	Yes
		AP	Application problem	0	N/A
		AW	Adjusted wrong, calibration incorrect	0	N/A
		CU	Cosmetically unacceptable	0	N/A
		DR	Clogged, plugged with foreign material, dirt/debris	0	N/A
		ID	Indeterminate	[redacted]	Yes
		IO	Inoperative	0	N/A
		LO	Leaks oil	0	N/A
		MA	Misassembled	0	N/A
		MI	Campaign	0	N/A
		MM	Mismachined, oversize, undersize, incorrect protrusion	0	N/A
		NO	Noisy	0	N/A
		RP	Replaced	0	N/A
		SE	Seized, stuck, scored, scuffed, spun	[redacted]	Yes
		TI	Timed incorrectly	0	N/A
		WM	Workmanship	0	N/A
		WO	Worn	0	N/A
		WP	Special (wrong parts used in assembly)	0	N/A

ISX3 – Claims per Failure Mode and Potential Cause

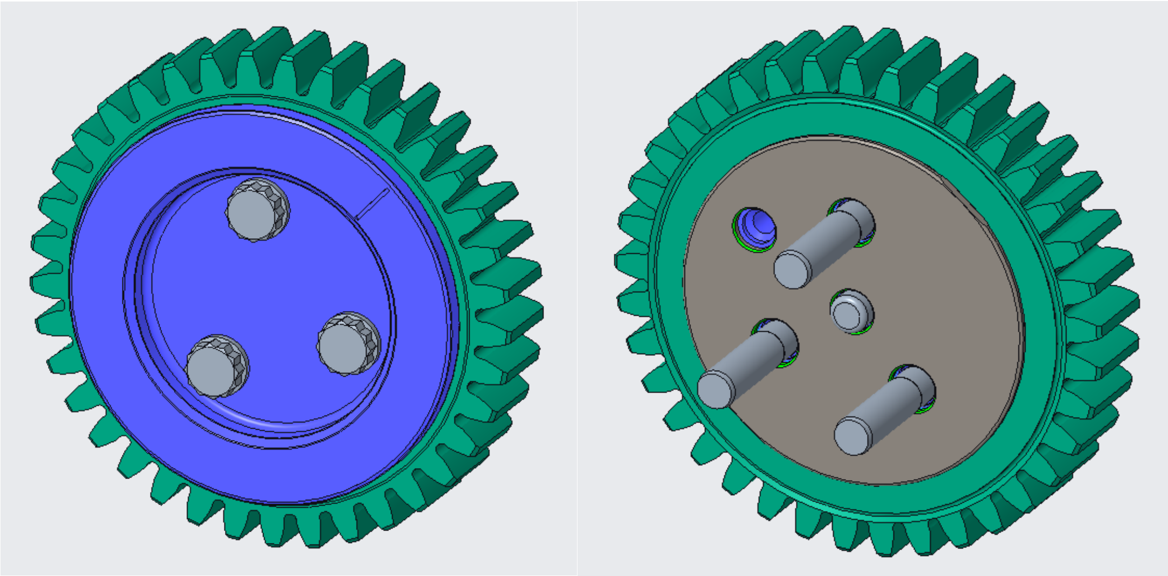
Failure Code	Part Failed	Failure Mode	Failure Description	Number of Cases	Potentially caused by slipped thrust ring?
BKIF	Fuel Pump Idler Gear	BR	Broken, cracked	[redacted]	Yes
		BE	Bent, distorted	0	N/A
		ER	Eroded, pitted, flaked, debonded, fretted	[redacted]	Yes
		AP	Application problem	0	N/A
		AW	Adjusted wrong, calibration incorrect	0	N/A
		CU	Cosmetically unacceptable	[redacted]	Yes
		DR	Clogged, plugged with foreign material, dirt/debris	0	N/A
		ID	Indeterminate	[redacted]	Yes
		IO	Inoperative	0	N/A
		LO	Leaks oil	0	N/A
		MA	Misassembled	[redacted]	Yes
		MI	Campaign	0	N/A
		MM	Mismachined, oversize, undersize, incorrect protrusion	[redacted]	Yes
		NO	Noisy	0	N/A
		RP	Replaced	0	N/A
		SE	Seized, stuck, scored, scuffed, spun	[redacted]	Yes
		TI	Timed incorrectly	0	N/A
		WM	Workmanship	0	N/A
		WO	Worn	0	N/A
		WP	Special (wrong parts used in assembly)	0	N/A

ISX3 – Claims per Failure Mode and Potential Cause

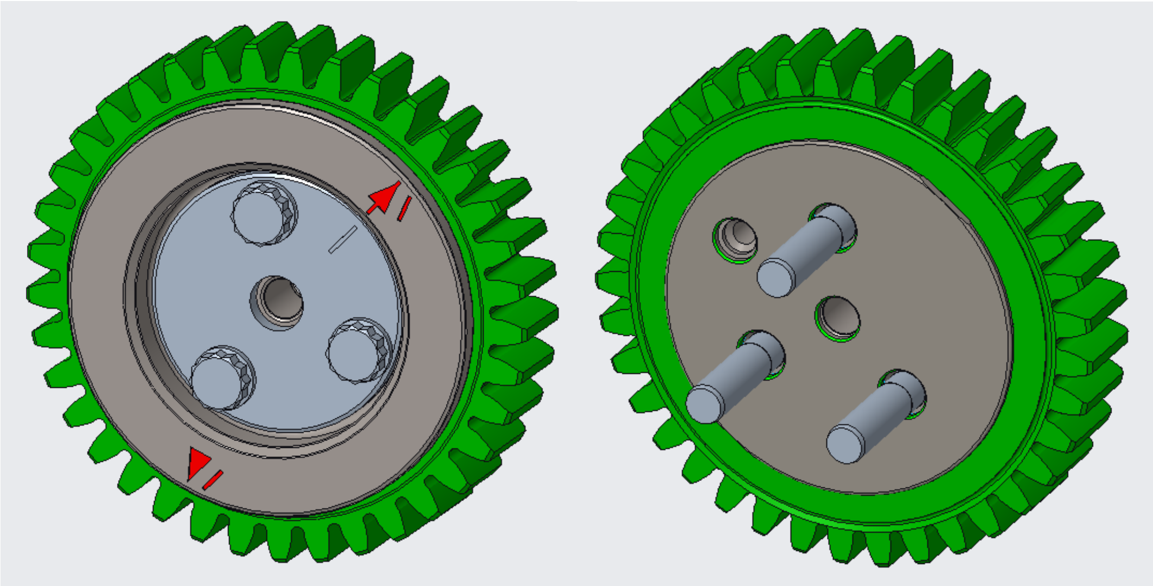
BKIS	Idler Shaft	BR	Broken, cracked	[redacted]	Yes
		BE	Bent, distorted	[redacted]	Yes
		ER	Eroded, pitted, flaked, debonded, fretted	0	N/A
		AP	Application problem	0	N/A
		AW	Adjusted wrong, calibration incorrect	0	N/A
		CU	Cosmetically unacceptable	[redacted]	Yes
		DR	Clogged, plugged with foreign material, dirt/debris	0	N/A
		ID	Indeterminate	[redacted]	Yes
		IO	Inoperative	0	N/A
		LO	Leaks oil	0	N/A
		MA	Misassembled	[redacted]	Yes
		MI	Campaign	0	N/A
		MM	Mismachined, oversize, undersize, incorrect protrusion	[redacted]	Yes
		NO	Noisy	0	N/A
		RP	Replaced	0	N/A
		SE	Seized, stuck, scored, scuffed, spun	0	N/A
		TI	Timed incorrectly	0	N/A
		WM	Workmanship	0	N/A
		WO	Worn	[redacted]	Yes
		WP	Special (wrong parts used in assembly)	0	N/A
			TOTAL:	[redacted]	
			TOTAL RELEVANT TO SLIPPED THRUST RING:	[redacted]	

Redesigned Assemblies

Fixed Design:



Adjustable Design:



DVA Tolerance Analysis – Thrust Bearing / Idler Shaft

System Type and Configuration	Measurement	Parts Involved	Dimension	Direction	Value [mm]	Tolerance ± [mm]
All systems, aligned	All edges	Idler Shaft	Radius	-	39.18	0.0035
		Commonized Thrust Bearing	Radius	+	45.25	0.2500
				RESULT	**6.07**	**0.1901**
Non-Adjustable, maximum misalignment	Misalignment due to thrust bearing center hole and dowel pin	Dowel Pin	Radius	-	9.99	0.0130
		Commonized Thrust Bearing	Center hole radius	+	11.00	0.5000
				RESULT	1.01	0.3848
	Narrowest edge	Idler Shaft	Radius	-	39.18	0.0035
		Commonized Thrust Bearing	Radius	+	45.25	0.2500
		Thrust Bearing / Dowel Pin	Misalignment	-	1.01	0.3848
				RESULT	**5.07**	**0.4404**
	Widest edge	Idler Shaft	Radius	-	39.18	0.0035
		Commonized Thrust Bearing	Radius	+	45.25	0.2500
		Thrust Bearing / Dowel Pin	Misalignment	+	1.01	0.3848
				RESULT	7.08	0.4404
Adjustable, maximum misalignment	Misalignment due to thrust bearing screw holes and cap screws	Cap screw	Radius	-	5.00	"+0/-0.11"
		Commonized Thrust Bearing	Cap screw hole radius + displacement	+	6.01 + 0.51	0.1250
				RESULT	1.58	0.1242
	Misalignment due to idler shaft screw holes and cap screws	Cap screw	Radius	-	5.00	"+0/-0.11"
		Idler Shaft	Cap screw hole radius	+	6.50	0.2500
				RESULT	1.56	0.2288
	Narrowest edge	Idler Shaft	Radius	-	39.18	0.0035
		Commonized Thrust Bearing	Radius	+	45.25	0.2500
		Thrust Bearing / Cap screw	Misalignment	-	1.58	0.1242
		Idler Shaft / Cap screw	Misalignment	-	1.56	0.2288
				RESULT	**2.94**	**0.4185**
	Widest edge	Idler Shaft	Radius	-	39.18	0.0035
		Commonized Thrust Bearing	Radius	+	45.25	0.2500
		Thrust Bearing / Cap screw	Misalignment	+	1.58	0.1242
		Idler Shaft / Cap screw	Misalignment	+	1.56	0.2288
				RESULT	9.20	0.4185

DVA Tolerance Analysis – Thrust Bearing / Idler Shaft

System Type and Configuration	Measurement	Parts Involved	Dimension	Direction	Value [mm]	Tolerance ± [mm]
Original adjustable system, maximum misalignment	Misalignment due to thrust bearing screw holes and cap screws	Cap screw	Radius	-	5.00	"+0/-0.11"
		Plate Thrust Bearing	Cap screw hole radius	+	5.50	0.1250
				RESULT	0.56	0.1242
	Misalignment due to idler shaft screw holes and cap screws	Cap screw	Radius	-	5.00	"+0/-0.11"
		Idler Shaft	Cap screw hole radius	+	6.50	0.2500
				RESULT	1.56	0.2288
	Narrowest edge	Idler Shaft	Radius	-	39.18	0.0035
		Commonized Thrust Bearing	Radius	+	45.25	0.2500
		Thrust Bearing / Cap screw	Misalignment	-	0.56	0.1242
		Idler Shaft / Cap screw	Misalignment	-	1.56	0.2288
				RESULT	**3.96**	**0.4185**
	Widest edge	Idler Shaft	Radius	-	39.18	0.0035
		Commonized Thrust Bearing	Radius	+	45.25	0.2500
		Thrust Bearing / Cap screw	Misalignment	+	0.56	0.1242
		Idler Shaft / Cap screw	Misalignment	+	1.56	0.2288
				RESULT	8.18	0.4185

#	Part Name - Feature Description	+ or -	Drawing Nominal (Used in Formula)	Drawing Tol (Used in Formula)	Input Ppk	ST	Formula Nominal	± Formula Tolerance	Tolerance Squared	100.00%	Rank % Cont
1	Adjustable design maximum misalignment - narrow side	+	2.94	0.4185			2.94	0.4185	0.1751423	91.46%	1
2	Idler gear - inner diameter	-	83	0.013			83	0.013	0.000169	0.09%	3
3	Idler shaft - diameter	+	78.351	0.007			78.351	0.007	0.000049	0.03%	4
4	Bushing - thickness	+	2.667	0.127			2.667	0.127	0.016129	8.42%	2

	Output Distribution Results:	Std. Dev.	Nominal	Total ±	Min	Max
	Worst Case	N/A	0.9580	0.5655	0.3925	1.5235
	RSS (± 3 Std. Dev.)	0.1459	0.9580	0.4376	0.5204	1.3956
X	**MRSS (± 3 Std. Dev.)**	0.1414	0.9580	0.4241	0.5339	1.3821