



# Optical Alignment, Thermal Growth, & Machinery Movement

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President

# Introduction

Our customers' often seek help achieving precision alignment of their critical machinery when 'standard' alignment techniques do not provide satisfactory operation.

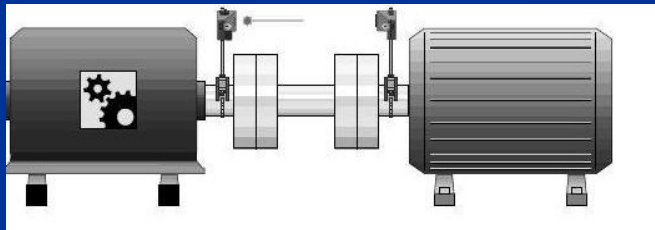
While helping them achieve the 'simple' goal of good hot alignment, we've identified many mechanical issues using Optical Alignment ("OA") that were not intuitive to those involved, and were not previously solved using vibration analysis or other techniques.

We would like to share some OA background with you, and how we apply OA to optimize shaft alignment and eliminate machinery problems.

# Basic Shaft Alignment

How do we define the (mis)alignment of two machine shafts?

- Parallel misalignment: coupling 'rim' offset between two shaft centerlines
- Angular misalignment: coupling 'face' deviation from parallel
- Combined – the usual field condition....



# Alignment Factors

How accurate do we need to be? What factors might you consider?

More Critical:	Less Critical:
High speed ( $\Rightarrow$ 1,800 rpm)	Low speed ( $<$ 1,800 rpm)
Rigid couplings	Geared Couplings
Disc-pack couplings (for offset)	Flexible Couplings
Short coupling spans	Long coupling spans

What criteria do you have?

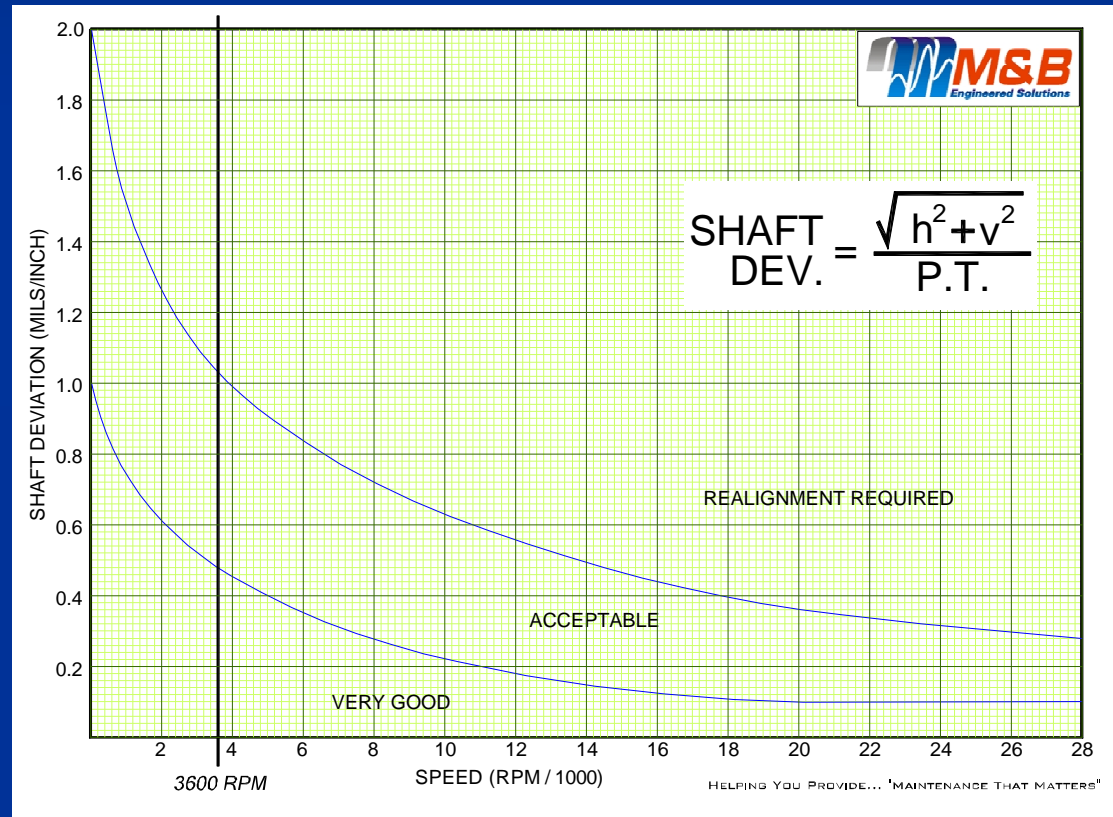


# Alignment Criteria

The Alignment Tolerance Chart ties speed, coupling span, and misalignment in the horizontal & vertical directions together to assess alignment accuracy.

Shaft deviation is calculated for each side of the coupling (h & v) and plotted as a function of speed to determine if alignment is required.

We can see that at 3,600 rpm, deviation much beyond 1 mil/inch should be realigned.



# Alignment Accuracy

So, once again: How accurate does our alignment need to be?

To muddy the water just a bit more:

What is the point in setting a cold shaft alignment within 0.002" if adjacent bearing housings move 10 – 20 mils (or more!) in different directions due to thermal growth and static deflection?

If we set a 'perfect' cold alignment, with the shafts collinear, it is a "sure bet" that thermal growth and static deflection will ruin our alignment when the machine is operating.

This is where Optical Alignment will provide significant improvement in our operating (hot) alignment accuracy.

# What is 'Optical Alignment'?

“OA” - The use of high-precision optical instruments (jig transits, sight levels, alignment telescopes) and special tooling to measure the relative alignment of machinery.

OA can help us answer these questions with high accuracy:

- Is it straight?
- Is it level?
- Is it plumb?
- Is it square?

Applications of OA include:

- Align bearing & seal bores
- Align diaphragms
- Set rolls parallel
- Level base & sole plates
- Check flatness
- Align & level machine cases
- Measure thermal growth
- Measure static deflection

# Why Optics?

What advantages does optical equipment have for determining “Is it Straight, Level, Plumb & Square?”

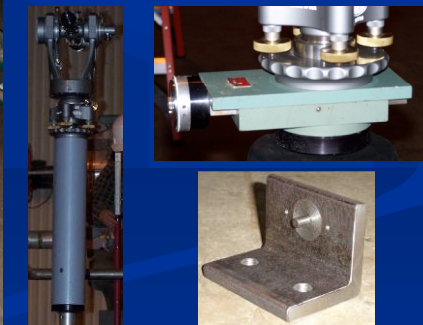
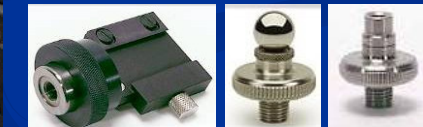
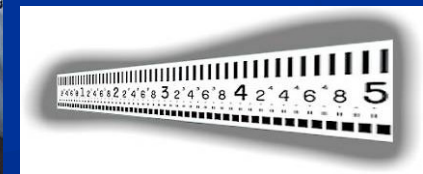
- Measurement flexibility – horizontal; vertical; axial; bores; casings; split-lines; diaphragms; rolls; baseplates; soleplates; foundations; rolls; etc.
- Many measurements quickly
- References (Benchmarks) allow absolute comparison of components
- Easy to setup in multiple locations around any machine
- Easily portable
- Excellent repeatability between surveys
- Excellent accuracy



# Optical Alignment Equipment

Several essential pieces of gear comprise a typical OA kit:

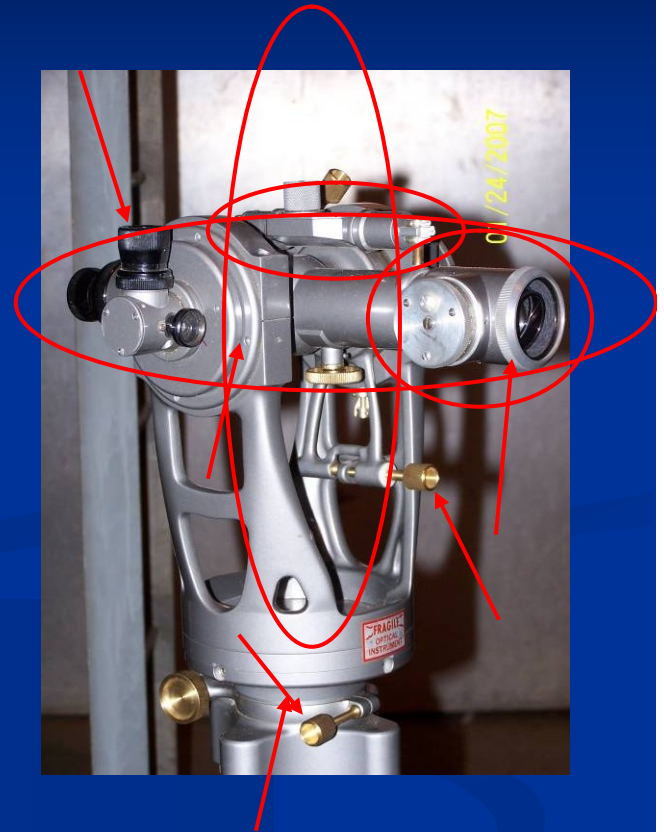
- Jig transits; alignment telescopes
- Precision Scales
- Scale Levels
- Invar Kit
- Tripods
- 'Tubes'
- Cross-slides
- Mounting Hardware / Tooling
- Benchmarks
- Tool kit



# Brunson 76-RH Jig Transit

Brunson 76-RH Jig Transit key features & functions:

- Main Telescope: 30X magnification; focus 2" to Infinity (and beyond)
- Main scope sweeps horizontal & vertical planes
- Fine-motion tangent screws for adjustment
- Cross Telescope: 45X magnification; provides sights at precise right angles to the main scope
- Coincidence Level: precision leveling (1 arc-sec)
- Optical Micrometer: offset measurements (0.001")
- Extreme Accuracy - bearing runout < 0.000025"
- Calibration can be verified on-site for every job



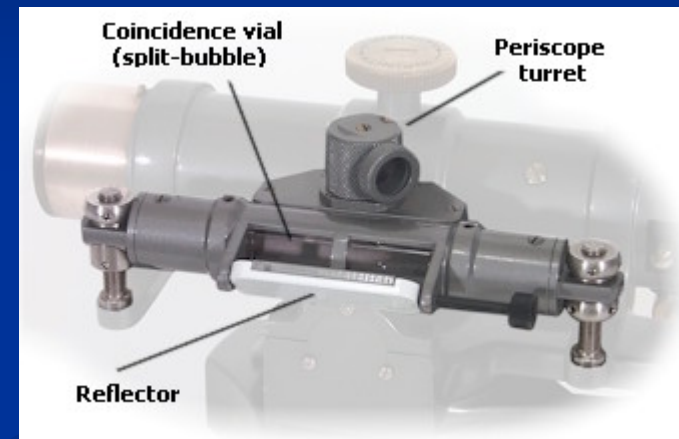
# Coincidence Level

The coincidence level system is the key to the jig transit's accuracy.

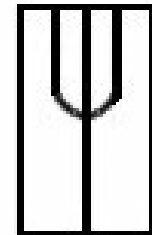
Vertical tangent screw on transit subtly tilts the telescope to dead-level the line of sight.

When viewed through the turret, both ends of the coincidence level 'bubble' are optically 'folded' and brought together, side-by-side, using a 2.5X mirror path.

The human eye is very good at evaluating coincident patterns and can detect the tiniest deviation from level.



**No**



**Yes**

## How sensitive is this system?

We can easily detect 1 arc-sec of tilt

1 arc-sec = The width of dime viewed from 1 ¼ miles away

In practical terms, 1 arc-sec = 0.0013" (1.3 mils) at 17 feet

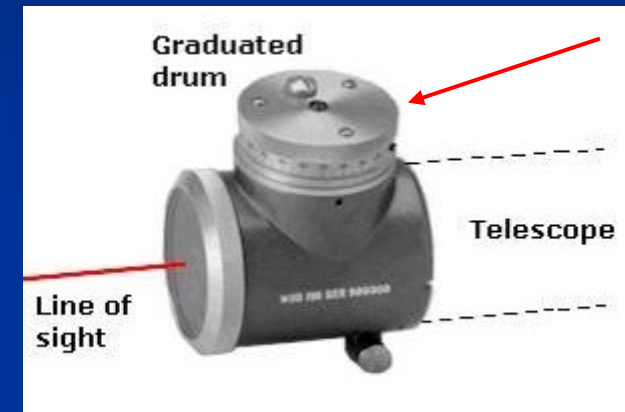
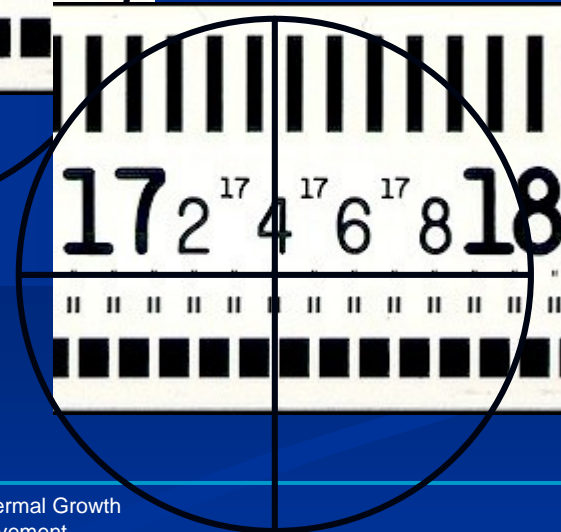
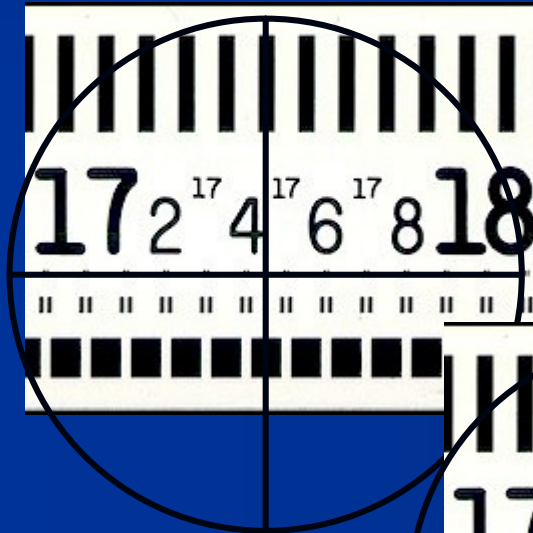
# Optical Micrometer

Optical Mics and Scales provide the means to make measurements....

The “mic” uses a drum graduated in 0.001” increments to act as a vernier when reading scales

For example, after sighting a scale between 17.4” and 17.5”, the mic is adjusted to move the reticle to 17.4, and the amount moved is read from the drum, 0.040”,

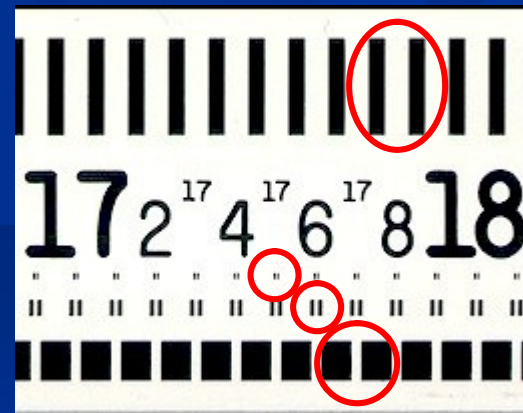
This gives a reading of 17.440”



# Optical Scales

A little bit more sophisticated than the old wooden ruler...

- Hardened tool steel
- Matte white surface
- Glare reducing top-coat
- Various sizes, 3", 10", 20", 40"
- Graduated in inches and tenths
- Accuracy +/- 0.001"
- Varying 'tic' spacing for different sight distances
  - 0.004" (closest)
  - 0.010"
  - 0.025"
  - 0.060" (farthest)





# Invar Kits

Invar comes in various lengths, and is assembled as needed to mount scales in the desired line-of-sight.

Invar's extremely low coefficient of thermal expansion makes it perfect for consistent measurements in any machinery environment. Compare growths of a 5' rod over a 30°F  $\Delta T$ :

- Aluminum: 0.024"
- Steel: 0.017"
- Invar: 0.001" !!

Tolerance:  $\pm 0.0003$ " per tube, std.  
Total stack-up error per kit  $\pm 0.001$ "



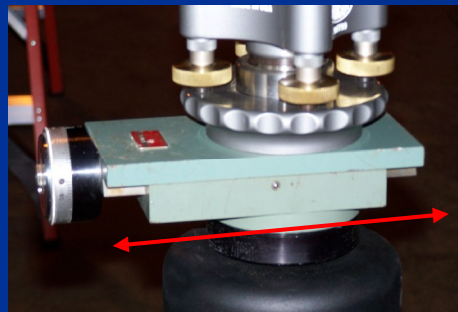
# Tripods, Tubes & Cross-Slides



Stable bases are critical for reliable data. Quickset's 'Hercules' tripods have proven rock solid, light weight & portable.

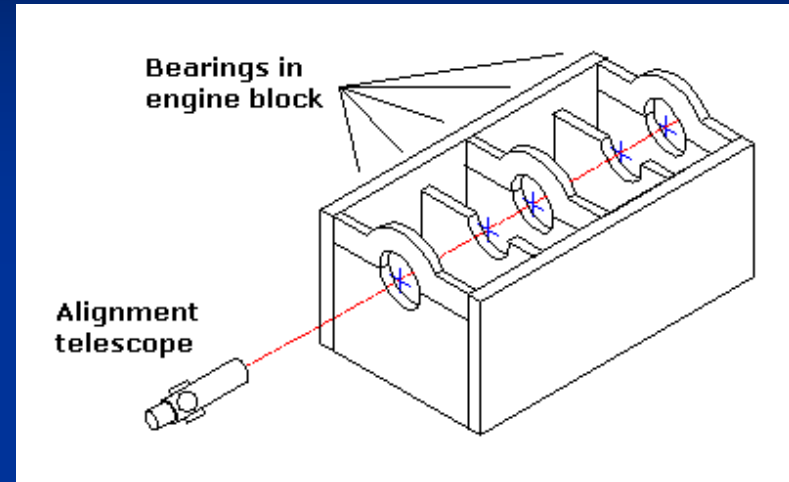
The tripod's elevator lets us adjust scope height, and 'tubes' allow us to reach high locations.

Cross-slides provide lateral movement to let us 'buck-in' the instrument to a desired line-of-sight.

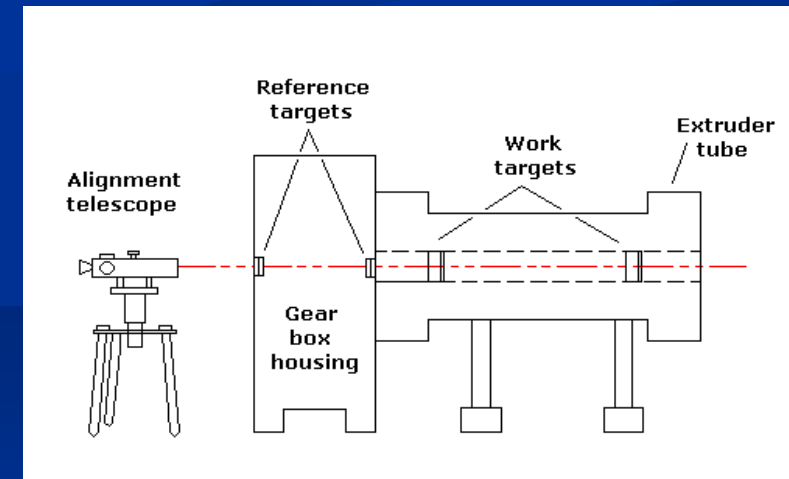


# OA Applications

Internal alignment of  
crankcase bearings  
(bore alignment)



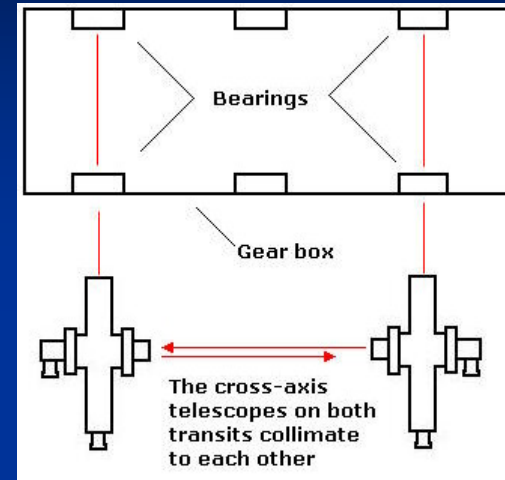
Alignment of gearbox  
bearings to extruder bore



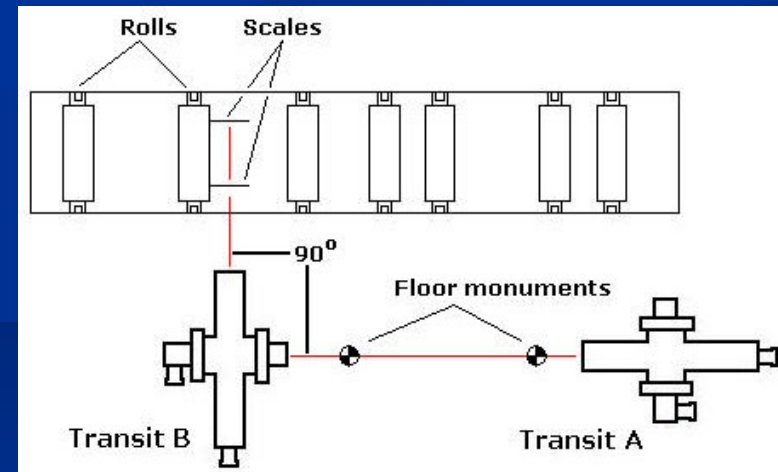


# OA Applications

Establishing parallel gearbox bearing bores

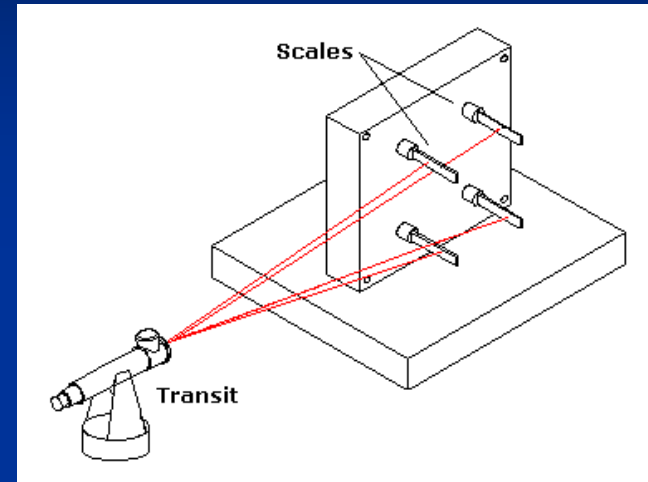


Setting parallel roll position (& heights) in paper / steel mills

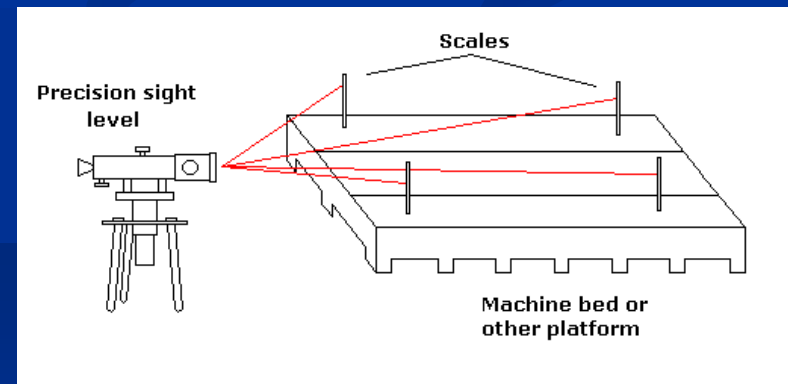


# OA Applications

Plumbing columns / surfaces;  
measuring horizontal deflection

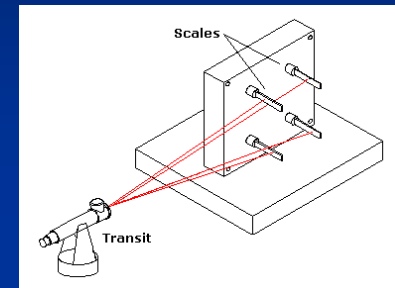


Leveling; checking flatness;  
measuring vertical deflection

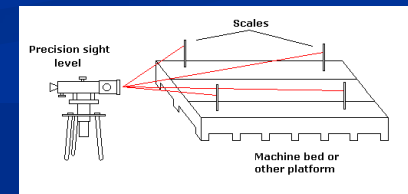


# OA Applications

The measuring of horizontal and vertical movement forms the basis for determining how machinery moves from off-line to running conditions.



By measuring how each bearing in a machine moves, we can determine exactly how the 'cold' alignment should offset to produce an accurate 'hot' alignment when operating.



This movement is sometimes referred to as “OL2R”, but most folks lump it into the term “Thermal Growth”.

# Thermal Growth

Thermal Growth is often just considered to be the Vertical change in bearing or shaft position due to temperature changes ( $\Delta T$ ) in the machine casing, bearing supports, and foundations.

Movement due to  $\Delta T$  can be easily calculated. For steel, a coefficient of thermal expansion of  $\{6.8 \times 10^{-6} \text{ in / in / } ^\circ\text{F}\}$  is typically used.

For example, a bearing pedestal 30" tall that was  $45^\circ$  hotter when the machine was running would 'grow' by:

$$(6.8 \times 10^{-6}) \times 30 \times 45 = 0.0092", \text{ or } 9.2 \text{ mils (not too bad...)}$$

But, if the  $\Delta T$  were  $150^\circ\text{F}$ , the change would be:

$$(6.8 \times 10^{-6}) \times 150 \times 45 = 0.0459", \text{ or } 45.9 \text{ mils}$$

*hmmm...so much for our cold alignment*

Do you know of any machines operating  $50^\circ$  or more above ambient?  
What effect is that  $\Delta T$  likely having on the alignment?

# Static Deflection

The Thermal Growth on the previous slide only considered vertical calculations. This is how many machinery OEMs derive their cold alignment offsets. And while it is a good starting point, it is only part of the equation.

We should also consider the horizontal bearing housing movement. Machine casings will often show equal horizontal thermal expansion on both sides of a bearing due to casing symmetry. However, many (most?) machines also exhibit static deflection due to the effects of torque transmission.

Other issues such as grout deterioration, pedestal or foundation flexure, and soft-foot will compound both the horizontal and vertical movements seen while operating.

It is easy to see how our good, cold alignment can quickly become unacceptable while the machine is operating. This is where Optical Alignment can provide us with the measurements to properly align the machinery.

# Case Study #1 – A Tale of 2 Boiler Feed Pumps

Or, One of these things is not like the other....

## Machinery Configuration

Motor: 3,585 rpm ; 4,500 HP  
Cplg: Disc-Pack  
Pump: 11 Stage; 2030 gpm; 7520' hd.

## Customer Problem:

Poor reliability on #1 BFP inboard pump seals  
(~6 months)

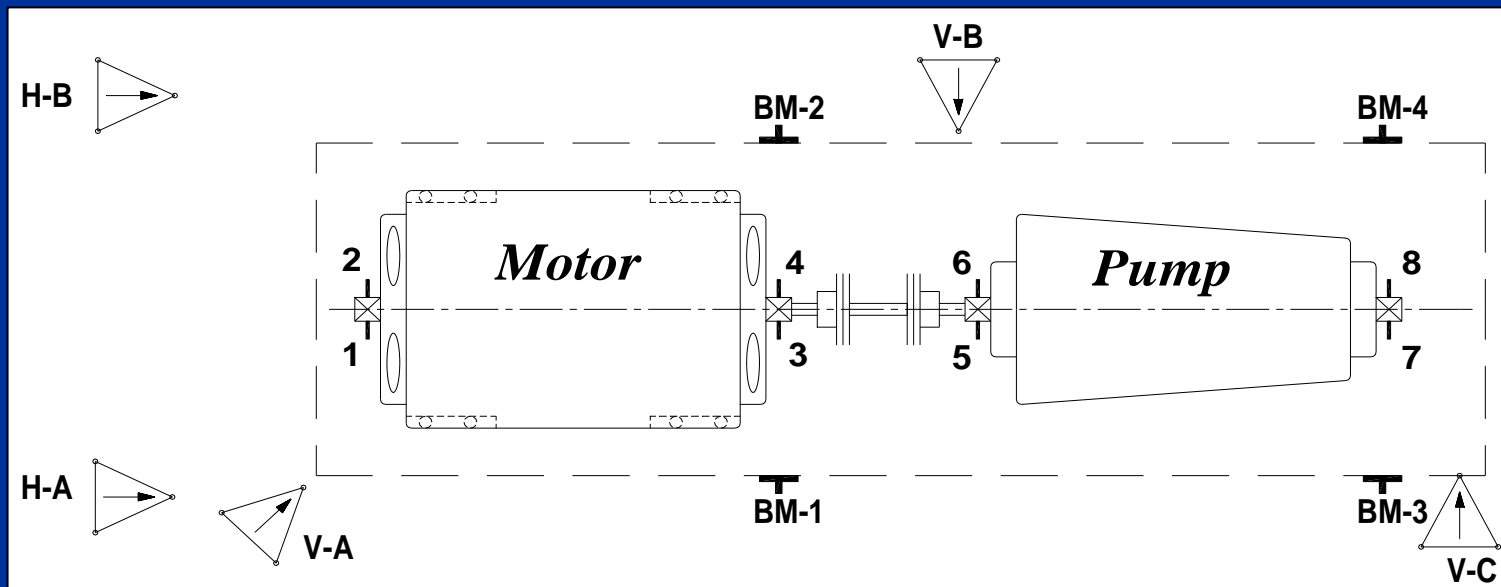
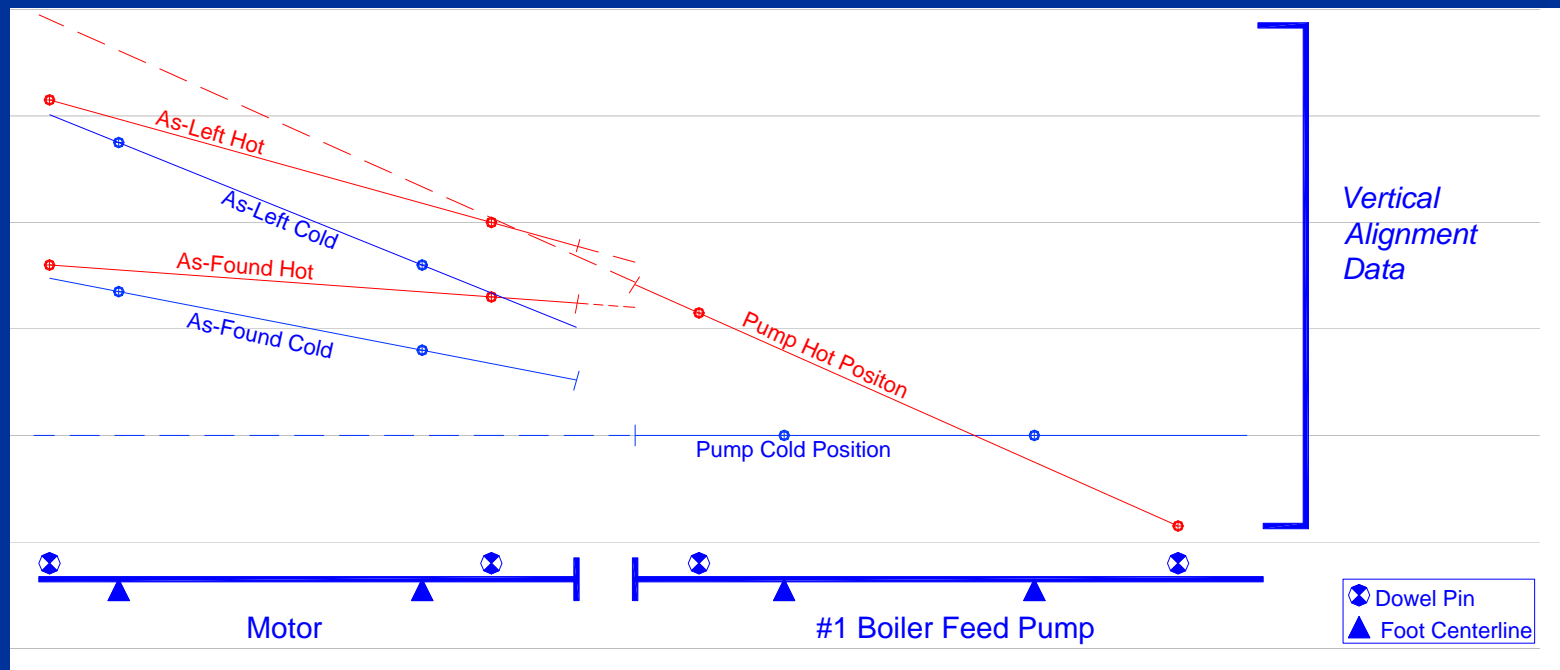


Diagram showing dowel-pin measurement points (1,2,3, etc.), benchmarks (BM-x), and jig-transit locations used.

# Case Study #1, continued

## Alignment Study Results – #1 BFP Vertical Data

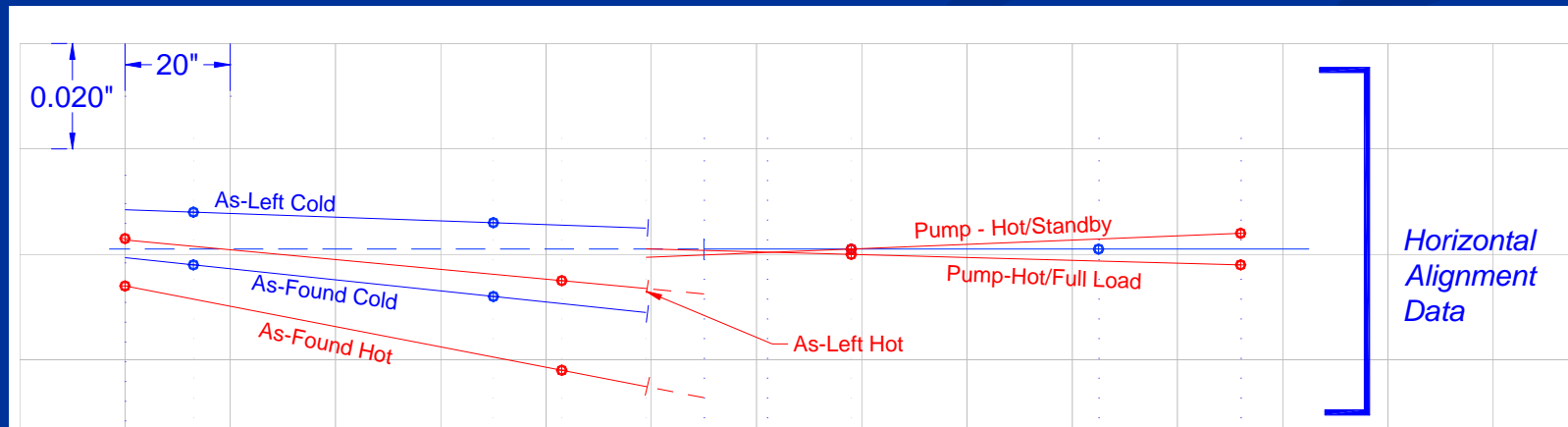
The pump pivoted very nearly about the outboard pedestal, causing the inboard bearing to go upward, likely due to pipe strain, thus loading the bearing & seals. The inboard bearing moved upward 0.023", while outboard went down 0.017". The motor moved upward 0.002" on the outboard bearing, 0.013" inboard. This required the motor to be set nearly 0.060" high on the outboard bearing, and 0.032" on the inboard bearing. Not your typical motor alignment....



# Case Study #1, continued

## Alignment Study Results – #1 BFP Horizontal Data

The motor outboard bearing moved 0.005" to the right, while the inboard bearing moved right 0.013". The pump outboard bearing moved about 0.004" right, while the inboard bearing was essentially steady. This required the motor to be offset to the left to achieve reasonable horizontal alignment. The motor was found to be bolt-bound and could not be moved to the ideal position.

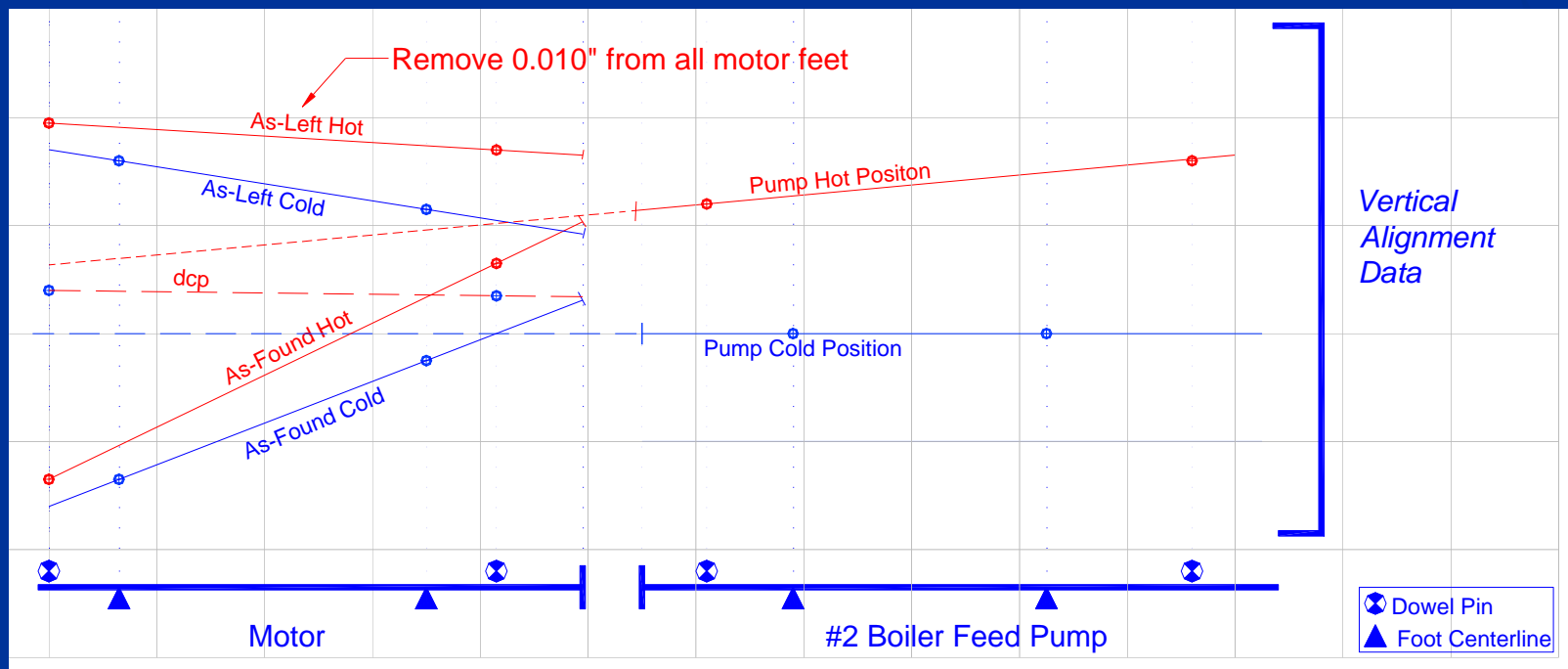




# Case Study #1, continued

## Thermal Growth Results – #2 BFP Vertical Data

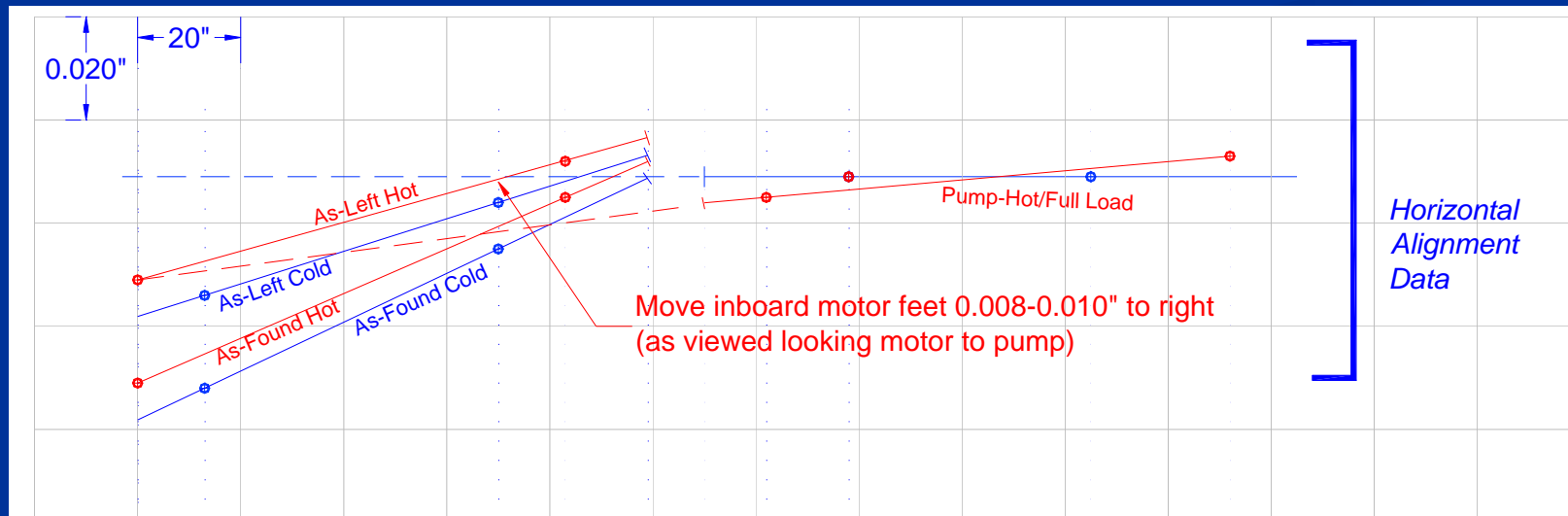
The motor and pump demonstrated much more typical responses, although the pump was found to grow more significantly than the pump vendor had anticipated for this center-hung design. Final vertical motor alignment required removing 0.010" from all feet, which was performed at a later date.



# Case Study #1, continued

## Alignment Study Results – #2 BFP Horizontal Data

Unlike #1 BFP motor, this motor moved 0.006" to the left at both bearings. The pump showed a similar twisting motion as #1 BFP, but was more pronounced. This resulted in the motor needing to be offset 0.025" at the outboard bearing, and 0.016" at the inboard bearing. Once again, not your typical alignment.....



# Case Study #1, continued

## Conclusions

The two otherwise “identical” boiler feed pumps, mounted only a few feet away from each other, required significantly different cold alignment offsets to produce acceptable alignment while operating at full-flow conditions.

The required offsets, especially on #1 BFP, were far outside the values recommended by both the OEM and a pump repair specialist that was on site.

Following realignment to the required position, and re-adjustment of the inboard bearing seal, the #1 BFP ran without alignment-related seal problems for over 18 months. #2 BFP was later realigned and has run very well.

# Case Study #2 – Large Turbine-Generator

Rigid couplings & short bearings spans need attention....

## Machinery Configuration

Turbine: 3,600 rpm

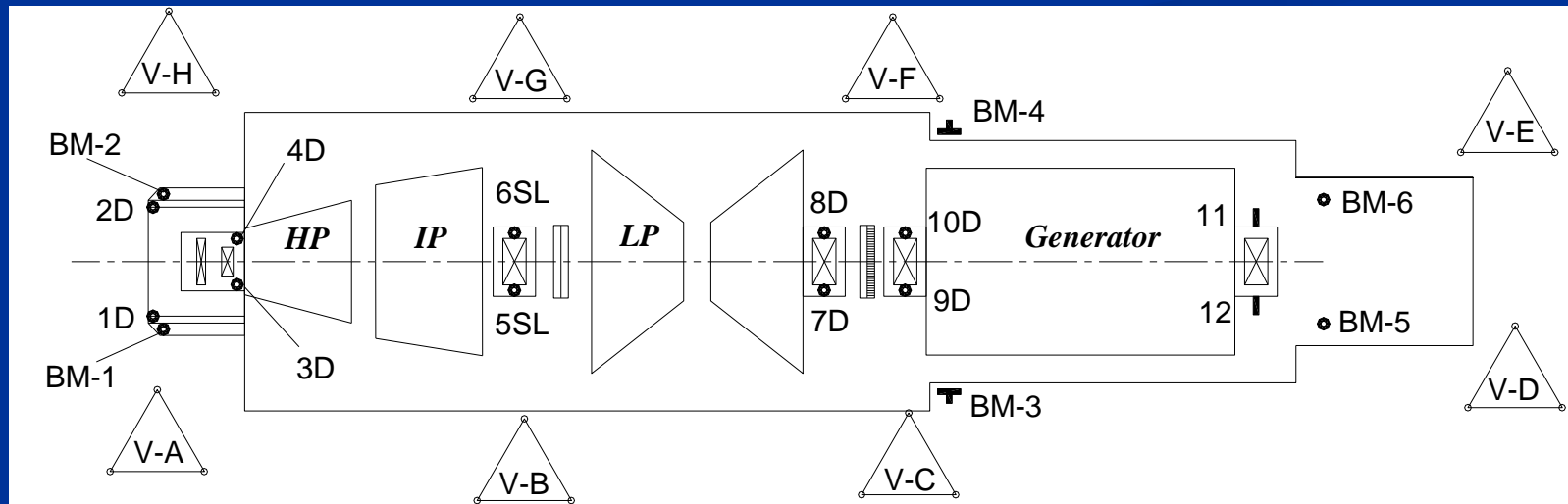
Coupling: Rigid, rabbetted-fit

Generator: 75 MW

## Customer Problem:

OEM set alignment during outage. High vibration and seal rubbing experienced during startup.

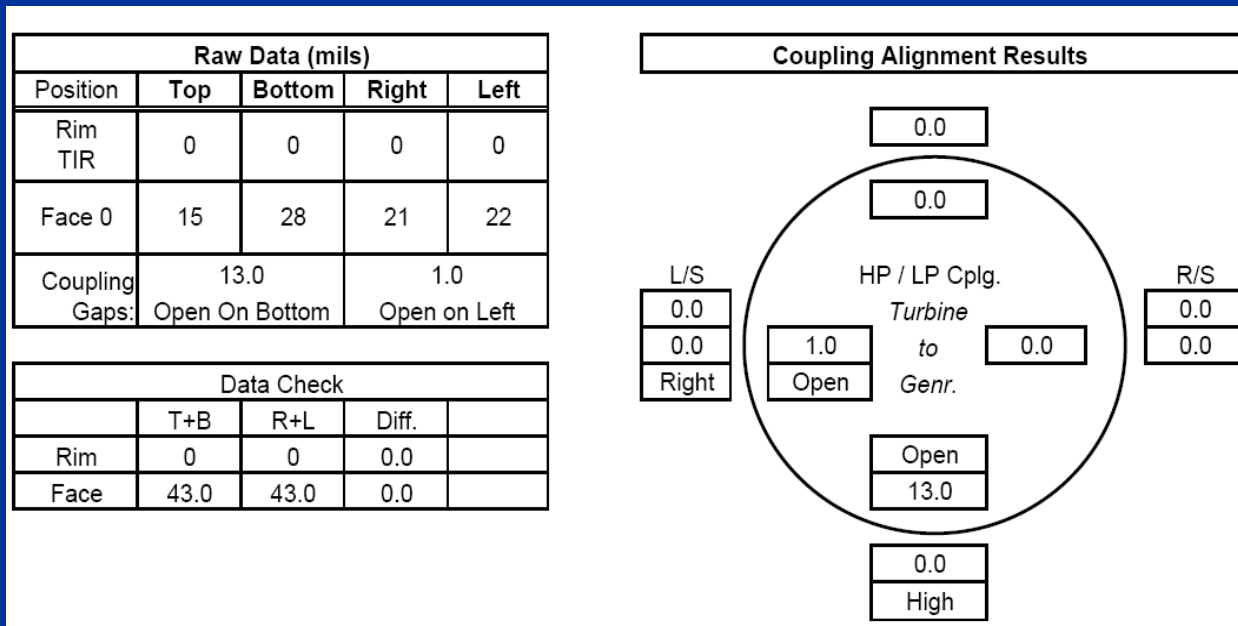
Orbital & shaft centerline data analysis confirmed the measured misalignment.



# Case Study #2, continued

## HP to LP Turbine – As-Left OEM Alignment

Coupling faces were left “open” 0.013” (13 mils) on the bottom, placing bearing #1 at 0.104” above the coupling, and bearing #2 about 0.010” high to the coupling. No significant offsets were used.



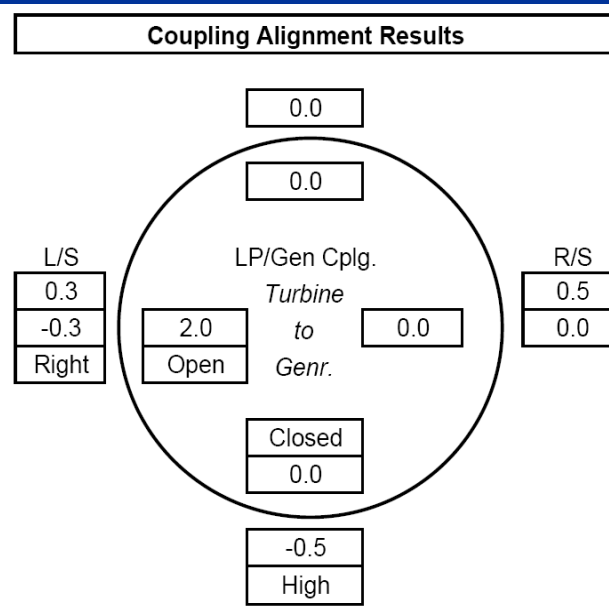
# Case Study #2, continued

## LP Turbine to Generator – As-Left OEM Alignment

Coupling faces were left approximately fair, with no significant offsets.

Raw Data (mils)				
Position	Top	Bottom	Right	Left
Rim TIR	0	-1	1	0.5
Face 0	0	0	-1	1
Coupling Gaps:	0.0 Closed on Bottom		2.0 Open on Left	

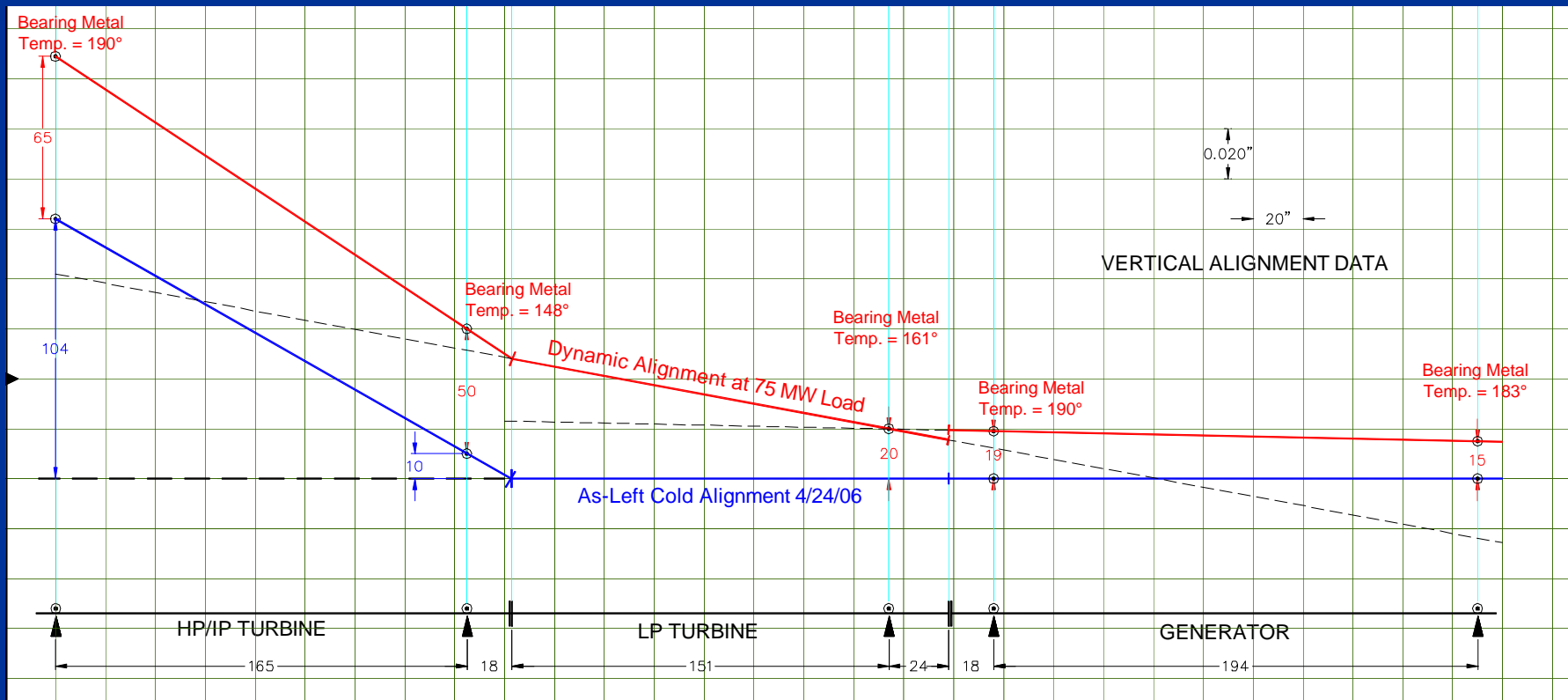
Data Check				
	T+B	R+L	Diff.	
Rim	-1	1.5	-2.5	
Face	0.0	0.0	0.0	



# Case Study #2, continued

## Alignment Study Results

We found 0.065" growth at bearing #1 (turbine front standard), with 0.050" at bearing 2. Bearings #3, 4 and 5 showed 0.020", 0.019" and 0.015", respectively. The cold coupling and combined hot alignment data are shown below. Note high bearing metal temperatures of 190° at bearings #1 & #4.



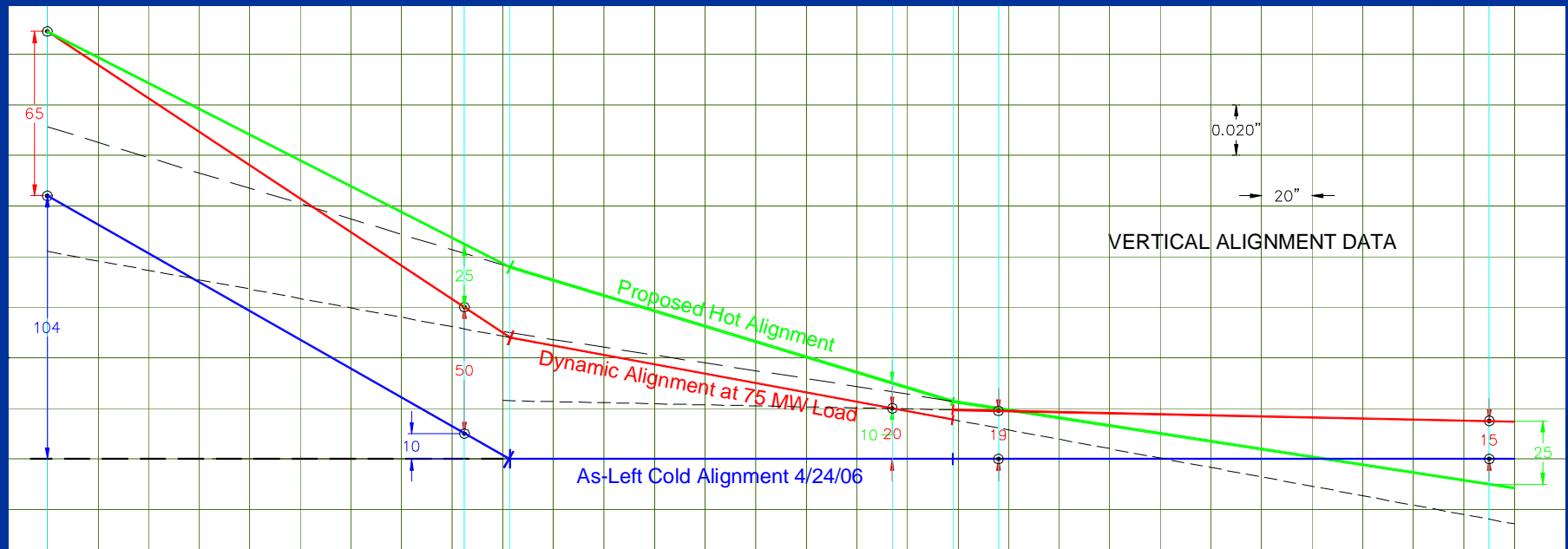
# Case Study #2, continued

## Conclusions

To normalize bearing loadings, we recommended the following shim changes (shown in green below):

- Bearing #1: no change
- Bearing #2: + 0.025"
- Bearing #3: +0.010"
- Bearing #4: no change
- Bearing #5: - 0.025"

Customer has yet to make any changes, and has since had fluid-induced instability at bearings 2 and 3, and mechanical problems at bearing 1.





# Case Study #3 – Process Compressor Train

High speed requires high precision....

## Machinery Configuration

Turbine: MHI; 4,831 rpm; 27,000 HP

Couplings: all disc-pack

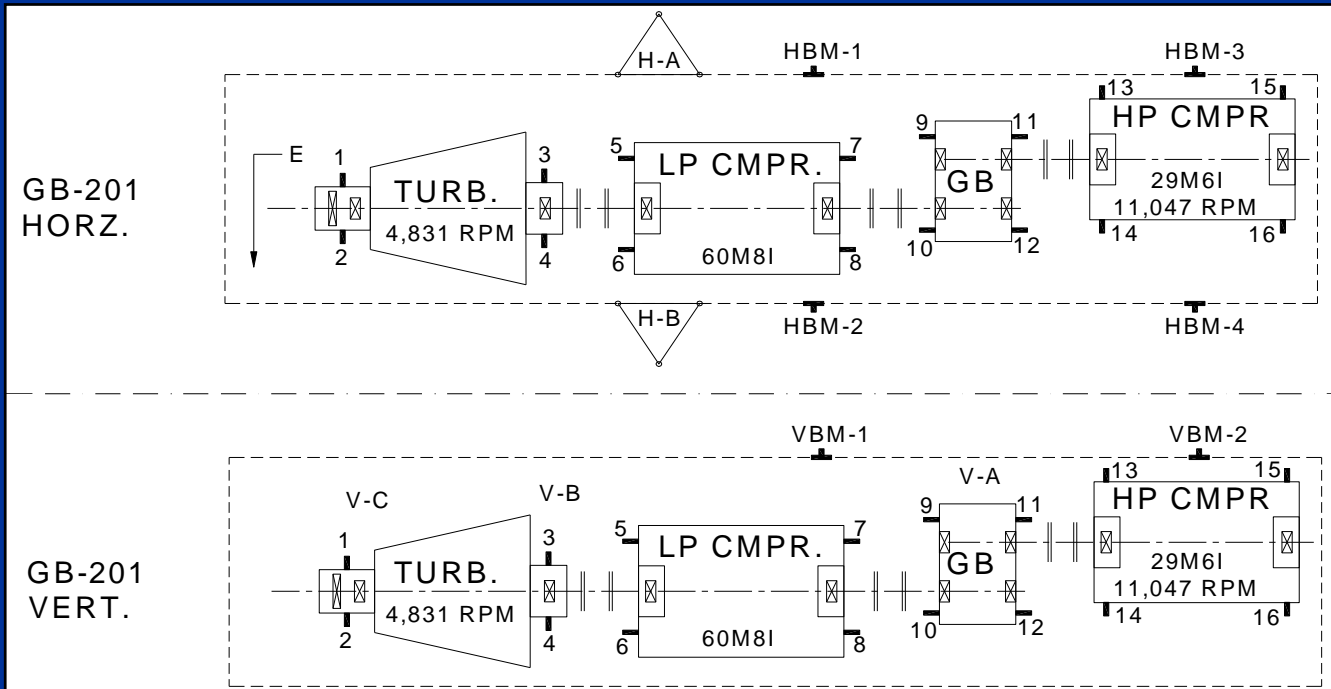
LP Cmpr: Elliott 60M81; 4,831 rpm

Gearbox: MAAG

HP Cmpr: Elliott 29M6I; 11,047 rpm

## Customer Problem:

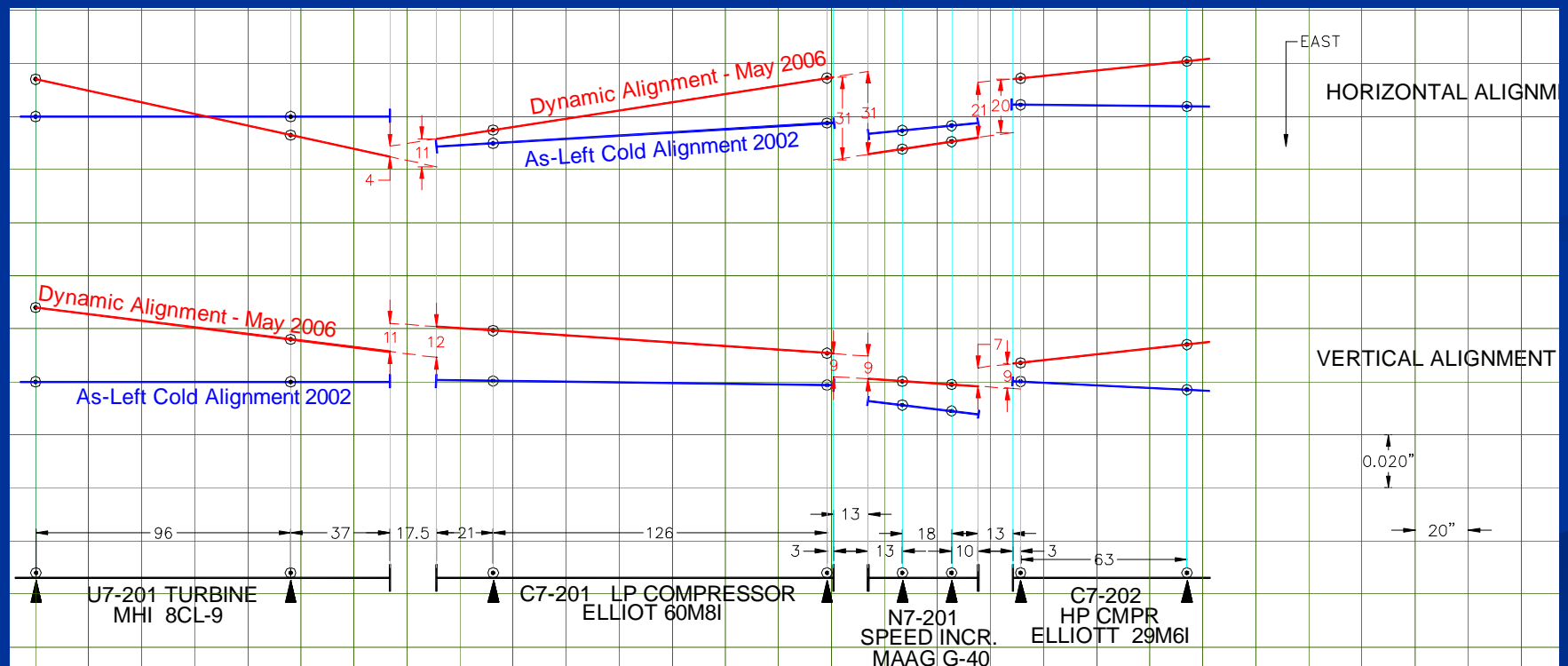
High 1X-filtered vibration on LP compressor since water induction event. Misalignment & unbalance suspected.



# Case Study #3, continued

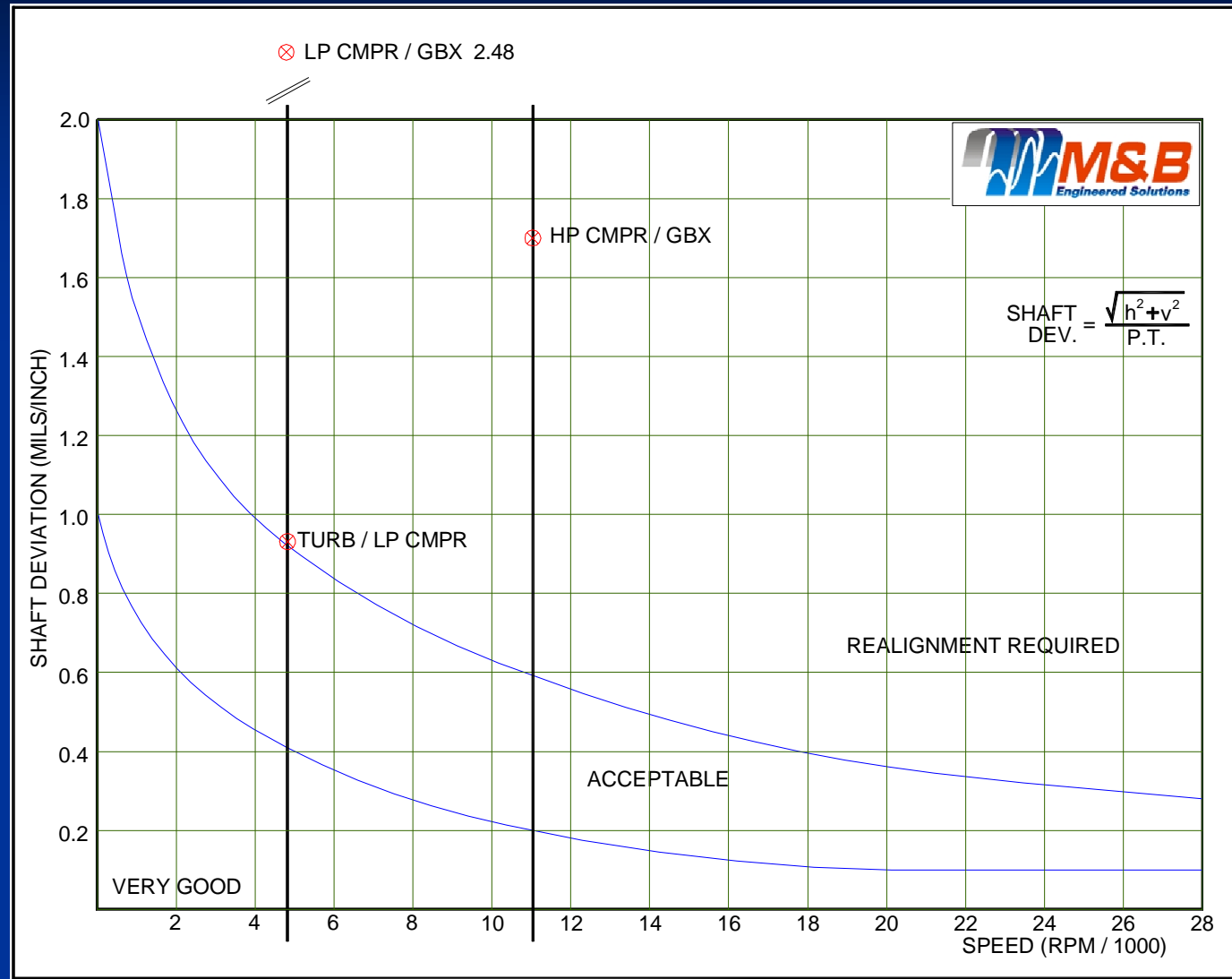
## Alignment Study Results

Using prior cold shaft-alignment data and measured thermal growth data, the results below were obtained. While this graph is 'busy', we can see the hot offsets present at each side of each coupling. Shaft Deviation values were calculated for each coupling, and are shown on the Misalignment Tolerance Graph on the next slide.



# Case Study #3, continued

## Results



# Case Study #3, continued

## Conclusions

Significant misalignment was found on the LP Compressor to Gearbox coupling, and was suspected to be a major contributor to LP Compressor vibration. The large horizontal offsets caused a 1X 'crank-effect' across the disc-pack style coupling. This contributed to the residual mass unbalance in the rotor, and caused unacceptably high vibration. Significant misalignment was also found on the HP Compressor to Gearbox coupling.

Alignment changes were recommended to the customer, but the site has yet to shut down the process to allow corrections to be made.

# Case Study #4 – Generator & Exciter

High stiffness coupling sensitive to offsets....

## Machinery Configuration

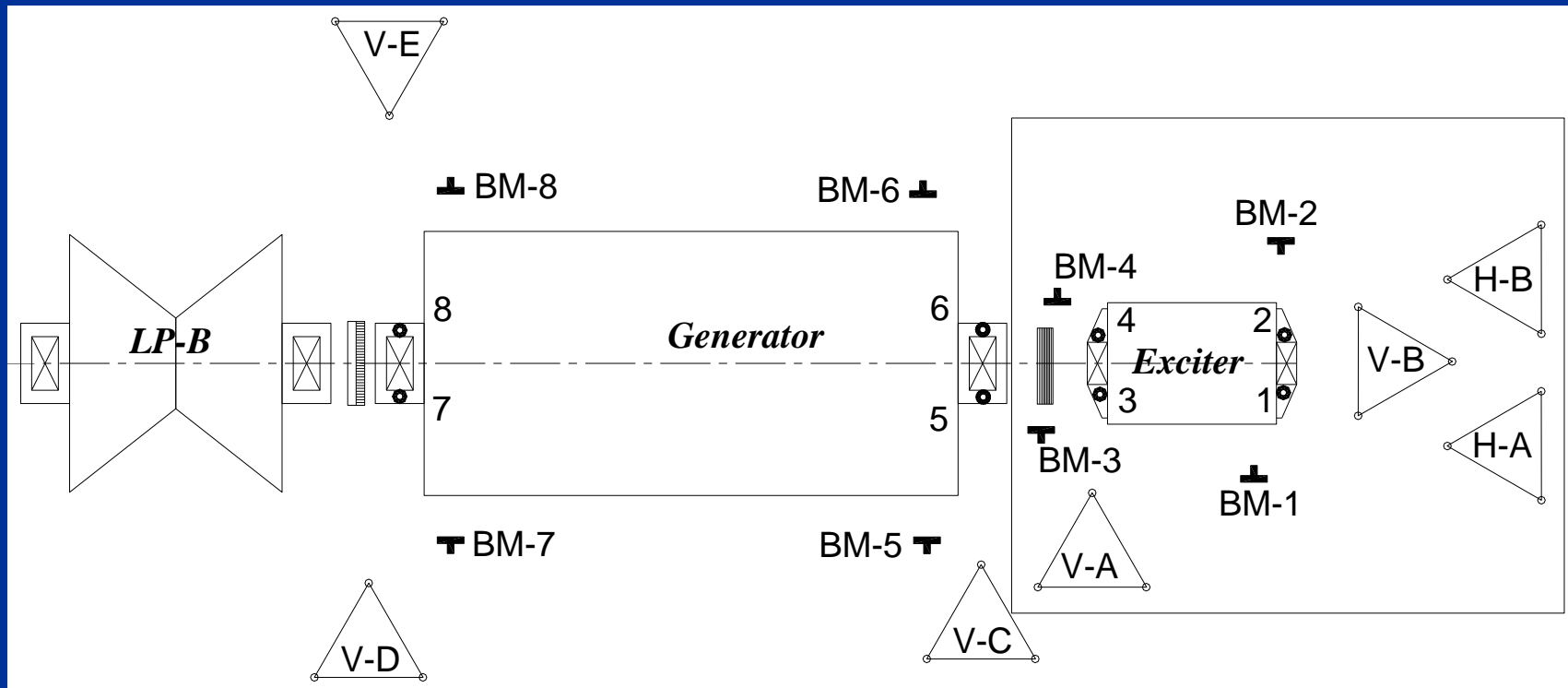
Generator: 850MW; 1,800 rpm

Coupling: large disc-pack

Exciter: 2-bearing; 1,800 rpm

## Customer Problem:

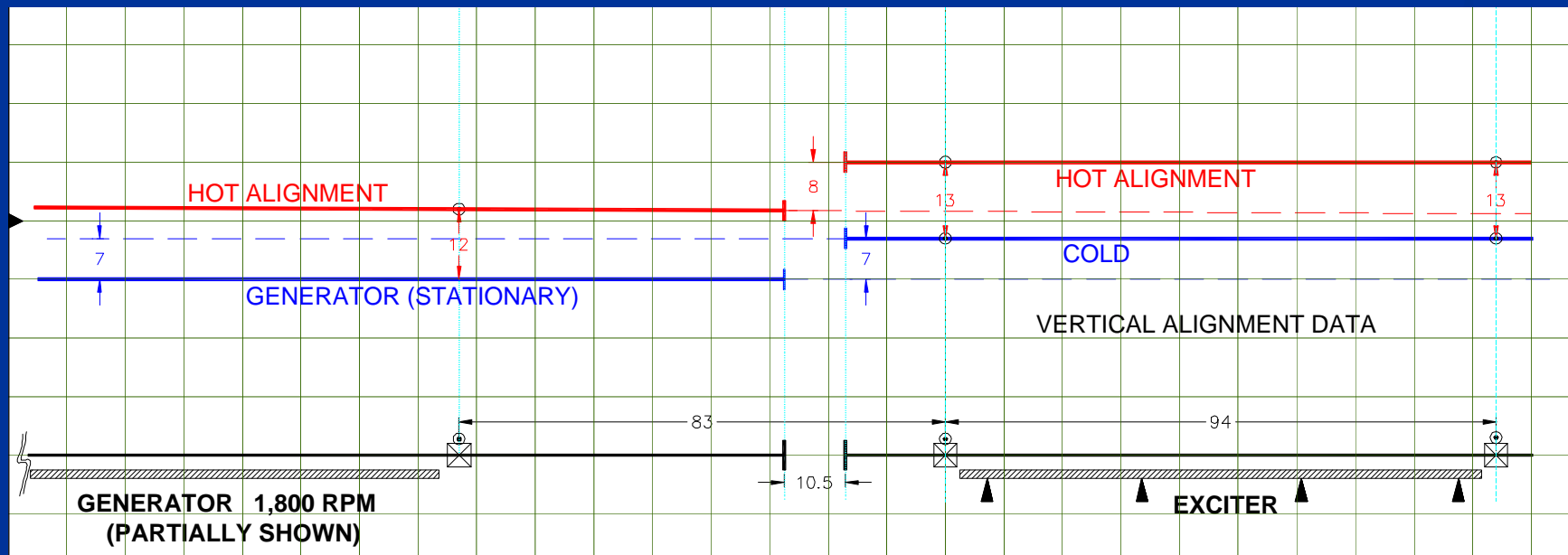
High 1X-filtered vibration on exciter bearings prompted alignment & vibration study.



# Case Study #4, continued

## Alignment Study Results

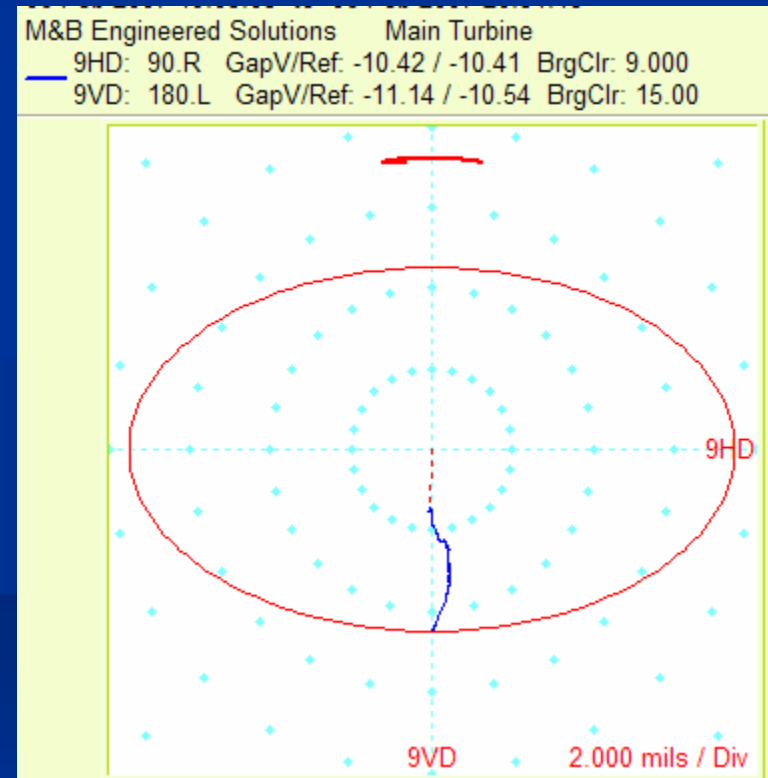
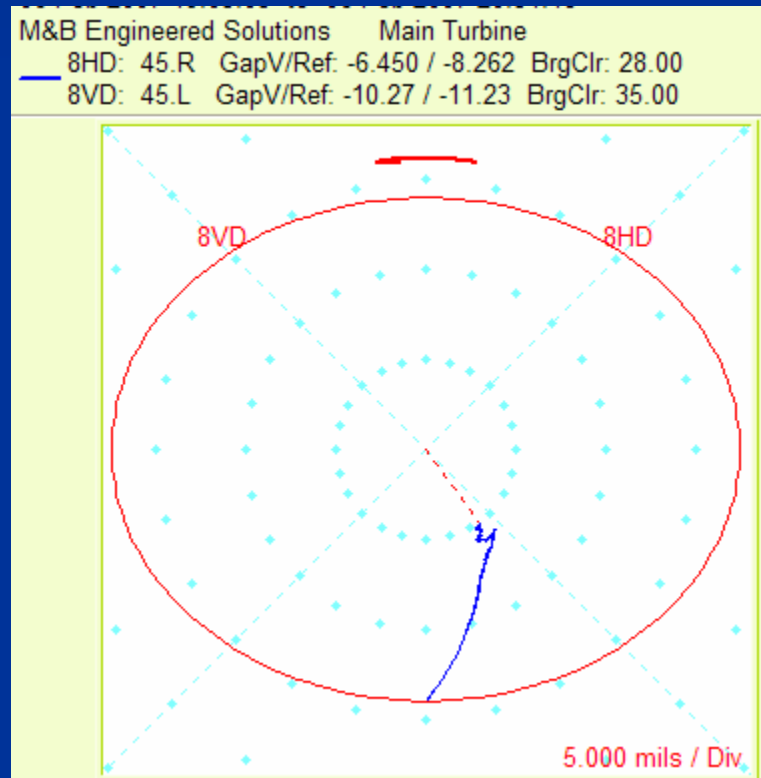
Using a 0.007" parallel offset alignment, as supplied by the customer, and adding the thermal growth for the generator and exciter bearings, we have the hot alignment shown below. It was interesting to note nearly equal vertical thermal growth on the generator and exciter bearings.



# Case Study #4, continued

## Shaft Centerline Data

Proximity probes were used to gather vibration and shaft centerline data from the generator and exciter bearings. During startup from zero to 1,800 rpm, the shaft at bearing 8 (exciter-end of generator) moved upward 0.010" and to the right 0.003". Bearing 9 (drive-end of exciter) moved up 0.003" toward bearing center.



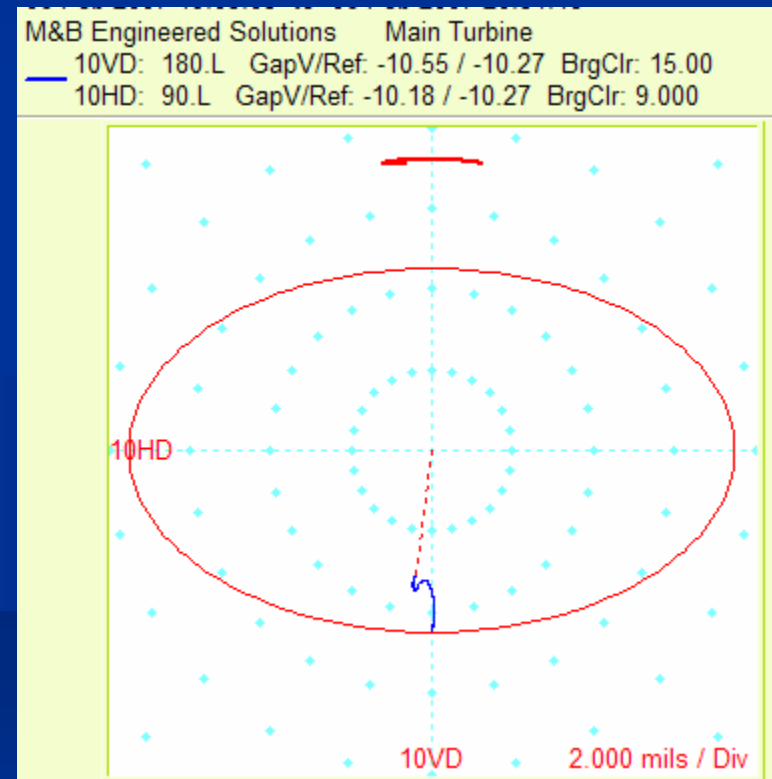
# Case Study #4, continued

## Shaft Centerline Data

Data from bearing 10 showed the shaft moving up only about 0.0015", and slightly to the left, about 0.0005".

### Note:

For counter-clockwise rotation (viewed from generator to exciter), we normally expect the shaft to rise and move to the right due to the lubricating oil forming a wedge in the lower-left quadrant of the bearing beneath the shaft. As the shaft rotates, this wedge creates direct and quadrature stiffness components that lift and push the shaft toward the lower-right bearing quadrant.

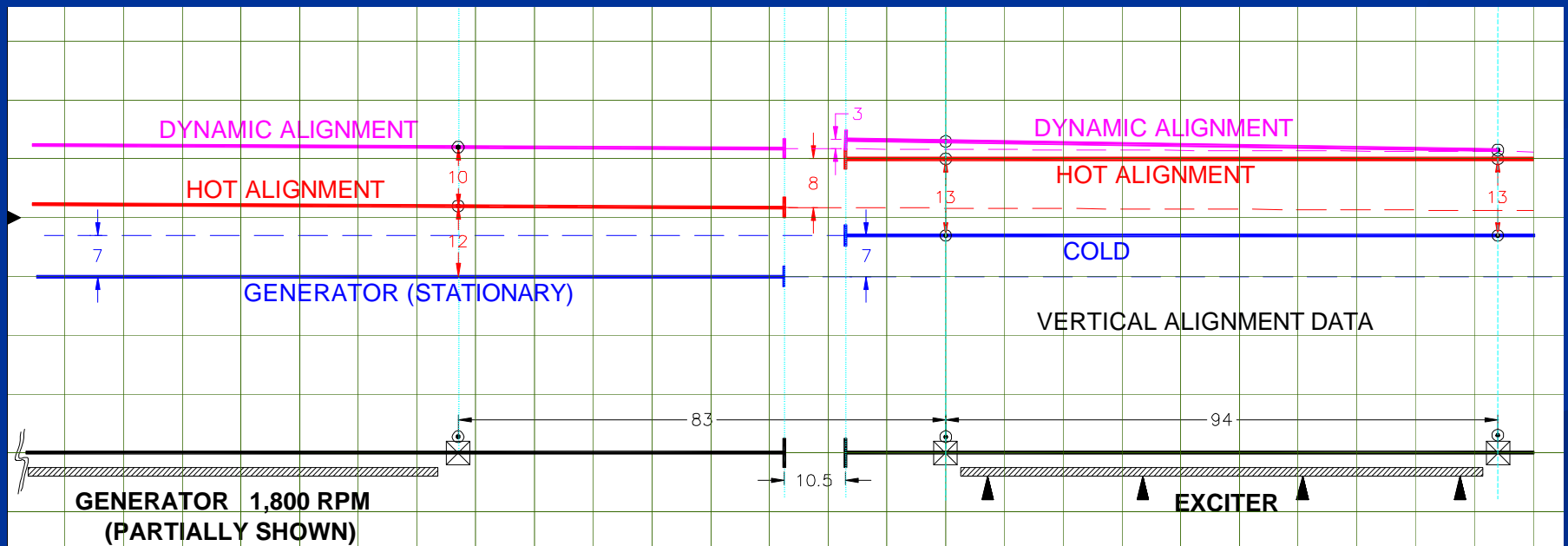




# Case Study #4, continued

## Alignment Study Results

When we add the shaft centerline movement within the bearings (due to oil wedge effects) to the hot alignment, we arrive at the dynamic vertical alignment conditions shown below. The rotors appeared to be well aligned, with only a 0.003" offset at the coupling in the vertical direction.



# Case Study #4, continued

## Conclusions

The rotors appeared to be well aligned, with only a 0.003" offset at the coupling in the vertical direction. Horizontally, we did not have thermal data, but cold alignment and dynamic offsets also yielded less than 0.003" total offset.

The customer indicated the large disc-pack coupling was not loosened during the last alignment check. Due to its size, it will have an impact on the exciter's alignment readings, especially any offset readings at bearing 9.

We have recommended a coupling inspection, including runout checks of all hubs, and a re-check of the cold alignment with the disc-pack bolts loosened. This will allow an accurate indication of the exciter shaft alignment. Soft-foots checks of the exciter frame will also be performed to reduce frame foot vibration.



Thank You – Any Questions?