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14. ABSTRACT Spindles for large diamond turned mirrors are not readily available. Oil hydrostatic spindles that are large enough to carry the load cannot run fast enough because of the heat generated by viscous forces. Air bearings have the potential to meet the speed requirements due to the lower viscosity. Classic metal-to-metal air bearings are expensive at large sizes and can fail catastrophically. Porous graphite bearings have the potential to resolve these problems. Preliminary requirements have been identified for a bearing to support a 3 meter mirror. Discs of porous graphite have been prepared for flow testing and a surplus air bearing rotary table has been located. A prototype spindle has been designed to work with the table.					
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Very High Load Capacity Air Bearing Spindle for Large Diamond Turning Machines

Contract No. NNX10CF18P (SBIR 2009-1) (MSFC)

Mirror Technology SBIR/STTR Workshop

June 7th to 9th, 2010

Millennium Harvest House, Boulder, Co.

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OUTLINE

- **INTRODUCTION**
- **AIR BEARINGS vs. OIL HYDROSTATIC BEARINGS**
- **PROTOTYPE SPINDLE DESIGN**
- **PROGRESS TO DATE**
- **FUTURE WORK & SUMMARY**

Introduction

- **DT is a proven method of manufacturing aspheric off-axis mirrors to visible quality.**
- **Vertical turning machines are used for very large and heavy parts.**
- **The need for very large diamond turning has been recognized for at least 30 years.**
- **Attempts to meet the need have all failed because no suitable spindle was available.**
- **Oil hydrostatic spindles large enough to carry the load cannot run fast enough because of viscous frictional heat generated as the 4th power of the bearing radius.**
- **Air bearings can run at sufficiently high speed to be practical because the viscosity of air is three orders of magnitude less than the lightest liquid lubricant.**
- **Classical metal to metal air bearings do not work for very large capacity because of prohibitive cost and catastrophic failure modes.**
- **Porous graphite air bearings are proven to be sufficiently rugged and reliable.**
- **Development of a giant capacity air bearing spindle is enabling technology for a giant diamond turning machine suitable for manufacture of giant aspheric optics.**

Cranfield Precision (CUPE) – LDTM 1982



LLNL 1983 – Large Optics Diamond Turning Machine



Comparison of Oil Hydrostatic and Air Hydrostatic Bearings

Oil hydrostatic bearings tolerances are 25-75 microns (0.001-0.003”)

Oil hydrostatic bearings and air hydrostatic bearings both have flow induced instability issues “water hammer” which must be carefully controlled.

Oil viscosity provides important squeeze film damping which aids control of flow induced instability. Air bearings are very much more sensitive to water hammer effects.

Viscous shear frictional heating limits large oil hydrostatic spindles to less than 100 rpm. This slow speed is unacceptable for diamond turning because the finish requirements of optics require a very small tool advance per revolution.

Dimensional accuracy requirements demand extreme thermal stability and this requirement increases with part size. The large heat generation of oil hydrostatic spindles at even unacceptably low spindle speeds is a severe problem.

Air bearing tolerances are extremely small because of the requirement that the air film must be no greater than about 6 microns (0.0003”) to provide the required very high bearing stiffness for diamond turning. Flatness, roundness, squareness < 0.5 μm (0.00002”).

Spindle Requirements for Giant Optics Diamond Turning

Fixture weight is usually orders of magnitude heavier than the optic it is designed to hold in a strain-free condition. This spindle development is aimed at producing 3 meter diameter components. This requirement results in the following spindle specification goal.

Working load capacity: > 89,000 N (20,000 lbf.)

Rotational speed: > 1000 rpm

Max. spindle motion error, radial, axial, tilt: < 125nm (5 μ inch)

**2.48 Meter Aluminum Mirror Weight: 3000 lb.
Fixture Weight: 3000 lb.
Spindle Thrust table weight: 3000 lb.**



Porous Graphite Air Bearing Technology

Porous graphite air bearings for ultra-precision turning were developed starting in the early 1960's at the Oak Ridge, Tenn. Y-12 Plant for use in manufacture of nuclear weapons components. This spindle development utilizes the experience of the principal investigator and various others at Oak Ridge in building large air bearings.

Prototype Air Bearing Spindle

A prototype air bearing spindle will be used as a vehicle for developing the manufacturing methods to be used on the larger air bearing suitable for use as part of a very large diamond turning machine.

Major precision components of the air bearing spindle.

- Flat thrust bearing plate/spindle faceplate. (lapped)**
- Main thrust bearing graphite bearing material. (lapped)**
- Radial bearing shaft. (Diamond turned NiP plated steel.)**
- Radial graphite bearing. (Lapped to size w/ DT laps.)**
- Bearing pre-load components. (Smaller porous bearing.)**
- Spindle drive shaft and pulley. (Flat belt drive.)**
- Spindle housing and air supply plumbing.**

POROUS GRAPHITE TEST AND SELECTION

- **Porous graphite samples will be tested to determine air flow properties.**
- **Selected graphite material will be fabricated into test bearings for evaluation of impregnation and stability against “water hammer” flow induced instability.**
- **The bearing performance testing will select graphite grade for fabrication of the large air bearing parts.**
- **Eight grades of graphite from five suppliers are in testing at this time.**

Disks of porous graphite ready for flow testing.



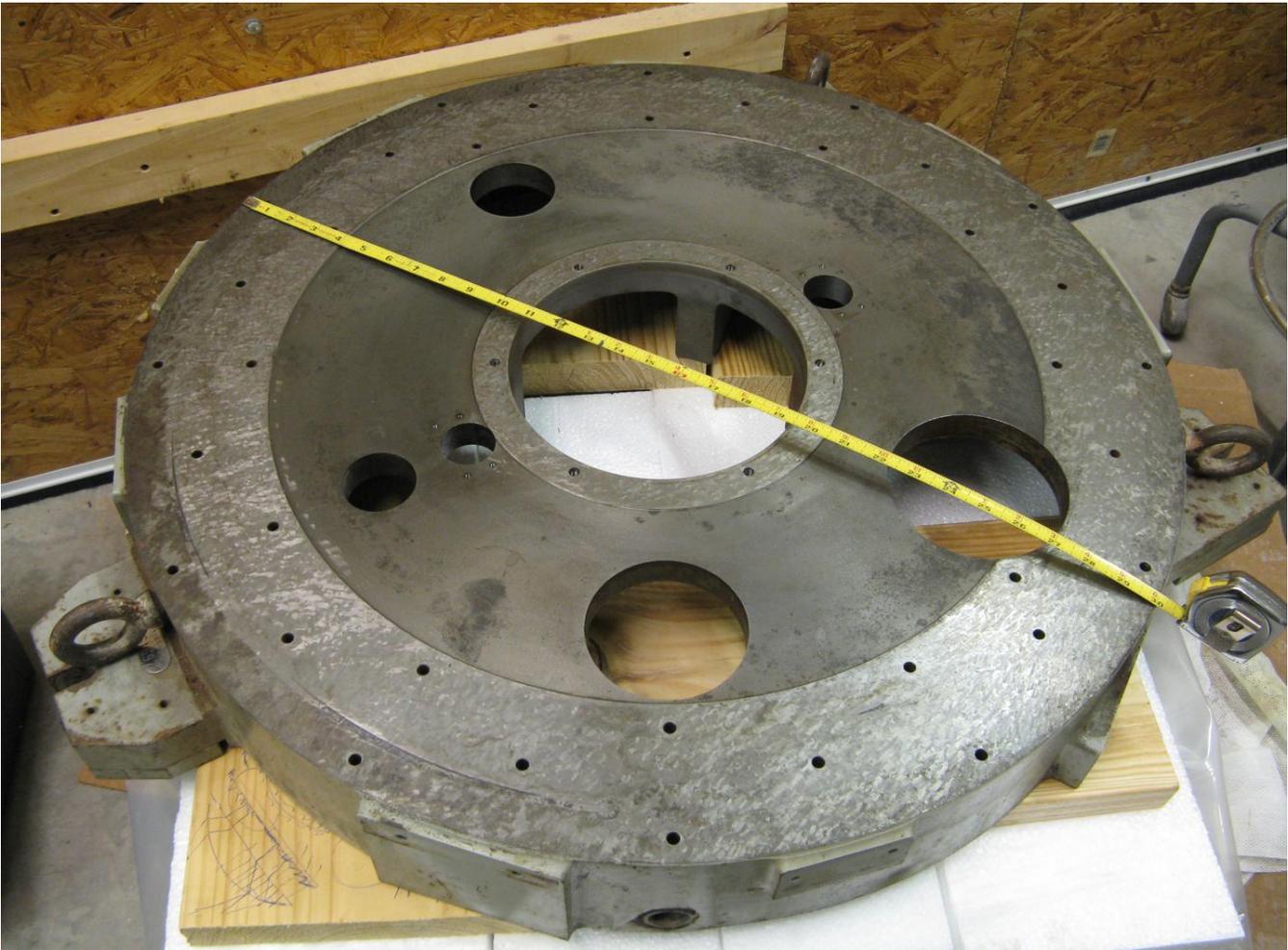
SURPLUS METAL TO METAL AIR BEARING ROTARY TABLE



THRUST BEARING PLATE/FACEPLATE OF 30" DIA. AIR BEARING ROTARY TABLE



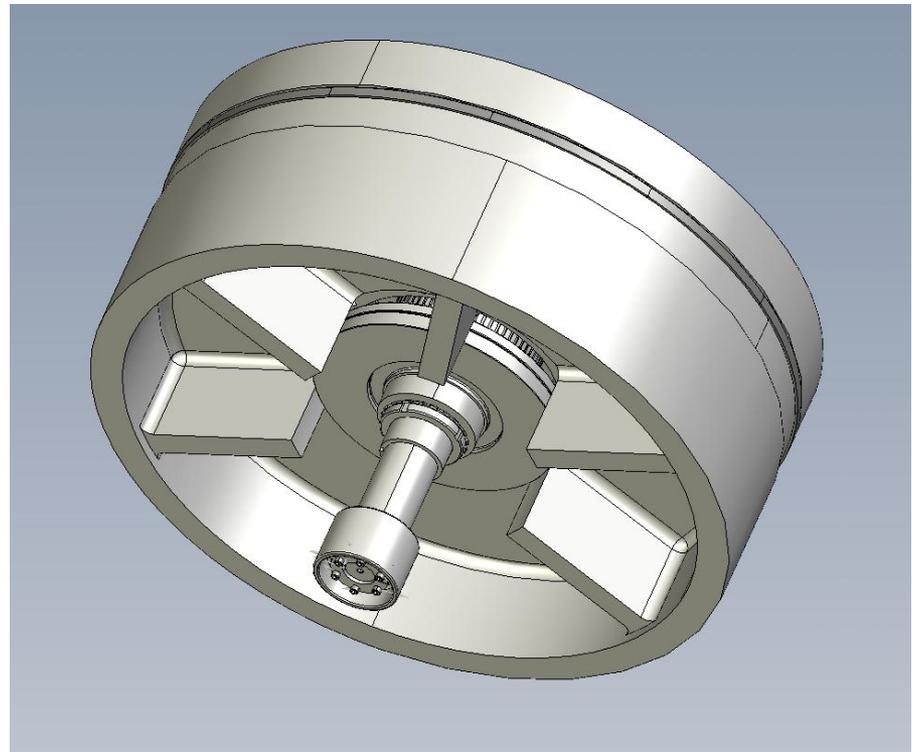
Housing of Air Bearing Rotary Table to be Modified



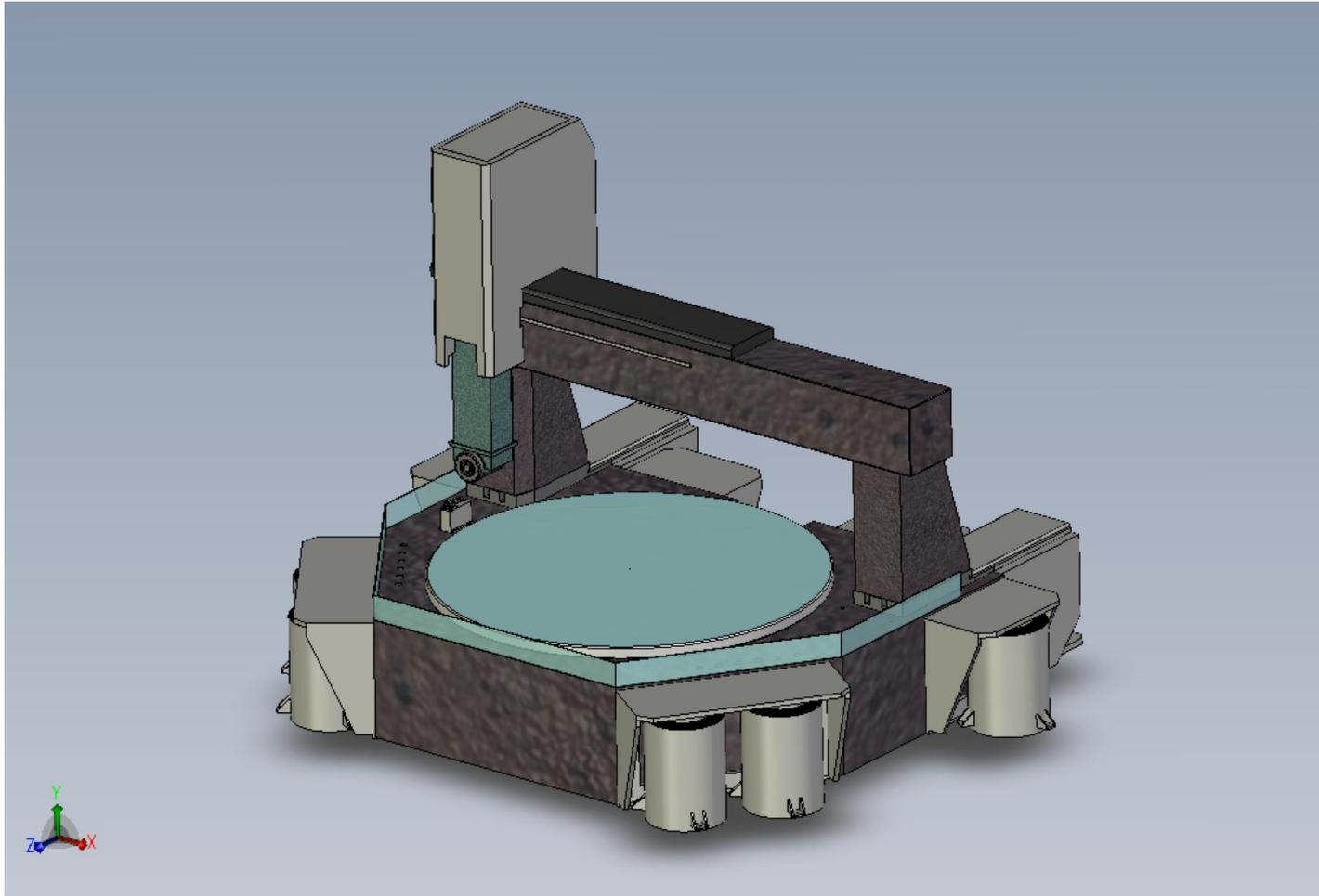
PROTOTYPE AIR BEARING SPINDLE DESIGN

Drawings for all the components of the prototype spindle are complete and fabrication of the required metal components is underway at this time.

Expected load capacity of the prototype spindle: 16,000 lb. max; 8000 working cap.



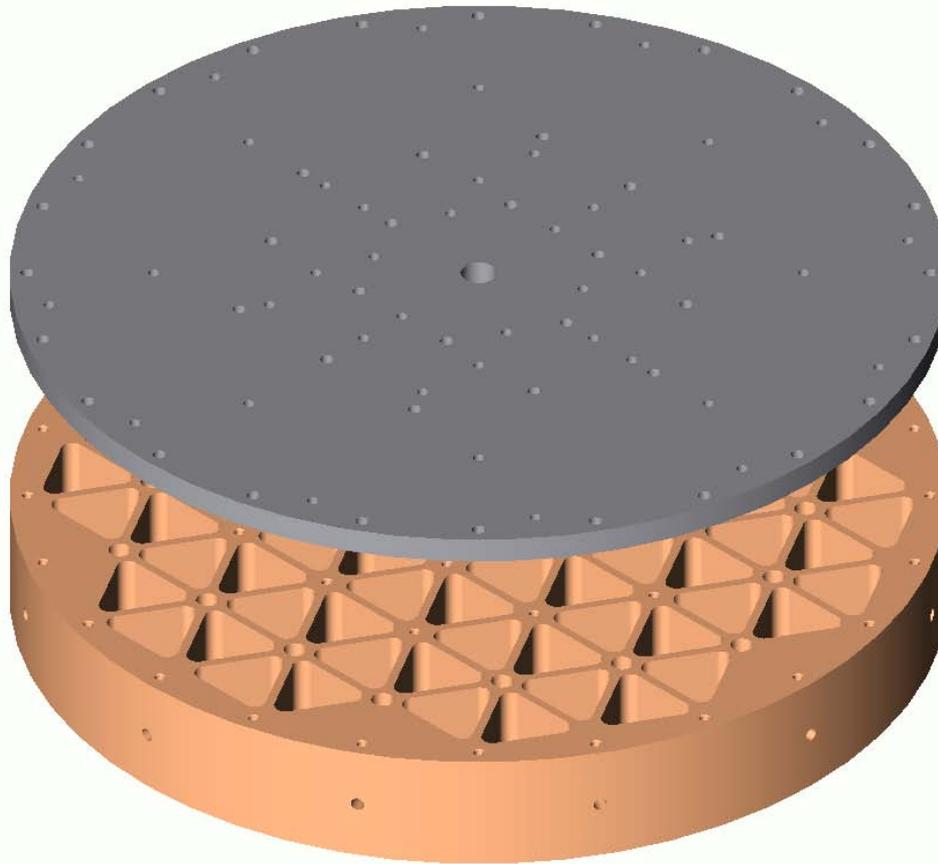
Moore Tool Co. Three Meter Diamond Turning Machine Concept



Diamond turning of an X-ray telescope mandrel is a similar process to be used in diamond turning the air bearing radial bearing shaft.



Design of 98KN (20,000 lb.) Capacity Air Bearing Spindle



SUMMARY

Diamond turning can produce visible quality highly aspherical surfaces very quickly with machined reference surfaces to allow easy alignment of multiple complex optical contours.

Diamond turning enables high rate production manufacture of large light weight mirrors at an affordable cost.

- **The very large load capacity porous graphite air bearing is the key to enabling a practical very large optics diamond turning machine.**
- **The porous graphite air bearing can run at high speed without the excessive heat generation of oil hydrostatic spindles.**
- **Porous graphite allows a very high reliability, very rugged spindle.**