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AN ORDER OF MAGNITUDE IMPROVEMENT IN THERMAL STABILITY WITH USE OF LIQUID SHOWER ON A GENERAL PURPOSE MEASURING MACHINE

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ABSTRACT

Over the past 25 years, LLNL has been developing and contributing to the technology of precision machining and diamond-turning. Advancement of the accuracy of machine tools has made it necessary to upgrade inspection tools as well. This paper describes the upgrading of a Moore Special Tool Co., No. 3 Measuring Machine. The results show that the liquid shower approach can be engineered to provide a simple and practical system having a dramatic improvement in thermal stability.

INTRODUCTION

Over the past 25 years, LLNL has been developing and contributing to the technology of precision machining and diamond-turning. Our two existing diamond turning lathes in the Materials Fabrication Division routinely produce contoured surfaces within plus or minus 10 microinches, and can produce surfaces within 2 microinches if necessary. The development of these cutting machines has made it necessary to upgrade our inspection tools in order to measure the precision parts coming from these machines.

About 6 years ago the Metrology Group began a project to upgrade our Moore Special Tool Co. #3 measuring machine. The goal was to convert it into a general purpose 3-axis coordinate measuring machine and improve the accuracy capability by a factor of 10 from that of the original machine. That goal has been achieved by the addition of laser interferometry and temperature control by means of an oil shower. The oil showered machine is shown in Figure 1. It has been in use for over a year in the Division's Inspection Laboratory. We believe it is the world's first oil-showered general purpose measuring machine.

Repeatability

The most important characteristic of the upgraded machine is repeatability. A measuring machine cannot be depended upon for accuracy unless the apparent non-repeatability is minimized. The term "apparent" non-repeatability is used because each influence is in itself repeatable if the conditions affecting it are repeated. When the nature of the influence is understood, we are able to bring it under control.

In the field of close tolerance work, experience has shown us that the thermal effect is the largest single source of apparent non-repeatability. Other sources of apparent non-repeatability are sliding oil films, Coulomb friction, and vibration. Figure 2 illustrates the thermally induced drift of the machine in an air conditioned room with the oil shower turned off. Basically this drift test result indicates the repeatability of a measurement taken at different times of the day. With addition of the measurement of room temperature also presented on the chart one can see the influence of temperature upon the repeatability. This illustrates the need for temperature control.

Temperature Control

Once the necessity for improved temperature control is recognized, the question arises as to the best means to achieve it. We feel the best means for achieving high quality temperature control is liquid shower. Our experience in oil showering two diamond turning lathes and three special purpose measuring machines was applied to this general purpose machine.

The primary advantages of liquid shower are its greater heat removal capability and the fact it is easily directed to the critical areas of the machine and workpiece surfaces. The effectiveness of a coolant is measured in terms of a film coefficient (h = BTU/hr-ft^2 - °F). The film coefficient in slowly moving room air is about 1.0. This can be increased by increasing the velocity of the air up to a limit at about h = 10.0 (above 800 ft./min.) which is approximately the lowest limit for water in natural convection. Liquids in forced convection have film coefficients several hundred times that of slowly moving room air.

Liquids have a higher heat capacity than gases. This characteristic allows removal of heat with corresponding lower temperature differences. The heat transfer characteristics of liquids make accurate temperature control easier and from any initial condition, all machine components, including the workpiece, will reach the desired temperature 10 times faster.

Alternatives to liquid shower for temperature control are conventional room air conditioning, open and enclosed air shower, liquid submersion, and complete isolation from heat sources in an air conditioned room.

We will define conventional room air conditioning as having air velocities between 2 and 20 feet per minute. Even the best room of this type is hopelessly inadequate in controlling the temperature of a machine with varying heat loads around the machine. This kind of room control is expensive to install and is a permanent part of the room.

An air shower of 800 feet per minute is about five times better than conventional room air conditioning. The most common delivery scheme for a high velocity air shower is a ceiling-to-floor circulation. The air enters the workspace through a perforated ceiling from a large plenum above. The exhaust is drawn off near the floor. The workspace may be the entire room, a portion of a room, or a single enclosure.

An open air shower, has the serious disadvantages of operator chill and noise. Air at 68°F with a velocity of 800 ft./min. is roughly equivalent to still air at 55°F as far as human comfort is concerned. This is an unacceptable work environment.

An enclosed air shower system avoids the wind chill problem. A built-in air circulation and temperature control system provides the necessary temperature control and high velocity. Doors allow the operator access to the workspace during part loading, set-up, and maintenance. Air shower noise is also minimized by the enclosed flow system.

Complete submersion of the machine in a tank of temperature controlled liquid has been suggested. This approach is inferior to either liquid or air shower. The reason is that in a liquid at rest, heat transfer occurs by conduction. Natural convection produces bulk movement to keep lower temperature fluid in contact with the surfaces to be cooled. Natural convection is less effective in liquids than it is in still air because of the higher viscosity.

Complete isolation and remote operation of a machine in a special air conditioned room is a technique that is used for diffraction grating ruling machines. It takes weeks to rule a grating on one of these machines. Several days of soak out time after set-up is acceptable. This is not practical for a general purpose measuring machine.

The Measuring Machine

Before proceeding with a discussion of the details of the liquid shower system, it is desirable to have a general description of the measuring machine to which it is applied. Figure 1 shows the upgraded machine.

This Moore Special Tool Co. #3 Measuring Machine was built in 1960 and has been a part of the inspection laboratory since then. It is a plane way machine using the double-vee concept with X & Y slide travels of 18 and 11 inches respectively and a Z slide travel of 16 inches. The Z slide has been converted to hydrostatic bearings.

Displacement of the X and Y slides in the original design was measured by reading the graduated drum attached to the end of the precision leadscrew. The Z axis had no displacement measuring device. Laser interferometry has been added to the machine for displacement measurement of all three axes.

A rotary table was mounted on the X-slide. The machine can therefore be used not only as a 3-axis coordinate measuring machine but also a 'Y-Z' or 'X-Z' measuring machine. In this mode, axisymmetric parts can be rotated on the C-axis to produce circumferential sweeps. Most of our very high precision parts to be measured are axisymmetric.

The electronic gauge stylus is typically a ball or spherical radius tipped, single axis, linear, variable-displacement transducer (LVDT) carried and positioned by the vertical Z-slide. The axis of the LVDT is typically mounted at a 45-degree angle with respect to the Y and Z axes. (It may be used at any other angle however as long as the proper corrections are made). Figure 3 shows the LVDT mounted in the horizontal position. A correction is required for the cosine error introduced when the direction of travel of the LVDT is not normal to the part surface. The LVDT travel does not represent the workpiece error and must be corrected by a multiplication factor of $\cos\theta$, where θ is the angle the LVDT axis makes with the normal to the part surface at the point of contact. Data may be taken in the form of circumferential sweeps about the axis of the part or longitudinal sweeps through the part pole. Display of data is analog in the form of either polar or linear charts as shown in Figure 4.

The Liquid Shower System

Figure 5 shows a schematic diagram of the flow circuit for the liquid shower. Starting at the machine sump, the oil flows through a filter located on the suction side of the pump, through the pump to a heat exchanger, onto the machine and back to the sump. The sump is a part of the collection base. The sides of the collection base extend upward near waist level to catch any splash and still provide easy access to the work area. Figure 1 shows the operator standing on a short stool. The final plan calls for an elevated floor 7" above the supporting floor. This is required since the entire machine is sitting up on the thick support base.

Visible in the lower left are one of the three cylindrical pneumatic isolators, the machine sump, and the suction line leading to the pump which is located in a closet adjacent to the machine. To avoid transmission of vibration from the pump and motors to the isolated machine, the suction pipe is cantilevered from the floor and does not physically contact the sump or machine. The same concept is applied to the plumbing which distributes oil over the machine.

The oil used for the liquid shower is a light weight mineral-base oil (225 Saybolt seconds at 68°). The viscosity is high enough to limit splash and airborne droplets while flowing readily over the surface of the machine. Various pieces of sheet metal and wire screen are used to direct and smooth the flow and minimize splatter. The flow is visible on the column in Figure 6.

Freon solvent is used to remove oil from the part or from the work surface during set-up. A solvent tank is nearby for washing large items. Evaporative cooling has no effect so long as the machine surfaces are separated from the free liquid surface by a layer of flowing oil. Samples of air around the machine show levels of oil in the air to be in the range of .02 to .18 mg/m^3 which is 1/25 of the allowable limit of 5.0 mg/m^3. The particular oil used is free of odor and fumes and has not been a problem.

The oil filter consists of a large (15 gal.) horizontal cylindrical container with a quick-opening hinged front cover. A felt liner material is supported within this cavity, spaced away from the walls by a perforated support, with oil entering the center and flowing outward. The life of the filter is about two years. A new element costs about $20.00. It is worthwhile noting that the oil shower keeps the machine quite clean.

The oil is pumped by a commercial 2 HP integral pump-motor unit. The pump is a constant displacement, rotary screw-type pump, very quiet, and capable of delivering 40 gallons per minute at 20 psi supply pressure. This pressure is adequate to overcome line losses and provide good distribution pressure at the shower nozzles. The suction head of 6 in. Hg through the suction line and the filter is well within the capability of the pump and does not cause cavitation of the oil.

The oil shower pump, filter, and heat exchanger are housed in a 3' x 5' closet only 8 feet from the machine. The closet allows these items to be kept out of sight as well as isolating the room from any pump noise.

Temperature Control System Design

The 40 gallons per minute of circulating oil is heated by the 2 HP pump. Therefore, it is possible to control the oil temperature by cooling only. The shell and tube heat exchanger is used as shown in Figure 5. The oil temperature at the exchanger outlet is sensed by a bare-bead thermister. An on-off controller actuates a solenoid valve to admit chilled water when the oil temperature exceeds 68°F and to bypass it when the temperature is below 68°F. It was found that our chilled water supply temperature varies as much as 5°F. This causes a variation in oil temperature of 0.05°F. A second shell and tube heat exchanger and an on-off control is used to control the temperature of the chilled water. In this case, heat is added intermitently to the chilled water. Plant cooling tower water supplies the heat. The result is that the average temperature of the circulating oil is held constant to ± 0.01°F.

The temperature oscillations of the oil have a amplitude of 0.08°F and a frequency of about 10 cycles per minute (6 seconds per cycle). At this frequency, the thermal inertia of the machine limits machine distortion. Thermal inertia is defined as the inability of an object to respond instantly to a change in liquid temperature because of its heat capacity.

Measuring Machine Performance

For a drift test to be meaningful, it should include a typical test part in the structural loop, and people in the vicinity of the machine during the test. It should also be setup in a direction most sensitive to temperature changes. For the drift test on the Moore Measuring Machine, we chose an 8 inch long aluminum cylinder. Aluminum, with a thermal coefficient twice that of steel provides a compromise between steel and plastics. Plastics have coefficients five times that of steel. We chose also to have a person working around the machine during the test to provide the additional amount of heat load to the machine that an operator would provide in normal use. The Z-axis of this machine is most sensitive to temperature changes due to geometry. The drift test was therefore set up in the Z-direction.

The drift test was conducted dry (without oil shower) and with oil shower. Figure 7a, taken without oil, shows a total drift of more than 70 μinches with a room air temperature variation of about 1°F. Note the correlation between the machine drift and the room air temperature. In contrast, Figure 7b with oil shower shows an order of magnitude decrease in drift or less than 5 μinches total for the eight hour period.

Soak out time for the oil showered machine is an order of magnitude faster than for a dry machine. Figure 8a shows a 60 microinch setup induced drift for the dry machine. Four hours of soak out time were required to reach equilibrium. Figure 8b shows the same setup with the oil shower on. The soak out time has been reduced to half an hour.

Other Features

The accuracy of measurement was improved by adding laser interferometry to all 3 axes of the machine. A Hewlett-Packard 5501 machine tool laser was mounted in a casting mounted on the rear of the column. The beam is split 3 ways to feed the 3 axes. Figure 9 shows the laser paths and the optical components. The plane mirror measuring system was used to obtain a 0.5 microinch resolution.

The paths of the measuring beam were chosen to minimize Abbe errors. The paths of the X and Y axes beams pass through the center of the working volume, hence minimizing the error due to varying Abbe offset. The vertical Z axis beam passes through the stylus tip, obeying the Abbe principle.

The laser paths are enclosed in either a casting, a pipe or a covered enclosure depending upon the location on the machine. The pathways contain room air and are slowly purged with filtered air to discourage the intrusion of oil. The intensity of the beam is severely lowered when oil is deposited on the optics. Enough oil will cause the system to fail. When the proper techniques of sealing and oil shower management are applied, reliability is very high.

The successful application of laser interferometry to this machine, in terms of accuracy, is due to total thermal control. Adding a laser system would otherwise be counterproductive. Most of the laser mirror and interferometer brackets are external to the machine's massive castings which protect the leadscrews. Exposed brackets quickly distort when exposed to temperature changes. These distortions are likely to cause measurement errors exceeding those of the original leadscrew. The temperature controlled oil shower eliminated thermal distortions.

The LVDT mentioned earlier is an air bearing type. The air bearing eliminates coulomb friction, a requirement when the direction of LVDT travel is not normal to the part surface. This LVDT also uses air pressure to maintain stylus force. The typical stylus force is 0.2 grams. Even when the stylus tip radius is as large as .1 inch at a force of 0.2 grams, the oil does not keep the ball from following the part contour. We have found that the presence of flowing oil on the part is not a problem in contact gaging.

Positioning and holding a part on the rotary table can be difficult in the presence of oil, especially when the parts are small or of relatively low density. The oil tends to get under the part and lift it. In this case a vacuum chuck is used as in Figure 3. Centering is accomplished with an X-Y micrometer stage. We have added micrometer heads that have built-in piezo-electric crystals. The part can first be roughly centered with the micrometer dial and then finely centered 'hands-off' by adjusting the voltage supply to the piezo crystals . Adjustment of tilt is built into the rotary table top.

As stated earlier the Z slide's plane ways were replaced with hydrostatic bearings. This was done to eliminate the Coulomb friction. The weight of the Z slide is held by a roller chain which moves over 2 sprockets to a counter- weight inside the column. One of the sprockets is driven by a handwheel on the side of the machine. The static friction in the original design made it impossible to position the slide with any resolution.

The solution was oil hydrostatic bearings. They have the advantage of eliminating static friction, they are stiff, and are relatively easy to retrofit to the geometry. The leaking oil from the bearings is of no consequence since the machine is oil showered. The bearings are fed with shower oil. A small portion of the filtered shower oil is directed through a high pressure pump to feed these bearings.

The positioning of the Z-slide in the present configuration is done with the bicycle wheel shown in Figures 1 and 6. The bicycle wheel replaces the original handwheel. The Z-slide can be positioned to one microinch in a time period of less than 10 seconds using the bicycle wheel.

Conclusions

Accuracy and repeatability errors in a measuring machine should be significantly less than the errors in the part being measured. An order of magnitude is the goal in many areas of manufacturing. At LLNL, for the past 12 years, the temperature controlled diamond turning lathes have produced parts which had errors less than the measuring machines used for inspection. Now for the first time in 12 years we have a general purpose inspection machine more accurate than our diamond turning machines. It is primarily the result of thermal stability.

There has been, and will be, psychological resistance to oil showered inspection machines. We believe that this initial resistance will be overcome by the need to progress and the lack of practical alternatives.

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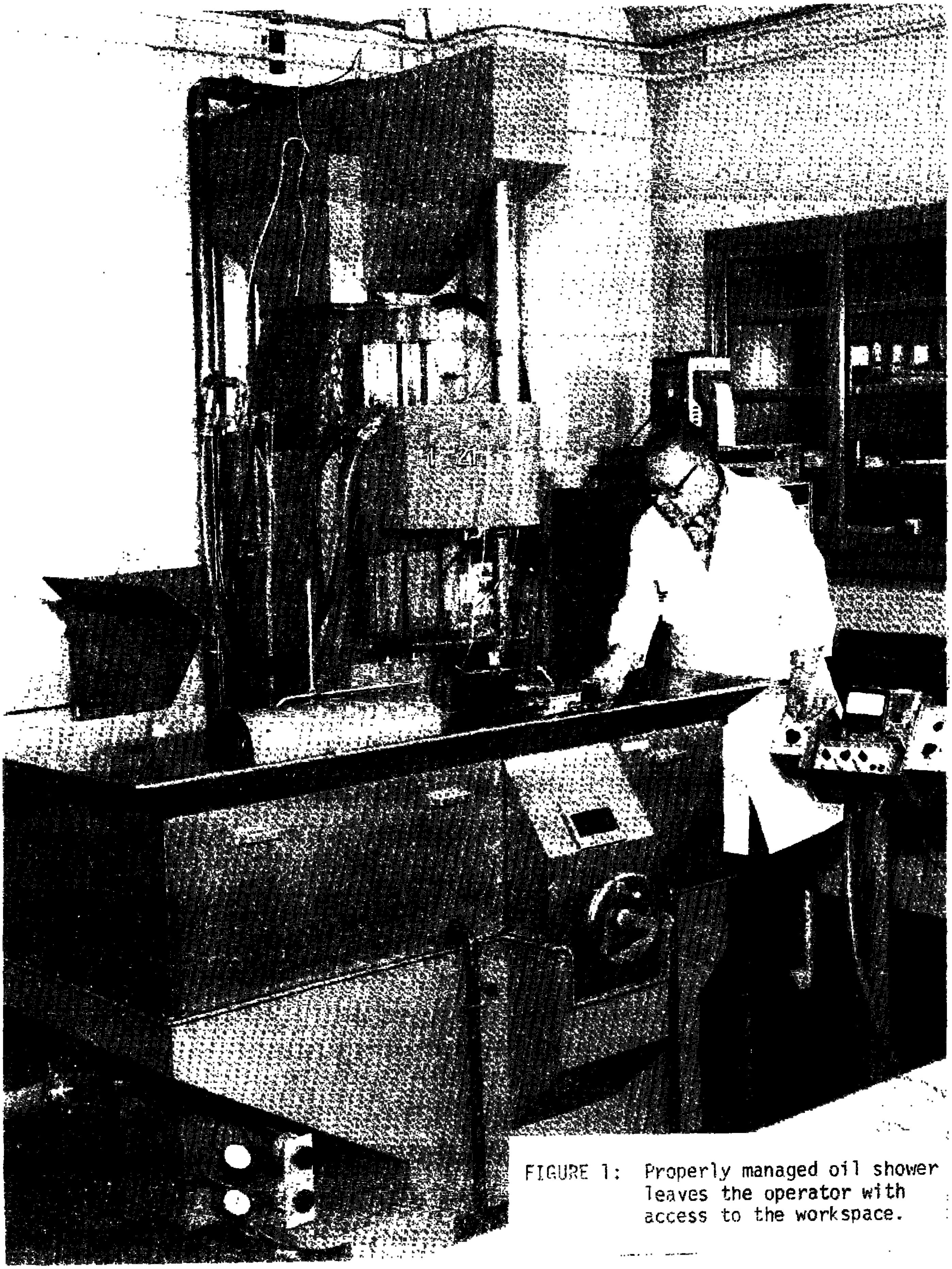


FIGURE 1: Properly managed oil shower leaves the operator with access to the workspace.

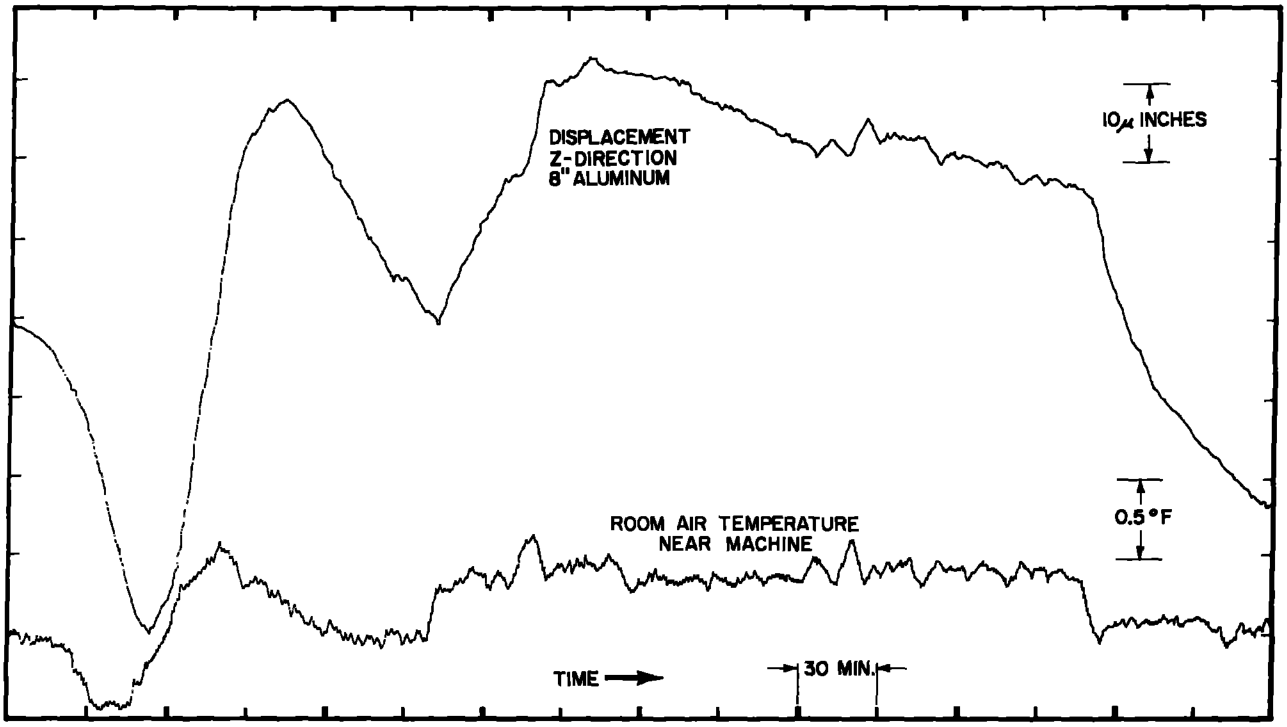


FIGURE 2: A drift test conducted without oil shower over an 8 hour period shows how the observed measurement of an 8 inch tall aluminum cylinder changes with varying room temperature. Note that the room temperature is being held to ± 1/2°F.

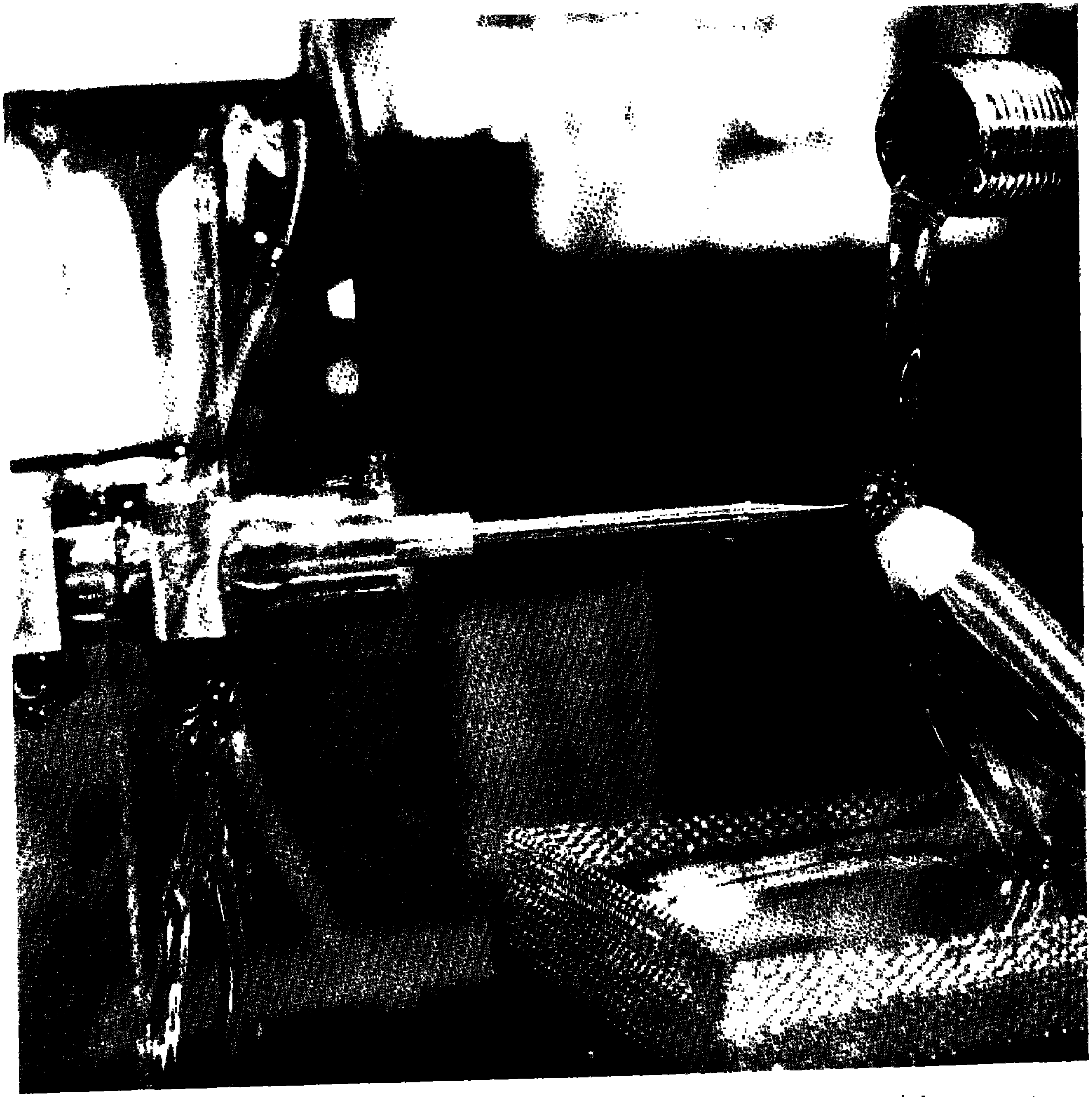
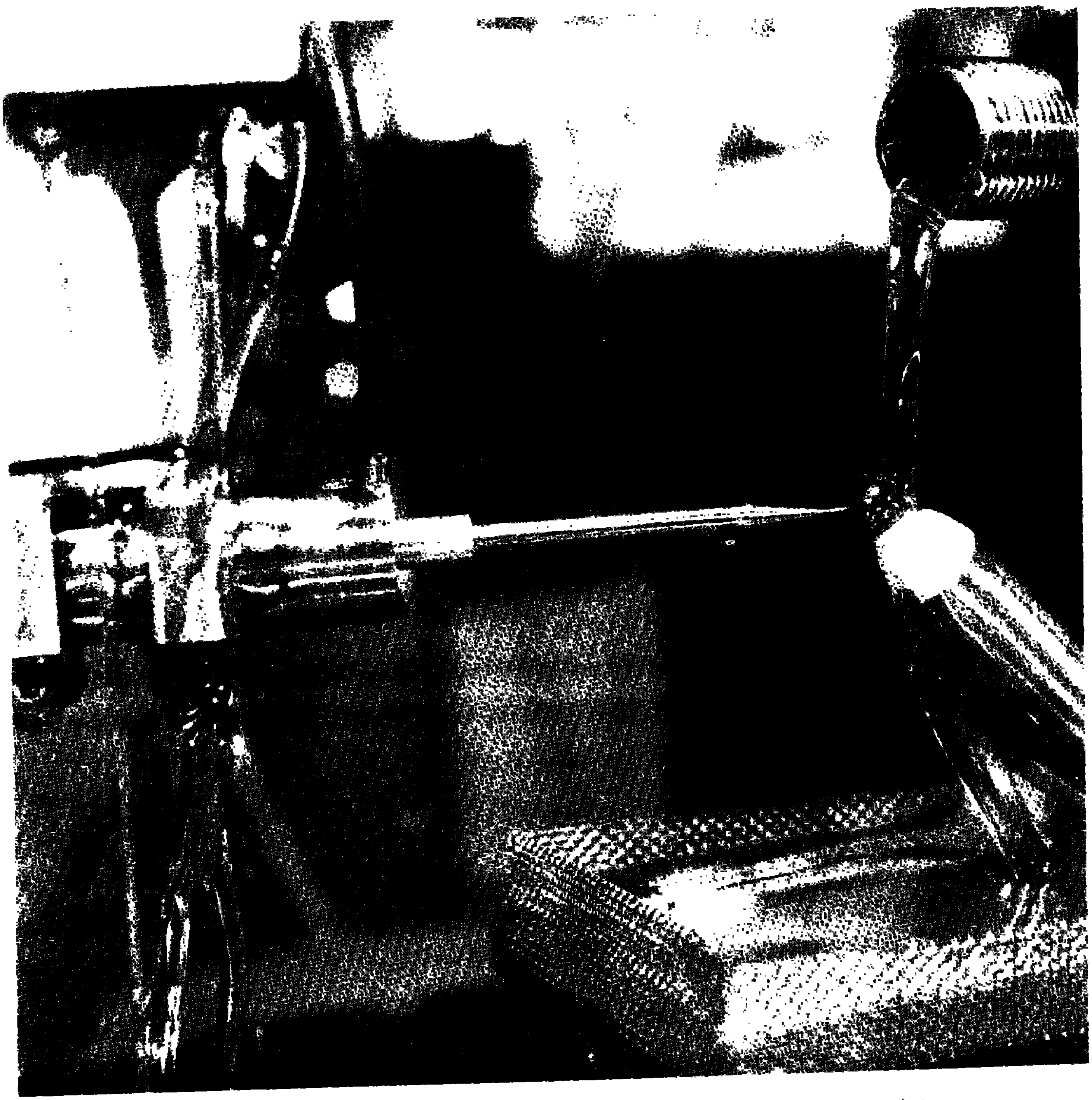


FIGURE 3: The air bearing LVDT bracketed from the Z-axis slide is used to measure size and contour of a ball. The stylus force is adjustable. A force of 0.2 grams is typical.

FIGURE 4: The resolution of the digital displacement displays (X, Y and Z) is 0.5 microinch. Recording of the LVDT analog signal is by either the polar or the linear recorder.



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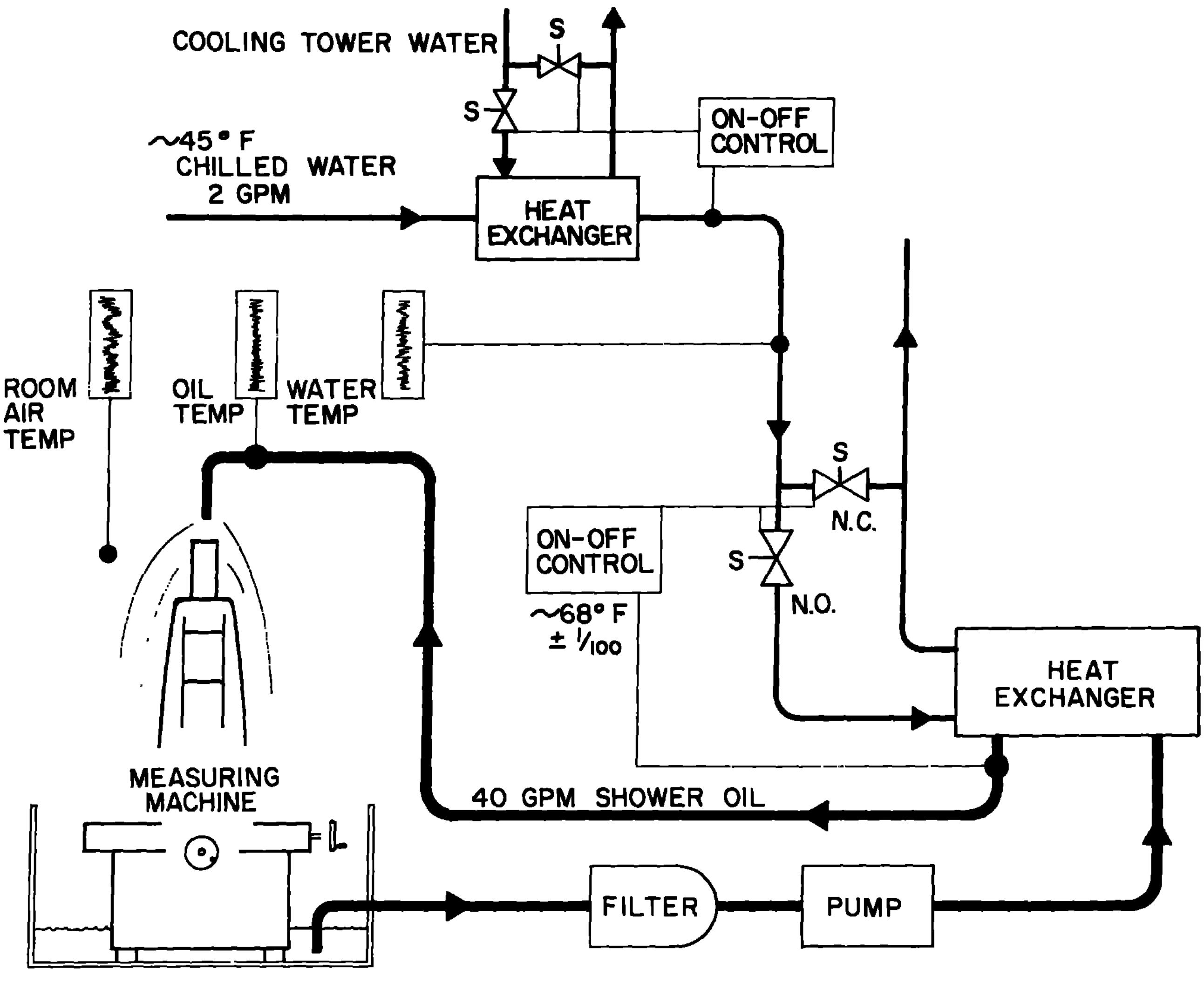


FIGURE 5: The control system maintains the shower oil at a nominal 68°F. The maximum temperature variation, when averaged over 30 seconds, is 0.01°F.

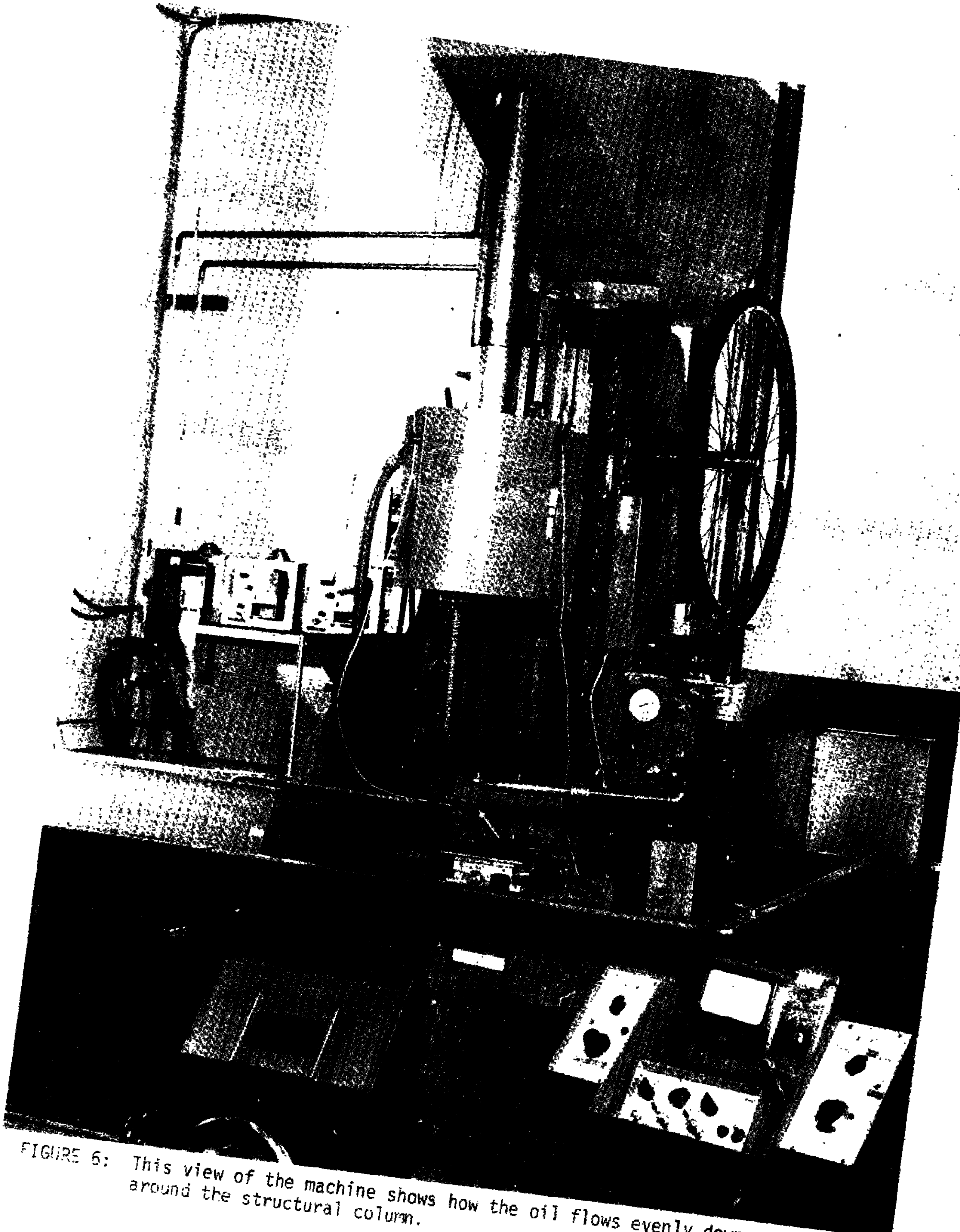
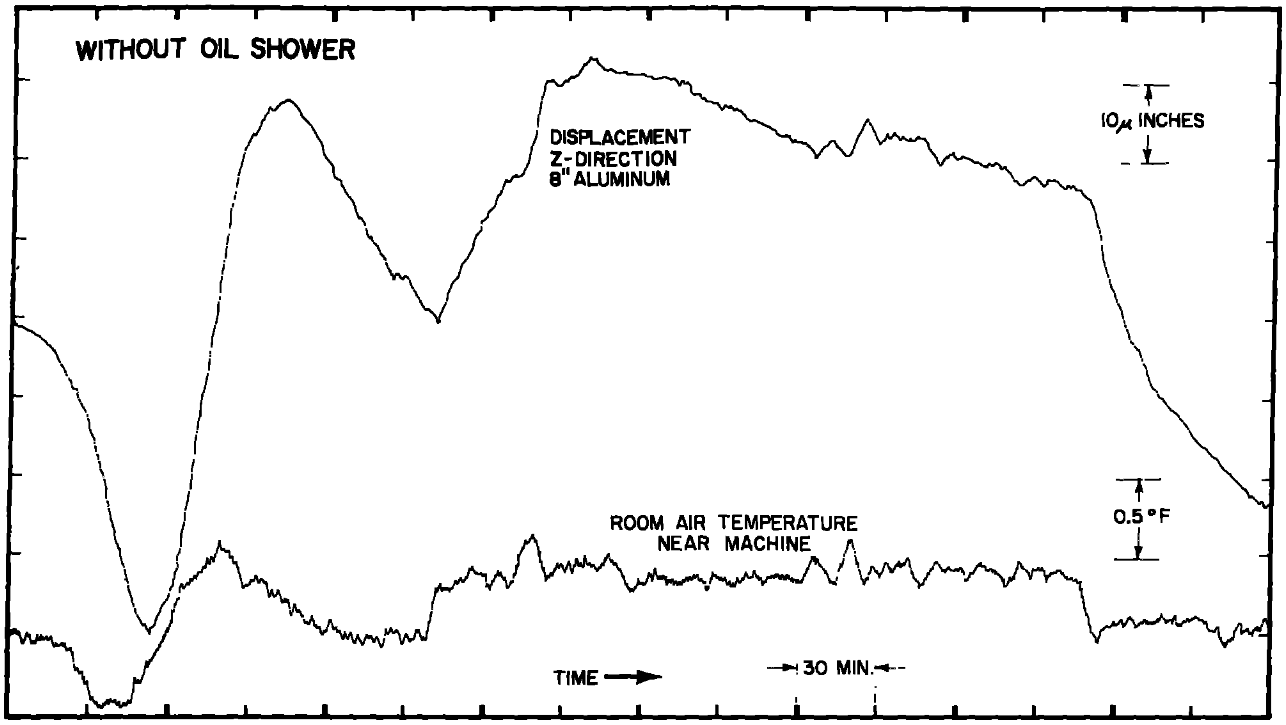


FIGURE 6: This view of the machine shows how the oil flows evenly down and around the structural column.



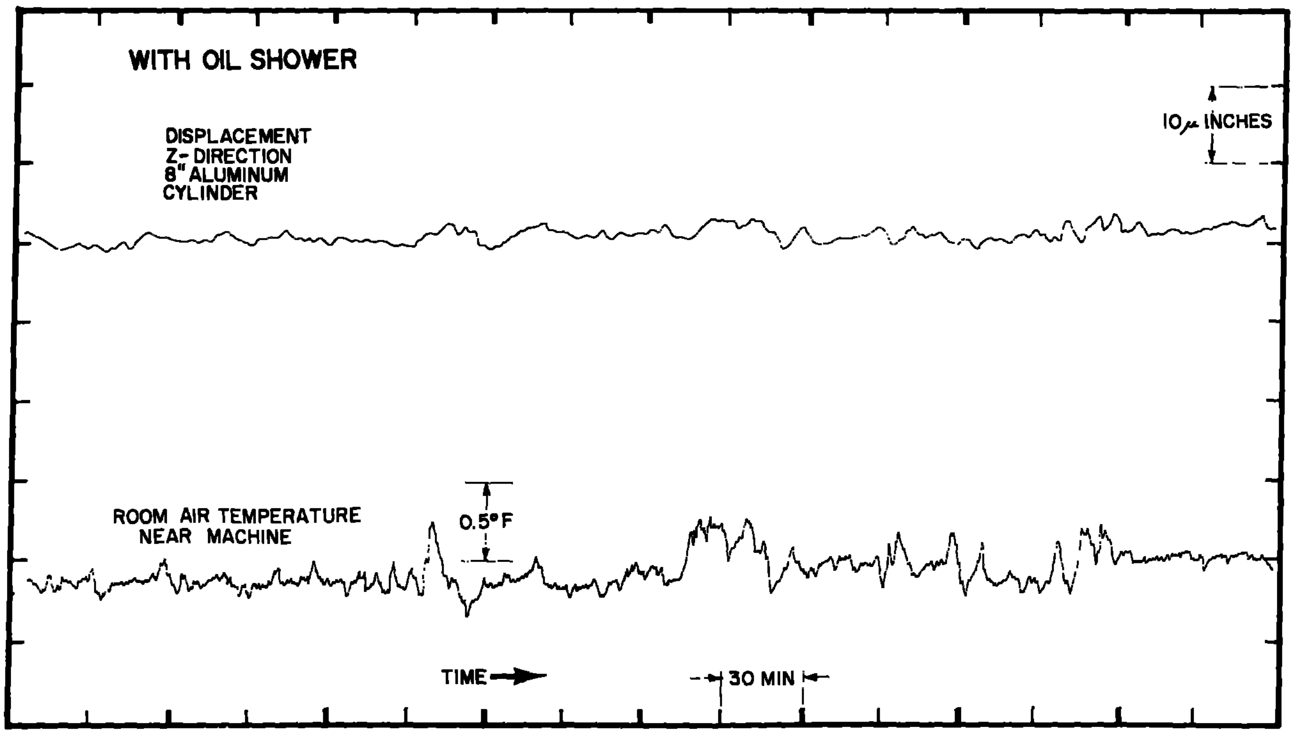
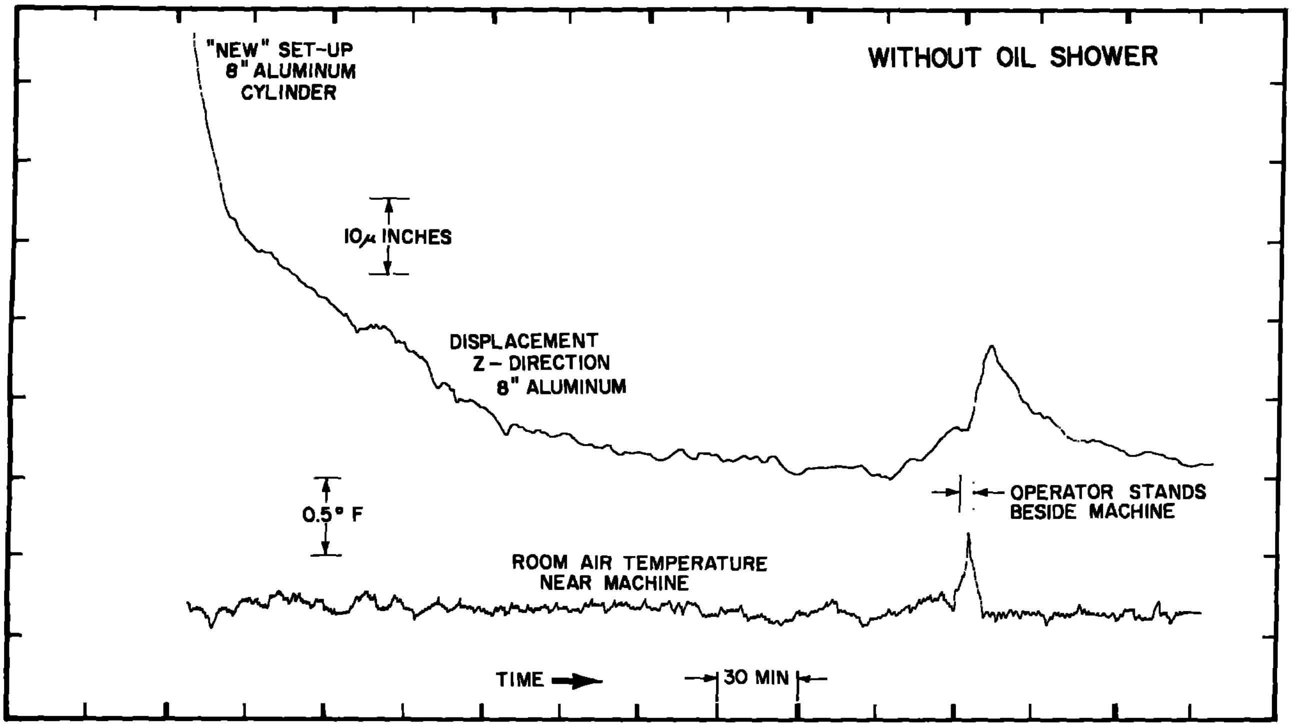


FIGURE 7: An order of magnitude improvement in thermal stability with the use of liquid shower is demonstrated with these drift test results.



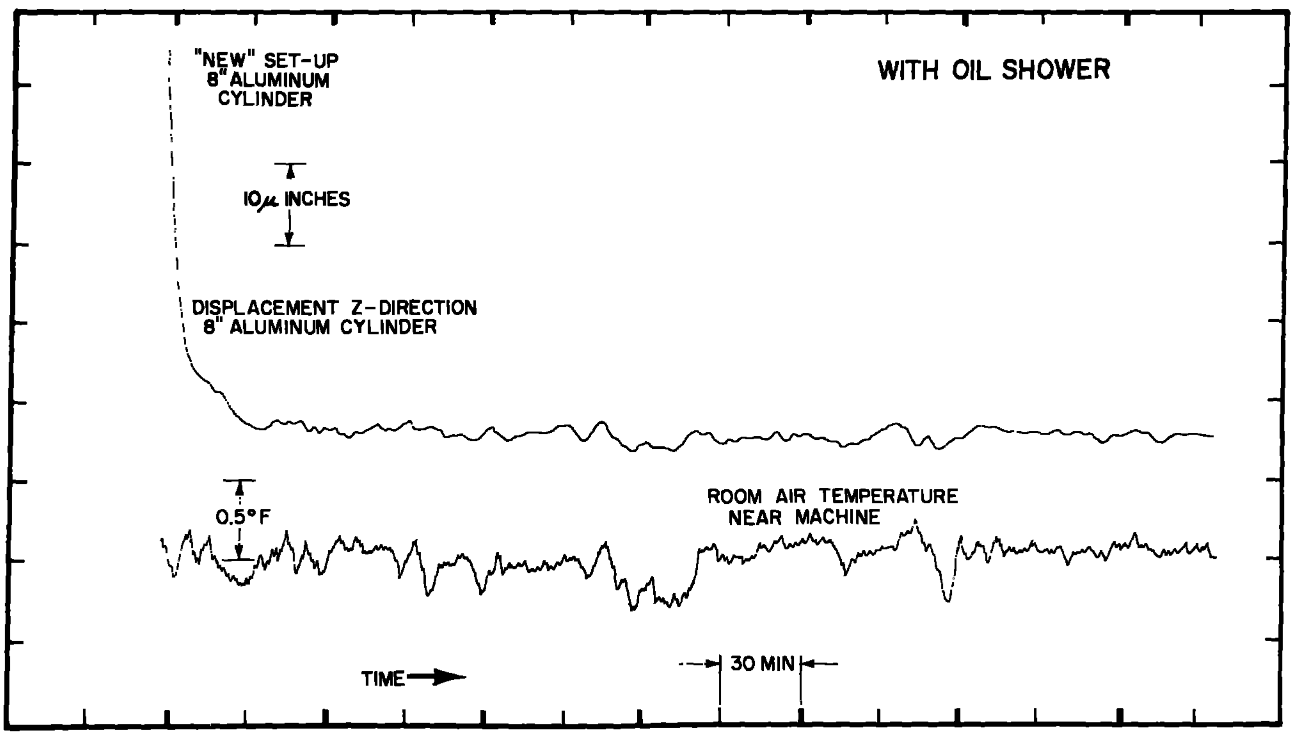


FIGURE 8: The soak out time with oil shower is an order of magnitude faster than without oil shower.

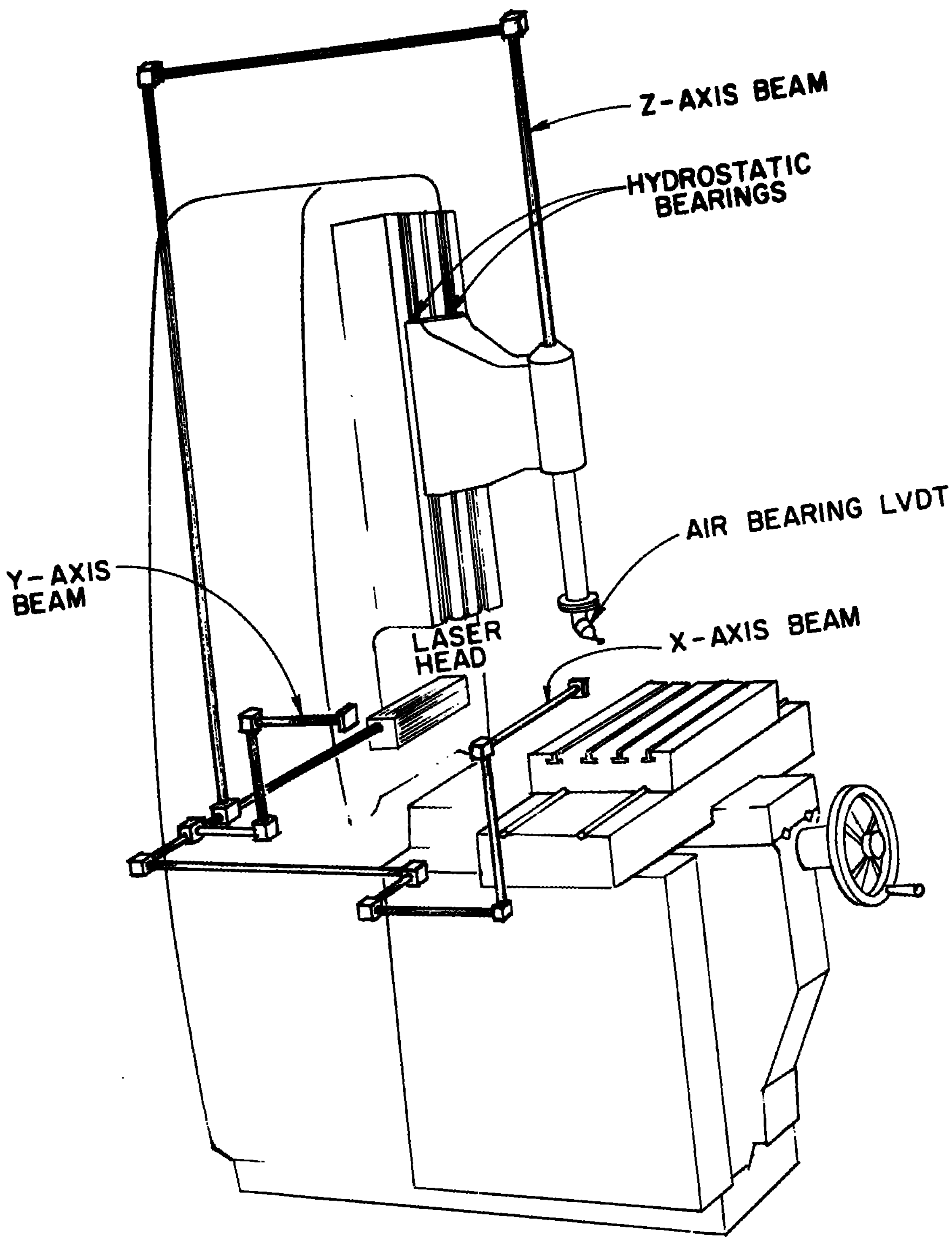


FIGURE 9: Placement of the laser paths satisfies the Abbe Principle in the Z-axis and minimizes the Abbe offset in the X and Y-axes.