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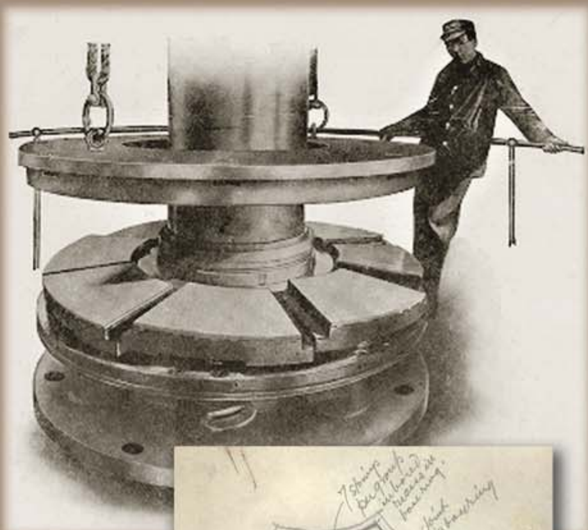
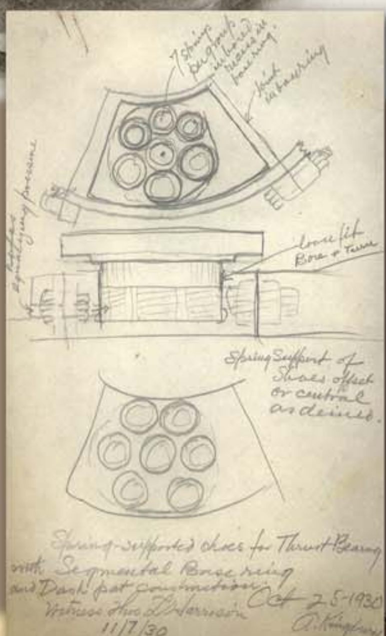
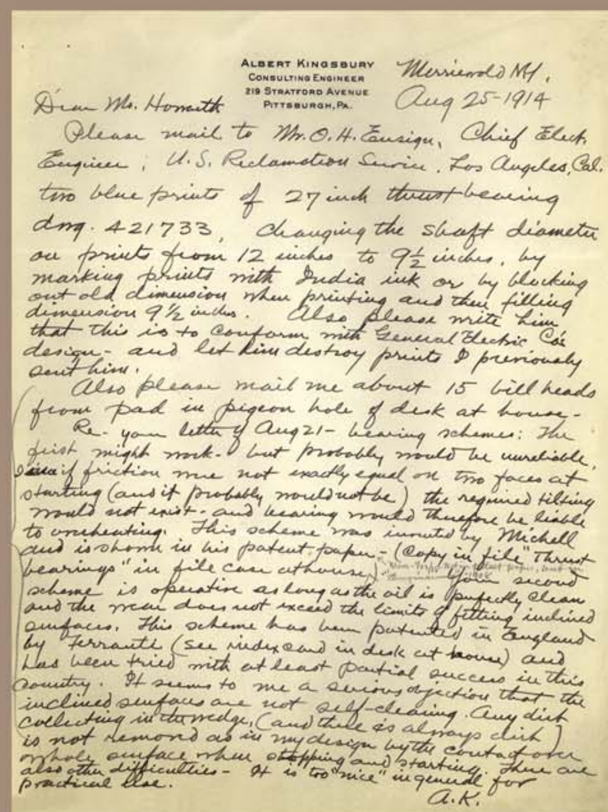
MACHINERY RELIABILITY OCTOBER 2003

Kingsbury Bearings







ALBERT KINGSBURY
CONSULTING ENGINEER
219 STRATFORD AVENUE
PITTSBURGH, PA.

Merriewold N.Y.
Aug 25-1914

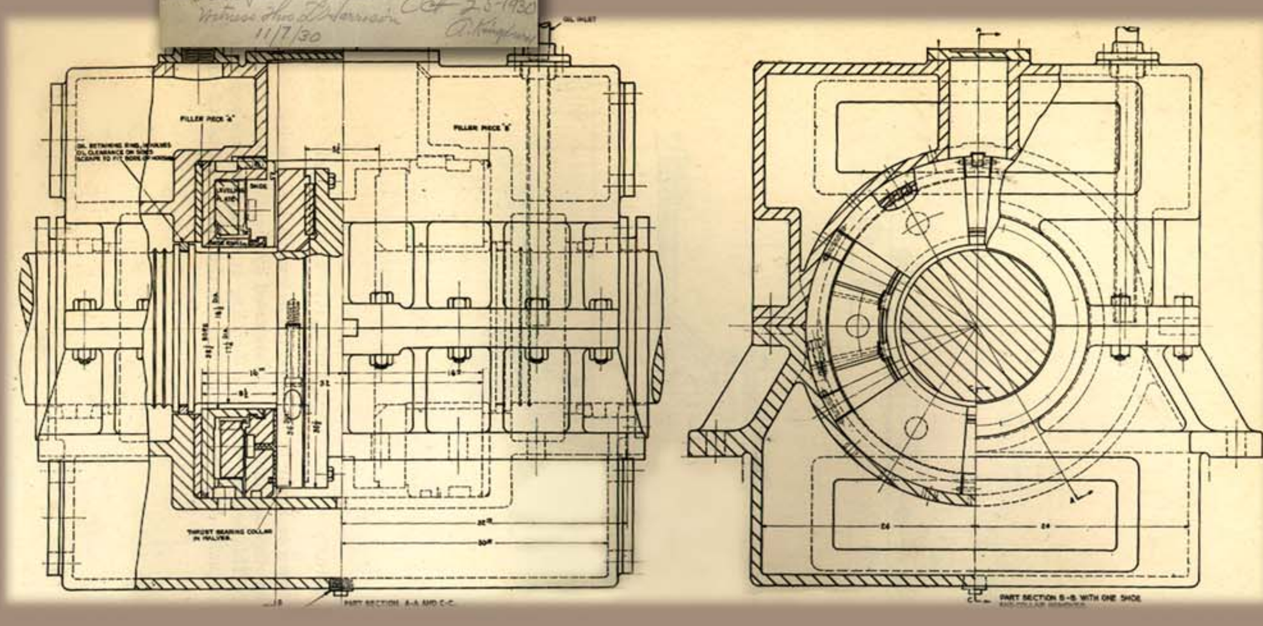
Dear Mr. Howarth

Please mail to Mr. O. H. Ensign, Chief Elect. Engineer; U.S. Reclamation Service, Los Angeles, Cal. two blue prints of 27 inch thrust bearing drg. 421733, changing the shaft diameter on prints from 12 inches to 9½ inches, by marking prints with India ink or by blocking out old dimension when printing and then filling dimension 9½ inches. Also please write him that this is to conform with General Electric Co's design- and let him destroy prints I previously sent him.

Also please mail me about 15 bill heads from pad in pigeon hole of desk at house-

Re- your letter of Aug 21- bearing schemes: The first might work- but probably would be unreliable, Sau if friction were not exactly equal on two faces at starting (and it probably would not be) the required tilting would not exist- and bearing would therefore be liable to overheating. This scheme was invented by Michell and is shown in his patent paper- (copy in file "Thrust bearings" in file case at house.) Your second scheme is operative as long as the oil is perfectly clean and the wear does not exceed the limits of fitting inclined surfaces. This scheme has been patented in England by Ferranti (see index card in desk at house) and has been tried with at least partial success in this country. It seems to me a serious objection that the inclined surfaces are not self-cleaning. Any dirt collecting in the wedge, (and there is always dirt) is not removed as in my design by the contact over whole surface when stopping and starting. There are also other difficulties- It is too "nice" in general for practical use.

A.K.



Albert Kingsbury – His Life and Times

Jim McHugh, Consultant, Tucson, Arizona

This article is a tribute to a great American inventor, teacher and entrepreneur. His invention of the tilting pad thrust bearing more than 100 years ago eventually revolutionized thrust bearing designs, permitting a more than ten fold increase in acceptable unit thrust loads on rotating machinery while simultaneously drastically lowering frictional losses. This article briefly traces how the unique qualities of Albert Kingsbury brought about this fundamental innovation despite the obstacles he faced.

The tilting pad thrust bearing was first conceived and tested by Albert Kingsbury (Figure 1) more than 100 years ago and eventually revolutionized thrust bearing design. It allowed a more than tenfold increase over existing design unit loads, with a simultaneous reduction in frictional forces of the same or greater magnitude. It is a design concept of elegant simplicity which has remained essentially unchanged since its introduction. It has been applied to perhaps hundreds of thousands of rotating machines with unparalleled success – to ship propeller shafts, steam and gas turbines, hydro-generators, pumps, compressors, etc. The use of this bearing has added immeasurably to the life, reliability and economic performance of such machines now for scores of years.

The story of how this bearing concept was born and carried into fruition is largely the tale of how one man's practical training, education, insight and determination combined to persevere over obstacles and skepticism. But the story of the tilt pad bearing alone does not convey the contributions of this individual. It was undoubtedly his most important invention, although not his only one. A review of the Patent Gazette shows that over fifty patents were issued to Albert Kingsbury from the years 1902 to 1930 alone. The list includes patents on a friction clutch, a gear cutting machine, collector rings for a dynamo-electric machine and a standard measuring machine, to mention just a few.

Albert Kingsbury started with little except his native talents. At the close of his life, he was a highly regarded educator and philanthropist, a businessman who founded his own company and spawned many others and a major contributor to the science of tribology. Those whose lives he touched directly through his teaching, research and business regarded him as a gentleman. He was a unique, admirable not only for his times, but for ours as well.

To fully appreciate his contributions, we need to step back and visualize the times into which he was born, educated and persevered through uncertainties to make his place in lubrication history.

A Glimpse of the U.S. in Kingsbury's Youth

Albert Kingsbury was born in Morris, IL in 1863 at the time when Abraham Lincoln was serving as a controversial president, both loved and hated. Civil war was raging between the States and the outlook for peace was not promising. It was the year of Lincoln's Emancipation Proclamation, freeing three million slaves. Within two years, Lincoln would be assassinated and the war would be over. Andrew Johnson would be president. The Massachusetts Institute of Technology would open its doors, but the existence of the University of Chicago would still be 27 years in the future.

Seventeen years later, Kingsbury was one of three boys in the first high school graduating class of eight students at Cuyahoga Falls, OH. In the year of his 1880 graduation the United States consisted of only 39 states. The land expanse from "sea to shining sea" was interrupted by territories, such as Idaho, Montana, the Dakotas, and New Mexico. The entry of Arizona, the last territory, into the Union was still 32 years distant.

At the time of Kingsbury's birth the United States population was less than 40 million; most people lived on farms or in small villages. By the time of his high school graduation in 1880 the total population of the United States had increased 25% to 50 million people. New York City ranked No.1 in population with 1.2 million. Only 20 cities had populations more than 100,000, compared with 195 cities in 1990. In 1880 the city of Springfield, IL ranked 100th with nearly 20,000 people. The average American earned less than $10 per week. Women, of course, could not vote or even own property in many states. It would have been difficult to believe that the United States nevertheless was poised at the threshold of a major shift from a farming economy to an industrialized nation.

Following his high school graduation Kingsbury continued studying for a year at what is now the University of Akron in a Scientific-Latin course. Dropping out for three years from his formal education, he worked as a machine apprentice in Cuyahoga Falls doing "heavy work" on machinery for wire drawing and clay making. As Kingsbury subsequently noted, this practical experience was to be of great value later as he advanced his engineering career.

He resumed his formal studies at Ohio State University in September 1884 as a freshman in mechanical engineering. After two years, being "low in mind and funds," he again dropped out of school to go to work for a year. Part of that time he worked as a machinist on 16 in. lathes at the Warner and Swasey Company, Cleveland, OH, making parts for the famous Lick Observatory telescope.

Once again Kingsbury was able to resume his engineering education, this time entering Cornell University as a junior in mechanical engineering in the fall of 1887. This was to be a critical decision, shaping his career by exposing him to Cornell Prof. Robert Thurston's deep interest in friction, its detrimental effect on machinery and ultimately the national economy (Figure 2).

What was life in the United States like when Kingsbury was pursuing his academic and practical training? Photographs obtained from the Cornell University Archives show some typical engineering student scenes of that time. Figure 3 shows Prof. Thurston lecturing to his class. Figures 4 and 5 show a drafting class and a foundry lab for Cornell engineering students.

Steam and electric carriages had already been in existence for many years, as well as internal combustion engines using mixtures of gas and air for fuel. But horse-drawn carriages and bicycles were still the predominant form of local transportation. The electric lamp was a laboratory curiosity. Illumination was provided mainly by lamps using kerosene rather than whale oil, since the Civil War had disrupted the availability of whale oil and doubled its price.

Oil had been discovered in Titusville, PA only three years before Kingsbury was born. By the early 1880s, when he was barely out of high school, 85% of the world's crude oil came from these Pennsylvania oil fields. Most of this crude oil was refined to produce kerosene. Electric lamps for common household use were more than 10 years away. Gasoline was considered a useless by-product of the distillation process. It would not emerge as a major distillation product for more than 30 years.

Science and technology – the application of science – were

Based on a paper presented at the 23rd Annual Meeting of the Vibration Institute, Orlando, FL, June 1999.

Figure 1. Albert Kingsbury.

Figure 2. Cornell University Professor Robert H. Thurston.

blossoming in the 1880s at an exhilarating rate. The American Society of Mechanical Engineers was founded in 1880 with the eminent Prof. Robert H. Thurston, then at the Stevens Institute, as its first president. Within a few years, as a professor at Cornell, he would have a pivotal role in shaping the career of young Albert Kingsbury.

Events and Innovations During 1880-1890

Among the major events and innovations of this period were:

- Establishment of a central electricity generating station by Edison in 1882 to provide power for his newly patented electric lamps.
- Completion of the Brooklyn Bridge in 1883.

Figure 3. Lecture hall, Sibley College, Cornell University (ca. 1885).

Figure 4. Drafting class, Sibley College, Cornell University (ca. 1885).

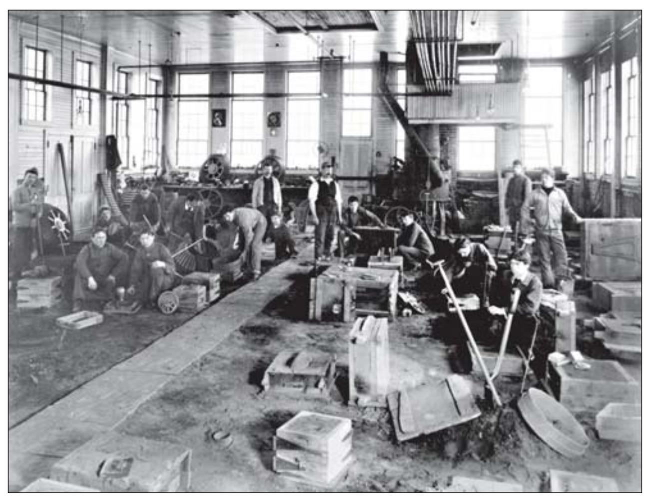


Figure 5. Foundry lab, Sibley College, Cornell University (ca. 1885).

- Invention of the first successful steam turbine by Charles Parson in 1884.
- Granting of a patent to George Eastman for photographic roll film in 1884.
- Building of the first skyscraper (10 stories tall) in Chicago in 1885.
- Building of the first hydroelectric station at Niagara Falls in 1886.
- Discovery of radio waves by Heinrich Hertz in 1887.
- Invention of the alternating current motor by N. Tesla in 1888.
- Assassination of president James Garfield in 1881.
- Succession of Chester Arthur to the presidency (1881-1885).

Albert Kingsbury would be only 27 years old at the end of

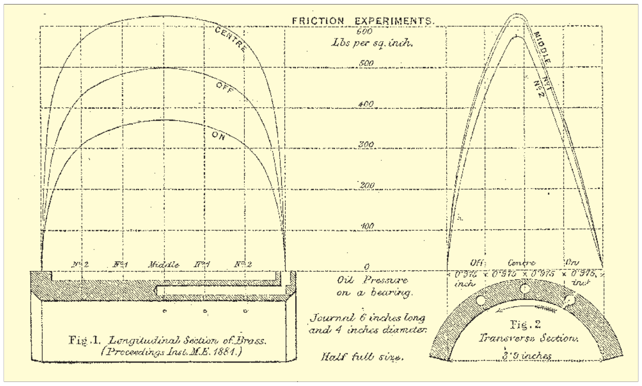


Figure 6. Tower's measurements of pressures developed in a journal bearing.

that decade. It would clearly be a time of great hope for a promising young man beginning a career.

The Status of Tribology in Kingsbury's Youth

The term tribology with its Greek roots for the study of rubbing did not come into existence until 1966, many years after Kingsbury's death. It seems likely, however, given his interest in classical languages, he would have been delighted to adopt this term with its broader meaning than lubrication. It is clearly impossible to do an adequate job of summarizing the status of tribology at that time in a few paragraphs. At best, only a very broad brush treatment can be given to provide some perspective.

Rolling element bearings had been in use for hundreds of years. Leonardo da Vinci had conceived of ball and roller bearings about the year 1500. John Garnett received a British patent in 1787 on a rolling element bearing containing the essential features of today's bearings – races, cages and balls. Many patents had been issued for carriage and velocipede axle bearings in the intervening years. The development of these bearings was hampered by manufacturing limitations on producing identical size balls, inability to calculate contact stresses produced by ball loading, and the low strength of available materials under cyclic stresses. Major steps forward were made when H. R. Hertz developed the equations for contact stresses in balls and rollers in 1881, and steel balls were first made in 1890 to a tolerance of ±0.001 in. In a few more years that tolerance would be cut in half.

Plain bearings (journal and thrust) had been in use since days of antiquity. Design of such bearings was mostly empirical, and long life was an elusive goal. The chief concern for many hundreds of years was to find a material or combination of materials which would reduce friction and wear. Da Vinci had tested a babbitt-like material consisting of "three parts of copper and seven of tin melted together" about the year 1500. Isaac Babbitt had received a U.S. patent in 1839 for a tin-based alloy, consisting of 89% tin, 9% antimony and 2% copper. A variety of materials had been tested over the years with various degrees of success: cast iron, steel, brass, wood and alloys of copper and tin. Studies of dry friction had been made in the 1600s by Amontons and nearly 200 years later by Coulomb, both of whom had formulated friction laws.

Railroads had assumed an increasing role in economic life both in the United States and abroad. By 1880, nearly 100,000 miles of track existed in the U.S. alone. This spurred a renewed interest in journal bearing friction, wear and the role of lubrication. G. A. Hirn in 1854 published the results of bearing friction tests using various lubricants, and was the first to observe lubrication only with air. N.P. Petrov published in 1883 the results of tests in Russia on the friction in lubricated journal bearings. As in the United States and England at that time, Petrov's tests were largely motivated by problems with railroad bearings.

In 1885 Prof. Thurston published his book *Friction and Lost Work in Machinery and Millwork*, which continued in print in updated editions until 1907. This book is widely credited with awakening interest in the economic cost of friction and wear.

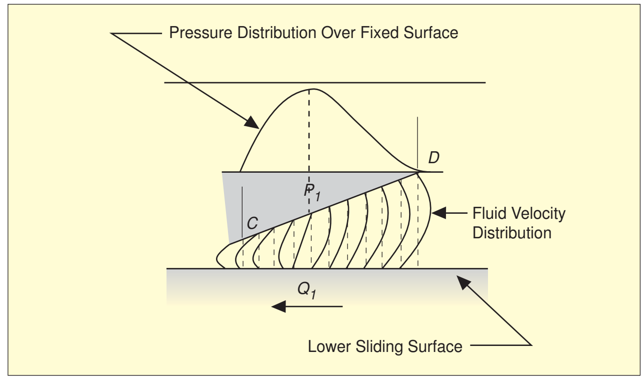


Figure 7. Pressure distribution in tapered slider (after Reynolds).

The most important events regarding lubrication in this period, however, were the accidental discovery of full film lubrication by Beauchamp Tower in 1883, and the subsequent explanation of the results by Osborne Reynolds in a landmark paper of 1886. These events marked the beginning of our current scientific understanding of bearings. At the time of Tower's tests, a 20-year-old Albert Kingsbury was working as an apprentice machinist. Neither he nor the already renowned Professor Thurston were aware of these developments, or could possibly foretell where they would lead.

Revolutionary Discovery of Film Lubrication by Tower

When Kingsbury was still a sixteen-year-old high school student, the Institution of Mechanical Engineers in England had formed a Research Committee. Its purpose was to propose proper subjects for research. As its third recommended choice, "should time and money be found to be sufficient," the committee recommended an investigation of "friction between solid bodies at high velocities."

By 1882 sufficient funds had been obtained to proceed, and the Committee had appointed Beauchamp Tower to build the test device and find "the friction of revolving shafts, the safe and unsafe load per square inch to put on the bearings at various velocities, with various materials, and with various lubricants . . ." Tower was to be engaged in these tests from 1882 to 1891.

He built a test device to measure friction forces on gunmetal half bearings 4 in. in diameter and 6 in. long, running on a steel journal at various speeds. Lubricant was to be supplied through a small hole at the top of the bearing, directly in the load line. Tower quickly found out that the friction coefficient varied so much under a given set of conditions that he could not assign a value to the coefficient. He decided to plug up the top lubricant supply hole, and place the journal lower half in an oil bath.

Tower found out in two attempts to block the supply hole that the plugs were forced out by oil pressure developed during rotation of the journal. Pursuing this discovery by drilling more holes in the brass, he mapped the pressure existing over the bearing surface. The integrated product of measured pressure times bearing area (7988 lbs) was found to be almost exactly equal to the applied load (8008 lbs). Tower correctly concluded that the entire applied load was being carried by a thin film of oil. Although he did not know why this happened, he did know that the oil bath made it possible to get a consistent friction coefficient for a set of test conditions. He had discovered full film lubrication.

When Tower presented the results shown in Figure 6 to the Research Committee, the potential significance was not lost on its members. One comment was "the chief advantage derived from the experiments was that they showed that, if the bearing was perfectly lubricated by immersion in an oil bath, almost any load might be put on;" another stated that "if the bearing was fully supplied with oil it was more a question of the nature of the oil than of the nature of the materials."

Tower himself expressed the opinion that "the important practical inference was that it was actually possible so to lubricate a bearing that metallic friction be altogether done away with . . . but metallic wear and tear would also be done away with." In other words, a new phenomenon was discovered that might put an end to hundreds of years of searching for the perfect bearing material.

However there were skeptics outside the Research Committee. One person wrote in response to an editorial in the *Engineer* (1884), "I anticipated that, Mr. Tower's researches would have some practical value; but as far as I can see they might just as well never have been undertaken . . . It seems to be the fate of the Institution of Mechanical Engineers to always carry out investigations of no practical value to anyone."

It was a criticism remarkably similar to one made several years later when Albert Kingsbury published his studies on friction in screw threads. In the course of those tests he had accidentally observed air lubrication. The myopia of Tower's critic is on a par with much later ones who doubted that the gas turbine engine had a role to play in aviation.

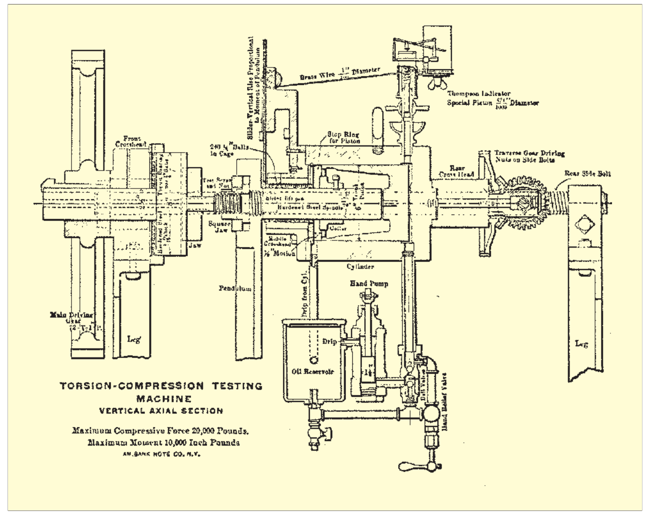


Figure 8. Kingsbury device for measuring friction in screw threads.

The Theory of Film Lubrication by Osborne Reynolds

Tower's results clearly proved the existence of a load-carrying oil film, but he did not advance an explanation or theory as to why this phenomenon occurred. That was to come within three years after the publication of Tower's results. The experiments had come to the attention of Professor Osborne Reynolds at the University of Manchester in England. Reynolds had already distinguished himself by his classical paper on the flow of fluids in pipes and channels. This paper showed that there was a critical ratio of fluid parameters at which fluid resistance changed with velocity from a simple ratio to its square, i.e., the Reynolds number.

Reynolds applied his considerable mathematical talent and insight to produce a comprehensive 77 page paper in 1886 that explained Tower's results. The Reynolds lubrication equation presented in this paper became the starting point for most scientific lubrication papers for the next 100 years.

In essence, Reynolds demonstrated that a converging wedge or clearance in the direction of motion was required to develop pressure in a journal bearing as shown in Figure 7. In a journal bearing, the converging wedge is produced by the displacement of the journal in the bearing. A pressure is developed in the wedge to match the imposed load. The distribution of pressure in the wedge depends on the bearing clearance, the surface speed and the lubricant viscosity.

The clearance of the bearing in Tower's tests was not known, nor was the lubricant viscosity, which changes with temperature. Reynolds ran tests to establish the relationship between viscosity and temperature for olive oil, an accepted lubricant of the time, and formulated an equation for it. He was able to infer the clearance from Tower's careful measurements of bearing friction and temperature. Taking these factors into account, he could match theoretically the lubricant pressures measured by Tower. He could then state that his hydrodynamic theory was "in complete accordance with the experiments of Mr. Tower."

In addition to the case of a rotating cylindrical surface within a stationary sleeve (the journal bearing), Reynolds also studied the case of parallel surfaces approaching one another (the squeeze film) and the case of sliding surfaces with a taper in the direction of motion (the tapered slider). The complexity of the equations, however, prevented him from their solution except in certain limiting cases. Nevertheless, the paper remains a classical work both for its mathematical development and the clarity of its illustrations.

Kingsbury's Tests on Journal Bearings at Cornell

The year after Reynolds's paper had been published in the *Philosophical Transactions of the Royal Society of London*, Albert Kingsbury entered Sibley College of Cornell University as a 24-year-old junior in the mechanical engineering class. The head of Sibley College was Robert H. Thurston, whose work in the field of lubrication had already earned him an international reputation. In England, Tower's Research Committee was well aware of Thurston's work. His research on friction in bearings had shown that the friction coefficient of a loaded journal decreased with increasing load until a certain minimum was reached. Then the coefficient increased rapidly with further load increases. This behavior contrasted sharply with Amonton's laws of dry friction in solids formulated nearly 200 years earlier. Similarities also existed in Tower's apparatus and Thurston's earlier device for friction measurements. But neither Thurston nor Kingsbury was then aware of Tower's tests or Reynolds's explanation.

In an interesting parallel to the tests of Tower, which were largely motivated by railroad bearing problems, Professor Thurston also had a contract with the Pennsylvania Railroad to test different candidate bearing materials. The objective was to establish which were best from a friction and wear standpoint. Kingsbury was assigned by Thurston to continue with these tests, many of which had been previously tested by other students with widely varying results.

Kingsbury approached this task by using the skills he had acquired as a machine apprentice. He carefully fitted the half-bushings to the journal by scraping. As we now know, this hand fitting produces the small diametral clearances which promote film lubrication. When Kingsbury ran tests on the five bearing samples, none showed any measurable wear. He reported this fact to Thurston, who had no explanation for this totally unexpected result. He suggested that Kingsbury try kerosene as the lubricant to show a difference among the materials.

Further tests produced the same results – no wear on any of the materials. But they did show a friction coefficient of 0.0005, lower than had ever been previously reported. Since the tests showed no difference among the materials, the Pennsylvania Railroad concluded that there was no point in further testing. They canceled the contract with Thurston. Rather than killing his interest in this field, this experience left Kingsbury with an unquenched desire to fathom the mystery he had observed. It was the beginning of his life long interest in understanding the phenomenon of lubrication.

Kingsbury graduated from Cornell University in 1889 at 26 years of age. His thesis was the design of a 16 in. lathe, demonstrating that his interest was not confined to research, but included the manufacturing side of engineering as well.

Kingsbury – The Teaching Years

Prof. Thurston had recommended the new graduate for an open teaching position at a college in Hanover, NH which would later move to Durham and become the University of New Hampshire. He was offered $100 a month, which seemed to him a princely sum, after having worked for years to pay for his

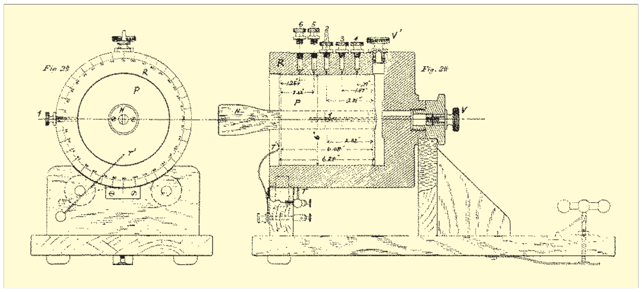


Figure 9. Kingsbury air bearing device.

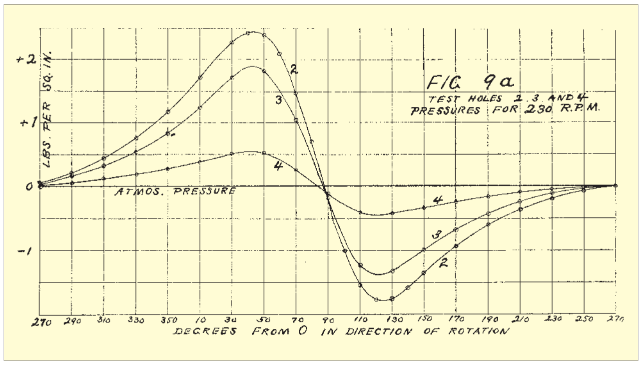


Figure 10. Kingsbury pressure measurements on air bearing model.

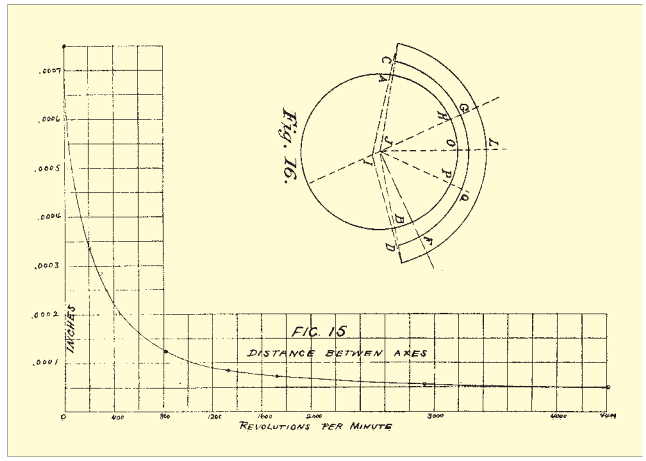


Figure 11. Kingsbury film thickness measurements on air bearing model.

college expenses. He taught courses in physics and mechanical engineering to 18 students. After a year teaching, he resigned from the University to help develop a brick-making machine invented by his cousin. When he was offered a full professorship at $2000 per year, he returned to the University. He became involved in its move to the new campus at Durham and was also placed in charge of its machine shop.

In his new position, Kingsbury was able to continue his interest in lubrication by building a test machine to measure the friction in coarse pitch, lubricated screw threads at loads up to 14,000 psi on the engaged thread surfaces. The novelty of the tester was that it provided a graphical trace of screw thread friction moment versus applied load. From this graph it was easy to establish the coefficient of friction for the test conditions.

A key component in this device (see Figure 8) was a hydraulic piston to absorb the applied thrust on the screw without resisting torque. The friction torque or moment on the screw then would be proportional only to the swing of a pendulum containing the nut for the screw thread. To minimize friction on the 6-inch diameter piston, it had no seals or packing. Instead, the 22-pound piston was very closely fitted to its mating cylinder with a diametral clearance less than 1 mil.

Kingsbury presented the screw thread test results at a meeting in December 1895 of the American Society of Mechanical Engineers. Following its presentation, Prof. Thurston commented that "this is the only considerable work which gives us reliable information . . . (on) friction of heavily loaded screws . . ." But another discusser stated, "I do not see how we people who have to use these things (screw threads) practically are going to derive very much benefit from the action of the apparatus shown."

In discussing his tests, Kingsbury brought up an interesting phenomenon he had observed with the piston-cylinder. With the cylinder in the vertical position and the piston given a whirl, it would spin quietly for more than five minutes with no contact with the cylinder wall. Moreover, even in a horizontal position the piston would spin without contact. He concluded correctly that a film of air was supporting the weight of the horizontal piston while it was spinning. He had discovered air lubrication, but did not know what mechanism produced this effect.

Kingsbury was intrigued by this observation and pursued it by building a heavier, solid piston weighing 50 pounds with a clearance of 1.6 mils on a 6 in. diameter. He also provided taps in the cylinder so he could measure the air pressure at various points around the rotating piston (see Figure 9). Unknown to him at that time, this is precisely what Tower had done several years earlier.

Kingsbury first learned about the work of Tower and Reynolds when he was demonstrating his device to the Navy. One of the audience was aware of the experiments of Tower and the lubrication theory advanced by Reynolds. He brought it to Kingsbury's attention. After studying these papers on his return to Durham, he recognized that they indeed resolved the mystery of his Cornell bearing tests nearly a decade ago, and explained his current air lubrication phenomenon.

In 1897 he published the results of his continued study in the Journal of the American Society of Naval Engineers as "Experiments with an Air-Lubricated Bearing." But Kingsbury had gone a step further than Tower, by providing a sensitive measuring device to measure the air film thickness as well as the developed pressures as shown in Figures 10 and 11. With it he was able to measure film thickness values to an accuracy less than 0.0001 in., an impressive achievement.

Hirn was the first to observe air lubrication, but Kingsbury was the first to carry out systematic tests on this phenomenon, even running tests with hydrogen. Air lubrication plays an important role in today's computers, providing the thin film which allows the read-write heads to function effectively.

The fertile mind of Albert Kingsbury saw in the theoretical work of Reynolds a possible solution to the long-standing, troublesome problem of thrust bearings. Reynolds had clearly shown that two flat surfaces undergoing relative sliding would develop a load-carrying pressure if there were a slight inclination between them. Kingsbury also recognized that a center of pressure existed for that pressure distribution. He reasoned that if one of the flat surfaces had a pivot located at the center of pressure, it would tilt automatically to form the converging wedge.

Kingsbury envisioned a new type of thrust bearing consisting of several stationary arc segments facing a thrust collar on the rotating shaft. Each segment would have a boss on the side away from the thrust collar, allowing it to tilt and form an oil wedge that would carry the thrust as shown in the sketch of Figure 12. But the theory of Reynolds required that the pivot point be somewhat beyond the midpoint from the leading edge. For reverse rotation, the pivot would then be in the wrong place to create oil film pressures.

Kingsbury decided to try out his concept, using a centrally pivoted pad, despite the existing theory. Modifying his screw thread testing machine to test his thrust bearing concept, he carried out successful tests at unit pressures up to 4000 psi with a speed of 285 rpm. This pressure exceeded by a factor of 80 to 100 common design values for collar-type thrust bearings.

In 1889 Kingsbury left Durham to accept a position at Worcester Polytechnic Institute, which permitted him to pur-

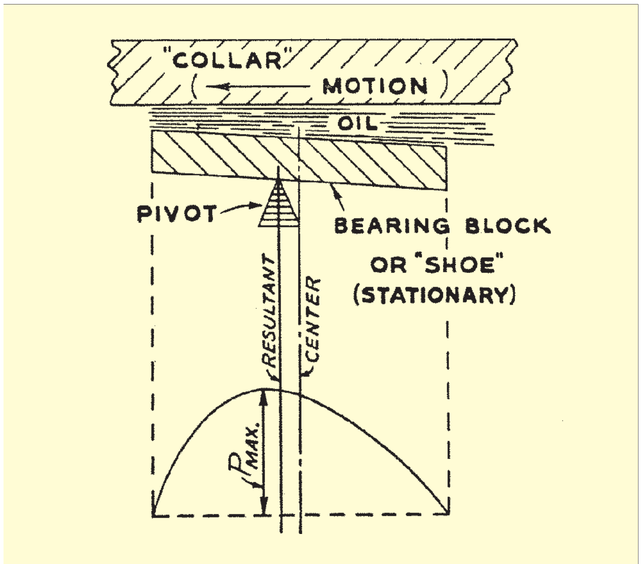


Figure 12. Kingsbury's sketch of pressure distribution in offset shoe.

sue his interest in lubrication. He was able to expand the laboratory facilities by persuading his former college president to transfer most of his test machines to Worcester. He also continued his tests on a centrally pivoted thrust bearing with the aid of his students.

Kingsbury – The Westinghouse Years

After fourteen years of teaching and research, Kingsbury changed roles to become a "general engineer" with Westinghouse at their East Pittsburgh Works. This gave him an opportunity to expand his store of knowledge to include electrical equipment. It also gave him the opportunity to promote the use of his thrust bearing concept for large vertical electric motors, which currently relied on rolling element bearings.

His first attempt in 1904 to use his bearing was unsuccessful – the bearing ran hot and was discarded. He concluded later that he used too conservative a unit thrust load (50 psi), and the bearing was therefore too big, and prone to run hot. Five years later he was able to persuade Westinghouse to give him a second chance, again on a large vertical motor. But he had to pay for the bearing parts out of his own pocket.

Despite the success of his oil film bearing in shop tests, the motor was shipped with the original ball-bearing, which had already shown distress signs after only a day or two of shop running. Kingsbury had the satisfaction, however, that 14 years later the U.S. Army Corps of Engineers requested that the existing ball bearing on that motor be replaced by his own design.

Kingsbury tried to persuade Westinghouse to pursue a patent on his bearing, with the understanding that he would assign them the patent rights, in return for a fair price to be established by the Company. Although the proposal had the backing of the V.P. of Engineering, the company president would not approve it. Hence Kingsbury paid further expenses himself to obtain a patent.

The original filing of his patent application in 1907 was rejected. Unknown to Kingsbury, a British patent had been granted in 1905 to A.G.M. Michell, a highly respected Australian engineer, on essentially the same concept. Michell had published outstanding analyses of the slider bearing shortly before he received his patent. But Kingsbury's tests in 1898 while at the University of New Hampshire had preceded Michell's work. It would be three years later, in 1910, when Kingsbury would finally be granted his patent, No. 947242 (see Figure 13).

During the next two years, Westinghouse conducted a series of tests of the bearing on a 3600-rpm steam turbine, in anticipation of taking out a license from Kingsbury if the tests were successful. The thrust bearing area was reduced in stages until the babbitt facing reached crushing limits: 7000 to 8000 psi. The tests were an unqualified success. Westinghouse took a license and worked under it until the patent expired.

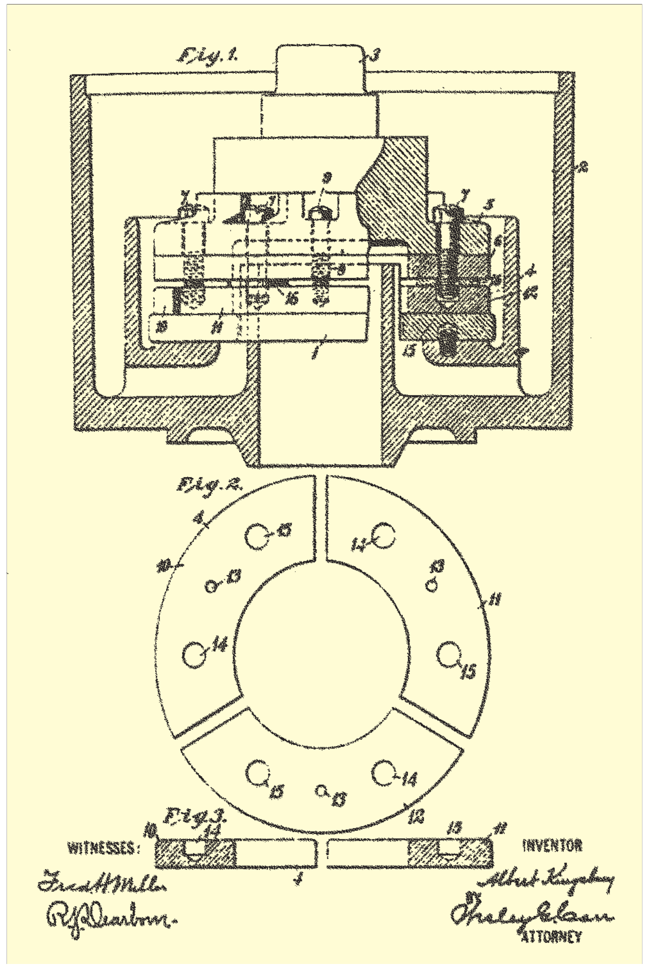


Figure 13. Kingsbury tilt-pad bearing patent.

Kingsbury – The Independent Years

In 1912 Kingsbury was in business for himself and had the opportunity to try his bearing on a hydroelectric generator at the Pennsylvania Water and Power Co. on the Susquehanna River (Figure 14). The original roller bearings used on the 200-250 ton unit were expensive in initial cost, maintenance and repairs, and the company was willing to try a new approach.

The Westinghouse Machine Co. built the bearing for Kingsbury, but only after being assured that he could pay for it. Fortunately, Kingsbury had a $5000 endowment insurance policy mature at that time, so he was able to meet Westinghouse's demand. The bearing was installed in the unit; it failed immediately and totally by babbitt wiping, but Kingsbury did not lose faith in his concept. He persuaded the Company that the failure arose from the fact that the thrust runner had been scraped but not polished.

The Company agreed to give Kingsbury a second chance. The bearing was reworked and replaced in the unit, where it ran without a problem for the next 25 years. When it was removed for examination at that time, the wear was so slight that the plant engineers calculated a "probable life of 1300 to 1700 years." Nine more hydroelectric installations quickly followed.

By the time the U.S. entered World War I in 1917, Kingsbury thrust bearings were specified by the U.S. Navy for propeller shafts. This usage was probably spurred by the fact that the Royal Navy was already using Michell bearings to absorb propeller thrust. Previous thrust bearing designs had used multiple flat faced collars on the shaft and horseshoe-like stationary plates. There was of course no assurance that the multiple collars would share the thrust load.

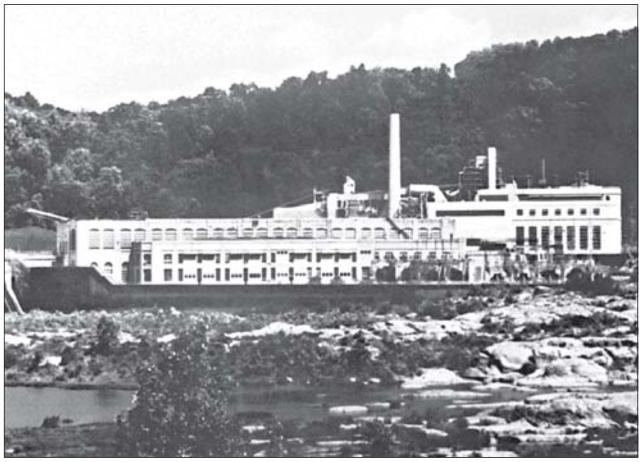


Figure 14. Holtwood generating station.

Figure 15. Kingsbury Hall, University of New Hampshire.

Figure 16. Kingsbury Plaque.

The impact of the tilting pad thrust bearing can be judged by some tests that were made in 1919 on an interned German ship. The original thrust design used 21 shaft collars; 14 for ahead thrust and 7 for reverse thrust. One thrust collar was removed and replaced with a single Kingsbury bearing. It took full thrust in either direction.

By 1921 Westinghouse could no longer keep up with the demand for the bearing, and Kingsbury built his own manufacturing plant. By World War II the Kingsbury bearing was on all major USN ships. The five Missouri class battleships were equipped with 36 bearings, including four bearings of 49 in. on the propeller shafts. Even larger hydroelectric units used the bearing, such as the 1.8 million lb TVA unit at the Fort Loudoun Dam, with a 93 in. bearing.

Despite the unparalleled success of his bearing design over those years, Albert Kingsbury continued his research to understand the phenomenon of lubrication and bearings. One of the difficult analytical problems in bearing design is in accounting for the effects of side leakage of the lubricant. In 1931, long before computers had arrived and made this problem more tractable, Kingsbury saw a way to resolve it. He recognized an analogy in the equations for lubrication and those for electrical flow in a conductive fluid of variable depth. With this experimental technique, better predictions of slider load capacity became possible.

Kingsbury is credited with coining the term 'oiliness' to describe differences in lubrication behavior for fluids with the same viscosity. He recognized that lubricant heating affected bearing performance, and published studies on its effect. His interest did not wane with the success of the business he had brought into being.

A Glimpse at the Character of Albert Kingsbury

During his lifetime, Albert Kingsbury received many awards, including the Gold Medal of the American Society of Mechanical Engineers (1931); the Elliot Cresson Medal of the Franklin Institute; and honorary doctorates from the University of New Hampshire and Worcester Polytechnic Institute. He was awarded the highest distinction of the ASME in 1940 when he was named an Honorary Member. In 1950, seven years after his death, the University of New Hampshire dedicated Kingsbury Hall (Figure 15) and friends established a scholarship in his memory.

In appreciation of the work of Osborne Reynolds and the impact he had on his own life, Kingsbury established a fellowship at the University of Manchester. The first recipient of that award was Reynolds's son, who was studying problems with screw propellers.

Perhaps the best glimpse of Kingsbury's character was offered by his friend Prof. E. B. Davis at the dedication of Kingsbury Hall in 1950:

"Kingsbury became recognized throughout the world as an authority on the science of lubrication . . ." but "His interests were not confined within the limits of his professions of teaching and engineering. He lived with even greater satisfaction a broader life in the world of arts, history and letters . . . As he grew older he devoted more time to the study of foreign languages . . . Italian, Spanish, Greek, French . . . and several others . . .

He was a strong man physically as well as mentally . . . He had a keen sense of humor, a ready wit, and quick repartee . . . From them (his Quaker parents) he inherited an iron will, calm ways, and . . . a sincere concern for the welfare of all associated with him in any capacity . . . He was generous and philanthropic; in every way he was the courteous gentleman."

Summary

Albert Kingsbury's final years were spent in Greenwich, CT, where he died on July 28, 1943. During his life span enormous events had taken place: a wrenching Civil War had occurred; the United States had been involved in major external wars and business depressions; two presidents had been assassinated; the United States now stretched unbroken from coast to coast, with three times the population at his birth; and a staggering array of new inventions covered the land, from gasoline powered automobiles to airplanes, steam turbines, huge electric generators and electrical grid systems. The United States had emerged as the predominant industrial nation in the world. He lived in a time of great changes and in that time his character and contributions had made a substantial and positive difference.

The plaque, shown in Figure 16, in the lobby of Kingsbury Hall at the University of New Hampshire admirably and succinctly sums up his life.

ALBERT KINGSBURY
1863-1943
FIRST PROFESSOR OF MECHANICAL ENGINEERING
AT THE
UNIVERSITY OF NEW HAMPSHIRE
IN DURHAM
1891-1899

INVENTOR OF THE KINGSBURY THRUST BEARING
INTERNATIONAL AUTHORITY ON
BEARINGS AND LUBRICATION
A BELOVED TEACHER AND INSPIRING ADVISOR
A GREAT AND HONORABLE MAN

Acknowledgments

The writer wishes to acknowledge the sources for much of the information contained in this article, particularly the outstanding book by Professor Duncan Dowson of the University of Leeds, England, titled *History of Tribology*, Longman Group Ltd., London, 1979; the Mechanical Engineering reprint of December 1950 by Albert Kingsbury titled "Development of the Kingsbury Thrust Bearing;" selected technical papers by Kingsbury; the paper by Beauchamp Tower, "Second Report on Friction Experiments," *Proc. Inst. of Mech. Engrs.*, (1885), and the paper by Osborne Reynolds "On the Theory of Lubrication and Its Application to Mr. Beauchamp Tower's Experiments . . . ," *Phil. Trans., Royal Society of London*, (1886), Vol. 177.

The prize winning book *Titan – the Life of John D. Rockefeller, Sr.* by Ron Chernow, Random House (1998) provides a valuable view of life in the U.S. during Kingsbury's time as well.

In addition, the writer wishes to express his appreciation to Ms. Tracey Harvey at the University of New Hampshire for supplying information and photographs on the dedication ceremony of Kingsbury Hall, and to the Cornell University archivist, Ms. Elaine Engst, for historical photographs from the Cornell University Division of Rare and Manuscript Collections, Carl A. Kroch Library.

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