Property of EM Lab - Ontario Science Centre

THE FIRST NORTH AMERICAN ELECTRON MICROSCOPE 1938

This brochure has been prepared
to commemorate the fortieth anniversary
of this achievement
1938-1978

Introductory Remarks

Forty years ago in the University of Toronto, a group of young physicists constructed the first electron microscope in North America. With Toronto as the host for the 9th International Congress on Electron Microscopy in 1978, it is an unique opportunity to commemorate this Canadian achievement. In the summer of 1977, Cecil Hall, who was involved in this achievement, wrote in a letter about this commemoration: "It is only a ceremony, of course, a symbolic summation to a story that many of us know. It is a good story". That it is more than a "good story" became clear while material was being gathered to write the historical account of the construction of the Toronto microscope.

In publishing the following historical account, it is by no means our intention to underestimate the pioneer work done in Europe in the early 1930's. For its theoretical basis the Toronto microscope owes almost everything to European scientists. The significance of the instrument constructed in 1938 in the Department of Physics at the University of Toronto lies essentially in what it achieved in practical terms, and in this respect it has to be regarded as a major engineering success of the first half of this century. It is well-known that the Canadian microscope was the prototype of the first RCA instruments and contributed directly to the development of the large commercial series of electron microscopes constructed by this firm during and after the Second World War. These microscopes soon became widely distributed throughout the world, and contributed to the development of ultrastructure research in Physics, Materials Sciences, Biology and Medicine. It is in this context that the electron microscope constructed in Toronto made a fundamental contribution to modern technology.

There are many other reasons why this "story" had to be recorded. Firstly, it should be emphasized that this microscope was made in Canada by Canadians. Why do I emphasize this? Canadians suffer from an inferiority complex; shy by nature, they do not like to publicize their own achievements. It is necessary from time to time to remind ourselves of what has been done, and how it has been done. It is also important for the rest of the world to realize that Canada is one of the leading inventive and industrialized countries of the world, and is no longer "the few acres of snow" described by Voltaire.

This "story" is also a splendid example of technology in service of humanity. Professor Burton instigated the project at the University of Toronto because he was convinced that such an instrument would be of great help to our understanding of the mechanisms of human disease. In particular, he hoped that the better resolving power would provide new insights into the lung diseases which affected many Canadian miners and into cancer. There is a striking similarity in the development of both the Siemens microscope and the Toronto instrument in that both were developed for the benefit of mankind. This scientific attitude merits emphasis.

Finally, this "story" gives us an example of the enthusiasm of young scientists working day and night to realize their project in record time. In 1938, times were not better than they are today. Funds were not available, many scientists were unemployed, and Canada had not fully recovered from the Great Depression. Despite the difficult conditions, these young scientists achieved their goal. Today, as in 1938, the economic and political situation might not be the best. However, it appears that many of our scientists in waiting for better times have lost their enthusiasm.

It is my sincere hope that in the coming years, somebody will write the entire history of electron microscopy. May the following historical account of the construction of the 1938 Toronto microscope be a contribution to this work.

G.T. Simon

A History of the First North American Electron Microscope

U.M. FRANKLIN, G.C. WEATHERLY, G.T. SIMON

North America's first Transmission Electron Microscope — and the first of immediate practical application anywhere — was designed by two graduate students in the Department of Physics at the University of Toronto over the 1937-38 Christmas holidays and was built during the first four months of 1938. By April it produced consistently promising micrographs and before the end of the year, demonstrated magnifications of 20,000 diameters with resolution better than 140Å. The resolving power had been pushed to less than 60Å (30 atom diameters) within another ten months. The design of this microscope was adopted by the Radio Corporation of America and developed into the prototype of a commercial series. It was this RCA production model, based directly on the Toronto microscope, that was the equipment selected by laboratories throughout the world for a generation. This represented an extraordinary achievement for the two young Canadians: Albert Prebus and James Hillier.

At the time when Prebus and Hillier began their work, the attempt to design and build an electron "supermicroscope" had been under way in Europe for almost a decade. The basic principles and capabilities had been determined theoretically. The essential lens design, with pole-pieces to concentrate the magnetic field, had been worked out by Ernst Ruska and his colleagues at the Berlin Technische Hochschule, and Ruska had constructed the pioneer two-stage transmission model in 1933. Experimental models had also been built by Ladislaus Marton in Brussels, and by L.C. Martin, R.V. Whelpton and D.H. Parnum in England. Nonetheless, as Hillier noted in his M.A. Thesis, the literature at the time contained more details of the problems than the solutions. The lenses showed chronic astigmatism and field interference. The few resulting micrographs were blurred and distorted, and often the specimens had been destroyed by the electron beam. Above all, unknown factors were limiting the theoretical resolving power. Of the three experimental models, only that of Ruska achieved, after two years of continuous modification, resolution levels beyond that of the light microscope. Ruska, together with his brother-in-law Bodo von Borries, later interested Siemens and Halske in developing the electron microscope commercially. However, outside Europe work had not been done in this field before 1938. In the United States, for example, leading microscopists did not believe in these new instruments, and labelled the project as "impossible" and the electron micrographs as "fakes".

It is in this context that the Canadian achievement was so unexpected, even exotic. It is also partly for this reason that the construction of the Toronto instrument has been largely unnoticed and is rarely mentioned in the history of electron microscopy.

The Toronto Milieu in the 1930's

According to the description of programmes for doctoral studies, the Department of Physics of the University of Toronto offered "exceptional opportunities...in (a) low temperature research including temperature of liquid helium; (b) spectroscopy with the use of glass and quartz spectrographs and interferometers of all types, and gratings including a twenty-one foot concave grating, and a three metre vacuum grating; (c) x-rays and cathode rays; (d) high frequency currents; (e) geo-physics with the use of specially designed instruments for field and laboratory research and (f) colloidal solutions". This shows the range of activities in the Department of Physics.

Until 1932, the Chairman of the Department was Sir John Cunningham McLennan who, among other accomplishments, founded the cryogenic laboratory. It is of interest to mention that he was the second in the world to prepare liquid helium. During the First World War, he had acted as a scientific consultant to the British Admiralty, and supervised the construction of two helium-extraction plants in Canada. At the end of the War, he obtained this equipment and the helium supplies for the Department which, with Berlin, Leyden and Washington, D.C. was only one of four centres in the world capable of helium production.

It is to the credit of McLennan that the Department became a well-known centre for both experimental and theoretical research. Besides the low-temperature work, the Department was known also for its studies with superconductors and colloids and for its contributions in the fields of x-rays and of spectroscopy. The Department at the time consisted of three full professors including McLennan, two associate professors, an assistant professor, and more than 20 lecturers and demonstrators. By the early 1930's it had more than 50 graduate students each year. McLennan considered them as "his" students, and his name appeared as co-author on most of the papers published. He visited England yearly establishing ties with scientist friends, and many distinguished scholars reciprocated to lecture in Toronto on recent developments. The Department developed by McLennan, with its facilities and its workshop, provided the atmosphere which was conducive to new ideas and projects such as the construction of the electron microscope.

The Man Behind the Idea - E.F. Burton

Professor Eli Franklin Burton, who succeeded McLennan as head of the Physics Department, was a man of great enthusiasm who initiated the construction of the electron microscope. There is no full biography of Burton. However, from accounts of the 1930's and 1940's and the recollections of his colleagues and students, he was a remarkable man. He had wide-ranging scientific interests and at the same time, a strong commitment to the Canadian community. For example, during the Second World War, he created and directed single-handed a program of radar training in Canada despite government indifference. He was humorous and capable of the unexpected, such as ending a lecture with "God Save The King" played by dropping pieces of wood which were tuned to pitch on the desk.

Burton was born near Toronto in 1879 into a family of six children. Although one of his brothers went into business and founded one of the largest Canadian department stores, Eli Franklin Burton decided to devote himself to science. He graduated with Honours in Mathematics and Physics at the University of Toronto in 1901, and worked for two years as a demonstrator under McLennan. Then he won an Exhibition Scholarship which brought him to the Cavendish Laboratory at Cambridge University, where the electron had just been discovered by the head of the laboratory, J.J. Thomson.

In Cambridge, he earned a B.A. for his work on colloidal solutions, which remained one of his main interests. He returned to Toronto in 1906 to become a senior demonstrator and, after completing his Ph.D. in 1910, he was promoted to associate professor.

During the First World War he co-operated with McLennan in the development of the helium-extraction process. He became full professor in 1924 and succeeded McLennan in 1932 as Chairman of the Department and director of the laboratories.

Burton directed the Department with a different style. He reduced administrative work to a minimum, and condensed the compulsory annual reports to the President so much that they often did not reflect the ferment of activity in the Department. More important, his co-workers became more independent and the scientific papers were published under their own names. The Department broadened its scope to applied physics and to fields which today would be classed as biophysics. Burton was concerned with solving problems in which both medical research and physics had to be applied. He went so far as to collaborate with a physician, A.C. Hendrick, to study the possible use of colloidal arsenic solutions in the treatment of cancer. This new direction that Burton gave to Physics in Toronto may be related to his chronic health problems, being a diabetic. In the same connection, it is worth mentioning that in Germany, the decision of Siemens and Halske to develop an electron microscope was made after the strong intervention of one of their Directors who, like Burton, had health problems and foresaw the use of electron microscopy in biomedical research.

Since his year at Cambridge, Burton had followed closely the major developments in electron theory and the feasibility of the construction of an electron microscope. He knew about Louis de Broglie's hypothesis of 1924 that electrons had wave properties, and Hans Busch's demonstration in 1926 that magnetic or electric fields having axial symmetry acted as lenses for an electron beam. The excellence and extraordinary diversity of Burton's knowledge resulted in his being invited in 1926 by the Mayo Foundation to participate in a series of lectures on "<u>Biological Aspects of Colloidal Chemistry</u>". The titles of his presentations were significant: "Physics of the Ultra-microscope" and "The Optical Properties of Suspended Particles and Colloidal Cells". It should be noted that Burton was already using the term "ultra-microscope" in 1926. Although the construction of the Toronto electron microscope occurred more than a decade later, Burton has to be considered as the man who promoted this achievement.

<u>The Catalyst - W.H. Kohl</u>

In the autumn of 1930, Walter H. Kohl arrived in Toronto from Dresden where he had studied at the Technical University. He worked as a research physicist with a Canadian company, Rogers Radio Tubes Ltd., who were involved in pioneer work in television. In his new field, Kohl was involved with the deflection of electron beams by means of magnetic and electrostatic fields, following essentially the European experiments in this domain. In order to be informed on the newest developments, Kohl established ties with the Physics Department at the University, and from 1932 on, Burton asked him to give several series of lectures and seminars. Kohl kept a meticulous record of all these lectures. It is striking to note, for example, the following titles: in 1935, "The Fundamental Principles of Electron Optics", and "The Electron Microscope"; in 1936, "Electrostatic Lenses", "Electromagnetic Lenses", "The Electron Microscope" and even "Applications of the Electron Microscope". After having repeated some of Bruche and Johannson's experiments on the electrostatic and electron microscopes, he demonstrated such an instrument in April, 1934, producing images of oxide cathodes. This was probably the first demonstration of the kind in North America.

Kohl's lectures and demonstrations encouraged Burton to initiate the construction of an electron microscope. This was reflected in the fact that Burton asked Kohl to be the co-author of his book, <u>The Electron Microscope</u>. In the acknowledgements, Burton writes, "First...I wish to thank my co-author, Dr. W.H. Kohl, for the great help he gave the Department of Physics of the University of Toronto, at the beginning of the work on the electron microscope..." In 1938 and the beginning of 1939, Toronto newspaper articles were published on the construction of the transmission electron microscope. Burton had mentioned to the press that Kohl participated actively. This kind of recognition led to the belief that Kohl not only accelerated the project, but supervised directly. However, in his recollections (printed at the end of this article), Kohl himself states, "This was a generous gesture, but hardly justified, since I had no part whatever in the design and construction of the instrument."

Cecil Edwin Hall

In the President's report of 1935-36 Burton mentions the Physics Department's first attempt to build an electron microscope: "...C.E. Hall, B.Sc., Alberta (holder of the Alumni Federation Fellowship) has been working in the new field of electron optics and has completed almost entirely by his own efforts an electron microscope of the electrostatic type. This work is so promising that the National Research Council has given the department an assisted research grant for the continuation of this work during the session of 1936-37."

In the summer of 1935 Burton attended a meeting in Berlin on the possible areas for application of the electron microscope. In the autumn of the same year, Hall, a graduate student from the University of Alberta, joined the department. Burton assigned him the project of constructing a simple electrostatic electron emission microscope for his M.A. degree. With this instrument he obtained photographic images of hot cathodes, and repeated the quantitative measurements of Johannson.

During the Depression years, financial support for research was reduced to a minimum. In Germany, Ruska had to halt his investigations in 1933, and worked for four years for a firm developing television before finally resuming his research with Siemens and Halske. In Belgium, Marton had to search flea-markets for some of the components for his instruments. In Canada, the economic situation was no better. However, due to the excellent results obtained by Hall, Burton obtained a grant of $800 from the National Research Council to cover both equipment and a stipend. Thus Hall was able to extend his project and construct a magnetic emission microscope which allowed him to obtain images of the cathode at a magnification of about 3000 x. In May, 1937, Burton returned to the National Research Council to report this success and to ask for further funds. "The next step in this research," he explained in his written application, "is to attempt to take electron pictures of sections of some substance placed in the electron stream. For the purpose of carrying out this extension of the work, the Laboratory has purchased from its funds a second gas valve tube, and it is now necessary to purchase a condenser for use with the tubes that will stand up to 50,000 or 100,000 volts." Burton asked for $774.50, mentioning that $250 was for the condenser and the balance was for payment of the investigator's salary at the rate of $62.50 a month. On the grounds that the work could be assigned to a scholarship holder, the National Research Council refused to assist the project.

Therefore Hall had to leave, and joined the research laboratory of the Eastman Kodak Company in Rochester, New York, where he developed the first electron microscope in the United States, in 1939. His work in Toronto was recorded in his M.A. Thesis in 1936 and was never published in a scientific journal. However, his achievements and Thesis served as the basis for the construction of the 1938 microscope by Hillier and Prebus.

Albert Prebus and James Hillier

After Hall left, Burton found students to continue the work: James Hillier, a Physics senior, and Albert Prebus, who had just received a M.A. degree from the University of Alberta. They started to work together in the beginning of the winter of 1937, and designed a microscope over the Christmas holidays. They constructed the instrument in the astonishingly short period of four months in the beginning of 1938. To accomplish this, they had at their disposal the Thesis of Cecil Hall and the publications of Knoll, Ruska and Marton. They "borrowed" two high tension condensers from the University of Alberta, and obtained fluorescent screens from Kohl. The rest of the instrument was manufactured by themselves, with the help of the workshop technicians. In their recollections, Hillier says, "Our greatest mechanical challenge was the design and construction of the components of the instrument..." and Prebus states, "The shop work was done on a two-shift basis. The professional machinists worked the day shift. Without their unreserved approval, Hillier and I worked the night shift, often until 4 a.m., and occasionally until the day shift was about to start." Many parts of the design were innovative; most of the theoretical assumptions were later justified, and some of the fine machining was remarkable. Making things round is so difficult that someone has called the pole pieces in an electron microscope's lens

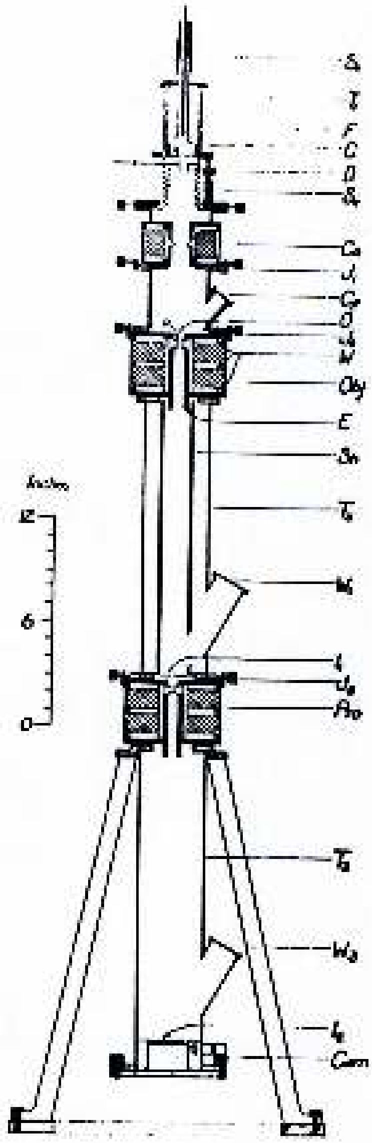

Figure 1. Schematic design of the electron microscope built early in 1938, by Prebus and Hillier. (From Prebus and Hillier, 1939).

"the most expensive holes in the world." Hillier and Prebus from the beginning achieved the accuracy for the microscope to work properly.

The Instrument

The first transmission electron microscope to be built in North America is now displayed at the Ontario Science Centre in Toronto. The design of the instrument is shown in Fig. 1. It was constructed in six sections which were sealed together by means of plane-lapped grease joints. The first section contained the electron source (or electron gun) and the condenser lens. The decision to use a hard vacuum thermionic source for electrons was a difficult one. In one of their papers, Prebus and Hillier state that, "after gas discharge tubes of various designs were tried..., a choice was made in favour of a hard vacuum thermionic tube because of its ease of control and constancy of operation". However, Prebus in his Ph.D. Thesis mentions that a great deal of effort was expended on gas discharge sources before they were abandoned. A maximum voltage of 45,000 volts could be applied to the gun, and the filament current was supplied by two 2V batteries. The filament was made from 6 mil tungsten wire and the radius of curvature at the tip (F) had to be less than 0.5 mil to ensure that the emission approximated that of a point source. However, a hairpin bend, sharp enough to simulate a point source, limited the filament's life to as little as 10 hours under high voltage. The filament could be raised or lowered with respect to the rest of the cathode by a screw and bellows arrangement (S_1), and the whole cathode assembly was sealed by wax to the upper end of the glass tube (T_1). This wax sealing had to be water-cooled during operation, creating difficulties. To replace the filament, the seal had to be broken, and this seal was eventually replaced by a neoprene joint (12), so that a filament could be changed in a few minutes. The adjustment of the filament position with respect to the cathode shield (C) ensured efficiency and point emission of electrons from the hot cathode.

The condenser lens ($C_\,$) was the conventional design and was sealed with vacuum grease to the ground surface (J) on the top of the object chamber. This sliding joint permitted the electron source, beam trap (B) and condenser lens to be moved as a unit in any direction perpendicular to the axis of the microscope. This was essential for the correct alignment and re-alignment of the instrument.

The second section of the microscope contained the object chamber. Specimens were inserted through a simple conical grease joint opening (Op), and rested on a hollow cartridge which fitted tightly into a collar, about 5 mm above the centre of the gap between the upper and lower pole pieces of the objective lens. The specimens were suspended over a small (0.05 - 0.3 mm) hole in the centre of a circular platinum diaphragm which was clamped at the lower end of the specimen holder. The lateral position of the objective could be adjusted by means of the flat grease joint (J_2).

The objective lens (Obj) in the third section was designed to give sufficient flexibility so that changes in pole-piece geometry (P), or the location of the objective aperture, could be easily accommodated. The original pole-piece design (Fig. 2) had matching upper and lower pieces (D and E) separated by a brass spacer (F) which fixed the length of the gap between the pole-pieces and aligned their axes of symmetry. The objective aperture was a platinum diaphragm (G) set in a capsule (H) with 4 set screws (I) to adjust the position. Micrographs taken with this pole-piece design showed a resolving power down to 140 Å. Unfortunately, the inevitable misalignment of the upper and lower pole-pieces was one of the limitations of the design. The objective lens was capable of magnifying the object 100 to 125 times, and the first-stage image could be viewed on a fluorescent screen (I) at the lower end of the brass tube (T_2) which constituted the fourth section of the microscope. Inside this tube was a soft iron cylinder (Sh) to shield the beam from stray magnetic fields.

The fifth section of the column consisted of the projector lens. The first image could be further magnified up to 330 times by this lens, giving a total magnification of approximately 40,000 times, and the final image was viewed on the screen (I_2). The projector pole-piece shown in Figure 2a is identical in design to the objective pole-piece. The alignment of the projector lens was accomplished through a third grease joint (J_3).

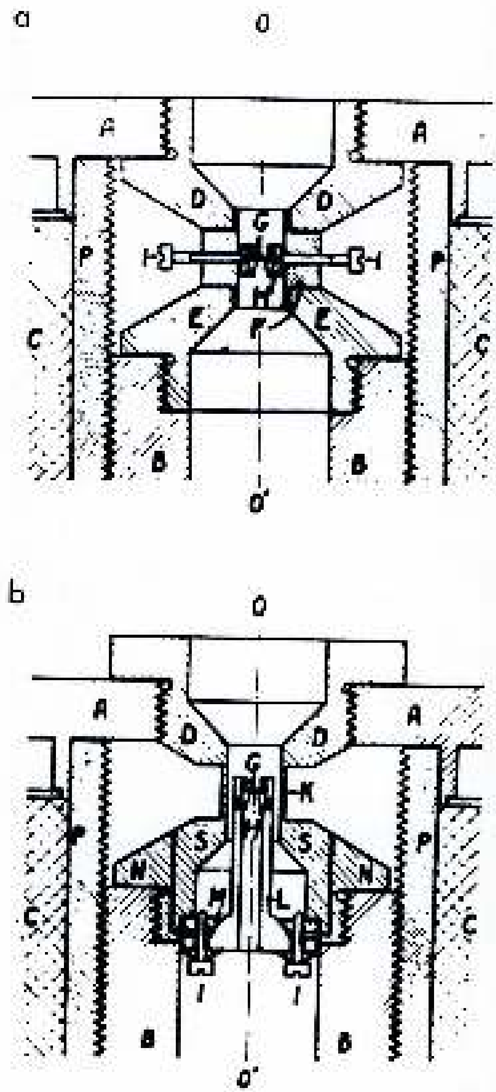

Figure 2. Designs for the pole pieces
for the electron microscope
a) original design
b) modified design

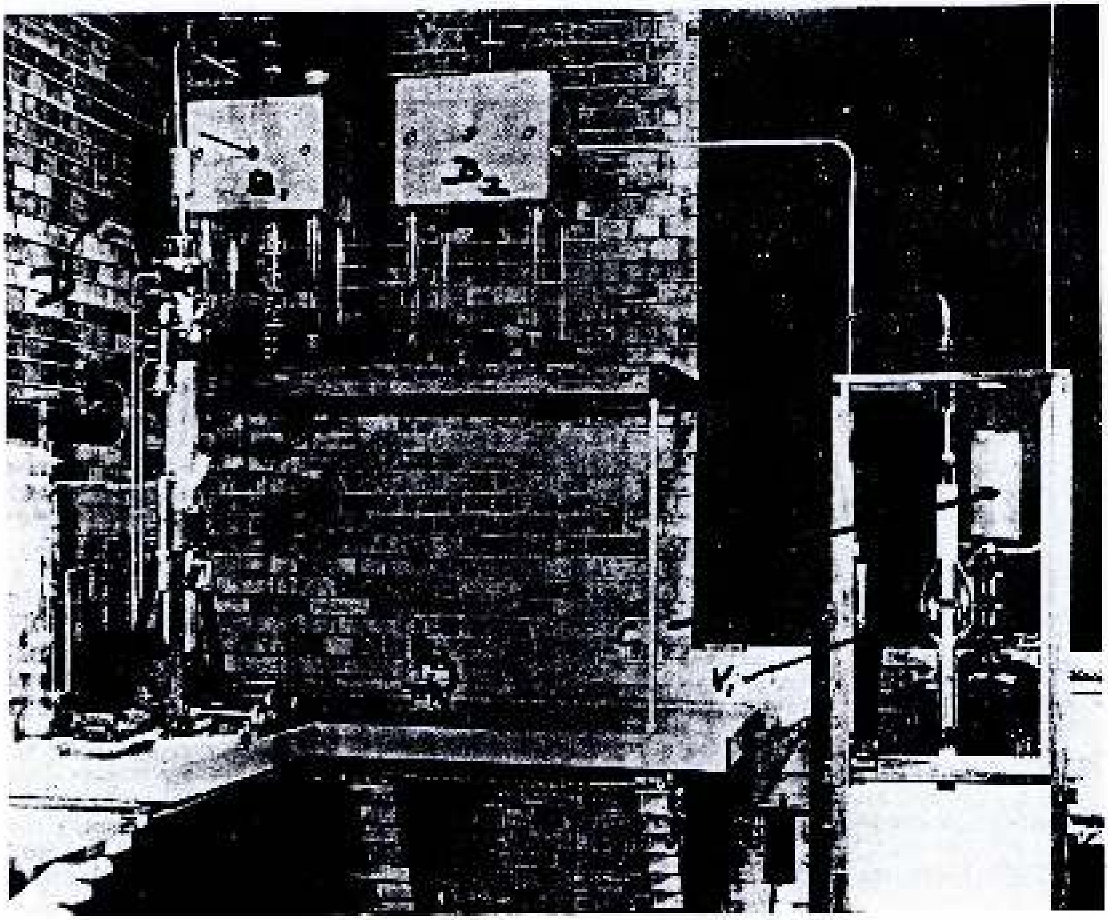

Figure 3. Original picture of the 1938 microscope in the Department of Physics, University of Toronto. Note the light microscope in the centre!

The last section contained the camera and final image screen, which could be lifted by means of a conical grease joint fixed in the wall of the brass tube (T_3). A forechamber was later added, so that a series of exposures on a 2"X10" plate could be recorded and the plates changed without letting air into the main body of the microscope.

The high-tension system consisted of a step-up transformer, hard vacuum half-wave rectifier and a filter system. All of the high-tension apparatus and connecting leads were carefully shielded. The fluctuation in accelerating potential was less than 1 volt in 50,000 volts. The high-tension system and microscope column are shown in Figure 3, which is reproduced from Prebus's Thesis, and shows the equipment in its original location in the old McLennan laboratory.

Developments

As already mentioned, the University community learned about Hall's achievement from a few lines in the President's report. The success of Hillier and Prebus is reported nonchalantly as follows: "Mr. James Hillier, assistant demonstrator, and Mr. Albert Prebus, holder of a studentship from the National Research Council, have continued the work of perfecting the electron microscope, and have succeeded in taking many photographs of sub-microscopic structures up to a primary magnification of 30,000 times. This is equivalent to being able to separate two points on an object at a distance of .0000004 inches, or .00000100 cm, or 100 A.U. apart. In addition to the studentship held by Mr. Prebus, the National Research Council gave a small grant during the present year to enable these two workers to continue the work during the summer vacation of 1938. The electron microscope is so promising that assistance has been offered by the National Research Council and the Banting Institute to keep these two workers employed full time for the next calendar year, beginning July 1, and we are hoping for some outstanding results." This note appeared in the President's Report 1938-39.

From the beginning the resolving power of the microscope was very good, and the pictures produced were of excellent clarity. The first reproductions of these pictures appeared in an article written by Burton for the Toronto newspaper "Saturday Night" on December 17, 1938, and in another article by the journalist R.E. Bennish for the Macleans' Magazine, Toronto, on April 1, 1939. The Saturday Night article contained a short explanation of the potential of an electron microscope in terms of resolution, and an acknowledgement to Kohl, Prebus and Hillier. It was illustrated by light micrographs and one electron micrograph of a diatom at about 5000 times magnification. The first scientific paper was published in the "Canadian Journal of Research" in April 1939, followed in December of the same year by a note sent to the "Physical Review", announcing that the resolution of the instrument was better than 60Å. To achieve this improvement, a new pole-piece (Fig. 2b) was developed. The brass spacer (F) was replaced by a thin-walled (0.5 mm) tube of iron (X), so that the upper and lower pole-pieces and spacer could be made from a single piece of metal. It ensured high precision in the axial symmetry of the surfaces of the pole-piece unit, and the wall tube was sufficiently thin that it was saturated by the field between the gap and yet retained mechanical strength. Finally, to ensure good contact between the pole-pieces and the upper disc (A) and sleeve (B), the contact surfaces were ground together. The micrographs reproduced in this brochure were all taken with the modified pole-piece. One of the main objective lens aberrations was astigmatism and it was only in 1946 that Hillier, with the co-operation of E.G. Ramberg, developed a stigmator to correct this aberration.

Ruska and Von Borries described in 1938 their new Siemens "Elmiskop" in an article published in the "Zeitschrift fur Technische Physik". They indicated that their instrument had a resolving power of approximately 100Å. It is difficult to establish which group reached this resolving power first. However, in his Thesis defended in May, 1940, Prebus states, "Comparison of the reproductions of better photographs of the German workers' with prints of the best photographs obtained with the apparatus described herein, indicates that a higher resolving power has been obtained with the Toronto apparatus."

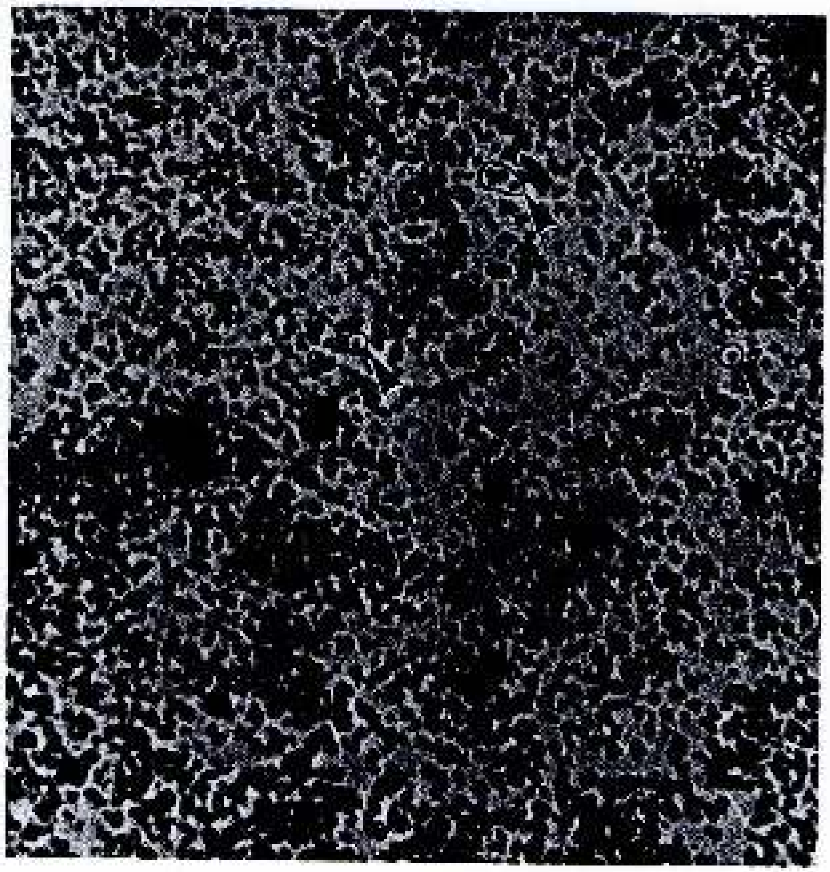

Figure 4. Electron micrograph taken in 1939 of colloidal carbon in a film of nitrocellulose. The spatial resolution (arrows) is better than 90 Å. Mag: 50,000 approximately. (From Prebus, Ph.D Thesis, 1940)

Figure 5. Electron micrograph of vole bacilli.
Mag: 7500, approximately.
(From Watson, Ph.D Thesis, 1943)

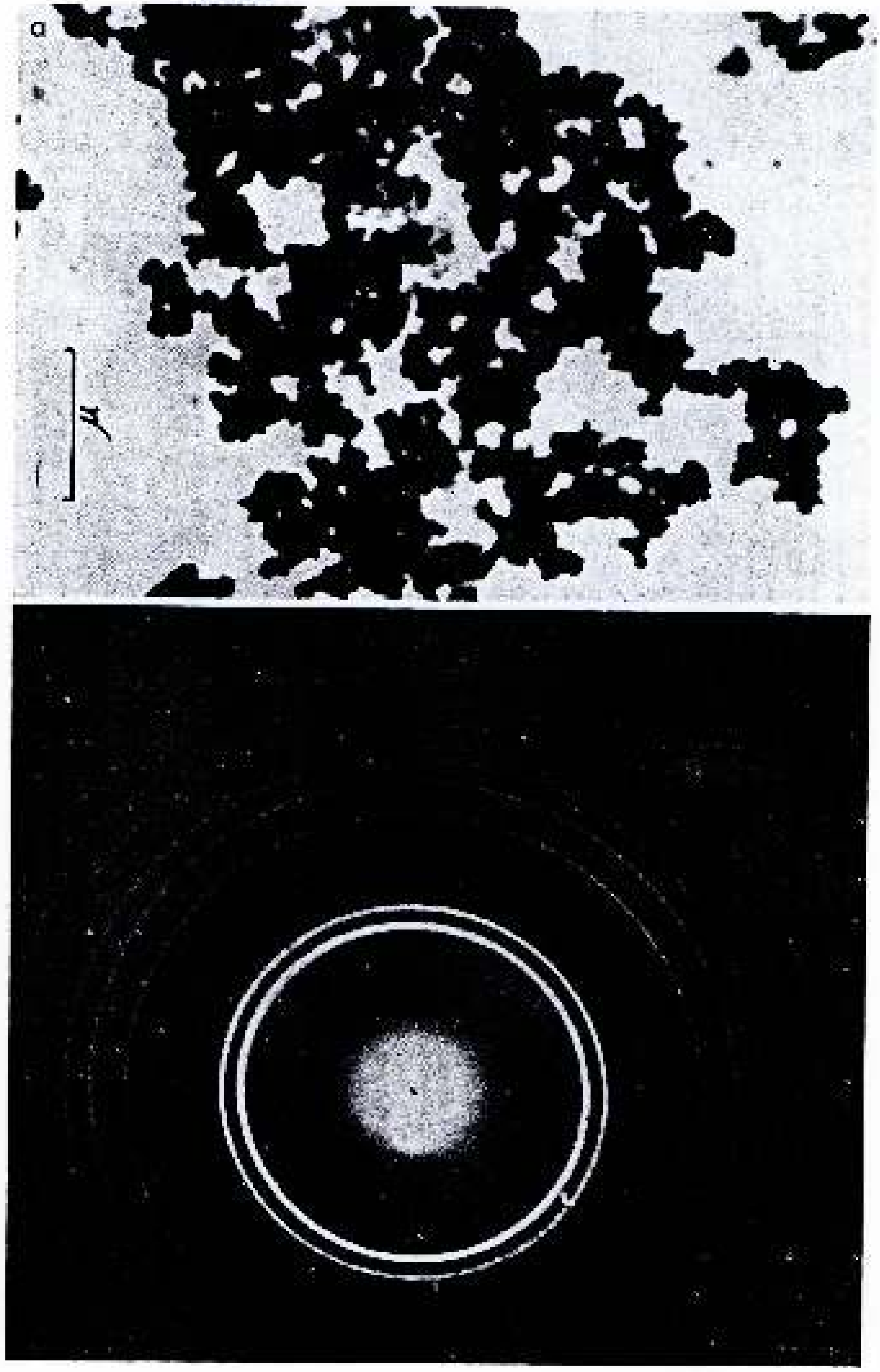

Figure 6. Titanium oxide (TiO_2) a) Transmission electron micrograph. Mag: 16000, approximately. b) Diffraction pattern from the same preparation. (From Watson, Ph.D Thesis, 1943)

Epilogue

In the fall of 1939, W.A. Ladd and J.H.L. Watson joined Burton's group. With Prebus and Hillier, Ladd collaborated on the design and construction of a second microscope, underwritten by and intended for the Columbian Carbon Company of New York. Watson worked on basic electron-optical problems, plotting the magnetic fields through axially symmetric magnetic lenses. Then he improved the design of the second microscope and investigated a large range of specimens from biological and materials sciences. Among the improvements for the microscope, Watson described in his Ph.D. Thesis the replacement of the wax-sealing arrangement for the filament holder by a neoprene joint, the modification of the specimen holder and the replacement of vacuum grease seals with neoprene washers wherever possible. Specimen preparation techniques were improved also, and earlier problems of specimen charring and destruction were reduced. Two examples (Figs. 5 and 6) illustrate the quality of Watson's work.

The Toronto group gained experience in electron diffraction which helped in the construction of the third improved electron microscope. Unfortunately, very little of these early investigations was published by Prebus, Hillier, Watson and Ladd. As Watson rather regretfully comments later, "Looking back on the Toronto days I wish there had been someone like RCA's Zworykin to push us to publish...Not only did Toronto lose its investigators, it talked not at all about what it was doing...Not one publication of any of these first sightings and others ever appeared, except in the form of my Ph.D. Thesis and Burton's rather elementary book on the electron microscope..." Watson, however, published three papers, two in collaboration with D.H. Hamly from the Biology Department, and one describing the use of the electron microscope to obtain stereoscopic images. These represented only a small fraction of his work. The scarcity of published information was due mainly to the outbreak of the War in September, 1939 and partly to the fact that the electron microscope was considered as a tool to explore the ultrastructure of biological and non-biological materials, rather than the instrument being an end in itself. This attitude is reflected by Burton in the President's Report of 1940-41: "During the past year we have had delegations to us to see the work being done by the electron microscope from the Radio Corporation of America, the General Electric Company of Schenectady, the Eastman Kodak Company, Rochester, Ohio State University, the Massachusetts Institute of Technology, and Merck and Company, New York..."

In February, 1940, Hillier resigned to go to RCA, and Prebus went to Ohio State University. For Burton, the departure of his researchers were not losses, but successes, as he states in the same President's Report: "We are very proud to report that our former workers on the electron microscope, Mr. C.E. Hall, Mr. James Hillier and Mr. Albert Prebus have been doing very good work in various places in the United States, and have received very flattering appointments." Prebus and Hillier thought at one time of going into business and constructing electron microscopes. It was improbable that they could have obtained the funds to make the investment. Ladd left Toronto after the microscope for Columbian Carbon Company had been completed, and was hired by the firm to operate it. Watson also left in 1943. All the scientists involved in developing the electron microscope went to the United States. The reason for this "emigration" is that at this time, no Canadian company appeared to be financially able to undertake such a large project, whereas the economic position of the United States supported the venture of developing commercial electron microscopes.

During the Second World War, there was no mention of the Toronto facilities for electron microscopy since "ultrastructure research" had been classified as "secret". At the beginning of the War, the Toronto microscope was the only one available to the Allies. Watson, in his recollections published in the Bulletin of the Microscopical Society of Canada in 1974, discusses the nature of this secret work. The importance of electron microscopy to the War effort was demonstrated by the fact that, as soon as the RCA production model designed by Hillier, V.K. Zworykin and A.W. Vance was completed, four of these instruments were shipped immediately to Britain under Lend-Lease.

The development of electron microscopes in the Physics Department of the University of Toronto ended with the construction of a third microscope, completed in 1944, involving Watson, S. Glenn Ellis, G. David Scott, and Beatrice H. Dean. This microscope is described in the second edition of "The Electron Microscope" by Burton and Kohl. With the departure of Hall, Prebus, Hillier, Ladd and Watson, the development of transmission electron microscopes shifted away from Toronto. Nevertheless, the Toronto microscope was behind the massive production of electron microscopes by RCA, which in turn directly contributed to the ultrastructure research which continues in many scientific disciplines throughout the world.

Bibliography

Drasch, H. The Mirrored Spectrum 2: 59, 1974. Published by Ministry of Science and Technology, Ottawa.

Burton, E.F., Hillier, J., Prebus, A. Phys. Rev. 56: 1171, 1939.

Burton, E.F., Hillier, J., Prebus, A. Canad. Med. Ass. J. 42: 116, 1940.

Burton, E.F., Kohl, W.H. 'The Electron Microscope'. Reinhold, New York, 1948.

Gabor, D. In. 'Proceedings of 8th International Congress on Electron Microscopy", Canberra, Vol 1, 6, 1974.

Hall, C.E. M.A. Thesis, University of Toronto, 1936.

Hamley, D.H., Watson, J.H.L. Trans. Roy. Soc. Can. 35: 61, 1941.

Hamley, D.H., Watson, J.H.L. J. Optic. Soc. Amer. 32: 433, 1942.

Hillier, J. M.A. Thesis, University of Toronto, 1938.

Hillier, J. Can. J. Res. <u>A 17</u>: 64, 1939.

M. Knoll, E. Ruska. Ann. Physik, 12: 607, 1932.

M. Knoll, E. Ruska. Z. Physik. 78: 318, 1932.

Kohl, W.H. Unpublished Presentations, 1932-1947. In Archives of 9th International Congress on Electron Microscopy, Toronto, 1978.

Marton, L. Physica 3: 959, 1934.

Prebus, A. Ph.D. Thesis, University of Toronto, 1940.

Prebus, A., Hillier, J. Can. J. Res. <u>A 17</u>: 49, 1939.

Prebus, A. Can. J. Res. <u>A 18</u>: 175, 1940.

Ruska, E. Z. Physik. 87: 580, 1934.

Ruska, E. Z. Physik. 89: 90, 1934.

Ruska, E., Von Borries, B. Z. Tech. Physik, 19: 402, 1938.

Watson, J.H.L. Ph.D. Thesis. University of Toronto, 1943.

Watson, J.H.L. Can. J. Res. 21: 89, 1943.

Watson, J.H.L. Bull. Micros. Soc. Can. 2: 10, 1974.

Recollections

W.H. KOHL, C.E. HALL, A.F. PREBUS, J. HILLIER, J.H.L. WATSON

After the basic research on the history of the Toronto microscope was completed, the scientists who were involved in this major achievement were asked to write their own recollections of this time. These recollections are included in this appendix to the commemorative article. In addition to providing factual data, they contribute some interesting anecdotes.

Walter H. Kohl

"Since it has been acknowledged repeatedly by those who took part in the development of the first North American microscope that I was indeed the catalyst that brought it about, it may be useful to establish the historical record, so that excessive claims that have been made at times can be seen in proper perspective.

I arrived in Toronto as an immigrant from Germany in September 1930, after having obtained a doctorate in Engineering Physics from the Technical University in Dresden. My thesis topics were concerned with photo-electricity and secondary emission and I had not been exposed to electron optics during my formal education.

I obtained a position as Development Engineer with Rogers Electronic Tubes Limited at 100 Sterling Road, Toronto, in November 1930, when the depression was making its inroads to Canada. I stayed with that company for 15 years and when I left Canada in late 1945, I had advanced to Chief Engineer and had become a Director. Rogers Electronic Tubes, where the late H.W. Parker was chief engineer until 1943, produced receiving tubes for the radio sets marketed in Canada under the "Rogers Majestic" label and also power tubes for their broadcast station CFRB in Aurora, Ontario. A fairly large room was partitioned off at the end of the tube factory and became "The Laboratory", where I conducted the work to be described - for many years without any help even for routine manual labour.

At first I was involved in making photocells and Dynatrons and becoming familiar with the factory operations. Later various schemes for television were being considered. The decision was reached to develop Cathode Ray Tubes which at that time were not available on the American market other than the Western Electric Tube 422A for low-voltage applications. This was the beginning of my serious involvement with Cathode Ray Tubes including oxide cathodes and luminescent screens. Phosphors were being imported from Germany and I made some efforts toward producing them, rather than grinding hunks of Willemite ore, as I had been doing for some time. I studied most of the international literature on these subjects and derived great benefit from the facilities of the University of Toronto Library. The work done by Ardenne, Knoll, Borries, Ruska, Brüche, Scherzer, and Johannson thus became known to me and I could not resist the temptation of occasionally building some special tubes and repeating their experiments.

I attended the seminars at the Physics department regularly and had close contact with Professor E.F. Burton, who invited me to make an occasional presentation on the work I was doing. Thus I gave a talk on "Photocells" on November 24, 1932 and one on "Geometric Electron Optics" on January 26, 1933. On April 19, 1934 the subject of my presentation was "Electron Emission from Oxide-Coated Cathodes", during which I showed one of my specially constructed tubes and the electron optic image of the cathode produced on the 5½ inch diameter face of the tube by means of a Johannson immersion objective. This was no doubt the first demonstration of this kind in Canada.

In June 1935 I was appointed Special Lecturer in electronics at the McLennan Laboratory and this arrangement was renewed each year until 1939/40. I usually gave a series of about ten lectures on various aspects of electron physics. On May 22, 1936, I gave a lecture with demonstrations on "Electron Optics" before the Royal Society of Canada in Ottawa, to which I was invited on Professor Burton's suggestion.

Professor Burton was quick to realize the potential of the Electron Microscope as a research tool and the opportunity it offered to put the Physics Department on the map. Cecil Hall was the first graduate student in this field and studied the properties of an electrostatic Electron Microscope in 1935, using the immersion lens, and J. Hillier and A. Prebus undertook the design and construction of a magnetic Electron Microscope in the fall of 1937. On its completion, reports on this remarkable achievement were published by Professor Burton in Saturday Night (Dec. 17, 1938) and the Toronto Star (Jan. 5, 1939) mentioning me as an active participant. This was a generous gesture, but hardly justified, since I had no part whatever in the actual design and construction of the instrument."

Cecil E. Hall

"In 1935 I entered Graduate School at the University of Toronto. After discussions with Professor E.G. Burton, I became his first student to work on the problem of developing an electron microscope, which he believed might eventually become useful in the observation of biological and medical specimens. His expectations were viewed with extreme scepticism by nearly everyone at that time.

My work in this direction was preliminary at Toronto, and its main value was probably in establishing such studies as suitable for graduate student research. I joined the research laboratories of the Eastman Kodak Company early in 1937, where Dr. C.E.K. Mees, Director of Research, also had hopes for application of such an instrument. Mees was undoubtedly inspired in this by Dr. Burton, since they were good friends. In Toronto, the work was resumed by Albert Prebus, who was joined by James Hillier, and together the group produced the first high-resolution transmission electron microscope on this continent. I completed a similar instrument a little later at the Kodak Laboratories, substantially aided by my contacts with the group at Toronto. Mine would be the first in the United States, but it was directly related to the one in Toronto. In 1941 I joined the faculty at M.I.T. to work on electron microscopy in biology."

Albert F. Prebus

"I arrived in Toronto one morning in September 1937, pleased with the prospect of continuing my graduate work under the direction of the eminent spectroscopist, Professor M.F. Crawford. I had earlier that year earned an M.Sc. from the University of Alberta in atomic spectroscopy.

In my first meeting with Professor E.F. Burton, then head of the Physics Department, my plans to continue in this field were seriously perturbed. He suggested that a new field would broaden my outlook. The particular field he had in mind was revealed somewhat later in the conversation. It was, of course, electron optics, an area he had found intensely exciting during a European trip he had made some time earlier. His enthusiasm rapidly overcame my initial reluctance to switch from work that I had enjoyed to a field about which I knew very little, but which did offer many exciting possibilities.

Although Cecil Hall had been an undergraduate classmate of mine at the University of Alberta, we had not been in contact during the preceding year in which he had come under the influence of Professor Burton. He had earned a Master's degree in the process of initiating an experimental program in electron optics at the University of Toronto. Hall had put together an electrostatic electron microscope suitable for the examination of thermionic electron-emitting surfaces. He had then proceeded with the construction of a highly flexible two-stage electron microscope equipped with magnetic lenses, also designed primarily for the study of electron emitting surfaces.

Professor Burton was most anxious that his students should specialize in the "super" microscope domain of electron optics. He thought, correctly, that development would move more rapidly if he could persuade another student to join me. He had no difficulty in enlisting a bright young graduate student named James Hillier. Although Hillier had a teaching assistantship that demanded a great deal of his time and energy, he appeared to have an enormous supply of the latter and devoted most of it to our project. When we began work, in the fall of 1937, Ernst Ruska and his associates at the Technische Hochschule in Berlin had clearly demonstrated that the aberrations of magnetic electron lenses were sufficiently low to permit the attainment of a resolving power distinctly superior to the resolving limit of the light microscope, and that the successful development of a super (Über)-microscope was near to realization. There appeared to be no fundamental factors to prevent the attainment of resolution in the 1-10 Angstrom-unit range with a transmission microscope using electron beam voltages in the 20-100 kV range.

Hillier and I decided to try directly for the high resolution instrument with the only means available to us - the laboratory work shops and a very limited portion of the operating and maintenance funds of the University of Toronto Physics Department. We begged, borrowed and scrounged materials and components, including the essential high-voltage capacitors loaned to us by the University of Alberta. During the fall of 1937 we studied the literature, worked with Hall's electrostatic microscope for the benefit of the experience and formulated plans for our instrument.

At the end of the Christmas vacation we submitted a set of working drawings to Professor Burton for his approval. Shop work began in January, 1938 and the preliminary model was in operating condition at the end of April of that year. The shop work was done on a two-shift basis. The professional machinists worked the day shift. Without their unreserved approval, Hillier and I worked the night shift, often until 4 a.m., and occasionally until the day shift was about to start. We constructed most of the smaller components. Our night shift continued for most of the following year as modifications of electron gun, internal camera, lens pole pieces, and other components were required in the course of development.

I recall especially the instabilities, the pains and frustrations associated with the initial electron source, a cold cathode gas discharge tube. Our vacuum pumping system, despite the fact that it included the largest and fanciest mercury diffusion pump ever attempted by our glassblower, was simply too slow. We made little progress until we devised the tungsten hairpin filament gun. The self-bias feature, developed elsewhere several years later, greatly improved the performance of the gun and it became the electron source of commercial instruments.

Our first internal camera was designed for the use of roll film. After requiring an enormous amount of time to be outgassed, the film base became brittle and frequently fractured after the first exposure. We replaced this with a camera equipped with an air-lock and designed for the use of a two-by-ten inch glass plate. This plate size survived in the designs of a good many generations of commercial electron microscopes.

Following in the footsteps of electron diffractionists, our initial specimen supports consisted of platinum discs provided with a single circular hole. When specimens mounted on these supports were inserted in the microscope, there was a very low probability of finding an image when the beam was turned on. There was an even lower probability of survival of the nitro-cellulose supporting film that was suspended over the hole. Significant progress in our successfully recording micrographs came only after introduction of specimen grids that were made initially from bronze sieve screens.

These instrumental modifications made it possible to study and to reduce the various malfunctions to a degree that permitted us to obtain the few gratifying micrographs necessary to demonstrate the potentialities of the instrument. Our first publication covering the construction of the instrument was submitted to the Canadian Journal of Research in January, 1939, about one year after construction of the instrument was begun. It was published in the April issue of the Journal.

During 1939 we devoted much of our effort to the development of techniques of specimen preparation in a great variety of scientific areas. Professor Burton was most interested in the efforts directed towards the applications of the instrument. This work was frequently in severe conflict with the need to continue further development of the instrument and the need and desire on our part to pursue the study of the more fundamental questions concerning image formation and interpretation. In the area of industrial application at this time, we derived staunch support from a University of Toronto graduate, William B. Wiegand, then Director of Research of the Columbian Carbon Company. Toward the end of 1939 we were joined by two new students, John H.L. Watson and William A. Ladd, who were similarly oriented to the development of instrument applications. In periods of discouragement Watson never failed to delight us with a tune from Gilbert and Sullivan.

Throughout the period of initial construction and the preliminary cycles of trial and modification, we had always the conviction that our electron microscope would open entirely new avenues of research in the dimensional range of biological molecular structures. We believed, quietly, that the dimensional range ultimately would include, in the not-too-distant future, much smaller molecules and even the heavier atoms. In our efforts to convince members of the biological and medical science communities in Toronto of the importance of the instrument in their fields, we were often disheartened with our inability to produce really significant results.

It is now apparent that our specimen preparation techniques were inadequate for demonstration of the future role of the instrument and that the reliability of performance of our instrument left much to be desired — too much from the viewpoint of one accustomed to the unfailing performance of a light microscope. We lacked shadow-casting, replication, ultramicrotome sectioning, carbon films, and many other techniques which came into use, years later. Nevertheless, the publications of the dedicated European workers and our efforts in Toronto, followed by the introduction of commercial instruments by Radio Corporation of America, did stimulate and advance the very rapid growth of electron microscopy in North America. By November 1942, there were several hundred workers in the United States and Canada anxious to share their knowledge and experience. Many of these met in Chicago at that time for the purpose of organizing the Electron Microscope Society of America. The later conversion of the Microscope to Microscopy in the name of the organization demonstrates the early preoccupation with instrumentation problems."

James Hillier

"My first encounter with the concept of the electron microscope came at what would have been a noteworthy occasion under any circumstances. It was the spring of 1937, at the University of Toronto, my senior year. The late Professor H.J.C. Ireton, who was informally the assistant director of the Physics department, had called me into his office to discuss my plans for the future. Since I intended to go on to graduate work, the discussion quickly turned to the fields of research I might pursue. He listed all the fashionable projects under way at the University at the time. While I was quite familiar with them, I had not developed any enthusiasm for doing research on any one of them as the basis of my career.

Professor Ireton must have sensed this and, almost as an afterthought, mentioned the electron microscope. I had never heard of such a device and was curious both as to its nature and as to why I had not encountered it during my four years of study in the Department. Professor Ireton gave me a brief description of the work and explained that the project had been dormant for the past year because the graduate student (Cecil E. Hall) who had been working on it had left. Later I became convinced that he had not given me the full explanation for the low visibility of the work. In any case, I was "hooked" immediately. The emotional attractiveness of coupling two childhood enthusiasms, optics and electronics, to something new was overwhelming.

I immediately plunged into a literature search. I quickly discovered that, while the basic concept of the electron microscope was quite simple and not particularly new, the very few attempted experimental implementations had shown little success and that most of the literature covered the more exotic theoretical aspects of electron optics. Fortunately, I did not appreciate then that the underlying reason for the dearth of practical work was that the full spectrum of technologies needed for the implementation of the electron microscope had not yet been developed beyond their most primitive beginnings.

In the fall of 1937, Albert Prebus joined me on the project. He, too, was intrigued by the concept and had lost his enthusiasm for the research on spectroscopy that had been the subject of his Master's thesis at the University of Alberta. After a few months of getting our bearings by refurbishing and operating the emission-type electron microscopes left behind by Cecil Hall, we reached what now appears to have been a daring conclusion: the design and construction of a high-voltage transmission-type electron microscope was the only sensible route to an instrument with resolving power greater than that of a light microscope. We went into action and worked around the clock during the Christmas and New Year holidays to put a tentative design on paper. In our youthful exuberance we paid scant attention to the gross inadequacies of the shop facilities and equipment available to us.

Immediately after the holidays we reviewed our plans with Professor E.F. Burton, the Director of the Physics Department, and Professor Ireton. It is a tribute to Professor Burton's insight and wisdom that we left that meeting with approval to proceed and without the slightest dampening of our enthusiasm. In retrospect, I recognized that Professor Burton must have had some private misgivings concerning our ability to carry through - or his ability to support a project of such magnitude. On the other hand, he must have had faith that, if we succeeded, he could "stay ahead of us" -- a faith that later turned out to be justified.

It did not take us long to be confronted by some of the problems of the "real world". The machinist assigned to us was pleasant and accommodating. However his total prior experience had been in a locomotive repair shop. While he was excellent for large pieces like the magnetic coil spools, he was completely confounded by some of the very small, high-precision pieces we wanted fabricated. We solved the problem by becoming precision machinists ourselves. It was a skill I never used after I left Toronto, but one that proved to be invaluable to me in the design of later instruments. By contrast, our glass-blower was an artist and had an appropriate temperament. As a result we had to become practical psychologists, another skill that never lost its value.

Our greatest mechanical challenge was the design and construction of the components of the instrument so that when they were assembled, the inner chamber could be highly evacuated and a multitude of alignments, adjustments and manipulations carried out while the instrument was in operation without loss of vacuum. The only technology available to us was an adaptation of the ground-glass stopcock. As a result we spent many days hand-lapping conical seals for rotation controls and access ports and large planar surfaces as sliding seals for alignment adjustments. This operation was accompanied by tedious hours of gradually stirring pure gum rubber into a large beaker of melted Vaseline, heated by a Bunsen burner, to make stopcock grease of the right consistency and with adequately low vapor pressure.

After about four months, which now seems an incredibly short time, we finally had the instrument assembled and started to try to pump a vacuum. Not surprisingly, it leaked. Finding a vacuum leak in those days was a tedious process. Our pressure measuring instruments were a simple discharge tube and a McLeod gauge. At the working pressure we required, the latter device was the only one that could be used. Unfortunately, it required much manipulation and about a minute to obtain a single reading. After spending several days checking soldered joints, sealing-wax connections and grease joints to no avail, we were slowly being forced to the discouraging conclusion that one of the inaccessible soldered joints within the magnetic lenses must be defective. I clearly remember when Albert and I, in very low spirits, were discussing how to go about checking for such a possibility. In the middle of a sentence he happened to notice something glistening at the edge of one of the large sliding seals near the top of the instrument. He reached up and proceeded to pull out a long hair. The instrument immediately pumped down. I know now that not only had we done our work well but that we were also exceedingly lucky. In our rush to proceed we had not even considered the wisdom of checking each component individually.

After that we soon had an electron beam through the instrument and were elated to find that we did obtain focussed and magnified images of the silhouette of the edge of a piece of platinum foil that we were using as a specimen. The fact that the images were not nearly as good as we could have obtained with an inexpensive light microscope did not discourage us in the least. Many years later I really appreciated the magnitude of the difficulties that faced us. I am not sure my enthusiasm would have weathered such appreciation at the time.

The development of the electron microscope presented a pattern that was to repeat itself many times in later years when I was managing industrial research. The theoretical design of the instrument was simple. Furthermore, in its most elementary form, the instrument should have had, and later did have, resolving power at least two orders of magnitude better than the light microscope. The reason it did not in the beginning was to be found in the seemingly infinite list of disturbing factors to which the instrument was sensitive. Their identification and elimination became the real research problem. The difficulty was compounded by the fact that, at the time, the electron microscope itself was the only instrument that possessed the sensitivity to detect most of the disturbing factors and that the form of indication - the "read-out" - was a very non-specific blurring of the image. Thus, the detection, identification and measurement of each disturbing factor had to be accomplished with an instrument that was, simultaneously, sensing all the other disturbances that happened to be present. It is most difficult to project the emotions that accompanied the tedious and repetitive observation-deduction-hypothesis cycles that were necessary to enable us to inch slowly toward the theoretical performance.

Fortunately, this rather discouraging scenario had a compensating aspect that, like the carrot hanging in front of the mule, kept us struggling ahead. Because many of the disturbing factors fluctuated in magnitude and frequency of occurrence, we would occasionally obtain a micrograph that was significantly better than the average we had been obtaining at that particular stage of development. Those statistical "sports" continually prodded us with the knowledge that "it could be done".

This situation actually continued until 1945 when a sufficient number of the disturbing factors had been identified and eliminated to make it possible to identify and remove the remaining few "scientifically". This made dramatic step-function improvements in the performance of the instrument and quickly brought it close to its theoretical capability."

"Electron microscopy had its genesis on this continent in the Department of Physics at the University of Toronto during the middle and late 1930's as a result of the forethought, inspiration and energy of its chairman, the late Professor Eli Franklin Burton. Most, if not all, of those on the staff of Physics at the time were of the belief that "Bunny" Burton (as he was rather affectionately called because of his habit of blowing out his cheeks and lips in a rabbity sort of way as he hummed to himself) was "off his rocker" about this electron microscope business. The prevailing departmental opinion seemed to be that electron optics, and microscopy in particular, would be of use chiefly in its relation to commercial television.

In my own case the subject had its beginnings by reason of a popular article dealing with the new Hillier and Prebus microscope which I read in Maclean's magazine late in my graduating year at McMaster University in Hamilton, Ontario. At a lucky moment for me, and as a direct result of reading the article, I wrote to Professor Burton, offered him my services as a graduate student in electron microscopy and, wonder of wonders, he accepted me. This was in 1939. The first scientific reports on the instrument were also published in 1939. The appearance of these reports stirred other investigators. Cecil Hall completed in 1939 at Kodak Laboratories an electron microscope that owed much to his earlier work in Toronto and contacts with the group there. Radio Corporation of America's Zworykin hired Marton, a Belgian, and put him to work. The Columbian Carbon Company, inspired by its research director, Mr. W.B. Wiegand, established a research fellowship at the University of Toronto to provide for a continuance of research on carbon blacks, an activity which was already in progress with the '38 instrument. This fellowship also met the costs for construction of a second Toronto microscope, which went to the Columbian Carbon Company after its completion. In those days, when you wanted an electron microscope you didn't order one from a supply house, you built it yourself! Bill Ladd, a 1939 graduate in Physics at Toronto was assigned for M.A. work to Hillier who was working on his Ph.D., and in the same autumn I was assigned to Prebus. Bill's work took him primarily into the development of the Columbian instrument which was later transferred to their Brooklyn laboratory. I was to work on basic electron-optical problems.

Looking back on the Toronto days, I wish that there had been someone like RCA's Zworykin to push us to publish. With the departures of Hall, Hillier and Prebus and the instrument proven, extensive work, including the construction of a third instrument, was done by those of us who remained, without encouragement by senior staff to publish our results. And yet we were examining a great variety of both biological and industrial specimens during the 1939-44 period. I became quite facile in the use of such appellations as *Pleurosigma angulatum, Synedra delicatissima* and *Amphipleura pellucida*. I continued to visit the Connaught Laboratories every two or three weeks for my "shots", so that I could work on a variety of micro-organisms, including those of typhus and typhoid as well as vaccinia virus, the vole and the tubercle bacilli. In my case I was a student first and a writer as a distant second. It was only later I learned the phrase "publish or perish".

Of course, there was also a legitimate reason, and a large one to account for lack of publication by those working in the Toronto laboratory after 1939. The Second World War had begun and much of our work was now labelled "secret".

Even now the complete story is still open to speculation. I do know that from electron micrographs we were measuring the mean free space available across the surfaces of certain thin metal screens or grids. I remember that the holes in these screens were vari-shaped, were at first very rough in outline, and large, but that as time passed the holes in these screens changed, becoming smaller, more and more regular, and better formed. All we did with the screens was measure the sizes and shapes of their holes. It often seemed a rather pointless procedure to us. We wrote many reports and heard very little further about the reports, though I still have on my office wall a framed letter from a physicist of renown, J.J. Thomson, discoverer of the electron, thanking me for my "beautiful micrographs" of his "diaphragms" as he called them. It wasn't until the war was long over that I read a public report of the Manhattan Project in which the names of Thomson and others familiar to me from my Toronto days appeared and allowed me to put two and two together, and to guess that isotopes (of uranium, for instance) might be separated by diffusion through ultra-microscopic holes in thin metal screen. Not till then did I realize that our work might have had more significance than I had known.

It is remarkable that there were so few accidents during the Toronto days. We were obliged to perform many operations in the machine shops and elsewhere for which B.A. graduates are not generally prepared. Not the least of these was the use of torches to melt wax seals whenever the gun had to be removed to replace a burned filament. We removed the gun by fire, took it downstairs to the shop where we cut off an appropriate length of tungsten wire, bent this properly and spot-welded it to the gun electrodes. We then took the gun back upstairs where we adjusted the filament as best we could in the center of the cap and then by melting and remelting two glass seals we reassembled the whole cathode into the glass cylinder which separated it from the anode. All this had to be done without burning your hands off and without electrocuting yourself, and while guarding against any vacuum leaks, which would mean remelting the seals and starting all over again. Our vacuum seals were either glass-to-glass or polished metal-to-metal with a film of "vacuum grease" between. I use the term advisedly: as with everything else, we made our own. The graduate student was given a large quantity of vaseline with a supply of rubber bands, and was told to heat and stir.

The 1939 instruments were both operated with a high voltage supply filtered by several condensers of considerable capacity. These were set out in the room completely unprotected - one just had to remember to keep away from them. Prebus had had a potentially bad accident early on, when he had leaned against one of them which had not been completely discharged after use. I had a similar experience, albeit at a much lower voltage, when, needing one hand to hold a light to see by and two hands simultaneously to adjust the upper part of the microscope, I somehow took the cool part of a lamp assembly and its extension cord in my teeth, and then grasped the grounded body of the instrument with both hands. It was then I learned forcibly that extension cords and the lamps they bear are not always well maintained. However, I didn't drop or break the lamp, an important consideration to budget-conscious universities.

Still, we not only mastered the electron optics of the period, but we gathered knowledge of many subjects that even other experts did not and could not know about pigments, colloids, ceramics, metals, greases, oils, viruses, bacteria, tissues, aerosols, crystals - whatever we looked at. We studied them all with the electron microscope and were the first to do so.

To have been privileged to be a member of that small, original Toronto band of electron microscopists is something I treasure indeed."