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The Development of Nuclear Reactor Theory in the Montreal Laboratory of the National Research Council of Canada (Division of Atomic Energy) 1943-1946

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Abstract

In Canada, during the autumn of 1942, a group of physicists, chemists and engineers were assembled to work on what was to become the Canadian atomic energy project. The base for this work was Montreal. This paper concentrates on the contributions of a sub-group of those scientists, namely those working on the development of nuclear reactor theory. The members of that group comprised an international mix of Canadians, Britons and Americans. A few already had international reputations as theoretical physicists, but the majority were young men and women, generally under the age of 30, who were very talented but not yet famous. They worked under conditions of the utmost secrecy, initially with little help from the United States, and developed virtually from first principles most of the important aspects of modern reactor theory. The results of their work were issued as Canadian National Research Council reports with the prefix MT (Montreal Theory), and between 1943 and 1946 about 80 such reports were written. The theory described therein was fundamental to the later design and construction of the Canadian NRX reactor, which was a very successful research tool.

Soon after the end of World War II, a few of the MT reports were written up and published in either the Physical Review or the Canadian Journal of Research. However, more than 80% of the work was not published and therefore did not receive the formal recognition that it deserved. A few of the reports that went unpublished were so important that one wonders why they never appeared in the learned journals. To be sure, the work they contained was certainly used world-wide and the reports cited. However, human nature being what it is, after some years the original sources were forgotten and only the published papers which cited them were quoted. After a while those classic, early MT reports seem to have faded from memory. Thus it was that, when I recently tried to find one of them to check on a particular matter (in fact it was a paper by George Volkoff on the Wiener-Hopf technique) I found extreme difficulty in locating it. The work presented here describes the problems I met in tracking down, not only the Volkoff paper, but many of the others too. It was this difficulty which persuaded me that the MT reports should, after nearly 60 years, receive their due recognition. I am doing that by reprinting here the abstracts of all of the relevant reports, with some personal comments regarding their importance or historical value. In addition, where possible, I am publishing short biographies of the major players in Montreal during the period 1943-1946, thereby demonstrating how those young people's careers developed in the post-war years. Many went on to receive high scientific honours and academic prestige.

In order to put the articles in context, I have also reproduced the abstracts of some British Ministry of Supply reports which were written in the early part of the war (1940-1942), and which are relevant because several of the British scientists involved subsequently found themselves in Montreal. To give some background to the early Canadian work, I have reprinted part of an article by George Laurence (First Head of the Canadian Atomic Energy Control Board) who was an early contributor to research in neutron chain reactors, and whose enthusiasm and talent undoubtedly contributed to the decision to start the atomic energy project in Canada. Over the next few years, this journal or its companion, Annals of Nuclear Energy, will publish a selection of the more important MT reports so that they will be readily accessible to scholars and to practising nuclear engineers. One of these reports, written in 1944 by Boris Davison and which is of seminal value, is reproduced in this issue with kind permission of Atomic Energy of Canada Ltd.

Dedicated to the Men and Women of the Montreal Theory Group

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1. Introduction

There is always a great deal of concern expressed by the media and general public when historically important items of art or literature are lost or damaged; and quite rightly so. But can the same be said about old scientific writings of historical interest? I refer not to work published in 'Learned Journals', which we hope will remain with us for all time, nor to extreme examples of original manuscripts by Nobel laureates, but rather to those many internal reports which often have no formal recognition, other than a serial number, and are circulated in an *ad-hoc* fashion and produced in relatively small quantities. Classic examples of such items are the Manhattan Project Reports and the AECD reports which followed them. Many have never been formally published and can only be found (with difficulty) in a few national repository libraries and even then not all are available. Are such reports safe for posterity? This matter was brought home to me when I decided to write an appreciation of the contributions to reactor theory by a talented, but small (about 15), group of Canadians, Britons and Americans who worked in Montreal during the period 1943-1946. The work of this group was published internally as reports with the prefix MT (Montreal Theory) and some later became CRT and AECL reports; but not all.

Let me explain the background to all this. More than 40 years ago, when I was an 'apprentice' in transport theory, I gained a great deal by studying the works of Boris Davison (of Russo-British extraction, who later became a Canadian citizen). There was his wonderful book "Neutron Transport Theory" and, referenced within it, a large number of MT reports of which the book gave only a flavour. I was able to track down some of these reports, which were readily available from Government Offices 30 years ago, but many were not in the learned journals. I always felt they deserved a more formal dissemination. At a meeting on neutron thermalisation in Ann Arbor in 1967, I was fortunate enough to meet Steve Kushneriuk (alas now deceased), who had been a close collaborator of Davison, and no mean reactor theorist himself. I asked Kushneriuk whether there was any chance of AECL collecting together Davison's works and publishing them. To my amazement, he told me that such a project had been started some years earlier soon after Davison died in 1961 but, due to lack of personnel, it had been shelved. He promised, if it were possible, that he would re-activate the project. Some 12 years later, in 1979, 5 fine volumes of Davison's works were published under the auspices of AECL which include his first papers in Russian written in the 1930's to his last in Canada, published posthumously, in 1961. These were not published by a commercial publisher but issued by AECL in a semi-formal manner. I have a set and some libraries have them. Let us hope they do not get 'lost' in the system.

Whilst Davison's work became more widely available, and that includes all his 'MT' reports, the MT reports by other authors remained internal. To be sure, some had been re-written and published in the open literature but there were still many gems which had not received the exposure they deserved. Fortunately, in 1967 Steve Kushneriuk sent me a letter which included a complete list of those MT reports concerned with reactor theory, from MT-1 (The En(x) functions, by George Placzek) to MT-249 (The effect of fast neutrons on the utilisation of neutrons by an absorbing rod, by J.M.G. Fell). Thus I had a list of all the 'hidden' reports but possessed very few of them; rather like looking through a sweet shop window as a child but being unable to buy the goodies.

Recently I decided to investigate the feasibility of collecting all the MT reports together and having them published, partly as a history of reactor theory but also because they are still worth reading. So my first approach was to Atomic Energy of Canada Ltd. Alas the reports are not readily available and the Librarian at AECL could find no record of them although it was thought that copies may be in some subterranean repository. However, they promised to carry out a search. I then wrote to the Library at AERE Harwell and received the 'chilling' reply that the reports had been disposed of (destroyed) some years ago due to lack of space in the Library. Yet another avenue closed. So what to do next? I realised that the people who wrote these reports were either dead or quite old, nevertheless it was worth trying to contact them. Following a suggestion of Professor John Walker of The University of Birmingham, UK, I was fortunate in contacting Dr Robert Clarke of Carleton University in Canada who agreed to help and attempt to track down the old authors in the hope that they may still have some reports, and to persuade AECL to find the originals 'somewhere in a basement' at Chalk River. For my part, I continued to search for the elusive MT reports in the UK but not before some 'wag' had suggested that Moscow might have them! At the suggestion of my friend and colleague Professor R.T. Ackroyd of Imperial College, London University, I wrote to several other ex-UKAEA and AWRE sites (now called AEA Technology and AWE). These are at Winfrith, Dounreay, Aldermaston and Risley. Both Winfrith and Aldermaston responded courteously but did not have the reports. My letter to Dounreay, which was the home of fast reactor technology in the UK, was returned unopened and marked "*we do not have a library*". That really worried me, but just as I was beginning to give up hope I received a phone call from Andrew White, Manager of the Risley Information Centre, telling me that he had about 60% of the reports I was seeking. He also added that I was only just in time because, like all other AEA Technology sites, the library was being closed. I spoke to Andrew White in the middle of September (1999) and he advised me that he was currently arranging the disposal of all the Library's stock, including books and reports dating from the earliest days of nuclear energy research. I got my MT reports (and a few others too) but I could not help feeling a pang of regret at the demise of all that history. I should add that many of the reports that referred to safety issues were to be microfilmed and stored; however, the bulk of the collection was destroyed.

The point of this story is to raise a warning flag that we are in danger of losing our nuclear engineering heritage by attrition, apathy or ignorance. The current generation of nuclear engineers are no longer weaned on these old classics. A course based on a modern textbook on reactor theory, then into computer codes seems to be the form now. I am not saying that is wrong, indeed it produces people who are competent and can do the job effectively. However, it denies the student a fascinating background to his field and some real physical insight which could have some value even now, nearly 60 years on.

This harrowing experience made me even more determined to ensure that the Canadian MT reports are not lost to posterity. I also decided to widen the scope of my project to include some personal details of the authors of these reports, many of whom in later years distinguished themselves in other fields of physics. To this end, Bob Clarke, Mike Milgram and I have been contacting the 'old timers' (I use the expression with affection) to obtain background information on working conditions at the Montreal Laboratory during the second world war and other such personal and technical information that they can remember. We had to bear in mind though that these events took place some 55 years ago and very few of the major players are alive. One who is very much alive, however, is Professor Philip Wallace whose recent recollections on war-time Montreal will be discussed below and which answer many of the questions I had in mind.

At this point, I would like to be able to claim to be the saviour of the history of Canadian reactor theory. However, just as I was concluding this article I received some information from Lorna Arnold (a distinguished historian of nuclear science and technology) which directed me to the Public Record Office website, www.pro.gov.uk. It is an unusually friendly website and very soon I had located the section on "Records of the United Kingdom Atomic Energy Authority and its Predecessors". Under the class title "Department of Scientific and Industrial Research and successor: Directorate of Tube Alloys and successor: Anglo-Canadian Joint Project Reports", I found listed virtually all of the MT reports I had been seeking. In addition, there are reports on the engineering and chemical problems together with experimental nuclear physics. One can also find reports on the administration. In the list are the six famous lectures by George Volkoff, 'Lectures on Pile Theory' given in Montreal in 1944.

Under another heading, "Ministry of Aircraft Production and Related Bodies: Second World War Atomic Energy Research in Britain, Technical Reports", I found many British contributions by Dirac, Peierls, Davison, Frisch, Fuchs, Skyrme, Wilson and others. A short list of these and their Abstracts will be provided below to illustrate these contributions.

Although the somewhat tortuous route by which I have located the erstwhile missing reports illustrates my own shortcomings as a historian (not that I claim to be one), it might serve to help others who wish to make similar searches. However, my long way round had its benefits because I was introduced to a lot of very interesting people, whose enthusiasm about this project was equalled only by my own. It also confirmed my original thesis that these reports are not readily available to the interested reader. It should be added as well, that although the reports are lodged at the Public Record Office (PRO) at Kew in London, examining them is by no means a casual affair. For example, to gain access to the material; first one must know the 'Document Details', i.e. the classification number, secondly one must give at least 24 hours notice to the 'Advanced Requisition Service' at Kew and thirdly only 3 articles may be ordered at a time. The latter restriction is of little concern to someone who wishes to examine only one article, but for me who needed to study more than 30, it posed a logistical problem with which I will not bore the reader. It is also necessary to get to Kew. However, for those interested in accessing these documents and obtaining a copy, it is possible to order them 'sight-unseen' by post. But beware that you know the length of the article in advance, using the PRO estimating service, otherwise you could be in for an unpleasant financial shock.

Thus, the MT reports are not lost to posterity and for that I am truly grateful to the British Public Record Office which has done a remarkable job of collating all this old work. However, whilst the reports are not lost to posterity, whether they are readily available to students and research workers is debatable. It is for this reason, and because of their undoubted seminal character, that some of the more important reports will be reproduced in this journal over the coming years. For permission to do this I am very grateful to Atomic Energy of Canada Ltd who have been most supportive throughout.

It is useful at this point to list the authors of the MT reports with a short biography where possible. Following that, a complete list of those reports concerned with reactor theory is given. My ultimate goal is to reprint in this journal such reports as have historic and/or technical importance. This will be a lengthy job as we can only publish one report per issue. However, in about 3 years all the MT reports that are both traceable and of significance should be available to the readers of Annals of Nuclear Energy or the companion journal, Progress in Nuclear Energy.

2. The authors of the MT reports

F.T. Adler 1911-1979

Professor Felix T, Adler died suddenly on July 23, 1979, just a few days short of scheduled retirement, but, characteristically, in the midst of a full program of undergraduate teaching, graduate thesis direction, personal research, and influential participation in professional society activities.

Felix Adler was born in Zurich, Switzerland, attended schools there and earned the Ph.D. degree from the University of Zurich in 1938. His professional career included appointments in universities, in national laboratories and in industry. Altogether he was author or co-author of about sixty journal or symposium articles and about forty technical reports produced over a forty year period of continual activity. For many years his university research work was supported by contracts from the U.S. Atomic Energy Commission. His work as an author was complemented by service as a referee both for research articles and research proposals.

Following his Ph.D., Prof. Adler held postdoctoral appointments in the College de France, Paris and the Institute for Advanced Study, Princeton. The Second World war interrupted the normal development of Adler’s scientific career, as it did that of many other scientists at the time. For the years 1943-45 he was a Scientific Officer in the Canadian National Research Council and was stationed in Montreal and in Wisconsin. After the war, short appointments at the Universities of Colorado and of Wisconsin were followed by tenure appointment at the Carnegie Institute of Technology beginning in 1950. This ended when he went for two years 1956-58 to be a research section head at the General Atomic Division of General Dynamics Corporation.

Felix Adler's service at the University of Illinois began in 1958, when he was appointed Professor of Physics, with the understanding that he would devote a major part of his attention to reactor science and engineering. The appointment was an early part of the development of an Illinois program in nuclear engineering. He also held title as Professor of Nuclear Engineering beginning in 1959, and organized and taught for the first time a half dozen of the Nuclear Engineering courses. Over the succeeding twenty years, much committee work both from Physics and from Nuclear Engineering came to Dr. Adler, who always discharged his responsibilities with care and integrity.

The research contributions originating from Felix Adler over the years display truly remarkable physical insight coupled with in-depth, precise, and definitive quantitative analysis. The broad span of his work encompasses topics which include reactor control theory, reactor kinetics and stability, neutron slowing-down theory, neutron transport theory, chemical physics, operational calculus in electrodynamics, accelerator physics, and theoretical plasma physics. Professor Adler also maintained a continuing interest in neutron resonance phenomena and its applications in resonance capture analysis. In this latter area he collaborated extensively with his wife, Donatella Baroncini Adler, also a physicist, who is co-author of about forty papers.

In 1939 Prof. Adler published In Comptes Rendus, Vol. 209, a paper entitled "Growth of a Chain Reaction in a Mass Containing Uranium". This work contains a precise interpretation of the critical radius of an assembly of fissile material on the basis of the time-dependent diffusion equation. It was demonstrated by Prof. Adler that the neutron population in a super-critical assembly is unbounded in time, that the neutron population in a just critical assembly is asymptotic to a nonzero constant value, and that an initial neutron population in a subcritical assembly eventually vanishes. The second of these three cases occurs when the radius of a spherical assembly equals the critical radius. This dynamic interpretation of criticality is more representative of experimental facts than the interpretation which arises from eigenvalue problems of the Sturm-Liouville type.

The concept of the temperature coefficient of a thermal reactor appears in the May 13, 1939 issue of Nature, vol l43, in a work entitled "Control of the Chain Reaction Involved in Fission of the Uranium Nucleus". The role of 1/v and non-1/v neutron absorbers in the spectral hardening effect and the concept of spectral hardening itself were clearly perceived at this very early time in the development of nuclear energy.

The 1/E characteristic of the energy spectrum of the neutron flux in a fissile assembly is a classic result. By an ingenious application of the Laplace transform faltung theorem in obtaining an exact solution of the governing integral equation, Prof. Adler was able to show the origin of the 1/E flux spectrum as the contribution to the value of the Bromwich integral from the residue of the pole located at the origin of the complex transform plane.

Further specific examples of Prof. Adler's physical insight and analytic perceptivity are too numerous to be included here. His expository writings exhibit the clairvoyant incisiveness characteristic of the truly scholarly mind. The impact of Felix Adler's contributions has been and will continue to be invaluable in the progress of nuclear energy. The loss of further expository and research contributions from Felix Adler is irreparable.

His professional honours and activities included election as Fellow of the American Physical Society, election as Fellow of the American Nuclear Society, a decade of service in the 1970's as member and as chairman of the Advisory Committee of the Division of Reactor Physics, the Division of Reactor Engineering, and of the Idaho Division of Argonne National Laboratory, a decade of service to the American Nuclear Society beginning in 1967 as member of the National Program Committee including two separate terms of membership in the Physics Division Program Committee, a term on its steering committee, and involvement with the planning of topical meetings. He was a U.S. participant in the International Atomic Energy Authority Conference on Nuclear Data, Helsinki, in 1970 and in a subsequent conference in Budapest in 1972. Professional recognition and involvement came to Dr. Adler from four different divisions of Los Alamos Scientific Laboratory, to which he served as a consultant beginning in 1967. A member of the American Association of Physics Teachers, Dr. Adler always showed sincere and effective dedication to teaching. Carnegie Institute of Technology presented its Award for Excellence in Undergraduate Teaching to him in 1953.

Felix Adler's abilities and knowledge as a theoretical physicist were unusually broad. His talents as a teacher were exceptional. Joining these was what an acquaintance in 1945 called "a man of very gentlemanly, quiet personality." Another acquaintance of that time said "As to personal contact with students you may rely upon his being extremely generous with his time; with his enthusiasm for physics and his great patience, I would expect him to do most valuable tutorial work." These fine characteristics carried over his life together with a strong sense of loyalty, and formed the basis for Professor Adler's many contributions to the University of Illinois.
R.O. Simmons and R.A. Axford October 23rd, 1979.

A Memorial Statement in Memory of Professor Felix Adler by George H. Miley
(What follows is an excerpt from a personal reminiscence by George Miley)

I first met Felix Adler some 28 years ago when I entered freshman physics at Carnegie Mellon University and found he was one of two lecturers in the course. I felt fortunate since he had received the campus teaching award a year earlier, and I certainly wasn't disappointed. He left the University the following year to work at General Atomic, so our paths didn't cross again for a while. It was a pleasant surprise when I joined the Illinois Faculty in 1961 to discover that he had come here to help establish the then new Nuclear Engineering Program. Felix assumed a central role in many of the activities in Nuclear Engineering in those days. For example, the staff decided that a major thrust should be undertaken to develop research in reactor dynamics, since Illinois was the first university to own a pulsed TRIGA research reactor. The initial step in this direction was to offer a reactor kinetics institute for Faculty the summer after I arrived. Characteristically, Felix undertook the burden of lecturing for four hours per day for the 11 Faculty who attended the Institute from other universities. I was among seven of our own Faculty who sat in on the lectures. That experience clearly stimulated the other university staff, but, more importantly, it served to pull our faculty together, sparking much of the early research in reactor kinetics at Illinois. I could relate many other examples of the impact that Felix had on Nuclear Engineering in the early days of the program, but I would rather jump to some personal reflections from recent years. (*Author's note*: Dr Miley recalls the popularity of Professor Adler with students, his powers as a teacher and his unflagging willingness to take on responsibility for any new venture that came up, either from within the university or from professional bodies.)

Sources:
Memorial citation from the College of Engineering, University of Illinois at Urbana-Champaign, by R.O. Simmons and R.A. Axford.
Memorial statement in memory of Professor Felix T. Adler by George Miley.
The author is indebted to Professor Elmer E. Lewis of Northwestern University, a graduate student of professor Adler, for obtaining the above information.

Bengt Carlson 1915 -

The biography given below is taken verbatim from a letter to the author from Dr. Carlson, which was dated 16th February 2000 and was in response to a telephone call made by the author to Dr. Carlson in New Mexico. The letter is as follows:

"Dear Professor Williams, Your letter of December 2nd, 1999, was very much appreciated, and talking to you last week over the telephone likewise. I am glad that your efforts re the Montreal Project have met with success. Please excuse the handwritten letter. Here is the biography you asked for.

1. I was born in Southern Sweden on December 26th, 1915. The family moved to Stockholm in 1930. The regular schooling - 10 years at the time - ended in June, 1932.
2. University of Stockholm, 12/32 - 11/36, Statistical Clerk. Worked first in the Department of Actuarial Mathematics, Harold Cramer professor, Herman Wold immediate supervisor. Then from April of 1934 in the Department of Economics, Gunnar Myrdal professor, Dorothy S. Thomas visiting professor from Yale University immediate supervisor. I also helped others in the two departments, in particular Will Feller in transit from Germany to the USA. Professor Thomas had gotten her PhD from University of London, circa 1925. Her thesis 'Social Aspects of the Business Cycle' was quite a sensation at the time.
3. Yale University, 1/37 - 4/43, Research Assistant to Thomas to fall of 1939, then Instructor in Mathematics at Yale. At the same time a student, earning a BS in 1939, an MS in 1942, and - except for a thesis - the PhD. Never returned to finish up.
4. NRCC, Montreal, 4/43 - 5/45, in charge of a computing set-up with Max Goldstein as assistant all under George Placzek, head of the Theoretical Physics Division. I had been interviewed by Placzek just before Christmas, 1942, in a hotel near the Grand Central Station in New York City. He had gotten my name from Will Feller, then at Brown University.
5. Los Alamos, N.M., 6/45 - 9/76, first in Group T-8 with Placzek and Carson Mark, the Transport Theory Group. Then from the fall of 1946 Group Leader of a consolidation of computing activities, and from July 1951 Head of the Computing Center, this in preparation for the first IBM electronic computer to be delivered in 1953. In the 60's the Center became the largest such center in the world, maybe it still is. We had come from the Stone Age to the Silicon Age in less than 25 years. During my last eight years at Los Alamos, 1968 - 76, I led a revived Transport Theory Group.

I became acquainted with many of the British Mission people, among them Peierls, Fuchs, Skyrme, Titterton, Bretscher and Tuck; much later also with Jack Howlett of Harwell, Oxford, and ICL. We had much in common, regrettably he passed away last year. It was the time of my life, that whole experience, Montreal and Los Alamos, mingling with all those astonishing people!"

There is an interesting memo in section 4 on personnel, from Carlson to George Placzek, about the need for computational assistance in the theory group. Dr Carlson is well remembered for his pioneering work on numerical methods to solve the integro-differential form of the transport equation using the SN method, described in LA-1891.

Henry H. Clayton 1906-1989

Hank Clayton was born in England into a family whose military tradition went back several generations. At the outbreak of war in 1914 he was at school in Bermuda where his father, an officer in the Royal Engineers, commanded the garrison. He once remarked that most of the soldiers he then knew were killed within a few months. When peace returned, the family lived for a while in the Channel Islands and then in Brittany; as a result Clayton was proficient in French. Next the family emigrated to British Columbia to try farming.

After working in a bank and trying his hand at hard-rock mining and trapping, Clayton entered the University of British Columbia in 1931. He graduated in physics in 1935 and earned a master's degree in 1937. Then he went to Purdue University to begin work on a Ph.D.

Clayton joined the Canadian army in 1939. Before he could be shipped overseas his physics background was noted, and he was sent to Halifax to work on de-gaussing ships to be used on the Atlantic. Eventually he transferred to the artillery and was sent to Italy. After brief service in Belgium and Holland he ended the war as a lieutenant-colonel.

Clayton joined the Montreal Laboratory in 1945 and moved to Chalk River in June 1946, when the laboratory was still headed by Sir John Cockcroft. Clayton became head of the Theoretical Physics Branch in 1950 and retained that position until he retired in 1969. His name first appears in the MT series in MT-240 (issued May 18, 1946), though MT-241 was apparently issued on May 11. In this period his energies were almost entirely concentrated on practical problems related to the design of the NRX reactor, culminating in a reactor-physics treatise on the NRX "Pile'. Later he was deeply involved in planning for the NRU reactor, which led to the heavy-water moderated and cooled CANDU power reactors.

In 1959 Clayton went to London for two years to open the first Atomic Energy of Canada office in Europe. During this period he made frequent visits to the International Atomic Energy Agency in Vienna and became familiar with other atomic-energy establishments in Europe.

Sources:
Private communication from Graham Lee-Whiting via Michael Milgram, Feb., 2000
Obituary by Jack Veeder in the North Renfrew Times, Sept. 27, 1989

Ernest David Courant 1920 -

Courant was born in Germany in 1920 and came with his family to the United States in 1934. Courant's father was the famous mathematician Richard Courant. Courant became a naturalised US citizen in 1940. He graduated with a BA at Swarthmore College in 1940 and gained an MS in 1942 at The University of Rochester and a Ph.D in 1943 at the same university under the supervision of Victor Weisskopf. It was Weisskopf who advised Courant to join the Montreal project under his friend George Placzek. Courant spent 3 years, 1943-1946, working with Placzek, Volkoff and Wallace. It is worth noting that the paper on neutron density fluctuations in piles co-authored with P.R. Wallace, is a classic and continues to be quoted to this day (see details in section on Wallace).

After the war, Courant went to Cornell as a "post-doc" working with Hans Bethe in nuclear physics and in 1948 he joined the newly created Brookhaven National Laboratory to work on the beam dynamics of the Cosmotron (the world's first GeV accelerator). As a result of his work, Courant became one of the trio which originated the idea of "strong focussing" accelerators leading to the Brookhaven AGS, the CERN PS and just about all the big accelerators since. He retired in 1990 but still consults at Brookhaven.

Ernest Courant has won many academic honours for his work, including the Fermi Award 1986, R.R. Wilson prize of The American Physical Society 1987, The Boris Pregel prize 1979. He is also a Member of the US National Academy of Sciences, NY.

Sources:
Personal communication to MMRW (1999)
Who's Who in America.

Boris Davison 1908-1961

Davison was born in Russia and educated there. He graduated from the University of Leningrad in 1931 and was engaged in hydrological work for about 7 years. Through his English grandfather he had a tie with the UK and when in 1938 he was requested by the Soviet authorities to either renounce British nationality or leave the USSR he elected to go to England. After a period of ill-health, Davison joined the atomic energy research team at the University of Birmingham under the leadership of Professor Rudolph Peierls. Whilst there, Davison made several important contributions to neutron transport theory and in particular he obtained the point source solution in an infinite medium by methods involving Fourier transforms. Some of this work was written up for his Ph.D which was awarded by the University of Birmingham in 1944. Curiously, part 2 of his thesis remains classified to this day.

Davison joined the Montreal Laboratory of the joint United Kingdom-Canada atomic energy project in 1943. His association with George Placzek was especially productive and he wrote many seminal papers on integral transport theory with an emphasis on small, highly absorbing spheres and cylinders. In 1947, Davison returned to the UK as a member of the Theoretical Physics Branch of the Harwell Laboratory, then part of The Ministry of Supply. In 1953, when there was great concern over security, it was decided by the British government that anyone who had been born in Russia and whose parents were still in the USSR, should not be employed on nuclear work. Davison therefore returned to Canada where he joined the staff of the computation centre in The University of Toronto. During Davison's time at Harwell he completed a number of chapters of his classic book "Neutron Transport Theory" (Oxford University Press, 1957) with the collaboration of J.B. Sykes. I recall John Sykes telling me that it was an experience he would always cherish.

Davison's style of work is well-described by Philip Wallace, with whom he collaborated in the Montreal Laboratory, as follows: "His manner of working was a delight to observe. Unlike the rest of us, he rarely passed through the stage of rough drafts and back-of-the-envelope scribblings. He worked neatly and methodically producing, it seemed, finished work from the start. He had an instinct for difficulties and delicate points. For a while he would gallop ahead, formulae filling the pages, then sensing trouble, he would slow down to a crawl, cautiously exploring obstacles and making his way through them with painstaking care. Emerging again on the open road he would regain full speed ahead. I never knew him to come to a full-stop".

Sources:
Obituary of Boris Davison, Nature , Vol 190, (1961) 306 by W.H. Watson

Impressions of Boris Davison by R.E. Peierls in vol 1, collected papers of Boris Davison, published by Atomic Energy of Canada Ltd, 1979. Also in Progress in Nuclear Energy, vol 8, (1981) 53.
Editor's note: Davison must hold the record for having his name mis-spelt in the literature. I have seen: Davidson, Davisson and Davyson. I am sure there are more.

Max Goldstein 1920-1992

Max Goldstein, one of the pioneers of the computer era, a key figure during the early years of the computing division at the Los Alamos Scientific Laboratory, and subsequently the leader of one of the first large university computing centres at the Courant Institute of Mathematical Sciences at New York University, died at his home in New York City on August 23, 1992, at the age of 72.

Goldstein received a B.A. from Brooklyn College in 1940, and an M.S. from New York University in 1942. He entered professional life as a numerical analyst in the theoretical division of the National Research Council of Canada in 1943. He was at the Montreal Laboratory as a Computing Assistant from 1943-46, where he worked under the direction of Bengt Carlson as part of the Atomic Energy Project. He then went to Los Alamos and was employed there from 5th June 1946 until 15th September, 1958. While at Los Alamos he served as Group Leader of T-2 in the Theoretical Division. From Los Alamos, Dr Goldstein moved to the Courant Institute of Mathematical Sciences to take charge of the computer operations of its Atomic Energy Commission Computing and Applied Mathematics Centre (subsequently sponsored by the Department of Energy, the successor of the AEC).

This Centre was the first established by the federal government at a university, and it served as a central computing facility for research scientists at the Courant Institute and for AEC-sponsored research and development at other institutions and AEC subcontractors at a time when mainframes were not readily available to most groups. From 1966 to 1977, Goldstein held the title of associate director of the Centre, which later served as a model for the creation of a University-wide Academic Computing Facility under his direction. In 1969 he was one of the founders of the Computer Science Department at the Courant Institute, in which he was appointed Professor of Computer Science. For many years he served as associate chair of the department. He retired in 1990 officially, but he continued to teach and be active in the administration of the University until his death.

Professor Goldstein had a long and distinguished career in scientific computation as well as in administration. He wrote early codes for Bessel functions which are still in use, pursued interests in symbolic algebra and significance arithmetic, and investigated problems of parallel computing and numerical linear algebra. He was very active in helping and encouraging the many applied mathematicians on the faculty and staff and visiting the Courant Institute to see the computer for what it was, - an essential ingredient of effective scientific research. He started the first formal training program for New York City high school teachers in computing in the mid 1960's, and encouraged others with programming skills to teach.

Goldstein was deeply interested in computer components and systems, from the days of the IBM 7094 and CDC 6600 mainframes and the first microprocessors, through a broad range of later products to which he managed to get access either remotely or by providing a test site: among them, VAX, Convex, Sun, Alliant, ELXSI, HEP, and a number of others. Goldstein was among the first to introduce time-sharing on the 6600. He continually sought out the latest techniques and technologies. In more recent days he orchestrated and encouraged NYU's participation in ARPANET, MFENET, the New York State regional network, NYSERNet, access to the NSF Supercomputer Centres, and in the Consortium for Scientific Computing for access to the John von

Neumann center. His approach was always pragmatic, favouring the use of large central machines, personal computers, workstations, and computers in networked environments in whatever mode was appropriate.

Max also had to deal with periods of great stress, of a kind that people who are responsible for computing facilities are likely to recognise. Most striking was the occasion of the installation of the CDC 6600. It was the fourth unit off the line of the first (and only) batch of six built at the Cray shop in Wisconsin, hand-tailored and hand-trimmed, rather than at the production centre in Minnesota. With its 10 peripheral processors (in parallel!) it ran like a dream ... when it ran. It was put to active use shortly after arrival with acceptance to be based on sustained performance. (This was in the days before alpha-tests and such). Unfortunately, the software being developed on the West Coast was not quite ready so the Centre had to use a capable but rough-and-ready operating system and compiler that the Chippewa Falls people had cobbled together for their own use. But then there was the hardware. Many of the components had not been burnt in, and they frequently failed. And because of the hand-tailoring, many could not be replaced without elaborate re-tuning and re-timing of many circuits, - all of which required highly skilled technicians and engineers drawn from the Cray team who were in a hurry to get back. This put Max in a very hot seat: Users grumbled and screamed (especially people with tight deadlines) at Max, naturally, (who else?) because schedules were not kept and the machine could not be relied on in the first few months for even a full hour of error-free operation. CDC management on the other hand, eager to be paid, added up the times during which the computer was not down, and claimed that the totals satisfied the acceptance criteria. And they screamed, and badgered Max with their figures, and threatened retribution. And Max, inescapably, was at the focus and had to be the one to say WHEN, with millions of dollars in the balance. This went on for four or five months (!) until, in the fullness of time, the machine began to settle down, payment was made, the Centre survived, and Max survived. His harried look went back to normal, and those who shared that period with him now look back nostalgically to the good old days.

Goldstein is fondly remembered by his colleagues and subordinates (the two were synonymous for him) as an unassuming, friendly man, who worked quietly behind the scenes to take care of difficulties as they arose without asking for recognition for his efforts. He strongly encouraged personal and professional development and urged his staff to follow up subjects of interest. His humour frequently helped himself and others to cope with the frustrations that are inherent in the operation of a computer centre. His door was always open, and anyone could walk in to discuss their favourite project or problem whenever the visitor's chair was vacant, and get an attentive ear and advice. Max used to tell the story of his return to Los Alamos after his first year at New York University. He was provided with an office for the week or two of his visit. The day after his arrival, a scientist at Los Alamos appeared there, settled into the visitor's chair and started off: "Now, about that problem we were talking about, ..."

In honour of Professor Goldstein there is an annual undergraduate prize awarded at the Courant Institute.

Sources:
Obituary that Lazer Berman prepared for SIAM.
Professor Jerome Berkowitz's address at the annual presentation of the Max Goldstein Prize in April 1997.

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Edward Armand Guggenheim 1901-1970

Edward Armand Guggenheim was Professor of Chemistry and Head of the Chemistry Department at the University of Reading from 1946 to 1966. He was a scholar, who was recognised internationally for his contributions in the field of thermodynamics and statistical mechanics. He was responsible for building Chemistry at Reading into a well found and well established Department.

Guggenheim was educated at Charterhouse, and at Gonville and Caius College Cambridge where he obtained a first class in the mathematical tripos (part 1) and in the natural science tripos (part 2). He studied under Professor R. H. Fowler in Cambridge, and then under Professors Brønsted and Bjerrum in Copenhagen. In the 1930's he held academic positions at Stanford University in California, and at the Universities of London and Reading. He wrote two books in the pre-war years: *Modern Thermodynamics by the methods of Willard Gibbs*, and *Statistical Thermodynamics*, jointly with R H Fowler; these books established his reputation and revolutionised the teaching of these subjects.

During the war he worked at the Admiralty, where he made significant contributions to solving the problems posed by magnetic mines, and then at Montreal in Canada where he worked on diffusion methods for separating uranium 235 for use in the atomic bomb. In 1946, at the age of 45, he was elected a Fellow of the Royal Society, and in the same year he was appointed to the chair at Reading. He wrote many further books, always with a simple clear logic that established his reputation as a scholar. The successive editions of his monograph *Thermodynamics*, published during his years at Reading, are perhaps his greatest memorial.

Although he was primarily a theoretician, Guggenheim set an example in the careful analysis of experimental data which had a wide influence. He also made large contributions to the precise and economical use of words and symbols in science, both through his writing and through his contributions on national and international committees. He could not tolerate inexactitude, and he made enemies as well as friends in the scientific world. To his relatively few pupils he was a warm and human person, a great teacher and friend. After his death in 1970 his many admirers subscribed to a fund in his memory, the income from which is used to support the Guggenheim Memorial Lectures in the Chemistry Department at Reading.

Sources:
Private communication from Professor Ian M. Mills, University of Reading, UK.
A more detailed account of Professor Guggenheim's career can be found in Biographical Memoirs of Fellows of the Royal Society, Vol 17, p.303-326 (1971).

Steve Alexander Kushneriuk 1923-1984

Kushneriuk was born in Saskatchewan, the son and grandson of prairie farmers. After Normal School and a brief career as a teacher he entered the University of Saskatchewan whence he graduated with honours in mathematics in 1944. He then worked briefly for the navy in Halifax. In June 1945 he joined the Montreal Laboratory of the National Research Council, where he formed the computation section of the Theoretical Physics Branch. He first appears as an author in the MT series in MT-207 (issued in 1945-46) with Davison and Seidel as co-authors. In July 1946 Kushneriuk was one of only three members of the theory branch to move to Chalk River. Between 1947 and 1950 he studied for his Ph.D. at the University of Toronto, with M. A. Preston as advisor for a thesis on scattering phase shifts in the two-nucleon system; he spent the summers working at Chalk River.

Until his retirement in 1983 Kushneriuk remained in the Theoretical Physics Branch at Chalk River. As time went on, the original strong emphasis on neutron transport theory declined until only Clayton and Kushneriuk remained in the field. After Clayton's retirement in 1969 Kushneriuk was left as the sole depository of the tradition in the branch. Though plagued by ill health, he continued to be active in research and to provide much valued assistance to reactor physicists. He acted as external thesis advisor to at least one Ph.D. candidate: Michael Love, Queen's University. Mike Love later spent two years at Queen Mary College, London University, where the author met him. He was full of praise for Steve Kushneriuk both as a theoretician and as a colleague and friend.

Professor Phil Wallace recalls the lighter side of life in Montreal and Steve Kushneriuk's sense of humour, he relates the following story:

One of the young members of the theory group was a recent graduate named Steve Kushneriuk. Steve worked as an assistant to the senior members of the theory group, most particularly Boris Davison, from whom he learned quickly. Steve was generally a quiet young man, but we soon discovered that he had a lively sense of humour. A story he told to someone in the group (I do not remember who) quickly circulated through the whole laboratory. Steve's story was the discovery that there were mountain goats which inhabited the higher levels of a conical volcanic mountain. They had to circle round the upper levels of the mountain in search of food. This was awkward because the feet on one side had to be above or below those on the other to maintain equilibrium. Therefore, in the course of time, they evolved to have the legs on one side shorter than those on the other, so they could stay upright as they circled the mountain. There were, however, difficulties. To begin with, they could only go around the mountain in one direction, either clockwise or counter-clockwise As a consequence there had to be two sorts of goats, clockwise ones and counter-clockwise ones. If a clockwise mother bore a counter clockwise baby, she would find it almost impossible to suckle her infant. Only goats of the same orientation could mate to have kids.

A very personal and informative obituary of Steve Kushneriuk was written by Dr. Hank Clayton for the North Renfrew Times, September 1984:

"With the passing of Steve Kushneriuk on September 4, 1984, Deep River has lost one of its earliest citizens and the Canadian Atomic Energy fraternity one of its earliest practitioners. And those of us who worked with him have lost a friend most admirable for his personal qualities. Steve Kushneriuk was born in 1923 in Buchanan, Saskatchewan, where his grandparents had farmed since coming to Canada in 1892 and his father also was a farmer. He was the fourth son in a family of six sons and four daughters. He attended high school in Yorkton, then normal school and taught briefly before going to the University of Saskatchewan whence he graduated with honours in mathematics in 1944. After a brief spell of working with the navy in Halifax he went in June 1945 to the Montreal laboratory of the National Research Council, where the early work on heavy water reactors was being done, forming the computation section of the theoretical physics branch. In July 1946 the branch moved to Chalk River. From 1947 to 1950 he studied for his Ph.D at the University of Toronto but spent the summers at Chalk River. In 1953 he and Catharine Jewett, who was then the public health nurse in Deep River, were married. They have three children, John in Ottawa, Pauline in Toronto and Robert in Thunder Bay. To all who knew Steve his most striking characteristic was his invariable good nature and his readiness to put his special skills to the service of others. It is perfectly right to say that in all the years I knew him I never saw the slightest expression of impatience or annoyance with others. In his younger days he was a good skier and canoeist, and always ready for a ramble in the bush during the lunch hour. In later years he suffered much from ill health but not even that perturbed in any way his friendly nature and indeed he never even alluded to it, gently rebuffing instead any reference to it. He will be sorely missed by his family and by all his friends." H.H. Clayton

Sources:
Private communication from Professor P.R. Wallace, January, 2000.
Private communication from Graham Lee-Whiting via Michael Milgram, February, 2000.
Obituary by H. H. Clayton, North Renfrew Times, Sept. 1984
V. F. Sears, Fifty Years of Theoretical physics at AECL: 1943-1993, Physics in Canada (July,1993)

Jeanne LeCaine 1917-2000

Jeanne LeCaine was born in Port Arthur, Ontario in 1917. She earned her BA at Queen's University in Kingston, majoring in mathematics with a minor in economics. This was followed by an MA also at Queen's. She received her PhD from Harvard University and her Advisor was Garrett Birkhoff. It is interesting to have this episode in her life in her own words which are taken from an autobiography which appeared in the Queen's University Alumnae Association publication 'Still Running…'. In it Dr LeCaine says:

"Harvard was ostensibly an all-male school. I lived in a Radcliffe graduate dormitory; I enrolled at Radcliffe; I wrote my exams at Longfellow Hall at Radcliffe; and I graduated in the Radcliffe ceremony at Sanders Theater. But everything else I did at Harvard. My mathematics classes were in Sever Hall; I studied in Widener Library; all my professors were Harvard professors; and my fellow students were all Harvard men, with the exception of Anne O'Neill. We felt in every way like Harvard students.

During the first year I had a course in Complex Variables under Dr G.D. Birkhoff. It was obvious that he was indeed what he was reported to be, one of the greatest American-born mathematicians. He was also able to convey the excitement of his subject. We might have to go back over the lecture notes to fill in some details, but that was unimportant compared to the insight he was able to give us. True to my first decision, I also took a course in mathematical economics from Professor Leontief, who later became famous in that field. Although I found it interesting and valued the opportunity to study with him, I decided that my first love was mathematics, that I would like to proceed to a PhD and perhaps even have Dr Birkhoff for my major advisor. Dr Birkhoff accepted me but not without some slight hesitation-yes, because I was a female. His previous female advisee had married and become the mother of five children. I do not know whether or not she ever used her mathematics in any way, but apparently it was his opinion that she had wasted time which he otherwise might have spent with some more mathematically productive student. In the present climate I should have been angered at this discriminatory attitude. I am ashamed to say it did not occur to me to be angry. He was a good advisor, hard-working and encouraging and, most unusual, prompt in responding to questions and in returning potential pieces of my dissertation. The dissertation took shape for the most part at the cottage on Thunder Bay, an ideal place to think and create. Sometimes it moved quickly and *sometimes* at such a snail's pace that I feared I had gotten into the wrong business entirely. I had promised to write Dr Birkhoff reporting on my progress, and it seemed to me I had nothing to say. I did write him, telling him what little I had been able to invent, and then commenting on the difficulty I was having trying to operate the old motorboat that my father had made in my early childhood. I received his reply almost by return mail, making encouraging comments about my ideas and then giving me a long account of his experiences one summer with a recalcitrant motorboat."

In 1987 Queen's University honoured her with the LLD and in 1989 a similar honour was conferred by Lakehead University, Ontario. Dr LeCaine's first teaching post was as an Instructor in Mathematics at Smith College. It was while working at Smith College that Dr LeCaine met her future husband, a young history student called Theodore Agnew, and they were married on Christmas day, 1942. A few days later he was sent on duty to Hawaii, where he remained for 27 months. With a war waging in Europe and Canada in the thick of it, Dr LeCaine wanted to contribute in an appropriate way. It is best to use her own words to describe her feelings, which are taken from the autobiography cited above. Dr LeCaine says (now Mrs Agnew, but she retained her maiden name for her work in Montreal):

"During my years at Radcliffe, and especially during my year at Smith College, I became increasingly conscious of the fact that I was a Canadian, and proud to be one; that my country was engaged in a devastating, thankless, yet necessary war; that it had supported me in my years of need and helped me get the education I so much cherished; and therefore that I ought to be doing my share in the war in which Canada was so deeply involved. I left Smith to work for the National Research Council, and was soon sent to Montreal to be a part of the Canadian branch of the Atomic Research Effort."

Dr LeCaine shared an office with Carson Mark who encouraged her in her work and allowed her to share his delightful family. This was an important association for her. At the end of the war, Dr LeCaine's husband completed his dissertation at Harvard and then they both eventually were offered tenure-track teaching positions at Oklahoma Agricultural and Mechanical College, which later became Oklahoma State University. During her tenure at the University, Dr LeCaine won many honours as a teacher, and national recognition as an educator. She and her husband were appointed Professors emeritus in 1984.

Sources:
Private communication from Dr Theodore L. Agnew
'Still Running…', Personal stories by Queen's women celebrating the fiftieth anniversary of the Marty Scholarship. Edited by Joy Parr, Forward by Pauline Jewett, MP, Queen's University Alumnae Association, 1987. (Note from Michael Milgram: Pauline Jewett is Steve Kushneriuk's sister-in-law).

J. Carson Mark 1914-1997

Mark was born in Lindsey, Ontario, Canada and received his BA from the University of Western Ontario in 1935 and a Ph.D in mathematics from the University of Toronto in 1939. He was a mathematical instructor at the University of Manitoba from 1938 until 1943 when he moved to the Montreal office of the National Research Council of Canada. Here he carried out original work on neutron transport theory with particular emphasis on the spherical harmonics method and applications of the Wiener-Hopf technique to half-space problems. In the spring of 1945, Mark moved to Los Alamos to work on the Manhattan Project as part of the British mission. In 1947 he took charge of the Los Alamos theoretical division from George Placzek (see Placzek later in this report), and despite a staff shortage due to the return of many scientists to their universities, he managed to improve the design and efficiency of the nuclear weapons.

Those who worked with Mark thought highly of him as an innovative scientist and as a leader. He knew exactly what his team members were doing and how well they were doing it. His judgement was sound and his counsel was sought not only at Los Alamos but in the wider world of science. Mark also encouraged his staff to branch out into fields unconnected with nuclear weapons. For example, the work on detecting the neutrino led to a Nobel prize for Frederick Reines. He also helped form the Jason group which offers advice to the United States government on a variety of topics. Because of his deep knowledge of nuclear weapons Mark appreciated the need to ensure they were never used. Thus he was a member of various safeguards committees and contributed to the Pugwash conferences.

In correspondence with Mrs Kathleen Mark, I learned that during the early part of the war Carson Mark was in Toronto on a family visit and took the opportunity to ask his former professor, J.L. Synge, if he knew of any way in which he (Mark) could assist in the war work. Synge told him that some very interesting and important work was going to start in Montreal. In order to be prepared to contribute to this work Synge suggested that Mark should take a couple of rather special summer courses at Brown University. This was because Mark's degree was in abstract mathematics and Synge thought he would benefit from some applied mathematics and physics training. As a result of this, Mark spent the summers of 1941 and 1942 in Providence taking courses which gave him an excellent background in nuclear physics.

Sources:
Physics Today, October 1997 (A.G. Petschek, George I. Bell and Hans A. Bethe)
Kathleen Mark, Private communication to the author, January, 2000.

Robert E. Marshak 1916-1992

Marshak was born in the United States, the child of an immigrant. He graduated from Columbia University in 1936 and as a graduate student at Cornell University, under the guidance of Hans Bethe, he did pioneering work in astronomy with a special interest in white dwarfs. After gaining his Ph.D. he joined the faculty of the University of Rochester, but moved to the Manhattan Project during the second world war and worked at Los Alamos. He is credited with inventing a variational method that was crucial in understanding neutron transport in critical assemblies. It is likely that this work was actually carried out in Montreal since he was resident there from early 1943 until late 1944. His Montreal reports MT-49 and MT-55 are both concerned with this topic.

Marshak's major contributions to physics came after his return to Rochester in 1946, namely his seminal work on mesons which culminated in his book 'Meson Physics' in 1952. He also established, with Sudarshan, the universal V-A weak interaction theory in 1957. It was the starting point of the present standard unified electroweak theory and is claimed to be an outstanding contribution to particle physics.

Marshak was also an outstanding teacher and was likened in his tradition to that of Arnold Sommerfeld and Hans Bethe. In 1970, Marshak became President of the City College of New York at a time when higher education was undergoing fundamental changes. Under the most difficult circumstances Marshak transformed CCNY but he found that his calling for physics was too strong and he returned to the life of a physicist in 1979. He was appointed to a Distinguished Professorship at Virginia Polytechnic Institute and was also active in the American Physical society.

Sources:
Physics Today, November 1993 (H.Lustig, S. Okubo and E.C. George Sudarshan)

George Placzek 1905-1955

Placzek was born in Czechoslovakia, moved to England but eventually became a U.S. citizen (at the time he was working in Canada, Placzek was classed as a British citizen). According to Professor P.R. Wallace, Placzek was an exemplary leader of the theory group in Montreal and had the necessary stature to be on equal terms with all the leading scientists of the Manhattan Project. Aside from his brilliance as a scientist who made contributions in many fields of nuclear physics, he never criticised and was always enthusiastic about the work done by the members of his group and contrived to make everyone feel a vital member of the team.

In 1945, Placzek succeeded Hans Bethe as leader of the Theoretical Physics Division at Los Alamos. Unfortunately, due to a heart condition he was unable to withstand the rarefied atmosphere on 'The Hill' and left to work in the Research Laboratory of The General Electric Company in Schenectady and later moved to The Institute for Advanced Study at Princeton.

Aside from his brilliance as a theoretical physicist, Placzek must also have been a very popular man. In virtually every scientific biography, one reads of Placzek and what a charming character he was. According to Rudolph Peierls in his *'Bird of Passage'*, Placzek was very absent-minded and would often miss trains or emerge at the last moment trying to keep things from falling out of a half packed bag. According to Segre in *'A Mind Always in Motion'*, Placzek was a remarkable linguist picking up Italian almost overnight. This is re-inforced by a comment of Otto Frisch in his *'What Little I Remember'*; "George Placzek was a Bohemian in every sense of the word, he spoke ten languages more or less fluently and with a fine range of naughty verse in most of them". He did, however, have some reservations over Hebrew which he complained could not cope well with modern physics. Placzek was also an experimentalist and worked with Frisch on the measurement of neutron capture cross sections. There are many Placzek anecdotes in Frisch's memoirs. In his autobiography, John Wheeler describes Placzek as "a wonderful person, a man of the highest integrity, he was often a delightful and thorough-going sceptic about new ideas, and sceptic in 1939 in particular about the idea that U235 was responsible for the fissility of natural uranium". He made a bet with Wheeler on the outcome of this, the odds being $18.46 on Wheeler's part to $0.01 on

Placzek's part, this being the ratio of the proton-electron mass. Following the crucial experiment Wheeler says that he received a money order for $0.01 with the message "Congratulations".

PHYSICS TODAY published Placzek's obituary in the June 1956 issue, page 41. The obituary is written by Emilio Segre and says:

George Placzek, permanent member of the Institute for Advanced Study, Princeton, N.J., died unexpectedly last October at the age of fifty in Zurich, Switzerland. Born in Brunn, Czechoslovakia, he studied at Vienna and later, in the early thirties in Holland, France, Denmark, Italy, Germany, Israel, and Russia. During this period he mastered the languages and assimilated the best of the culture of the countries in which he resided and struck friendships which lasted deep and close for life. His scientific work was mainly in the field of molecular physics and of neutron diffusion. It was characterised by a deep and thorough understanding of complicated phenomena. He simplified whatever he could, but never at the expense of completeness. His work on the Raman effect is a classic and dominates the field. The European turmoil of the thirties brought him to the United States and during the war he worked at the Canadian atomic project and later at Los Alamos. After the war he spent sometime at the General Electric Company, but he found his last task at the Institute for Advanced Study. Unfortunately his health became poor during the war and his last years were marred by physical disabilities endured with smiling stoicism. His published scientific work, although it does not reflect his real contribution, is a permanent record of the scientist. It is hardly possible to give an adequate picture of the man. I believe that his friends felt clearly his human greatness. Certainly he had an unerring judgement of human affairs, tempered by benevolence, and fortified by vast experience. The loss to science is great, the personal loss to his friends irreparable.

Sources:
British Scientists and the Manhattan Project, The Los Alamos Years, by F.M. Szasz, MacMillan, 1992.
At Home in the Universe, John Archibald Wheeler, American Institute of Physics, 1994.
The Neutron and the Bomb, Andrew Brown, Oxford University Press, 1997
What Little I Remember, Otto Frisch, Cambridge University Press, 1979
A Mind Always in Motion, Emilio Segre, University of California Press, 1993
Bird of Passage, Rudolph Peierls, Princeton University Press, 1985.
Physics Today, June 1956. Published by the American Institute of Physics who hold the copyright.

Maurice Henry LeCorney Pryce 1913-

Pryce graduated at Trinity College, Cambridge University in 1935 and became successively a Fellow of the College and an Assistant Lecturer in 1937. He was Reader in Theoretical Physics at the University of Liverpool from 1939-45 and during the period 1941-44 was engaged in radar research. He joined the British-Canadian atomic energy project in Montreal in 1944 and spent a year there working on neutron multiplication problems in small spherical bodies and related matters. However, even before going to Montreal, Pryce had applied the variational method to obtain the critical conditions in a sphere of U235 (see sources below).

After the war, Pryce was Wykeham Professor of Physics at Oxford University and the H.O. Wills Professor of Physics at the University of Bristol. After 1964 he moved to North America with positions at the University of Southern California, Princeton University and Duke University. He spent his final academic years in the physics Department of the University of British Columbia in Canada. Pryce was elected a Fellow of the Royal Society of London in 1951.

Sources:
Who's Who 1999.
Critical conditions in neutron multiplication, British Ministry of Supply Report MS.P.2a (1943)

John Donald Stewart 1908-1997

John Donald Stewart was born in Edwardsburg Ontario in 1908 and died in Ottawa, Ontario in 1997. He earned BA and MA degrees from Queen's University in Kingston, and, after lecturing there for a year he studied at Princeton and Leipzig Universities. Much later, during his working years at Chalk River Nuclear Laboratories he submitted some of his work to Cornell University, and was awarded a Ph.D. degree (according to some accounts, after he had retired in 1971).

During World War II he was stationed in England as a radar officer in the RCAF. Along with other scientists he was brought back to Canada in 1944, to the NRC Laboratories in Montreal to join the developing Canadian nuclear program, moving to the new research establishment at Chalk River after about a year. He and G. M. Volkoff worked on neutron transport calculations for the ZEEP (Zero Energy Experimental Pile) reactor, and their predictions of its first critical moderator height, in September 1945, were very accurate. Their methods were also used for the criticality predictions of the much more complicated NRX research reactor in July 1947.

At Chalk River, he switched to crystallography theory for several years, but then returned to neutron transport theory in general, and neutron diffusion theory in particular. His most important contribution was the "source and sink" theory, which represented the fuel elements in a reactor as sources and sinks of neutrons. It was capable of predicting accurate critical sizes and neutron flux distributions, and led to the computer program MICRETE. This theory was developed independently of, but contemporaneously with, the work of Horning in the USA and Feinberg and Galanin in the USSR, but never appeared in the open literature until much later. Stewart's work on the source-sink method was issued as classified report NEI-13 in July, 1952. It was de-classified and re-issued in March 1962 as report AECL-1470, "A microscopic-discrete theory of thermal neutron piles". It appears that what has been hitherto called the F-G-H method, should now be referred to as the F-G-H-S method.

Sources:
Private communication from Roger Jarvis and Graham Lee-Whiting via Michael Milgram.

George Michael Volkoff 1914 -2000

Volkoff was born in Russia and came to Canada in 1924. He graduated at the University of British Columbia in 1934 and then did graduate work with Robert Oppenheimer on the theory of what were later to be called neutron stars. From 1943-45 he was Associate Research Physicist at the Montreal Laboratory of The National Research Council of Canada. After the war Volkoff became Professor of Physics at The University of British Columbia and was from 1950-1956 Editor of the Canadian Journal of Physics. In 1946 Volkoff was appointed M.B.E. and, in 1994, he received the Order of Canada. He is also a Fellow of the Royal Society of Canada.

During the Montreal period, Volkoff made several seminal contributions to reactor theory and was particularly in demand for his lecturing ability. Indeed, whenever he was in Montreal, Sir John Cockcroft would always attend the evening lectures on reactor physics given by Volkoff who was even then being groomed to succeed Placzek as Head of the Theoretical Physics Division. Volkoff's presence in Montreal in 1943 was due to the insistence of Dr C.J. Mackenzie, President of the National Research Council of Canada, who specifically asked The University of British Columbia for leave of absence as Volkoff was regarded by his Department Head, Dr G.M. Shrum in Vancouver, as "not only a mathematical physicist of outstanding ability, but also a first class experimentalist". One anecdote told by Mr Dennis Ginns, a senior engineer in the project, concerned some detailed reactor calculations that Volkoff had made on spherical lumps in a finite moderator. When Ginns said that in practice they would be more interested in rods, Volkoff replied "O dear, I hate cylindrical co-ordinates". Nevertheless, the calculations were duly carried out.

Sources:
Canadian Who's Who 1999
Cockcroft and the Atom by T.E. Allibone 1984, Adam Hilger publishers
Britain and Atomic Energy by M. Gowing, 1964, MacMillan
Canada's Nuclear Story by W. Eggleston, 1966, Harrap and Co.
Lectures on Pile Theory, G.M. Volkoff, TL-1 to TL-6, September December, 1944

Philip Russell Wallace 1915 -

Wallace was born in Toronto and graduated with a BA in 1937, MA in 1938 and Ph.D in 1940 from The University of Toronto. Following 3 years in the United States, Wallace was recruited as Associate Research Physicist to work in the Montreal laboratory in 1943. While there, he produced original work in neutron transport theory and in the theory of neutron density fluctuations in reactors in collaboration with E.D. Courant. It is interesting to note that this work, written up in a paper entitled "Fluctuations of the number of neutrons in a pile" and later published in The Physical Review, remains a classic to this day and has led to innumerable extensions by other workers in the field of random processes in nuclear reactors.

After the war, Wallace developed interests in solid state physics and in particular did some very important work on the effect of graphite under neutron irradiation. E.P. Wigner had predicted that graphite would shrink under neutron bombardment. As there was no experience in Canada of such matters, Wallace was sent to Bristol, England for several months to work in Sir Neville Mott's department. This led to his first paper on the band structure of graphite published in 1949. This was followed by another paper dealing with radiation effects which suggested a result contrary to that of Wigner: Wallace predicted an expansion of the lattice in the direction perpendicular to the planes by about 15%, which was verified experimentally. The trick was that the interstitial atoms formed diamond bonds with the carbon atoms of the layers. This must have been one of the rare occasions when Wigner was wrong.

Philip Wallace had a distinguished career in solid state physics and has written a number of controversial articles, and a book, on philosophical issues in quantum theory. At the time of writing (1999) he continues to contribute to the literature via his scientific reminiscences. He is a Fellow of the Royal Society of Canada.

In his recent recollections, printed in Physics in Canada, Professor Wallace describes how he was recruited into the Montreal theory group and talks about the people he met and how the work was allocated to each team member and many other personal and technical matters. His article answers virtually every question that I had wanted to ask and is a delight to read and to re-read.

Sources:
Canadian Who's Who 1999
Personal Communication to MMRW, 1999
The beginnings of theoretical physics in Canada, P.R. Wallace, Physics in Canada November, 1993, Pages 358-364.
Physics in Canada , "The Millenium Issue", P.R. Wallace, Vol 56, No 2, (2000), "Atomic Energy in Canada: personal recollections of the war-time years".

Biographies still needed

In spite of considerable effort, I was unable to establish any further details of these authors of the MT reports.
Wladimir.P. Seidel (Montreal Laboratory 1943, went to University of Rochester in 1947)
It is not clear whether Dr Seidel was on the full-time staff since his name does not appear in the staff list prepared by Varley Sears (see references).
Victor H. Rumsey (Montreal Laboratory 1945-48, went to Ohio State University about 1950, Electrical engineering Faculty)
J.M.G. Fell (Montreal Laboratory 1945-46)
Muriel Wales (Montreal Laboratory 1944-49)
A.S. Lodge (Montreal Laboratory 1945-46)

I have deliberately concentrated on the reactor theory aspects of the work carried out at the Montreal Laboratory. This in no way is meant to downplay the equally first-rate contributions of the engineering branch which was carried out under the general direction of Wallace Akers of ICI and his colleagues R.E. Newell and Dennis W. Ginns. In fact Mr Ginns is still active and has been very helpful in providing me with information about working conditions in Montreal during the war. For completeness, therefore, I give below a biography of Dennis Ginns.

Dennis W. Ginns 1912-
Dennis Ginns spent his early years as an apprentice with the machine tool makers, Alfred Herbert. He gained a Higher National Certificate and was a Whitworth Scholar. He graduated from Cambridge University in 1935 in Mechanical Sciences with First Class Honours. His research at Cambridge led to the award of the Wimboldt prize. In 1936 he joined the Alkali Division of ICI (Imperial Chemical Industries). The war years led to his secondment to the British-Canadian atomic energy project in Montreal in 1942. He continued this work with the British Ministry of Supply until 1949 working at Risley but then returned to ICI as engineering director of the plastics division. Dennis Ginns retired in 1973, but continued his work at Imperial College, London University as a Senior Research Fellow. He was a founder member of the Fellowship of Engineering.

Over a long and fascinating lunch at the Royal Society of Arts, Dennis Ginns told the author something about his time in Montreal during the war. He was on good terms with all the physicists and interacted frequently with George Placzek and George Volkoff, of whom he spoke very highly. The early years were apparently very frustrating for them all because the US had excluded all non-citizens from any information sharing; a situation created he believes by General Groves. This meant that the Canadians and British were working essentially independently. It is a tribute to the theory group, which in this case includes the engineers, that so much seminal work was developed from scratch. When eventually the 'exclusion principle' was abandoned, it transpired that the Canadian-British work was as good as, if not better than, the US equivalent. Ginns also told the author that much of the reactor theory was initiated by the engineers asking silly questions, such as 'why can't we use cylinders for the fuel elements rather than spheres?'. The paper by Guggenheim mentioned below, MT-137, on gas flow through a reactor also arose from a query by Ginns. The author also learnt the meaning of the acronym BBU, which means Billingham Bastard Units. Billingham was an ICI production site in England and the expression arose because of the need to marry metric units favoured by the physicists with Imperial units used by engineers; for example, a typical unit might be kgCal/hour/sq ft. Mr Ginns is of the opinion that the Canadian NRX reactor was for many years the finest research reactor in the world. And the reason for this was that the physicists were fully consulted before its design and they recommended plenty of beam holes and a thermal trap. I also heard a bit about security during the war years in Montreal. Apparently the visiting scientists were given false professions and Dennis Ginns was known as the 'Schoolmaster'.

One of the problems faced by Dennis Ginns, when in Montreal, was how to calculate the power output from a reactor. He did this by assuming a cosine axial flux profile and integrated the power produced along the fuel channel thereby leading to an equation which in the 1950's and 60's was called Ginns' equation. Unfortunately, like much of the Montreal work, this internal report was never published. It was issued as Montreal report ME-171, ME standing for Montreal Engineering, and it did appear in the literature some thirteen years later in a review article by Jack Diamond and W.B. Hall. This was entitled "*Heat Removal from Nuclear Power Reactors*" and can be found in The Institution of Mechanical Engineers, Proceedings of the Symposium on Nuclear Energy, 25th March, 1956, page 40. In the discussion following the paper, Dennis Ginns gives some interesting background information to his work. The reader will have noted that there exist another set of Montreal reports associated with the engineering work, designated ME; a history of these will I hope be carried out by a competent engineer.

3. Extract from an article by George C. Laurence 'Early Years of Nuclear Energy Research in Canada', published under the auspices of Atomic Energy of Canada Ltd, Chalk River Nuclear Laboratories, May 1980.

Dr Laurence was a pioneer of nuclear research, not just in Canada but internationally, and given more funds and pure material, the first man-made nuclear chain reaction might have been achieved in Canada in 1940. Indeed, I have it from Professor Robert Clarke, that Laurence set up a sub-critical graphite moderated pile in the basement of the National Research Council!

This is an extract from the report cited above which has the most bearing on the matters discussed in the present paper. It should be read in its entirety along with the article by Professor P.R. Wallace ("The beginnings of theoretical physics in Canada", in Physics in Canada, November 1993). The extract concerns the joint British-Canadian Laboratory established at Montreal.

At first there was greater progress in Britain than in America. It was predicted that if the uranium-235 was separated from the natural uranium in which it occurs it could be used as a very powerful explosive for military purposes. The British estimated the quantity that would be needed to make a bomb, and they proposed methods for the separation of uranium-235. It was shown by theory and experiment that the release of nuclear energy from natural uranium would be accompanied by the production of plutonium, and that plutonium like uranium-235 was fissionable. They also estimated the quantity of plutonium that would be needed for a bomb.

Halban and Kowarski, then in England, carried out their experiments that they had been prevented from doing in France with a uranium compound dissolved in heavy water and concluded that a great release of nuclear energy might be possible with a much larger quantity of such a solution. At first, the interest in a “boiler”, as they called it, using uranium with heavy water or carbon was based on the hope of using it as a source of energy for industrial purposes. With the discovery that plutonium was fissionable the boiler had added importance; it could be used to produce plutonium for the construction of a bomb.

It was suggested that the nuclear research in Britain should be moved to the United States. At first the idea was more acceptable to the American scientists than to some of those in Britain. By the spring of 1942 the advantages to Britain of moving the scientists from there to this continent were more obvious because the industrial resources and effort that would be needed to produce nuclear weapons were already committed heavily to other war purposes. In the United States, however, the work had become well advanced, and the help that might come from England no longer seemed so valuable. The Americans felt that it was too great a security risk because the senior members of the group that would be sent from England included refugees from countries that were occupied by the Germans and it was thought that they might be influenced by pressure on their relatives in Europe.

The British then suggested that a joint British-Canadian laboratory be established in Canada for nuclear research leading to the construction of a pilot plant for the production of plutonium. It would be staffed by some of the scientists from England directed by H.H. Halban, with Canadian scientists recruited into the project. Vannevar Bush, Chairman of the U.S. National Defence Research Committee, informed Sir John Anderson, Home Secretary of the U.K., that the

Americans would accept this arrangement and agree to the exchange of information on research that was relevant to the design of the pilot plant. On February 19, 1942 Malcolm Macdonald, the British High Commissioner to Canada, with Sir George Thomson and W.A. Akers called on Dr. Mackenzie to discuss this proposal. Later that day, Dr. Mackenzie introduced them to the Canadian Government Minister the Hon. C.D. Howe and acquainted him with the proposal. Sir George Thomson, Malcolm Macdonald and Professor R.E. Peierls discussed it again on June 15th, with Mackenzie and Howe, and also with the Canadian Prime Minister, Mr Mackenzie King.

Dr. Mackenzie visited Vannevar Bush in Washington and had discussed the possibilities of American cooperation with the proposed British-Canadian laboratory. The British raised the question again on August 17 and on September 2.

The objective was speculative; it was doubtful if it could be completed before the end of the war. It would divert scientists, equipment and material from other war work, it would commit Canada to the expenditure of many millions of dollars, and there would be difficulties in the procurement of materials, particularly the many tonnes of heavy water.

Dr. Mackenzie said later that the deciding consideration was that when peace returned atomic energy would be found to have applications of social and economic significance far beyond the possibilities of imagination and prediction, and the proposed Canadian-United Kingdom research effort would provide an opportunity for the training of Canadian scientists in this field. So, Mr. Howe agreed on September 2, 1942 that Canada would receive the scientists from England, provide the laboratory facilities and supplies and administer the project in Montreal as a division of the National Research Laboratories.

The first of the staff from England arrived about the end of the year 1942. They were P. Auger and B. Goldschmidt of France, G. Placzek of Czechoslovakia, S.G. Bauer of Switzerland, H. Paneth and H.H. Halban of Austria and R.E. Newell and F.R. Jackson of Great Britain. We temporarily occupied an old residence at 3470 Simpson street belonging to McGill University. Three months later, we moved into a 200 square metre area in the large, new building of the University of Montreal, and more scientists and technicians arrived from England. It was part of my job to recruit Canadian staff, and Professor David Keys (C), representing the Wartime Bureau of Technical Personnel, helped greatly in finding them, and in obtaining approval for their transfer from other employment. The staff grew quickly to over three hundred, of whom about one half were Canadian.

The project was started in a mood of enthusiasm and expectation of great scientific adventure. Never before had such a talented group of scientists been brought together in Canada with a single purpose.

Soon, however, we became impatient as we waited for the expected close collaboration with the American scientists to develop. American anxiety about the security of information increased on account of the mixed national background of the Montreal team. They proposed that the exchange of information with the Montreal Laboratory become much more restricted, and they stopped sending us copies of their scientific reports, and deeply offended the British. The administration of their security measures became very tight after the U.S. Army assumed control of the whole American nuclear program in June 1942, but it was the senior American scientists, Vannevar Bush and J.B. Conant, who resisted most strongly close collaboration with the scientists in Montreal.

The choice of Halban as Director of the Laboratory had seemed logical, but turned out to be unfortunate. He was involved in the unhappy circumstances that brought bitterness and distrust into the relations regarding nuclear energy between France and the United States. With Joliot, Kowarski and Perrin, he held patents which claimed control of the use of nuclear reactors for some of their most important applications. The interest of Imperial Chemical Industries in these patents provoked the American distrust of international cartels. An ill-timed visit by Halban to Joliot in France to discuss the patents aggravated American worries about security because Joliot was a member of the French Communist Party.

His associations with the National Research Council also did not always run smoothly. He was impetuous and vacillating in decisions and unreasonable in his demands of the administrative staff in Ottawa and unfair in criticising them. He failed to inform Dr. Mackenzie or any other Canadian about important decisions regarding the research program of the laboratory. Eventually, E.W.R. Steacie (C), then the Director of Chemistry division of the National Research Laboratories, acted as a part-time Assistant Director under him, but Dr. Steacie's influence came too late and was too remote from the administrative problems in Montreal.

At the Quebec Conference on August 17, 1943, Prime Minister Churchill discussed with President Roosevelt the very unsatisfactory state of British-American collaboration in nuclear energy research, including the work of the Montreal Laboratory. They agreed that arrangements should be made "to ensure full and effective collaboration between the two countries in bringing the project to fruition". A "Combined Policy Committee", under the chairmanship of H.L. Stimson, the U.S. Secretary of War, was named to work out the basis for implementing this agreement, but it rarely met. There was little progress towards effective collaboration, excepting a few scientific discussions on strictly limited topics. Morale in the Montreal Laboratory became very low. The scientists felt they would be better employed in other work.

George C. Laurence 1905-87

Born at Charlottetown in 1905, Dr Laurence was educated at Dalhousie and Cambridge Universities. He joined the staff of the National Research Council of Canada in 1930 and became active in improving the measurement of radiation dosage in the treatment of cancer and in promoting safety from radiation exposure. He was involved in nuclear energy developments in Canada since its beginning, continuing in the Montreal nuclear energy laboratory in 1943-44 and at the Chalk River Nuclear Laboratories. He directed the staff that did the preparatory research and development and the conceptual design of the NRU reactor. In 1946-47 he served as scientific advisor to the Canadian delegation to the United Nations Atomic Energy Commission in New York. In 1956 he was appointed Chairman of the Reactor Safety Advisory Committee set up by the Atomic Energy Control Board to advise on the health and safety aspects of nuclear reactors and power stations. In 1961 he left AECL to become the President of the Atomic Energy Control Board from which he retired in 1970. He was awarded the MBE for his scientific work during the war, the Canadian Association of Physicists medal for achievement in physics in 1966, the W.B. Lewis medal for the Canadian Nuclear association in 1975, and a number of honorary degrees.

4. Personnel problems at Montreal

The recruitment of first rate scientists to the Atomic Energy Project, and their retention, was by no means easy. At times, especially when there were difficulties with the United States, morale would drop and some staff members would look 'South' for more interesting work. The following letters, which are available from the Public Record Office, Kew, give a flavour of the problems, both of recruitment and of retention of personnel in the Theoretical Physics Division. These letters are in the custody of The Public Record Office, Kew, UK and may be found under classification AB 1/144 - Theoretical Physics Division in Canada in 1943-4. They are reproduced here in their original style and format.

4.1 Memo from George Placzek 9th February 1943

NOTE ON PERSONNEL SITUATION OF THEORETICAL PHYSICS DIVISION

I. - APPOINTMENTS MADE

A. - CANADIAN SIDE

1. Dr. P.R. WALLACE from M.I.T., Cambridge, Mass. Joined the Division on January 11th. Although his previous experience in theoretical physics (thesis with Infeld, subsequent work with Poldoski,- both on generalised field theory) does not qualify him for work with us, he was appointed upon the recommendation of Professor J.L. Synge whose courses in Applied Mathematics he had followed at the University of Toronto. During his short stay with us he has already made a satisfactory start.

(Author's note: Prof Wallace has told me privately that he did not work with Podolski, they were colleagues and friends at the University of Cinncinnati when Wallace was in his first academic post. Also note that in the above memo the name Podolski is mis-spelt. Wallace was Infeld's first graduate student at Toronto and so learned a great deal about Einstein, without actually ever meeting him.)

2. Professor G.M. VOLKOFF, University of British Columbia, Vancouver, B. C. Joins the Division on February 15th. Ph.D.- Berkeley (with Oppenheimer) 1939. He is definitely among the better ones of Oppenheimer’s pupils.

B. - U.K. SIDE

None.

II. - APPOINTMENTS AUTHORIZED OR UNDER CONSIDERATION

(a) with negative result:

A. - CANADIAN SIDE

3. Mr. MAX GOLDSTEIN, computer from New York. Was ready to join our group. His local Draft Board was approached by us and refused to release him. The Canadian Department of External Affairs will perhaps try to intervene, but we expect Mr. Goldstein to be in the army before this intervention even reaches the Draft Board and therefore consider the case as practically hopeless. *Author's note: Max Goldstein was appointed, see his biography in this paper.*

B. - U.K. SIDE

4. Professor GEO. E. UHLENBECK, University of Michigan, Ann Arbor, Mich. He had seriously considered joining us and his head of department had promised to help arrange for his release from the University. We have also, through private channels, obtained the consent of the M.I.T. project with whom he worked in a consultative capacity. Subsequently, however, a member of his department has arranged for him to do war work at the department in Ann Arbor, which he accepted.

5. Professor S. CHANDRASEKHAR, Yerkes Observatory, Williams Bay, Wis. Had previous commitments with the Aberdeen proving grounds (an organization of the War Department) who had told him that they considered his employment. He had, however, heard nothing from them for three months. He expressed the opinion that work with us would probably be of a more scientific character than the work he might have to do at Aberdeen and accepted our offer for the case that we should be able to arrange "gracefully" for his release from his commitments to Aberdeen. In view of the fact that he is a British subject, this should certainly have been possible if the proper channels to contact the American authorities had been available. When the authorities at Aberdeen were informed by him of our offer they arranged within twenty four hours for the signature of his appointment by the Secretary of War. In the absence of any intervention on our part he felt it his duty to accept the Aberdeen appointment.

6. Professor W. FELLER, Brown University, Providence, R. I. Apart from war teaching courses at Brown University, he was employed as consultant by a U.S. war project under the direction of Dr. Weaver. When we approached him he told us that be expected that Dr. Weaver would probably want to employ him full time in the near future and that he would prefer to work with us if Dr. Weaver would give his consent. He has approached Dr. Weaver who, after investigating the matter, refused to release him. Later Dr. Weaver and Brown University came to an agreement according to which he works half time with Dr. Weaver and half time at Brown. After the situation has proceeded so far, the only thing that remains for us to do is to try to arrange for a possibility of occasional consultations with Dr. Feller. In view of the fact that Dr. Weaver's arrangement with Brown University keeps Dr. Feller already more than fully occupied, it seems very doubtful whether even this will be possible.

It is common to all these cases that the persons concerned were in principle willing to join us and in some cases even enthusiastic about it and that we have lost them because of the lack of an official mechanism to ask in time for their release by the American authorities.

(b) Under consideration:

A. - CANADIAN SIDE

7. Professor CARSON MARK, University of Manitoba. Professor Mark is an abstract mathematician (thesis in group theory). During the past two summers he has attended courses in Applied Mathematics. Whether we can usefully employ him depends to some extent on the final composition of our group. We shall have to decide the question within the next four weeks. He is in principle ready to join us by May 1st.

8. Mr. J.D. STEWART. Graduated with B. A. (Honours) in Physics and Mathematics, Queen's University, Kingston, Ontario in 1929. Took M. A. degree in experimental physics, Queen's University, 1930. Instructor in mathematics Queen's University, 1930 -1931. Studied at Princeton under Professor E.U. Condon, 1931-1932. Studied at Leipzig under Professor Heisenberg, 1933-1936. Lecturer in mathematics, Queen's University, 1936-1938. Studied at Cornell University under Professor Bethe, 1938-1939. Enlisted in R.C.A.F. in 1940. At present scientific liaison officer with R.C.A.F. in England.

Although the war has prevented Mr. Stewart from getting his Ph.D., he is far superior to the average Ph.D. in training and experience (see the above data). His scientific qualification is of about the same order as Professor Volkoff's. He would be an extremely valuable addition to our team. Mr. Akers is trying at present to contact him in England.

9. We are trying at present to find in Canada two junior girls with some experience in mathematics to be trained by us as junior computers.

B.- U.K. SIDE

10. Dr. F. ADLER, University of Wisconsin, Madison, Wis. Was previously employed in France in a war project that dealt with our problems and did competent work there. His head of department has refused to release him to us and offered to free him of part of his teaching duties for consultation work with us. This proposal is unacceptable for practical reasons. We have now proposed that Dr. Adler be released to us immediately and promised that after six months when he has completed a training period here we would seriously consider sending him hack to Madison to do work there for us in conjunction with his teaching duties. This solution would be far from satisfactory for us, but it is all we can ask for under the circumstances and we are not sure whether it will be granted. This is again a case where an official approach of the head of department by the American authorities might have given better results.

11. Mr. BENGT CARLSON, Instructor of Mathematics, Yale University, New Haven, Conn. Mr. Carlson has long first-rate computing experience combined with good mathematical training. We should like to make him the head of our computing section which would include the task of training the girls mentioned under 9. He is in principle ready to join us and his head of department is willing to release him. He is at present being reclassified by his Draft Board. A first intervention with the Draft Board to obtain his release was not successful. The Draft Board is now going to be approached by the British Embassy. (*Clearly, this approach was successful*!)

12. and 13. Professors V. F. WEISSKOPF and W. SEIDEL, both from the University of Rochester, Rochester, N. Y. We contemplate their appointment as substitutes for Professors Chandrasekhar and Feller, respectively. Although they are not equivalent to the latter ones in previous specific training, they are both excellent men in their respective fields and probably the best substitutes available under the circumstances. We are going to approach them within the next few days in order to find out whether they would in principle consider an offer from us.

G. Placzek

GP: VL
Montreal, 9th February, 1943

4.2 NOTE TO DR. HALBAN

RE: PERSONNEL T.P.D

1 should like to have your reaction to the following:

Dr. W. Lamb - theoretical physicist, pupil of Oppenheimer - presently instructor or assistant - several papers on slow neutrons, - professor at Columbia; is so far not fully employed in the American war effort because his wife is an enemy alien (German). Do you think the man interesting for us in principle, or not? If the answer is in the affirmative, I should like to find out more particulars tomorrow in New York.

GP:VL, Montreal, 14th January, 1943 G. Placzek

Author's note: Willis Lamb was a future Nobel prizewinner. He did not work at Montreal but the reason is not known to me.

4.3 (MONTREAL LABORATORY)

P.O. Box 159, station H
Que., October 12, 1943

Secret

Mr. Lesslie R. Thomson,
Department of Munitions and Supply,
Temporary Building No. 1,
375 Wellington St. West,
OTTAWA - Ont.

Dear Mr. Thomson,

As you remember, we discussed at the last meeting of the T.C.R.R. Committee the need for computors in the Theoretical Physics Division. In the meantime it was found that we would have difficulty in obtaining them because, at the present moment, there are no positions open for them. I know that no new positions should be opened before the future of this laboratory and the collaboration with the U.S. is cleared, and as you will remember we showed understanding for this position at the last meeting. You were then under the impression that in the case of these two computors we could probably get over this difficulty, and this letter is to tell you how especially gratified we all would be if a way could be found.

It might be useful to add in this case that the Theoretical Physics Division is now producing results at a very accelerated rhythm. It is, as a matter of fact, the first division to show the success of the systematic building up of our organisation. They are actually held up in the production of the final results of a great deal of theoretical work by the lack of computors.

I think that it might be a wise policy to facilitate their position, especially in consideration of our relation to the U.S. Tube Alloy work. It is essential that at the moment at which collaboration starts, certain numerical results should be ready at our disposal. At the same time, I know from Professor Peierls that the results that this division has obtained are of significance for another part of the Tube Alloy field. I think, therefore, that it should be made possible to make the results of this division available to us, as well as to the Americans, to whom the reports that this laboratory has already produced have been sent. The addition of two computors to the team would mean a definite increase of the output of the scientists employed here, and in view of the tremendous scarcity of theoretical physicists among the United Nations it seems to me the right thing to make an economic use of them, which can only be done if numerical evaluation keeps pace with their work.

Yours sincerely,
H.Halban

HHH: MEM, VL.

4.4 MEMORANDUM TO - Dr. Placzek (from Bengt Carlson, October 13, 1943)

Concerning; the Computing Situation

At present there is a great amount of accumulated work in the computing section. In the following, a list is given of the projects ready for computation and the estimated time necessary for their completion with the present staff and equipment of the computing section:

Project and Estimated time

Density Distribution in systems with multiplication factor near 1 and non-multiplying reflector (Dr. Volkoff) -2 weeks

Integral equation for absorption in an aluminum slab. (Dr. Wallace) - 2 weeks

Solution of transcendental equations and calculations of residues in connection with slowing down problems (Dr. Marshak) - 2 weeks

Slowing, down length in water and related problems. (Dr. Marshak) - 3 weeks

Albedo problems. (Dr. Adler) - 1 week

Improved numerical solution of Milne equation. (Dr. Mark) - 1 week

Miscellaneous - 1 week

TOTAL, 12 weeks.

We have thus about twelve weeks of accumulated work. To improve this situation is impossible with the present staff, rather we expect it to become worse. We have also been advised of the desirability of an acceleration of output.

Since the current rate of work thus is considered insufficient and since it is besides a result of a somewhat forced tempo, more manpower and calculating machines are necessary. The most effective remedy, in my opinion, would be to hire two additional men, one with a College education including mathematics courses, and one with an excellent High School record to he trained here; and at the same time acquire two Marchant calculators, model ACRM.

If we have to operate with an increased staff before the new calculators arrive we might try to arrange a double shift, but such a step with the present type of work, which requires frequent decisions on my part and hence my presence, is at best an emergency solution. No computing project with which I have ever had contact left the staff without supervision during half of the day. That would be too much of a menace to accuracy and efficiency over an extended period.

Bengt Carlson

BC:VL
Montreal, October 13, 1943

4.5 (Montreal Laboratory)

P.O. Box 169, Station H,
March 29th, 1944.

MOST SECRET

W.A. Akers, Esq.,
Department of Scientific and Industrial Research,
Directorate of Tube Alloys,
16 Old Queen St.,
London, S.W.1.

Dear Akers,

Please excuse my not thanking you for your kind letter of March 7th. You will understand that since I was forced to send my two cables of March 17th in spite of this letter from you I wanted to delay sending you a written reply.

You can imagine that we were very pleased when the High Commissioner visited us yesterday to explain to us the intentions of the Chancellor in case we should not succeed in obtaining collaboration with the United States in the near future. The facts he reported in themselves as well as his very frank way of dealing with everybody, meant a terrific encouragement. In agreement with the High Commissioner we had assembled for this meeting all United Kingdom people with General Clearance plus Freundlich, that is, Auger, Jackson, Newell, Paneth, Anderson, Bauer, Ginns, Greenwood, Arrol, Gueron, Maddock, Penning, May, Pontecorvo, Seligman, Freundlich. Goldschmidt and Placzek were unfortunately not in Montreal.

We just despatched a cable to you which explains the position concerning the Theoretical Physicists. I am afraid that we are there in very great difficulties. You know how close friends Placzek and I are. The fact that the collaboration which we started in Copenhagen might have to be interrupted for quite a while will be hard for both of us. I see many of Placzek's reasons, and I am afraid that in this case we will have to bear the consequences of the policy of weakness which was discontinued too late. Of course Newell and I will do whatever we can to make Placzek agree to stay and we hope that Chadwick will help us in this endeavour, but I am not very hopeful of succeeding.

At present I am not yet able to foresee all the consequences of losing the complete Theoretical Physics team and I am not yet quite sure whether we will be able to carry on at all. The minimum we would have to do would be to gain the help of Volkoff and if possible also Courant. I should imagine that in the case of Volkoff this would be possible if one made certain concessions of seniority and salary. As to the seniority concessions, they would mostly mean giving him insight into the direction of the Laboratory, since he has shown great interest in having contact with the Experimental Physics Division as well as with the engineers and this could easily be arranged. Any concessions in salary seem more difficult since he is Canadian employed. My talking of retaining Volkoff whilst the whole Division wants to go looks inconsequential, but I am afraid that this is a case where consequential thinking won't carry us far. Volkoff might be inclined to stay alone because he might realise that there is sufficient work of general interest for one man. I know that Placzek disagrees with me on this point and he may know him better. Of course some gentle pressure might be exerted on Volkoff by The National Research Council. If we would lose all the Theoretical Physicists, I would have little courage to continue the whole effort.

I discussed the above letter with Placzek who would have liked me to wait somewhat longer before despatching it since the discussion with Chadwick might clear up some points. I told him that I did not think myself justified in leaving you uninformed of these difficulties. As a matter of fact we have tried for two weeks to see Chadwick and did not succeed. Placzek asked me to tell you that whilst the letter represents most of the facts correctly it does not mention at all that his reason for wanting to shift to other work is that he thinks that he and his team could be used in the next year or 18 months to more advantage in other fields of Tube Alloy work. He wants it to be very clearly understood that he does not want to abandon the Directorate of Tube Alloys, but he thinks it is his duty to ask to be employed where he thinks he could be most useful. I add this since he asked me, although I am convinced that you would have understood this point without my making it clear.

Yours sincerely,

H. Halban

HHH/MM

4.6 Letter to W.A. Akers from Dr H. Halban

FROM: THE HIGH COMMISSIONER FOR THE UNITED KINGDOM OTTAWA
TO: THE SECRETARY OF STATE FOR DOMINION AFFAIRS LONDON.

Cypher SENT: 11.30 a.m. 30.3.44.
No. 985 MOST SECRET

For Akers, D.S.I.R. from Halban

The High Commissioner visited the Laboratory on 28/3 and had conversations with all United Kingdom staff who have general clearance plus Freundlich. Placzek was unfortunately out of town. Everybody was considerably encouraged by the attitude taken by the United Kingdom Government, and cheered up by conversation with the High Commissioner. I am extremely thankful for this quick help which I trust will enable us to make everybody except the Theoretical Physicists hold on.

The position of' the Theoretical Physicists is as follows. Marshak has resigned and would like to try to get employment in site Y as a U.S. citizen. We know privately that Courant will get in the near future an interesting offer from another American group which we fear he will accept, particularly since were not yet able to increase his salary. Apart from these two cases, the whole Division has asked Placzek several months ago to get them as an entire group into immediate war work. Placzek asked them then to be patient. He is however of the opinion that in the case of construction in England, his group would not be needed for at least a year. On the other hand he has little confidence that anything will come out of the present Washington discussions. He therefore informed me that he would like to discuss with Chadwick how he and his division could be shifted immediately to other work in the Tube Alloy field. In this case Marshak would stay with the group. Such a shift might enable us to get Placzek and part of his staff at a later date back into Polymer work.

I am extremely depressed about Placzek's decision although I understand him well. He knows about yesterday's visit only through cautious telephone conversations but does not think it changes his attitude. My opinion is that we need permanently a first-class theoretician with a well organised staff if any work is done here. In case of work in England we would need him permanently as from a year after the beginning of construction of the Polymer factory and in the meantime for consultation. Placzek thinks that Volkoff or Courant could do for the intermediate period of a year if they were willing to come. This would of course be better than nothing but in my eyes not sufficient.

I do not see much hope to hold Placzek since his misgivings concerning the speed of getting large scale work started here and straightforward collaboration organized cannot be contradicted after our past experience. As to work in England, only a detailed programme indicating scale of production and time schedule as well as available amounts of uranium might show him that his staying is worth while.

Placzek, Newell and myself will discuss the situation at the end of this week with Chadwick in Washington and keep you informed.

icd/30/3 3 copies to Dr. Halban

4.7 Letter to Mr W.A. Akers fromDr H. Halban

FROM: THE HIGH COMMISSIONER FOR THE UNITED KINGDOM OTTAWA
TO: THE SECRETARY OF STATE FOR DOMINION AFFAIRS LONDON

Cypher
No. 1121 TOP SECRET SENT 12.40 p.m 13.4.44.

For Akers D.S.I.R. From Halban

Theoretical Physics Division. Marshak has handed in his resignation and in agreement with Chadwick, Placzek and I have entitled him to look for a job in the American Tube-Alloy organization. We will therefore lose him in the near future, and I suppose you agree to my accepting his resignation. The rest of the Division, with the exception of Courant is prepared to wait for events until the first of May, at which Chadwick promised, in case of nothing happening here, to get them useful employment in U.S.A.

Courant had a long conversation with me, explaining that he could get a job in the U.S. which would give him of the order of 3,800 to 4,000 American dollars. He would, of course, only have to pay U.S. taxes. He is in principle very willing to consider staying here since he likes the atmosphere of the Laboratory very much. He feels, however, entitled to ask for payment equivalent to what he would get in the country of which he is a citizen when doing war work there. He has given me time until the first of May to settle his salary position and asks for 3,600 U.S. dollars a year and compensation for the difference between Canadian and U.S. taxes as indicated in my letter of March 23rd He would expect the salary to be retro-active from first April because he made a first request for increase of salary during March and was told by us that correspondence being under way in this matter since February 15th, he should have a clear decision from the Department soon. He is also upset by the fact that the possibility for paying the difference between American and Canadian taxes existed without his attention being drawn to it, and asked whether this compensation could be paid to him for last year.

Courant is the first of a few typical cases by which we can now show that we are willing to do our utmost to keep this Laboratory together. Failure to reply to Courant’s request within the reasonable time he gives us would certainly involve his leaving the Laboratory and would be a great discouragement to others staying with us. I hope that this relatively simple request which I put to you during an extremely difficult time will obtain a reply which facilitates our task.

You know that Placzek and myself think very highly of Courant. He proved specially useful during the last few months when collaborating with the Experimental Physicists and Engineers. His loss would have to be considered irreparable.

If a letter or cable to us dealing with earlier correspondence should have left by the time you receive this cable, I would ask that the present cable should still receive a cabled reply provided the letter does not give full satisfaction to the request Courant makes now.

icd/12/4 3 copies to Dr. Halban

4.8 Letter from W.A. Akers to Dr. H. Halban

FROM: SECRETARY OF STATE FOR DOMINION AFFAIRS, LONDON
TO: 111011 COMMISSIONER FOR THE UNITED KINGDOM, OTTAWA

Cypher Sent 9.55 p.m. 20.4.44
No.1005 Top secret Recd. 9 p.m. 21.4.44

For Halban from Akers.

1. Your 1121 and letter of 2-/3. Courant. After consideration of your cable and Jackson's letters of 15/2 and 24/3 to Longair Hogg is quite positive that the limit to which the Department can go is to increase Courant's salary to Canadian dollars 3900 as from April 1st on the clear understanding that there is no question of any compensation for income tax differences past or future or further argument about it. I realise that this is so much less favourable than Courant's own request that he probably will resign. The only possibility of getting an improvement on Hogg's proposal is by invoking the direct intervention of the Chancellor and I do not want to do this now for the following reasons —

(1) The plan to go ahead with the pilot plant with high priority should enable you to get more Canadian members such as Stewart.

) During the next few weeks we are to review and settle priorities of the different sections of the British T.A. work and this should enable us to get additional men for your work either from inside T.A. or from other British projects.

) We would expect the Americans to want to send staff to Montreal and amongst them there might well be a man who could do the work that Courant at present does.

(4) The introduction of the pilot plant project means that the whole question of staff and administration will have to be taken up. It would obviously be better for this to be done as soon as Cockcroft arrives and not to anticipate it by action in individual cases.

I know that the loss of Courant will be extremely inconvenient for you even if we can replace him quickly and I have chosen this course of action only after the most careful thought but I believe it to be the right one.

bc / 21/4.
3 copies sent to Dr. Halban

4.9 Letter to Dr. H. Halban from Mr W.A. Akers

DEPARTMENT OF SCIENTIFIC & INDUSTRIAL RESEARCH

DIRECTORATE OF TUBE ALLOYS,
16 OLD QUEEN STREET,
WESTMINSTER, S.W.1

***Telephone:* WHITEHALL 1632**
(Extension 202.)

25th Apri1 1944.

Dr. H.H Halban
National Research Council
P.O. Box 159,
Station H,
MONTREAL,
Canada.

Dear Halban,

I feel very guilty when I think of the number of letters which I have received from you over the last fortnight without acknowledgement from me, but I know that you will realise that events have been moving so definitely that it has not been useful to reply to them.

<u>Courant</u>

I would like to take up the question raised in your letters of March 23rd and 29th and your cable 1121 of April 13th to me and my reply to you of April 20th, on the subject of Courant. I hope that the decision to go ahead in Montreal will have solved automatically the more serious difficulties which you foresaw in the event of the team having to be moved to England.

I assume for example that there is now no question of your losing Placzek or Volkoff. For that reason I took the attitude which I did towards the question of Courant's salary and extra income tax.

I am afraid that you will have been very disappointed at not being backed up by me in this matter; especially as I have always supported your proposals in the past. But this time I believe that Courant's salary would have been seriously out of step with other salaries, because D.S.I.R. held, quite rightly I think, that they could not give Courant a definite salary plus the difference between U.S. and Canadian tax. It would have been necessary to have given him a salary which included this difference.

I know that, in the past, D.S.I.R. has agreed, as a result of pressure from myself, backed by the High Commissioner's office or by the Chancellor, to starting American members of the British team at salaries which were estimated to leave them as near as possible in the same position as they would have been had they remained in the States. The Courant proposal goes a considerable step beyond this as the suggestion is that he should be given a salary which would leave him in the same position as if he accepted a fresh position in the States which he believed he could get. It may he that he could now transfer to the American team, but remain in Montreal; and they may be able to solve the problem.

However, although I realise the great inconvenience which follows from change of staff I believe that it will now be possible to get good theoreticians, such as Stewart, and also mathematicians from Canada now that the latter country is really interested in the project. I also believe that we will be able to get help from this country.

Yours sincerely,

Signed W.A. Akers

4.10 Letter from Dr. H. Halban to Mr Akers

FROM: HIGH COMMISSIONER FOR THE UNITED KINGDOM, OTTAWA, SECRETARY OF STATE FOR DOMINION AFFAIRS, LONDON

Cypher Sent 11.20 p.m. 26.4.44 No. 1228 Top Secret

From Halban for Akers, D.S.I.R.

Your 1005. Courant. Placzek and I prevailed upon Courant to accept the arrangements proposed in your para.1 temporarily. He does so in the expectation that it will be possible in the future to employ him as a member of the American group which is going to join us.

I hope very much that this is going to be the case, since we do not see any possibility for replacing him appropriately out of your suggestions 1 and 2.

I hope it will be possible to arrange immediately for payment of Courant's increased salary since a delay would be most embarrassing in this case.

bc/26/4.
3 copies sent to Dr. Halban

4.11 A letter from Dr. Ernest Courant to the Author, 5th April 2000

Dr Courant very kindly agreed to the above exchanges about his salary to appear here and also added some important comments on the various documents which show that you cannot always believe everything you read in official papers. Below is the text of his letter.

Dear Dr. Williams:
Thank you for sending me the draft of part of your report, and the attached letters. Of course I'll be glad to have you include that correspondence in your final version. I was really surprised by the correspondence regarding my salary etc. My recollection is that I was quite unhappy with my initial salary of $2700 (Can.), and negotiated to have it increased. Eventually (I don't exactly recall when) it was raised to $3900 and I decided that, since I really liked the work there, I would stay and not look for better offers from elsewhere. Also, beginning in the summer of 1944, I was courting Sara Paul, who worked as a lab assistant (even though she had no technical qualifications- she had been an English major at Queen's), and whom I eventually married. She and I have been together ever since.

Some recollections: When I first arrived in Montreal I found a room in a house on Cedar Ave., where several other Montreal Lab bachelors were also staying - including Geoffrey Wilkinson, Frank Morgan, Heinz Paneth and above all, Alan Nunn May. May had a room that was definitely superior to the others. But eventually he moved out to an apartment of his own. When Sara and I were getting married we needed an apartment, and he pointed us to an apartment in the same building as his. This undoubtedly led to difficulties later when it tuned out that May had passed information to the Russians - it was hard to get a US visa for Sara when I got my post-doc appointment at Cornell, quite possibly because our association with May led to suspicions. But eventually she did manage to join me.

In 1944 I worked with Halban on the problems of the neutron budget of (slow) breeder reactors, producing one of the MT reports (as I recall MT-40, entitled "Possibilities of Combined Operations"). Is this on your list? In the course of this work, Halban and his wife took me along on a steamer cruise on the St. Lawrence River down as far as the Saguenay - ostensibly so I could help him continue doing useful work while on the cruise. I don't recall whether we got very much work done on board.

I was pleased by the sketches of members of the group that you sent. I can find no fault in what you say about me, or any of the others that I know anything about - except that I believe the obituary of Max Goldstein that you cite is probably by Eliezer (Lazer) Bromberg, not Berman.- I am sorry I cannot help you with some of the names you list. We did run into J.M.G.(Michael) Fell a couple of times, but that was many years ago - at one time he was in Chicago, later (I think) in Philadelphia; my wife thinks that maybe he went back to his home base in Vancouver. Wladimir Seidel was a math professor at Rochester when I was getting my Ph.D. there in 1941-43; then he went to Montreal, and (as you say) back to Rochester, but I don't know what became of him. I do have fond memories of Marshak, Mark, Adler, Placzek, Wallace and Volkoff.

I think there may be a bit of confusion about Paneth. In Laurence's contribution (p.23) he mentions "H. Paneth of Austria" among the initial British contingent. He must have meant Friedrich A. Paneth, one of the pioneers of radiochemistry; his son Heinz R. Paneth (who has, I have heard, since changed his name to Henry Post) was a young physicist about my age.

Other people I remember are Pierre Auger, Bruno Pontecorvo, H. Seligman, Jules Gueron, Bertrand Goldschmidt, Brian Flowers, Denys Wilkinson, Solly Cohen, John Jelley. We kept up contact with Solly Cohen until his death in Israel some years back, and with John Jelley, who died about two years ago.

An incident with Seligman: My wife, Sara, was working in Seligman's lab. One day he seemed particularly agitated. He had to leave the lab, and told Sara, "Here is a vial of liquid - be very careful. Don't disturb it, touch it or even look at it!" She replied, "as soon as you leave I'll drink it". So he closed the door, went to the blackboard, and explained what it was - plutonium, and he told Sara what the project was all about (as an obedient soul, I had always heeded the rule that one could not reveal such classified information even to one's spouse). So that was how she found out about the bomb. Good luck with your project! Ernest D Courant

5. The Montreal Reports

As stated earlier, it was the inaccessibility of the MT reports that spurred me on to complete this project; namely, to make the MT reports as accessible as any published paper. To this end I will list the reports below as given to me by Dr S. Kushneriuk in 1967. They run from MT-1 to MT-249, but are not consecutive because there were also engineering reports published at the same time. For example, MT-137 is entitled "Compressible flow of perfect gas with heat input distributed symmetrically about middle of channel" by E.A. Guggenheim. I recently discovered that this work was requested by Mr Dennis Ginns and carried out by one of the reactor theorists, I am therefore including it for completeness and historical interest. Similarly, MT-243 by A.S. Lodge is "The temperature distribution in an infinite medium due to a spatially uniform plane source of heat"; this too is included. As noted earlier, there is also a series of Montreal reports dealing specifically with engineering aspects with the prefix ME.

The reader should also beware that the National Research Council of Canada introduced a new series of reports in 1953 concerned with fluid flow also designated by the prefix MT. Thus, for example, MT-22 of this new series is : "Circulation and distortion of liquid drops falling through a viscous medium" by P. Savic of The Division of Mechanical Engineering. MT-38 has the title "The contact angles of some bismuth-rubidium alloys on uranium dioxide" by E.H. Dudgeon, and so on. I am indebted to Professor Nils G. Sjostrand, Chalmers Technical University, Sweden for pointing out these anomalies to me. The nomenclature becomes even more confusing since, in 1946, many old MT reports were renumbered with a prefix CRT and/or AECL, but not with the same MT number. All, therefore, is not what it seems. However, the reader may be assured that the reports listed below are the original ones written during the period February 1943 to February 1947. In the cases where the report has been published in the learned journals, the relevant reference is given. However, even here the reader should note that occasionally the published version is a shortened version of the original report and some details may be absent.

6. Discussion of Reports

In this section I reproduce the Abstract of the report and in some cases make some comments regarding its importance. If the report was formally published in the literature, the reference is cited. I have also given the number of pages in the document for completeness. Occasionally, the authors use outmoded definitions and unusual nomenclature for units. These have not been altered in the interests of historical verisimilitude.

MT-1 The functions $E_n(x)$

G. Placzek (issued December 2nd , 1946, but see below, 38 pp)

The functions En(x) occur frequently in diffusion theory. This report gives a collection of formulae and expansions for the functions and their Fourier and Laplace transforms. A new expansion for En(x), by Dr. G. Blanch, useful for x+n>>1, is given in Appendix A. Appendix B contains a table of En(x), for integral values of n up to 20, at intervals 0.01 for 0<x<2 and 0.1 for 2<x<10. The recurrence relations between the functions En make interpolation relatively simple.

Comment: The major parts of this report can now be found in The Handbook of Mathematical Functions, Edited by M. Abramowitz and I.A. Stegun, Dover publications. Some of it is also reproduced in Introduction to the Theory of Neutron Diffusion Volume 1, by K.M.Case, F. de Hoffmann and G. Placzek, Los Alamos Scientific Laboratory, 1953. (However, this report is not all that easy to find). Although MT-1 is dated 1946, it is tempting to infer that it was being used in rough draft much earlier, otherwise why was it designated MT-1! Further investigation by Michael Milgram leads to the belief that MT-1 was completed in April 1943.

MT-4 Notes on diffusion of neutrons without change in energy
G. Placzek and G.M. Volkoff (issued April, 1943, 42 pp)

This report is based on a series of lectures given by G. Placzek and recorded and amplified by G.M. Volkoff. The text consists of 5 chapters and 2 appendices, with following titles:

I. Kinematics of streaming
II. The transport equation
III. Scattering without change in energy
IV. Stationary state: isotropic scattering law
V. Infinite medium: application of Fourier transform methods
Appendix A. Fourier transforms
Appendix B. Evaluation of the isotropic point source solution of the transport equation in an infinite medium by contour integration

Comment: This a very important document since it contains virtually all the one speed results including the integro-differential and integral forms of the transport equation. Many practical examples are worked out in detail.

MT-5 Milne's problem in transport theory
G. Placzek and W.P. Seidel (issued June 24th, 1943, 13 pp)
(Physical Review, **72** (1947) 550-555)

This report gives a modified derivation of the Wiener-Hopf solution of Milne's problem using the integro-differential form of the Boltzmann equation and Laplace transforms.

Comment: Although the classical Milne problem involving the transport of radiation from the centre to the surface of a star had been solved by Wiener and Hopf in 1931, MT-5 showed that the technique was of very wide application and could be applied directly to the integro-differential form of the transport equation as well as to the integral form as done by Wiener and Hopf. This extension made the application of the method to anisotropic scattering and to finite slabs and source problems much easier. There were subsequently many developments to multi-dimensional problems and to energy dependence.

MT-6 The angular distribution of neutrons emerging from a plane surface
G. Placzek (completed February 19th, 1943; issued September 30th, 1943, 6 pp)
(Physical Review, **72** (1947) 556-558)

The Wiener-Hopf expression for the angular distribution in Milne's standard case is transformed into a form suitable for numerical evaluation. The results of the evaluation carried out by the Mathematical Tables Project are given. They are nearer to Fermi's simple linear approximation than to some of the more complicated approximations found in astrophysical literature.

MT-7 Boundary conditions in elementary diffusion theory G. Placzek
This report has not been traced, although its contents are clear from the title. It is not in the Public Record Office collection. AECL have informed me that it was never issued.

MT-12 Elementary approximations in the theory of neutron diffusion
P.R.Wallace and J. LeCaine (issued August 1943, 172 pp)
(Nucleonics, **4**(2), 30-35, **4**(3), 48-67, 1949)

This report presents in systematic form the solutions of problems of neutron diffusion in a single medium, both with and without multiplication, on the basis of elementary theory. The stationary state diffusion equation with capture is assumed for the diffusion of thermal neutrons, and the diffusion equation of the time-dependent type, without capture, for the diffusion of non-thermal neutrons. The stationary neutron densities are derived for various shapes of the medium and various source distributions. The problems are treated in the following sequences: determination of the density distribution of: (i) thermal neutrons due to sources of thermal neutrons (ii) non-thermal neutrons due to sources of fast neutrons, (iii) thermal neutrons due to sources of fast neutrons, without and with multiplication. The problem of multiplying systems under critical conditions in the absence of primary sources is treated in a final section.

The material is arranged according to (a) type of problem (b) shape of medium (c) distribution of sources. Graphs are given to illustrate some of the more important distributions.

Comment: Aside from its value in dealing with most common problems in age-diffusion and one-group diffusion theory, this report is a very useful handbook for applied mathematical problems in heat conduction and other physical problems involving the Helmholtz equation. The figures are especially helpful in giving the reader a physical grasp of the underlying mathematics.

MT-13 A theorem on neutron multiplication
G. Placzek and G.M. Volkoff (~ 1943-44, 20 pp)
(Canadian Journal of Research, **A25** (1947) 276-292)

The asymptotic behaviour of the neutron distribution due to a point source in an infinite homogeneous medium in which a convergent chain reaction (multiplication constant k<1) takes place is investigated without special assumptions about the properties of the medium and the mechanism of neutron diffusion. It is shown under very general assumptions that at large distances r from the point source the neutron distribution always has the form $A\exp(-\mu r)/r$. General expressions for the constants μ and A of this asymptotic form of the distribution are given for any k<1 in terms of the Fourier transform of the spatial distribution of primary fission neutrons. These expressions reduce to particularly simple form for (1-k)<<1. The exact expression for the neutron distribution throughout the medium is given in integral form. Four special frequently occurring cases are discussed as illustrations of the general result.

Comment: This work anticipates a number of matters that were also under consideration by Manhattan Project scientists. In particular, in the Appendix there is a formulation of the energy dependent transport equation in terms of a general slowing down kernel, which was later praised by Alvin Weinberg in his review paper to the American Mathematical Society (Proc. Symp. in Appl. Math. Vol XI, Nuclear Reactor Theory, 1961, pp1-19) MT-13, which was published, remains a joy to read even after an interval of 52 years.

MT-14 Analysis of experimental data on the slowing down and thermal diffusion lengths in carbon G.M. Volkoff (issued September 15th, 1943, 20 pp)

Experimental data of Laurence and Sargent on the thermal neutron distribution due to a source of fast neutrons at the centre of a ten ton carbon sphere surrounded by a wax shell are analysed in order to determine the range of values of the slowing-down length L_s and the diffusion length of thermal neutrons L compatible with their observations. A considerable spread is found in the values of L and L_s which fit the experimental data reasonably well. This is due to the fact that the ten ton mass of carbon is not sufficiently large. To obtain better defined values of L_s and particularly of L a mass of carbon is required which is large enough to contain a region of the order of magnitude of *L* which is far enough away from the source of fast neutrons to have practically no neutrons of energy above thermal entering it, and in which the boundary effects are either explicitly calculable or negligible.

Comment: This early theoretical interpretation of the diffusion length experiment has highlighted all of the major sources of error and demonstrates a deep understanding of what, in 1943, was a fledgling subject.

MT-15 Neutron distribution in adjoining piles of slightly different properties
P.R. Wallace (issued September 16th, 1943, 18 pp)

The purpose of this report is to provide a method of determining the ratio of the capture cross sections of two samples of graphite from measurements of the thermal neutron density obtained in an experiment of Sargent. and Hereward. The graphite samples upon which the experiment was performed were arranged in the form of adjacent piles of equal dimensions, with a source of fast neutrons at the centre of their common face. Measurements were made in each sample along the axis of the piles perpendicular to the common face. The theoretical treatment is based on the assumption that the samples differ only with respect to (1) their densities, (2) their capture cross - sections. Both of these differences are assumed to be small, so that their products may be neglected.

Formulae are obtained for the thermal neutron distribution along the axis in each pile. It is found that the difference in capture cross-section may be determined most readily by studying the difference between these two distributions.

Comment: This report is an excellent example of how a theoretician can help the experimentalist by advising on the most economic way to proceed, i.e. how to avoid wasted measurements which are not relevant to the problem.

MT-16 The neutron density near a plane surface
G. Placzek (issued June 1943, 7 pp)

The solution of Milne's integral equation for the density is obtained by an iteration method. As a check, the angular distribution of the emerging neutrons, derived from this solution, is compared with the exact angular distribution given in MT-6 and is shown to agree at all points to within one per mille. (Author: one per mille is one part in 1000).

MT-17 On the slowing down length of neutrons in water
R.E. Marshak (completed May 1943, issued September 23rd, 1943, 7 pp)
(Reviews of Modern Physics, **19** (1947) 185-238)

A new derivation of the slowing down length of neutrons in water is given for general variation of mean free path. The result differs from a formula given previously by Fermi.

Comment: The value of this paper is the way it uses Fourier transforms to evaluate spatial moments of the energy dependent transport equation, thereby enabling the slowing down length to be reduced to the solution of an essentially infinite medium integral equation. Higher spatial moments can be obtained recursively, i.e. the system is closed. One of the conclusions of the report is that the formula for the slowing down length of neutrons in water given by Fermi (Ric. Scient. Vol 7 (1936) 13) is incorrect. The correct form of the slowing down length is derived directly from the moments method.

MT-18 On the moments of the distribution function of neutrons slowed down in heavy elements
R.E. Marshak (Appendix by Bengt Carlson, issued October 30th, 1943, 26 pp)
(Reviews of Modern Physics, **19** (1947) 185-238)

Accurate formulae for the second and fourth moments are derived for heavy elements by representing the variation of mean free path with energy as a polynomial with arbitrary coefficients. Formulae for the higher moments are also derived but they are less accurate. Comparison of our results with the elementary "age-velocity" theory confirm the usefulness of the elementary theory for heavy elements and not too rapidly varying mean paths. For carbon the slowing down length from 2.7 Mev to 1 eV, as predicted by the elementary theory, is only 3% less than the more exact value while the ratio $3\left[r^4\right]_{av} / 5\left[r^2\right]_{av}^2$ instead of being 1.00, is 1.07. For initial energies lower than 2.7 MeV, the deviations are even smaller.

Comment: This report evaluates the slowing down length and higher spatial moments for some practical moderators. There is much information on the expressions which enter the calculations, which are worked out algebraically for several cases in an Appendix written by Bengt Carlson. Some results on the extraction of complex roots of certain transcendental equations are worked out in detail.

MT-19 On the slowing down length of neutrons in mixtures
R.E. Marshak (issued September 30th, 1943, 25 pp)
(Reviews of Modern Physics, **19** (1947) 185-238)

Transport equation methods are used to derive formulae for the slowing-down length of neutrons in mixtures which are improvements on the elementary ("age-velocity") theory. One formula (eq.(30)) is valid for an arbitrary mixture of elements and is useful when the mixture does not contain hydrogen or deuterium. The second formula (eqs. (46) and (47)) holds for a mixture of two elements and will serve for mixtures containing hydrogen or deuterium or for mixtures containing only heavy elements when the variation of mean free path with energy is extremely rapid.

MT-20 Diffusion of neutrons without velocity change
G. Placzek
This report was never formally issued

MT-21 Critical conditions for a multiplying spherical core with an infinite reflector of the same multiplying properties
G.M. Volkoff (issued January 29th, 1944, 72 pp)

The report is divided into two parts. In part I the physical assumptions underlying the present treatment of the critical conditions in a multiplying spherical core with an infinite reflector are stated, the problem is formulated mathematically, the approximations used are qualitatively discussed, the formal results are collected together, and are applied to a specific numerical case of a graphite - uranium sphere with a graphite reflector. In part II, the mathematical details of the solution of the problem are presented and the approximations used are discussed quantitatively. The method used is a modification of the Hopf-Wiener solution of Milne's integral equation.

The formal results of this report have been obtained for a quite general type of slowing-down mechanism and for both multiplying and non-multiplying reflectors. All the numerical results, however, have been obtained on the basis of the elementary age-velocity theory of the slowing-down process and refer particularly to non-multiplying reflectors. On this basis the critical radius a of a bare sphere is given by

$$a_0 = \frac{\pi L_0}{\kappa\left(k, L_s / L_1\right)}$$

where L_1, L_s, L_0 are, respectively, the diffusion, slowing-down and migration lengths of the medium, k is the multiplication constant and $\kappa(k,\gamma)$ satisfies

$$\left(1+\frac{\kappa^2}{1+\gamma^2}\right)\exp\left(\frac{\kappa^2\gamma^2}{1+\gamma^2}\right) = k$$

and may be obtained from the graphs of Figure 1. The fractional reduction ε in the critical radius due to an infinite non-multiplying reflector is given as the sum of two terms:

$$\varepsilon = \frac{a_0 - a}{a_0} = \varepsilon_t\left(\kappa, L_2 / L_0\right) + \varepsilon_f\left(\kappa, L_s / L_1\right)$$

where the first term ε_t describes the effect of thermal neutrons and is given by the graphs of Figure 4, and the second term describes the effect of the fast neutrons and is given by the graphs of Figure 3. The formulae for the critical distributions of thermal neutrons and of thermal neutron sources, are collected in section l of part I, and are presented in graphical form in Figure 6 for a particular numerical example.

Comment: This is a particularly nice piece of work which employs the Wiener-Hopf technique to solve certain integral equations that arise in diffusion theory. The approach is explained every step of the way and, in addition to solving the problem, it provides an excellent introduction to the Wiener-Hopf technique for those wishing to use it. Part II is a *tour de force* which not only gives solutions, but also presents numerical work and points out some of the numerical pitfalls involved in the complicated integrals that arise.

MT-26 Milne's problem for anisotropic scattering
C. Mark (issued October 30th, 1943, 34 pp)

Scattering functions which are linear and quadratic polynomials in the cosine of the scattering angle are considered, and also a particular case of a cubic. It is shown that for a linear law the angular distribution of emerging neutrons is the same as for isotropic scattering and that the neutron density differs from that in the isotropic case only by a term proportional to the distance from the boundary. For a quadratic law the Laplace transform of the neutron density and an expression for the angular distribution of emerging neutrons are given, and also the neutron density at the boundary and the constant in the asymptotic solution for the density. It is shown that in this case the maximum variation caused by anisotropy in the value of the neutron density at the boundary is about 1.3%, and that the maximum variation in the distance from the boundary measured in transport mean free paths at which the extrapolated asymptotic solution for the density will vanish is about 0.44%. For the particular cubic considered, these effects are shown to be even smaller.

Comment: This report is essentially an extension of MT-5 for the Milne problem to include anisotropic scattering in the laboratory system of co-ordinates. The Wiener-Hopf technique is used, but it is by no means a trivial extension since it requires considerable work to locate the complex roots of an equation which provides the singularities of the solution. This paper has been the source of numerous extensions over the years to other transport problems involving finite systems and multi-group slowing down.

MT-29 Critical radius of a strongly multiplying sphere surrounded by a non-multiplying infinite medium
J. LeCaine (completed December 15th, 1943, issued April 15th, 1944, 11 pp)

In this report a method is given by which a relationship of the form

$$k = a^{-3}\left\{\phi_0 + \phi_1 a + \phi_2 a^2 + ...\right\}$$

or

$$a = k^{-1/3}\left\{\alpha_0 + \alpha_1 k^{-1/3} + \alpha_2 k^{-2/3} + ...\right\}$$

can be set up between the multiplication factor k and the critical radius *a* of a sphere with large multiplication factor, surrounded by a non-multiplying infinite medium. The method is based on the assumption that the slowing down mechanism and the diffusion coefficient for thermal neutrons are the same in the sphere and in the reflecting medium, and that the thermal neutron distribution in a homogeneous, infinite, non-multiplying medium due to a plane source of fission neutrons at x = 0 can be represented by a function $K(|x|)$ such that $K(x)$ is analytic in the neighbourhood of x = 0 and $K'(0) = 0$.

Since the series can be used in practice only for large values of k, the results have no physical application but they serve as a useful check on the validity of replacing the exact solution of the problem by the modified solution of the auxiliary problem, discussed in MT-21. It is found that the two methods agree very well even for large values of k and consequently the modified solution of the auxiliary problem which in MT-30 is shown to improve with decreasing k will give an even more accurate value of the critical radius for physically interesting values of k.

Comment: For anyone interested in seeing how to solve a practical problem, via an integral equation using the Fredholm method, this report makes essential reading.

MT-30 Application of "synthetic" kernels to the study of critical conditions in a multiplying sphere with an infinite reflector
G.M. Volkoff and J. LeCaine (issued April 15th, 1944, 35 pp)

The problem of critical conditions in a multiplying spherical core surrounded by an infinite non-multiplying reflector of the same scattering properties which was studied in MT-21 on the basis of the elementary age-velocity slowing-down theory (Gaussian kernel) is discussed in this report on the basis of an approximate formal description of the slowing down process in terms of "synthetic" kernels of which the Gaussian kernel is a limiting case. The adoption of this formal description of the slowing-down process is found to be useful for three reasons.

a) The values of the critical radius and the critical neutron distributions obtained in this report with the aid of "synthetic" kernels are found to be in very close agreement with the corresponding results obtained in MT-21 on the basis of the Gaussian kernel, provided the slowing down length does not exceed the diffusion length for thermal neutrons in the core (this condition is usually satisfied in practice). The results obtained with the aid of the "synthetic" kernels have the practical advantage of being in analytic form, thus avoiding the laborious numerical integrations of MT-21.

b) The approximation made in replacing the actual mathematical problem to be solved by the auxiliary two-interval problem could be checked only numerically in the case of the Gaussian kernel in MT-21. In the case of "synthetic" kernels both the actual and the auxiliary problems can be solved exactly, and the equivalence of the two solutions is shown analytically.

c) The "synthetic" kernel description of the slowing-down process in an infinite medium is shown to be identical with Friedman's schematic model of slowing down in which several groups of neutrons of various energies are assumed to diffuse without loss of energy within a group, but with transitions occurring between adjacent groups. The close agreement found between the results app1ying both the group (i.e. synthetic kernel) model and the age- velocity (i.e. Gaussian kernel) model of slowing down to this particular infinite reflector problem gives greater confidence in the results of applying the group model of slowing-down to other reflector problems which have not been solved on the basis of the age-velocity, slowing-down theory.

Comment: A powerful method of solving an integral equation with a mathematically complicated kernel is to replace the actual kernel by a sum of mathematically simpler expressions and to fix the arbitrary parameters by matching certain moments of exact and approximate functions. This is done very nicely here with exponentials replacing a Gaussian. It is a technique which has found innumerable uses in neutron transport theory ever since.

MT-34 Boundary conditions at thin absorbing shells and plates I
P.R. Wallace (completed January 4th, 1944, issued May 10th, 1944, 43 pp)

If two scattering and absorbing media are separated by a thin layer of strongly absorbing material, it may be desired to know the effect of the layer on the thermal neutron distribution. We are concerned chiefly with spherical shells of very large radius enclosing one medium and surrounded concentrically by another. In the inner and outer media, asymptotic density distributions (derivable, except for multiplying constants, from elementary diffusion theory) are attained at distances not greatly exceeding a mean free path from the shell. The purpose of this report is to derive boundary conditions to be imposed upon these solutions to determine the asymptotic distributions correctly.

Instead of treating the spherical problem, we determine the boundary conditions at a thin absorbing plate of the same thickness; these may be applied to the spherical problem with an error of the order (thickness of shell)/(radius of shell). This error is investigated in the simple model of elementary diffusion theory.

The main problem is treated on the basis of two different approximation methods: (1) based on an expansion in powers of α, the ratio of total to capture mean free path in the shell, and (2) based on an expansion in the ratio t / ℓ_i, where t = thickness of shell and ℓ_i = total mean free path inside. The first method implies no restriction on t / ℓ_i, the second none on α, provided in each case that only a small portion of incident neutrons are captured in the shell. For aluminium shells separating P-9 from graphite, the two methods give almost indistinguishable results for all thicknesses of practical interest.

The present report contains the analytic form of the boundary conditions under the assumptions of both isotropic and linear anisotropic scattering. It has only been possible up to the present to have numerical work done on the isotropic case. A second report (II) will contain numerical results in the anisotropic case, and applications to the problem of the effect of shells on critical sizes of P-9-metal systems with graphite reflectors.

Comment: This paper contains some very useful and physically illuminating transformations of the integral transport equation into another form using the infinite medium plane source solution. There are also some illustrative examples of solutions of this equation by iteration methods that converge rapidly. I have never seen this approach before in the published literature. A similar technique is used in MT-63.

The author asked Phil Wallace about the circumstances leading up to this work and received the following reply:

I remember that integral equation formalism well, because it reveals a phenomenon that has always fascinated me. I arrived at it simply by playing games with the equations. When the result popped out I looked at it and said: My God, if I had been smart enough I could have written this down right at the start . It happened that Placzek was in New York at the time, and I flew down to report to him. I told him how it came about, which obviously amused him. So the answer to your question seems to be that I did not set out to solve any specific problem; I was "fishing". Once the result was there, anyone could use it. For me, I discovered the "problem" once I had the solution. I also learned a lesson about tieing your mathematics to its physical roots, which in turn had a significant effect on "Mathematical analysis of Physical Problems." (by P.R. Wallace, Holt, Rinehart and Winston, 1972).

MT-35 Neutron distribution in a multiplying pile with a plane source
P.R. Wallace (completed June 20th, 1943, issued January 13th, 1944, 4 pp)

If a Fourier analysis is made of the thermal neutron density in various cross-sections of a pile of multiplying material with a plane source of fast neutrons, it is found that at sufficient distances z from the source the various Fourier components decrease in intensity with z according to an exponential law. Using the experimental data of the “First Intermediate Pile’ (Report. A-200), graphs are given showing (1) the first Fourier component, and the first exponential in its analysis, and (2) their ratio.

Comment: This report discusses an early treatment of spatial transients near the source, the functional forms of which are required, in order to know at what distance an asymptotic distribution is established. Data from the 'First Intermediate Pile' are used. Presumably this is data passed on to Canada by Manhattan Project scientists.

MT-38 Critical radius of a multiplying spherical core surrounded by a non-multiplying reflector of finite thickness
G.M. Volkoff (isuued April 15th, 1944, 4 pp)

The critical radius a_∞ of a multiplying spherical core surrounded by an infinite non-multiplying reflector of the same scattering properties was found in reports MT-21 and MT-30. In this report we consider the modification introduced into the above results by taking the reflector to be of finite thickness *d* comparable to the diffusion length L_2 of thermal neutrons in the reflector, but still large compared to the slowing-down length. The critical radius *a* corresponding to a reflector of finite thickness *d* is found to exceed a_∞ by

$$a - a_\infty = \frac{2L_2 \exp\left[-2\left\{\frac{d}{L_2} - K\right\}\right]}{1 + \left(\pi L_2 / a_0\right)^2}$$

where a_0 is the critical radius of the core without a reflector, and K is a small numerical constant which depends on the description of the slowing-down process used and is given by expressions (2.13), (2.l9), (2.20) of this report. The whole treatment is valid only if *d* is large enough to make

$$\exp\left[-2\left\{\frac{d}{L_2} - K\right\}\right] \ll 1$$

Comment: In the case when the thickness of the reflector is comparable to the diffusion length but still large compared with the slowing down length, Volkoff has shown how the Wiener-Hopf method can still be used by modifying the boundary conditions. This leads to an explicit expression for the constant K in terms of the properties and size of the reflector.

MT-40 Production and consumption of fissile materials in one arrangement of producing unit
E.D. Courant (issued December 29th, 1943, 23 pp)

The report contains a theoretical study of changes in operating conditions with time for a particular case. Relations are derived and graphs presented showing the production of U233 and Pu239 in systems containing uranium enriched with U235, thorium and water. The question of practical feasibility of some of the schemes mentioned is not considered in detail; in practice, a very long operating time would be required before some of the conditions considered could be achieved.

Comment: This is one of the few MT reports that deals with the time variation of pile properties. The emphasis is usually on reactor statics. This work, however, considers what today would be called burnup of nuclear fuel with destruction of U235 and creation of Pu239 from neutron capture in U238. Interestingly, the symbol used for plutonium in the report is Pl239, so presumably in 1943 a standard symbol had not been agreed upon.

MT-49 Milne's problem for a sphere
R.E. Marshak and W.P. Seidel (issued April 15th, 1944, 29 pp)

The asymptotic neutron distribution in an infinite non-capturing medium surrounding a black spherical core is found on the assumption that a constant flux approaches the core. If *a* is the radius of the core, 4π the flux, and $\psi_0(r)$ the neutron density, then $\left[r\psi_0(r)\right] \to 3(r-r_0)/r_0$ where r_0 is a function of *a* alone and is the quantity to be determined. Two methods are given for finding r_0: the first approximates the angular distribution by a finite number of spherical harmonics and leads to more and more accurate values of r_0 as more harmonics are taken into account. The second method takes the integral equation formulation as starting point and enables us to derive rigorous upper and lower bounds for r_0. Reasons are given for believing the upper bound to be very close to the correct value. Fig.1 represents $(a-r_0)$ as a function of *a* with an overall accuracy of one percent. A comparison of the two methods shows that the successive approximations in the spherical harmonic method converge rapidly and that the use of five spherical harmonics gives an accuracy of better than three percent in $(a-r_0)$. Knowledge of the quantity r_0 is useful for problems of control and for obtaining an upper limit on the thermal utilization of a strongly capturing sphere.

Comment: This report contains what must be one of the earliest applications of the spherical harmonics method to spherical geometry. Numerical values up to P5 are given for the extrapolation distance r_0 and there are many useful expansions given in powers of the sphere radius. Also presented, is the same problem dealt with using the integral form of the transport equation. Some detailed derivations of the kernels of the integral equation are given which are very instructive and are not generally to be found in the textbooks. The introduction of a complementary variational principle to bracket the extrapolation distance must also be a first.

MT-50 The neutron density near a plane surface II
C. Mark (completed December 30, 1943; issued April 15, 1944, 12 pp)

The exact solution of Milne's integral equation for the density is obtained. This is done by reducing the inversion of the Hopf-Wiener solution for the Laplace transform of the density to a real integral with non-oscillating integrand. The integral involves the angular distribution function of the emerging neutrons, and is evaluated numerically using the tabulation in MT-6. It is now seen that the approximate solution for the density given by Placzek in MT-16, which was obtained by an iteration method, agrees everywhere with the true density to within 1.6 per mille. (Author: one per mille is one part in 1000).

Short notes are also given on: an interpretation of this problem in a half-space as a problem in an infinite medium; the values of the first three moments of the difference between the density and the asymptotic; and an expansion of the density for points near the boundary.

Comment: A major advance in this report was the representation of the total flux density for the Milne problem explicitly in terms of an asymptotic term containing the linear extrapolation distance plus a boundary transient given in terms of the angular flux at the surface. Details of the contour integration needed are given at some length, as also are some properties of functions that arise when using the Wiener-Hopf method. In the Public Record Office at Kew, London, I found a related report TPI-5 issued on October 25th, 1943, entitled "Terms in an expansion of the Wiener-Hopf solution of Milne's equation for small values of the argument". This has some bearing on the series solution given in MT-50. No other reference to TPI reports has been found and their purpose remains obscure; perhaps they were prepared as background information for the MT reports. It has been suggested by Michael Milgram that TPI means *Theoretical Physics Informal*.

MT-51 Energy conversion factors and nuclear constants
G. Placzek (completed February 2nd, 1943, issued April 24th, 1944, 2 pp)

Due to the varied aspects of TA work a number of different units of energy (physical, technical, chemical) have to be used at the same time. In the following, a table of conversion factors of energy units is given, followed by some other nuclear constants. The data are mainly based on Birge's work.

Comment: All of the data given here has been superseded, but in 1943 this table must have been very useful. It is interesting to note that Placzek, himself, compiled the table. One might have expected him to give it to a junior member of the team to collate. Perhaps Placzek already had the table in his personal papers, or understood the importance of getting such material right!

MT-52 Black utilisation
R.E. Marshak
This report was never formally issued.

MT-53 A rigorous formula for the slowing down length in an element of arbitrary mass.
R.E. Marshak (issued May 1st, 1944, 9 pp) (Reviews of Modern Physics, **19** (1947) 185-238)

A rigorous formula for the slowing down length of neutrons in an element of arbitrary mass and for arbitrary variation of mean free path with energy has been found. The formula is especially useful when there are resonances in the elastic scattering cross-section as a function of energy.

MT-54 On the slowing down length of neutrons in water: supplement to MT-17
R.E. Marshak (issued 23rd June, 1944, 6 pp) (Reviews of Modern Physics, **19** (1947) 185-238)

Using the rigorous formula developed in MT-17 and the observed scattering cross-sections in hydrogen and oxygen, a curve is given of the slowing down length of neutrons in water as a function of energy. Comparison is made with age-velocity theory to show where deviations set in. A graph is also given for an approximate representation of the mean free paths as functions of energy. Using this approximate representation, the effect of the finite mass of oxygen is estimated quite accurately.

MT-55 The application of variational theory to the determination of asymptotic neutron densities.
R.E. Marshak (Edited by W.P. Seidel and C. Mark and issued September 30th, 1944, 8 pp)

Inhomogeneous integral equations of the type appearing in connection with certain problems of neutron diffusion are treated by means of the variational method. It is shown how to obtain quite accurate values of the asymptotic neutron density in the following three cases: (a) Milne's problem for the plane, (b) infinite scattering medium surrounding black spherical core, (c) infinite scattering medium surrounding black spherical core with air gap.

Comment: Another early application of the variational method in reactor theory. A similar approach has been used in many applications during the past 50 years.

MT-56 Constants and expansions of Wiener-Hopf method.
C. Mark

This report was never formally issued. However, via the Public Record Office at Kew, London, I did find a related report TPI-5 issued on October 25th , 1943, entitled "Terms in an expansion of the Wiener-Hopf solution of Milne's equation for small values of the argument". This has some bearing on the series solution given in MT-50; however, it is not MT-56.

MT-59 Measurements in finite system of the total number of neutrons in an infinite system.
E.D. Courant (completed December 30th, 1943, issued May 10th, 1944, 17 pp)

The total number of neutrons that would be present in an infinite medium surrounding a point source is given by

$$S_{\infty} = 4\pi \int_{0}^{\infty} \rho r^2 dr$$

This may be approximated by

$$S = 4\pi \int_{0}^{boundary} \rho r^2 dr$$

taken along a line in a suitable finite system with a source at the origin.

In this report S / S_{∞} is obtained on the basis of elementary (age-velocity) slowing down theory for cylindrical and spherical systems. The medium is supposed to capture thermal neutrons so strongly that thermal diffusion is negligible. The effects of weak multiplication and of finite extent of the source are considered.

Comment: This is another example of the theoretician giving advice to the experimentalist. In particular, to show how measurements on finite samples of a moderator can give information about neutron behaviour in infinite systems.

MT-63 On the thermal utilisation of plates in the presence of linear anisotropic scattering
P.R. Wallace (completed May 15th, 1944, issued September 27th, 1944, 16 pp)

Assuming that scattering in both metal and moderator obeys a linear anisotropic scattering law, we obtain an integral equation for the density in a cell, in which the integrals are over the region occupied by the core only. This equation lends itself to numerical solution by the method of iteration. From the density in the core, the thermal, utilization U is then calculable.

The simpler “boundary condition method” of Placzek and Wallace “On the Thermal Utilization of Plates”, MT-59, is sufficiently accurate for practical purposes. This method is particularly useful if it is desired to know how U varies with the size of the moderating cell. *[Editor's note: MT-59 is by E.D. Courant, so there is some confusion here. The title cited is not in the list of MT reports.]*

In the case of the latter method, we solve the integral equation for the density in the metal and for the utilization, in an approximation which is valid if the half-thickness of the metal is of the order of a mean free path or smaller. If scattering is anisotropic only in the moderator, the results follow immediately from those for isotropic scattering.

Comment: This report derives an integral equation for an absorbing plate in an infinite moderator and applies Fourier transforms to solve it. There are some interesting 'tricks' described to get the absorptions in the plate. See also MT-34.

MT-65 Report on research in theoretical physics, February to July 15th, 1944
G. Placzek

This report was not formally issued. However, in the Public Record Office at Kew, London there are available, under the classification AB 2/452-478, all of the Theoretical Physics Division Progress reports from 24th March 1943 up to August 1946.

MT-66 Milne's problem with capture
F.T. Adler and C. Mark
This report was never formally issued

MT-67 Diffusion equations and critical conditions in a medium with varying mean free path
E.D. Courant (issued May 23rd, 1944, 15 pp)

The thermal diffusion equation and the age-velocity slowing down equation are derived from transport theory for a medium in which all mean free paths vary spatially in the same manner. For one particular manner of variation, the equations have the same form as in a uniform medium. Critical conditions for a sphere are determined for this particular case. The results are compared with those of Report CP-1069, which are based on slightly different assumptions; the agreement is quite good.

Comment: The Report CP-1069, cited above is a Manhattan Project report by Morehouse and Young, with the title "Some cases of pile activity flattening".

MT-72 Theory of the diffuse reflection of neutrons by a plane surface of a semi-infinite capturing medium
F.T. Adler (completed December 15th, 1943, issued October 26th, 1944, 28 pp)

We consider a semi-infinite medium with a plane boundary in which the neutrons are captured and isotropically scattered without loss of energy. The diffuse reflection of an incident beam of neutrons by this plane surface is determined as a function of the angle of incidence and of the ratio of scattering and capture probabilities. Expressions for the albedo, the emerging angular distribution and its average cosine, and the density at the surface are derived and discussed numerically. The process of establishment of an isotropic distribution by multiple reflections of an anisotropic one is also studied.

Comment: This report is yet another example of the power of the Wiener-Hopf technique applied to the integro-differential transport equation. There are some useful additional procedures described which extends the techniques given in MT-5. Also there is a large number of useful integrals evaluated using complex integration.

MT-88 Influence of a small black sphere upon the neutron density in an infinite non-capturing medium
B. Davison (issued November 29th, 1944, 41 pp)

In the present report we examine the neutron density in a uniform non-capturing medium surrounding a small black sphere, in the case when the density at infinity tends to a definite finite limit. "Small' sphere means small compared to the mean free path in the surrounding medium. The linear extrapolation length λ for the asymptotic solution for the density in the surrounding medium is determined as a function of the radius of the sphere. The method used is essentially the perturbation method, treating an infinite space with a constant density in the absence of the black sphere as the unperturbed system, and all the effects of the presence of the black sphere as small perturbations. Orders of magnitude of the successive perturbations were estimated and the first few were determined explicitly. This gave

$$\lambda = \frac{4}{3} - \frac{5}{9}a - \frac{2}{3}\left(\frac{\pi^2}{4} - 1\right)a^2 \log a - 1.4002a^2 + O\left(a^3 \log^2 a\right)$$

in which *a* is the radius of the sphere in units of the external mean free path.

Comment: The material reported here shows Davison at his best, with methods developed for expanding the integral equation in a series and the successive terms being evaluated analytically.

MT-89 A remark on the variational method
B. Davison (issued November 27th, 1944, 5 pp)
(Physical Review, **71** (1947) 694-697)

The nature of the extremum of the functional

$$\frac{\int q(x)\left[q(x) - \int q(y)K(x,y)dy\right]dx}{\left[\int q(x)f(x)dx\right]^2}$$

associated with the inhomogeneous integral equation

$$q(x) = \int q(y)K(x,y)dy + f(x)$$

is investigated. It is shown, under rather general assumptions about the kernel and the inhomogeneous term, that the extremum, which the functional reaches for the correct solution, is always necessarily a minimum and not a maximum, nor a "saddle point."

MT-91 Estimates of critical volume of polymer for pilot plant under various conditions
J. Stewart and G.M. Volkoff (Issued November 27th, 1944, 6 pp)

Estimates are given of critical amounts of polymer for the pilot plant under various operating conditions. The minimum quantity required to just start the chain reaction at zero power, and in the absence of cooling water, is estimated to be 9 short tons. The critical mass for designed power output is estimated to be 17 short tons.

Comment: This report contains some detailed numerical work on solutions of the diffusion equation and calculates the critical buckling (called here the Laplacian) for (i) bare cylinder, (ii) cylinder with finite reflector, (iii) cylinder with infinite reflector and (iv) a cylinder with optimal ratio of height/diameter with an infinite reflector. There are no expressions given for the buckling, neither are there any references to a source paper, however, it seems that they can found in MT-12. It is interesting to note that in Montreal heavy water was always referred to as polymer.

MT-92 The spherical harmonic method, I
C. Mark (issued November 30th, 1944, 52 pp)

A method of obtaining approximate solutions of the transport equation is presented in a form applicable in principle to any geometry. The approximation will give good results in cases where the angular distribution is not very anisotropic. The basis of the approximation is to, expand the density per unit solid angle $\psi\left(\vec{r},\vec{\Omega}\right)$ in spherical harmonic tensors formed from $\vec{\Omega}$, the unit vector in the direction of velocity, and to break off the expansion. A differential equation whose degree increases with the order of the approximation is obtained for the total density $\psi^{(0)}\left(\vec{r}\right)$. This equation has the form

$$\prod_i \left(\nabla^2 - \nu_i^2\right)\psi^{(0)}\left(\vec{r}\right) = 0$$

where the numbers ν_i depend on the order of the approximation and on the value of the parameter α of the medium, but not at all on the geometry.

When the equation for the total density is an ordinary equation, we simulate the physical condition of continuity of $\psi\left(\vec{r},\vec{\Omega}\right)$ at a boundary in a multi-medium problem by requiring that the spherical harmonic moments of $\psi\left(\vec{r},\vec{\Omega}\right)$ which we retain be continuous; and this determines the constants in the solution for $\psi^{(0)}\left(\vec{r}\right)$. The form of the solution for the total density and the necessary moments in an approximation of general order is given explicitly for plane and spherical symmetry; and for cylindrical symmetry the solution is given for two low-order approximations.

In a later report (MT-97, CRT—338, Revised) the application of the method to several problems involving plane and spherical symmetry will be discussed in detail and the results of a number of examples already worked will also be given.

Comment: This report must be the first definitive derivation of the spherical harmonics method for the neutron transport equation. A form of expansion of this type was known, however, in the 1920's in connection with rarefied gas dynamics (see Chapman and Cowling, The mathematical theory of non-uniform gases, Cambridge University Press, 1960 and references therein). Those gas problems, though, did not include boundary conditions, and Mark made great advances in inventing methods for dealing with these, i.e. 'Mark's boundary conditions'.

MT-93 Influence of a large black sphere upon the neutron density in an infinite non-capturing medium
B. Davison (issued November 30th, 1944, 15 pp)

In the present report we examine the neutron density in a uniform non-capturing medium surrounding a large black sphere, in the case when the density at infinity tends to a definite finite limit. "Large" sphere means large compared to the mean free path of the surrounding medium. The linear extrapolation length λ for the asymptotic solution for the density in the surrounding medium is determined and expressed in terms of the radius of the sphere. The method is essentially as follows. In zero approximation, and not too far from the surface of the sphere the density should be roughly the same as in a half-space bounded by a vacuum. In more accurate approximations, and if we consider any distances from the spheres the density will deviate from that in the half-space, but these deviations can be split into groups, viz.: the primarily long-range effects and the primarily short-range effects. The primarily long-range effects are taken into account automatically if we re-interpret our problem treating the neutron density of the actual problem times the radial coordinate as the neutron density in some fictitious modified problem. The primarily short-range effects can then be treated as a small perturbation, assuming the solution of Milne's problem as the unperturbed system. Evaluating the orders of magnitude of the successive corrections, working out the first few of them and returning to the original interpretation of quantities we have

$$\lambda = 0.7104 + \frac{0.5047}{a} + \frac{0.2336}{a^2} - \frac{\log a}{4a^3} - \frac{0.1704}{a^3} + O\left(\frac{\log^2 a}{a^4}\right)$$

in which *a* is the radius of the sphere in terms of the external mean free path.

Comment: This contains further evidence of Davison's mastery of the integral form of the transport equation, with neat expansion techniques in powers of the reciprocal radius of the sphere.

MT-97 The spherical harmonics method, II (Application to problems with plane and spherical symmetry)
C. Mark (issued May 31st, 1945, revised as CRT-338, June 1947, 65 pp)

The application of the spherical harmonic method to problems with plane or spherical symmetry is discussed in detail. The numerical results of some applications already made are included to indicate the degree of convergence obtained. Formulae for dealing with distributions of isotropic sources are developed. Tables useful in applying the method are given in Section 11.

(The revision consists in the inclusion of some material (subsection (ii) of section 8) omitted from the original declassified version (CRT-338) of this report and in an expansion of Tables XVII and XIX and of the part of Table XVIII pertaining to odd-order approximations. The corresponding Tables of CRT-338 had $0 \leq \alpha(0.1) \leq 1$.The present Tables have:
$-2 \leq \alpha(0.1) \leq -0.2, -0.2 \leq \alpha(0.1) \leq 0.2$ and $0.2 \leq \alpha(0.1) \leq 1$.

Comment: There are various applications, but of most importance is the introduction and discussion of boundary conditions at a free surface. Mark's boundary conditions are explained as are those of Marshak.

MT-106 Moments of the angular distribution in the asymptotic region
P.R. Wallace (issued April 24th, 1945, 16 pp)
(Canadian Journal of Research, **A26** (1948) 99-114)

We suppose that, in a general distribution of scattering and absorbing media, with arbitrary neutron sources, there exists a region in which $\alpha = \ell / \ell_c$, and q the distribution of sources, are constant. Suppose also that parts of this region which has constant properties are sufficiently distant from its boundaries that an "asymptotic" solution is established. The purpose of this report is to investigate the moments of the neutron angular distribution in this asymptotic region, and in particular to show, quite generally, that the asymptotic current is equal to $(-\alpha / \nu^2)$ times the gradient of the asymptotic density.

An expression is given for the asymptotic density in terms of the properties of the non-uniform ("external") regions.

The second moment is expressed in terms of derivatives of the zero moment. The nth moment may be expressed in terms of derivatives of the zero moment of orders up to "n".

Moments of the angular distribution relative to arbitrary directions in space are defined, and the second moment is calculated in various forms. In general it is found that the second moment depends on geometry and varies from point to point. Special instances in which it reduces to a constant are discussed.

Comment: Some very general expressions have been obtained for the asymptotic solutions of the transport equation in arbitrary geometry using tensor notation. Especially interesting are the expressions obtained for the mean and mean-square values of the cosine of the angular distribution of neutron flux.

MT-107 Effect of scattering on the capturing properties of plates and spheres
P.R. Wallace (completed April, 1945, issued July, 1946, 7 pp)

If a small proportion of scattering centres is added to a perfectly absorbing plate, the plate will absorb neutrons more strongly provided it is thin enough. An investigation is made of the similar problem for small absorbing spheres, but no similar effect is found. It is concluded that the effect in plates is due to the scattering into long paths, nearly parallel to the plate, of neutrons which might otherwise penetrate the plate.

Comment: This report contains the conclusion that neutron transport in plates often leads to anomalous results because of the almost infinite directions available nearly parallel to the plate. Such a conclusion was to lead to similar anomalies when time decay constants were analysed many years later. (J. Lehner and G.M. Wing, Com. Pure Appl. Math. **8** (1955) 217).

MT-112 Angular distribution due to an isotropic point source and spherically symmetrical eigensolutions of the transport equation
B. Davison (issued January 31st, 1945, 56 pp)

In sections 2 and 3 we give the angular distribution of neutrons due to an isotropic point source in an infinite medium, both with and without capture. The remainder of the paper contains the derivation of certain families of the spherically symmetrical eigensolutions and a preliminary discussion of their properties. It is shown, in particular, that the point source solution cannot be represented as a superposition of eigensolutions.

Comment: This somewhat modest abstract, provided by Davison, hides a very remarkable paper, and it is even more remarkable that it was never formally published, except in a very much abbreviated form in Davison's book 'Neutron Transport Theory'. It is remarkable because it contains the first ever statement of a 'singular eigenfunction' of the one-speed neutron transport equation in the form

$$f(\mu) = \frac{1-\alpha}{2}\left\{\frac{1}{1+\nu\mu} + C\,(\nu)\,\delta\left(\mu + \frac{1}{\nu}\right)\right\}$$

Davison shows that, for full-range completeness, it is necessary to expand the angular flux in terms of the discrete eigenfunctions plus the singular one. In Appendix B of the report, Davison even proves full range completeness of the eigensolutions for the plane case. This work was clearly the forerunner to all the singular eigenfunction problems introduced by Case and his co-workers who expanded the ideas to half-range completeness.(Case and Zweifel, Linear Transport Theory, 1967, Addison-Wesley). Report MT-112 is referenced by Case and Zweifel as is some later work by Wigner (Am. Math. Soc. Symp., **11**, (1959) 89). There is also some early work by Van Kampen on full-range completeness which is often overlooked (Physics **21**, (1955) 949).

MT-118 Milne's problem with capture and production
B. Davison and G. Placzek (issued March 5th, 1945, 16 pp)

The relation between the solutions of the inhomogeneous integral equation of the problem containing an arbitrary source term and of the corresponding homogeneous equation is investigated. It is shown that the former can be derived - in an elementary way - in terms of the latter. The discussion of the special cases of constant and exponential source terms, given in sections 2 and 3 yields, among other results, an elementary derivation of Adler's albedo formulae. The solution for a general source which amounts to the determination. of the Green function of the homogeneous equation is derived in section 4.

Comment: This report solves the Milne problem with capture by a clever use of the integral equation and shows how one can relate solutions of the Milne problem, the constant source problem and the Green's function. The Wiener-Hopf method could have been employed to solve this problem along the lines discussed in MT-5, MT-26 and MT-72. However, in many ways, the methodology of MT-118 is more elegant and extendable to three dimensional geometry. It is believed that Adler and Mark in MT-66 used the Wiener-Hopf method, but that report was never formally issued and is no longer available.

MT-119 Milne's problem with capture, II
J. LeCaine (issued April 17th, 1945, 53 pp)
(Canadian Journal of Research, **A28** (1950) 242)

The variational method is applied to the Milne problem with capture, to obtain, for the density and for the angular distribution, expressions which give quite accurate values and which have a relatively simple analytical form. Tables of the density and angular distribution are included. The extrapolation distances determined by the Variational Method agree to high accuracy with the exact values. The angular distribution determined by the Variational Method is shown to be accurate within .05% in all cases where exact results are available. Tables are also given for the density and angular distribution in the Milne problem with capture and constant production.

Comment: This work is a straightforward application of the variational method to the Milne integral equation with capture. It describes, however, some novel 'tricks' to evaluate the integrals and, at the time, provided very accurate values of the extrapolated endpoint for a range of values of c (or $1-\alpha$ as it was called then in Montreal) less than or equal to unity.

MT-124 Large spherical hole in a slightly capturing medium
B. Davison (issued March 26th, 1945, 40 pp)

The effects of a spherical cavity, situated in the otherwise uniform, slightly capturing medium are considered. The cavity is assumed large compared to the mean free path, but small compared to the dimension of the body in which this cavity is situated, so that the problem is in effect equivalent to the determination of the effects of the cavity in an infinite medium with a prescribed asymptotic behaviour.

The following quantities were determined;
(A) The angular distribution of neutrons at the centre of the cavity.
(B) The neutron density on the surface of the cavity. Both these quantities were determined, however, only approximately.

For the particular case when, if the cavity were absent the neutron density would have been given by $\rho = \exp(\nu z)$, the results of the present calculations are illustrated by tables and graphs.

Comment: Davison introduces some very practical methods for dealing with voids. These present a particular problem for spherical harmonic and diffusion theory methods, but are solved accurately using integral transport theory. There is also a very perceptive method described for dealing with overall leakage from a finite medium within the context of transport theory, by introducing transverse bucklings and its higher harmonics. Some very useful mathematical results are obtained when the buckling is incorporated into the integral equation and Davison presents these in detail.

MT-131 A table of integrals involving the functions $E_n(x)$
Prepared by J. LeCaine (issued March 6th, 1945, 40 pp)

Comment: This report contains the most comprehensive tabulation of integrals, both definite and indefinite, of functions of $E_n(x)$ to be found anywhere. The report runs to 40 pages and is of great help in solving transport problems involving the integral transport equation.

MT-135 Influence of a large black cylinder upon the neutron density in an infinite non-capturing medium.
B. Davison (issued April 28th, 1945, 60 pp)

In the present report we examine the neutron density in a uniform non-capturing medium surrounding an infinitely long black cylinder of a large radius, in the case when the density depends only upon the distance from the cylinder. "Large" radius means large compared to the mean free path of the surrounding medium. The linear extrapolation length λ for the asymptotic solution for the density in the surrounding medium is determined and expressed in terms of the radius of the cylinder. The method is essentially as follows. In zero approximation, and not too far from the surface of the cylinder the neutron density should be roughly the same as in a half-space bounded by a vacuum. In more accurate approximations, but still not too far from the cylinder the effects of its curvature can be treated as small perturbations. On distances comparable with the radius of the cylinder the above approach breaks down because all the successive corrections are then of the same order of magnitude. However, it is possible to determine the leading term, the next largest term, etc., in all the successive corrections simultaneously. And adding first all the leading terms in the successive corrections, next all the second largest terms and so on, we obtain an expansion valid on all distances from the cylinder. This expansion can be utilised to determine, to a given accuracy, the constants entering into the asymptotic solution, in particular the linear extrapolation length λ , for which we obtain the expansion

$$\lambda = 0.7104 + \frac{0.2524}{a} + \frac{0.0949}{a^2} - \frac{5\log a}{64a^3} - \frac{0.0256}{a^3} + O\left(\frac{\log^2 a}{a^4}\right)$$

in which *a* is the radius of the cylinder in terms of the external mean free path.

Comment: This report is in many ways the analogue of MT-124 for the cylinder. It treats the integral transport equation in cylindrical geometry in great detail and its solution by iteration. Also given are some useful integrals that arise in the calculation involving cylindrical symmetry. It is also another fine example of how to solve an integral equation, which is not available in the standard literature.

MT- 136 Neutron density at the centre of a small spherical cavity
B. Davison (issued May 25th, 1945, 34 pp)

In this report we calculate the neutron density at the centre of a small spherical cavity situated in an infinite uniform capturing medium, for the following cases:

(A) When there are no sources at finite distances but we have an arbitrary distribution of sinks and sources at infinity.
(B) When there is a single point source situated right in the medium at a finite distance r_0 from the centre of the hole, r_0 is assumed to be comparable to the total mean free path or larger.
(C) Same as (B) but the point source is surrounded by another small spherical cavity, while there are no sinks or sources at infinity.
The result obtained for the cases (A) and (B) is

$$n(0) = n_{unperturbed}(0)\left\{1 + \alpha\left(a + \frac{a^2}{2}\right) + \alpha(1-\alpha)\frac{a^2}{4}\left(\frac{\pi^2}{4} - 1\right) + O\left(a^3 \log^n a\right)\right\}$$

in which n_unperturbed(r) is the density which would have existed at the point r, if the hole were filled with the material; ***a*** is the radius of the hole in units of the total mean free path and α is the ratio of the capture mean free path to the total mean free path. The first term in the correction, i.e. $\alpha\left(a + a^2/2\right) \approx \alpha\left(\exp(a) - 1\right)$ is the leading term of the correction due to the indirect effects of the hole; the next term, i.e. $\alpha(1-\alpha)\left(a^2/4\right)\left(\pi^2/4 - 1\right)$ is the leading tern in the correction due to the indirect effects of the hole via the direct effects upon the density outside the hole. The quoted result is seen to be, if we neglect $O\left(a^3 \log^n a\right)$, independent of r_0, provided a / r_0 is of the order ***a*** or smaller.

The corresponding result for the case (C) is

$$n(0) = n_{unperturbed}(0)\left\{\begin{array}{l}\left[1 + \alpha\left(a_1 + a_1^2/2\right) + \alpha(1-\alpha)\left(a_1^2/4\right)\left(\pi^2/4 - 1\right)\right] \\ \left[1 + \alpha\left(a_2 + a_2^2/2\right) + \alpha(1-\alpha)\left(a_2^2/4\right)\left(\pi^2/4 - 1\right)\right] \\ + O\left(a^3 \log a\right)\end{array}\right\}$$

in which n_unperturbed(r) corresponds now to the case when both holes are filled with the material, a_1 and a_2 are the radii of the two holes and *a* is the bigger of a_1 and a_2. This result shows that in our approximation the two holes can he considered as acting independently.

Comment: Another solution of the integral transport equation for spherical geometry dealing with small voids. Solutions are obtained by an iteration-perturbation method. Recommended reading for all those wishing to gain experience on how to solve integral equations, or simply mathematical pleasure.

MT-137 Compressible flow of perfect gas with heat input distributed symmetrically about middle of channel
E.A. Guggenheim (completed April 30, 1945, issued May 2, 1945, 12 pp)

This report deals with the problem of the compressible flow of a perfect gas through a channel of uniform cross section with constant friction coefficient and a heat input distributed symmetrically about the middle of the channel. Relations are obtained between the rise of temperature, the drop of pressure and the increase in velocity. The procedure recommended is a compromise between accuracy and tractability. A numerical example is worked out in full and study of it indicates that the method is accurate for Mach numbers at exit up to 0.80.

Comment: This work was initiated by Dennis Ginns (see biographies) who was designing a reactor for construction in Britain after the war. The reactor was eventually built and called BEPO (British Experimental Pile O). It was air cooled and calculations indicated that the gas exit velocity of the coolant would approach the speed of sound; this meant that compressibility effects would be important in the cooling channel. Although Guggenheim was a physical chemist, he was given the job of working out the gas dynamics. He did a remarkable piece of work and it surprising that his method was never published in the learned journals.

MT-150 The critical size of a multiplying system surrounded by a reflector of different scattering properties
M.H.L. Pryce (issued June 20th, 1945, 9 pp)

The critical size of a nuclear chain-reacting system, surrounded by an infinite reflector, is derived, using the "two-group" model. The reflector is not assumed to have any scattering properties in common with the core, and may itself consist of a multiplying medium in which the chain-reaction is convergent. The result comes out in the form of a transcendental equation for the radius of the critical sphere: in the general case it is suitable for computation by successive approximations; in the special case when the diffusion coefficients are equal in core and reflector, the equation reduces to an explicit expression for the radius.

Comment: This is a standard two group, two region problem for the reflected, critical sphere. Clearly, Pryce was now looking at reactors rather than weapons, because his earlier work, see MSP2a below, involved the transport equation for small spheres. MT-150 ends with an acknowledgement to "Mr. Kushneriuk for carefully checking the algebra". Examination of the paper shows that was no easy task

MT-151 The evaluation of the life time of a radioactive substance from a small number of observations
M.H.L. Pryce (issued October 26th 1945, 7 pp)

The average lifetime of the element 85^{217} has been determined by Cranshaw (MP-162).

Essentially his experiments record the interval between the time of disintegration of the nucleus and some definite earlier time at which that nucleus was present (actually its time of birth). The number of disintegrations observed being only some 300, statistical fluctuations play an important part.

The present report describes how to derive from Cranshaw's observations the most probable value of the average lifetime and its standard error.

Comment: This is a very nice application of statistics and is based on a paper of R. Peierls in Proc. Roy. Soc. A149, (1935) 467. The method uses Bayesian inference, via the *a priori* and *a posteriori* distributions. Note that element 85 is Astatine.

MT-164 Requirements for the maintenance of critical conditions with changing material constants

E.D. Courant (issued August 4th, 1945, 5 pp)

It is shown that in a working system in which the Laplacian and the mean free path vary in space and time, critical conditions are maintained if

$$\int \alpha \ell_e \rho^2 dV + \int \lambda \left[\kappa^2 \rho^2 - (grad\,\rho)^2\right] dV = 0$$

where

α = initial time derivative of Laplacian at each point

λ = initial time derivative of transport mean free path at each point

ℓ_e = effective transport mean free path

κ^2 = Laplacian

ρ = neutron density

Comment: Essentially the author is treating the problem of the influence of burnup on criticality. In the paper he assumes linear variation with time of all the parameters and looks at the necessary conditions which must be obeyed by the spatially varying parts. No numerical results are given. Reference is made to a report by A.M. Weinberg "Critical size of heterogeneous pile: statistical weight", CL-574(7). By this time (August 1945) information was being received on a regular basis from the United States.

MT-166 Thermal utilisation in some systems having axial symmetry

E.A. Guggenheim, M.H.L. Pryce and G.M. Volkoff (issued August 10th, 1945, 12 pp)

The formulae for thermal utilization derived by Christy and Monk in C-104 for a lattice of circularly cylindrical uranium rods in a moderator are extended to apply to hollow tubular rods (of which solid rods are a particular case), each rod being surrounded by a number of other substances disposed in thin layers with axial symmetry around the uranium.

Comment: This is a 5 region cell problem using diffusion theory. There are no numerical results given.

MT-169 Determination of *f* for spheres

P.R. Wallace and B. Carlson (completed August, 1944, issued August 27th, 1945, 8 pp)

In problems of neutron utilization, the quantity

$$f = \frac{extrapolated\ asymptotic\ density\ at\ the\ boundary}{mean\ density\ inside}$$

calculated for an absorber in a surrounding medium, is of considerable importance. In this report the variation of *f* with mean free path in the outer medium is investigated. For finite mean free paths, results are obtained by the spherical harmonic method. For the limiting case of infinite outside mean free path, the problem is treated by integral equations. Numerical values are given for a particular case of interest.

Comment: The calculations referred to as using the spherical harmonics method are not described, but numerical values are given for f. The reader is told to look at Marks reports MT-92 and MT-97 for details. The calculations using the integral equation are fascinating. The authors calculate the first collision source in the sphere by assuming an isotropic incident distribution on the surface of the sphere from outside. This is then used as a source term in the integral transport equation for a sphere giving an inhomogeneous integral equation to solve. There is a nice blend of physics and mathematics in this paper. The iterative solution used is reminiscent of Carlson's later report AECD 2835 (USAEC) Neutron Diffusion Theory , December 15th , 1949.

MT-173 On seeding depleted piles
E.D. Courant (issued October 5th, 1945, 16 pp)

When a pile operates for a considerable time, the uranium is depleted of its 25 content, while 49 is produced. It is shown that, if the 49 is extracted and the depleted uranium remade into metal slugs, the same pile can be made to work using depleted uranium seeded in a small central region with a small fraction of the 49 produced. This can be done for all degrees of depletion. These calculations are carried out for a spherical pile having the same Laplacian as the NRX pile.

However, in order to produce 49 at the maximum efficiency, the depleted pile must be seeded over a much larger central region, using almost as much 49 as is produced. If this is done, more 49 will be produced than consumed until the depletion reaches about 75%, and the total amount of 49 produced will be about 37% of the original 25 content of the pile.

General formulae are derived for uniformly seeded piles, giving the maximum degree of depletion at which 49 is produced, the total net production of 49 as a function of depletion, and indicating whether critical conditions remain satisfied if the pile is left alone at any degree of depletion.

Comment: This is an early attempt at what is now called fuel management. Courant develops a method for shuffling the fuel around to gain maximum burnup and efficient use of the plutonium. His seeding corresponds to placing fuel elements of differing burnup in different positions in the core. The reactor under consideration is NRX and, as usual, the heavy water is referred to as 'polymer'.

MT-196 Capture of neutrons by cylindrical absorbing rods placed around a pile
J.M.G. Fell and G. Volkoff (issued January 9th, 1946, 14 pp)

The fraction *T* of neutrons escaping over the sides of a pile which will be captured by absorbing rods of radius *R* embedded in graphite and surrounding the sides of the pile in a single row with a regular spacing of 2*a*, and removed by a distance *b* from the edge of the pile, is given with the aid of a simple idealised model by:

$$\frac{1}{T} = \cosh\left(\frac{b}{L}\right) + \frac{a}{\pi L} e^{b/L} \left\{ \frac{2\ell_t \lambda \xi(\kappa R)}{3R^2} - \log\left(\frac{\pi R}{a}\right) \right\}$$

Here L = diffusion length of graphite=50 cm

ℓ_t = transport mean free path in graphite =2.7 cm

λ = capture mean free path for material of absorbing rod

$\frac{1}{\kappa}$ = "diffusion length" of material in absorbing rod.

$\xi(\kappa R)$ = ratio of thermal neutron density at edge of rod, to its average value over cross section of rod.

The values of $\xi(\kappa R)$, based on simple diffusion theory, may be read off the graph of figure 1.

Numerical values of T for thorium metal are given in figures II-V on the basis of the following assumptions:

Fig. II, b=0 cm, λ=5 cm, κ=0.45 cm
Fig. III, b=20 cm, λ=5 cm, κ=0.45 cm
Fig. IV, b=0 cm, λ=5 cm, κ=0.65 cm
Fig. V, b=20 cm, λ=5 cm, κ=0.65 cm

Comments: This report, apart from its physical interest, is a nice example of applied classical mathematics to the Helmholtz equation. The fact that it is attempting to calculate the flux around a cylindrical rod between two parallel boundaries, means that there is a mixture of Cartesian and cylindrical co-ordinates. The authors conclude that the rod can be replaced by a line sink of thermal neutrons and thus anticipate the work of E.R. Cohen (The thermal flux in a square lattice cell, Nuclear Science and Engineering, vol 1 (1956) 268 and of A.D. Galanin on the source-sink method (The thermal coefficient in heterogeneous reactor, Geneva Conference on the Peaceful uses of Atomic Energy 1955, paper P669).

MT-197 A note on the temperature distribution inside uranium rods with variable heat source density and variable conductivity
J.M.G. Fell (issued November 28th, 1945, 6 pp)

The central temperature T_{max} in a uranium rod of radius *a* can be calculated in three steps:

(a) the radial temperature drop $\Delta_0 = q_{av}a^2 / 4\kappa_0$ is first computed for the case of a <u>uniform</u> heat source density, equal to the average value q_{av} of the actual heat source density distribution, and a constant conductivity $\kappa_0 = 0.063$ cgs units.
(b) This is corrected for the heat source distribution by multiplying it by $\left(1-\beta/4\right)$ where β is the ratio of the difference in the values of q at the surface and the centre of the rod to q_{av}
(c) the result is again corrected for the variation of heat conductivity with temperature by reading off the attached graph the value of the actual central temperature T_{max} corresponding to the value of $\varphi_{\max} = T_{surface} + \Delta_0\left(1-\beta/4\right)$ which would be the value of T_{max} for constant conductivity κ_0.

Comment: This report develops a method to solve the conduction equation with a temperature dependent thermal conductivity and spatially varying heat source. Use is made of the Kirchoff transformation to reduce the conduction equation to one involving an effective constant conductivity. It might have been expected that this solution would be referenced in later books on heat conduction (e.g. Conduction of Heat in Solids, second edition by Carlslaw and Jaeger, Heat Conduction by Ozisik) but, presumably, because of its inaccessibility it was omitted.

MT-199 Fast fission in tubes
E.A. Guggenheim and M.H.L. Pryce (issued in November 30th, 1945, re-issued as AECL-92, 10 pp)

In order to calculate the effect of fast fission, one requires to know the value of the probability P that a fast neutron anywhere inside a piece of uranium should undergo a collision before escaping from it. In this report a formula is obtained for P in the case that the piece of uranium is a long tube. In the special case of a solid rod the new formula for P is equivalent to that given in CP-644, but the general formula for a hollow tube given in CP-644 is incorrect.

Comment: CP-644 is a Manhattan Project report, which presumably was passed on to the Montreal Laboratory for information (just as well it was !). Its authors are H. Castle, H. Ibser, G. Sacher and A.M. Weinberg, it is dated May 4th, 1943. Section C of that report is in error.

MT-201 Reduction of the two-group model to an equivalent one-group model
F.T. Adler (issued March 20th, 1946, 34 pp)

The linear combination

$$\rho_1(r) = \frac{\overline{\beta}_2^2 - \kappa_{th}^2 - \pi^2/h^2}{\overline{\beta}_2^2 + \beta_1^2}\rho_{th}(r) + \frac{D_f}{D_{th}} p \frac{\kappa_f^2}{\overline{\beta}_2^2 + \beta_1^2}\rho_f(r)$$
$$\approx \frac{L^2}{M^2}\left[\rho_{th}(r) + \frac{D_f}{D_{th}} p\rho_f(r)\right]$$

of fast and thermal neutron densities satisfies the usual one-group pile equation everywhere inside the reacting core of a pile. For $k-1 << 1$, the boundary conditions at the surface of a central absorber of radius *a* and at the outer boundary of the core may be expressed in the form

$$\rho_1(a) = \lambda_1(a)\rho_1'(a) \qquad \textit{and} \qquad \rho_1(R) = -\Lambda_1\rho_1'(R)$$

the constants λ_1 and Λ_1 are determined in such a way that the eigenvalue (the "critical Laplacian") of the "equivalent one-group model" equation for ρ_1 becomes identical with the Laplacian obtained from a two-group model calculation. If no central absorber is present the expression obtained for Λ_1 remains valid for any *k*. Explicit expressions for λ_1 and Λ_1 in terms of the properties of the multiplying core and the reflector are given for an infinite reflector in the case of spherical and cylindrical cores. The moderator in the core may be different from the moderator in the reflector. The ratios $(\rho v)_f / (\rho v)_{th}$ and $D_f\rho_f' / D_{th}\rho_{th}'$ are obtained at the inner and outer surface of the core.

Comment: The somewhat innocuous title of this report belies a very interesting and detailed 34 page report on effective boundary conditions and what was later called 'modified one-group theory' or even 'one and a half group theory'.

MT-202 Efficiency of control rods absorbing thermal neutrons only
F.T. Adler. The above title is that given in the Kushneriuk letter to MMRW in 1967. However, in MT-201, reference is made to MT-202 but its title there is "Effects of a central control rod in a pile". The report was never issued.

MT-207 Influence of a small black cylinder upon the neutron density in an infinite non-capturing medium
B. Davison, W.P. Seidel and S. Kushneriuk (issued in 1945-46, 71 pp)
(Proc. 2nd Canadian Mathematical Congress, Vancouver, BC, 1949)

This paper deals with one of a large number of problems of a similar character investigated by members of the Montreal Laboratory, National Research Council of Canada. The present problem is to examine the neutron density in a uniform non-capturing medium surrounding an infinitely long black cylinder of a small radius *a*, "small" here meaning that the radius is small compared to the total mean free path of the surrounding medium and "black" implying that all neutrons entering the rod are absorbed. We assume that the medium stretches to infinity and the density depends only on the distance from the surface of the cylinder. In particular, we determine the linear extrapolation length, defined as $\lambda = n_{as}(a) / n'_{as}(a)$ in which $n_{as}(r)$ is that solution of the differential equation of the diffusion approximation which possesses the correct asymptotic behaviour.

The iteration procedure adopted for the purpose of determining the general distributions of the neutron density is described in detail in Section 2, after the reader has been reminded of the integral equation (derived in Appendix A) governing our problem; the more rigorous justification of the procedure is postponed to Section 5. In Section 3 we determine the asymptotic behaviour of the correction introduced in the m^{th} iteration in terms of the density distribution in the $(m-1)^{th}$ approximation. In Section 4 we determine the deviations from the asymptotic behaviour in the first iteration, and then, by applying formulae developed in Section 3, determine the asymptotic behaviour of the second iteration, which may be interpreted as the first perturbation. In the present report we determine λ to the accuracy of *0(a)*, i.e., including terms of the order of *0(a)*, but neglecting terms of the order of $0(a^2 \log^2 a)$. The final answer to the above order of accuracy is given in Section 6.

Comment: Further solutions of the integral form of the transport equation in cylindrical geometry, with many useful 'tricks and dodges'.

MT-208 Effect of xenon poisoning on uranium-graphite piles
M. Goldstein and E.A. Guggenheim (December 17th, 1945, issued December 19th, 1945, 9 pp)

If Δ denotes the additive contribution of the xenon poisoning to 1/f, where f is the thermal utilisation factor, when the power per unit quantity of uranium is *H*, then the <u>local</u> relation between Δ and *H* is of the form

$$\frac{\Delta}{\Delta_\infty} = \frac{H}{H + H_h}$$

where Δ_∞ is the limiting value of Δ as $H \to \infty$ and H_h is the value of *H* at which an atom of Xe-135 has equal chances of being destroyed by neutron capture or by spontaneous β-decay.

The object of the present report is to investigate the relation between $\bar{\Delta}$ the effective contribution to the effective 1/f of the whole pile and $\bar{H}$ the average power output per unit quantity of uranium for the whole pile. It is found that for any circular cylinder with height comparable to diameter, the relation can with an accuracy of a few parts in a hundred be expressed in the form

$$\frac{\bar{\Delta}}{\Delta_\infty} = \frac{\bar{H}}{\bar{H} + 1.70\gamma H_h}$$

where γ denotes the ratio of average to maximum power output. Taking $\Delta_\infty = 0.03$ and $H_h = 2.4$ Mwatt/ton, the relation becomes

$$\bar{\Delta} = \frac{0.03}{1 + 4.03(\gamma / \bar{H}) Mwatt / ton} = \frac{0.03}{1 + (1.6 / \bar{H}) Mwatt / ton}$$

where the second equality holds for cylinders with heights and diameters between 5 and 7 metres, for which $\gamma = 0.40 \pm 0.02$.

CRT-272 (Supplement to MT-208) Xenon poisoning in a cubical pile
C.A. Rennie (issued July, 1946, 7 pp)

The method described in MT-208 for estimating the effect of Xenon poisoning in a spherical or cylindrical pile is here extended to the case of a cubical pile, giving for $\bar{\Delta}$ the increase in 1/f due to the Xenon poisoning:-

$$\bar{\Delta} = \frac{0.03}{1 + 4.20 \frac{\gamma U}{Q_{tot}}}$$

The variation of γ the average to maximum power ratio is discussed for the different types of pile and it is found that for the same value of κ (where κ^2 is the Laplacian), and for the same power output of the order of 1 M watt per ton of uranium, the poisoning effect is approximately in the ratio

$$\bar{\Delta}_{sphere} : \bar{\Delta}_{cylinder} : \bar{\Delta}_{cube} = 1 : 1.01 : 1.05$$

(Author: CRT means Chalk River Theory)

MT-214 Linear extrapolation length for a black sphere and a black cylinder
B. Davison and S. Kushneriuk (issued March 30th, 1946, 18 pp)

The results obtained in various previous reports (MT-93, MT-88, MT-97, MT-135 and MT-207) on the values of the linear extrapolation length λ for the determination of neutron density by means of the differential equation of the diffusion approximation for the cases of a black sphere and a black infinitely long cylinder in a uniform, non-capturing medium, are summarised and analysed in this report. It is shown that the approximation given in MT-88 and MT-207 for the linear extrapolation length λ in the case of radius *a* small compared to the total mean free path ℓ are valid roughly up to $a / \ell = 0.15$ and the approximations for the linear extrapolation length λ for the case of large *a* given in MT-93 and Mt-135 are valid beginning roughly with $a / \ell = 4.0$, though even for *a* as small as $a / \ell = 2.5$ the error is still reasonably small. The probable shape of the dependence $\lambda(a)$ for the intermediate values of *a* is suggested and given graphically.

Comment: Nice comparison of all the methods available for calculating the extrapolation distance for black spheres and cylinders. Includes spherical harmonics up to P7 and the integral transport solutions for large and small bodies.

MT-220 Thermal utilisation in a system containing two moderators
E.A. Guggenheim (Issued February 4th, 1946, re-issued as AECL-63, 10 pp)

A formula is derived for the thermal utilisation factor in a lattice consisting of uranium tubes (of which rods are a special case), separated from the main moderator by a subsidiary moderator disposed in a layer with axial symmetry around the uranium. For the sake of generality and without any extra complication gaps are assumed between the uranium and subsidiary moderator and between the subsidiary moderator and main moderator. Classical diffusion theory is used throughout. In the first place no approximation is made depending on the thinness of the subsidiary moderator. At a later stage this thinness is assumed and the formula becomes greatly simplified.

Comment: A straightforward calculation, but nicely explained and useful for those wishing to learn some simple reactor theory.

MT-221 Diffusion theory expressions for the thermal utilisation factor f in cells with slab, cylindrical and spherical geometry
V.H. Rumsey and G.M. Volkoff (issued May 30th, 1946, 23 pp)

The thermal utilization factor f in cells with slab, cylindrical or spherical geometry containing *n* thin, absorbing scattering and moderating sheaths separating the lump of fissile material from the principal moderator may be found on the basis of elementary diffusion theory in two steps.

a) The value of f_0 corresponding to the absence of thermal neutron sources outside the principal moderator is given to terms of second order in the sheath thicknesses by:

$$\frac{1}{f_0} - 1 = C_s G_0 + Y + C_m G_0 + C_m \left(M + G_0 P\right) + X\left(1 + C_s G_0 + Y\right)$$

The terms on the right represent respectively the "relative" absorption by the sheaths**,** the "blocking" term in the sheaths, and the "relative" absorption**,** the "blocking" term and the "excess absorption" of the principal moderator. C_s, C_m, Y, M and P are given in terms of the dimensions and neutron absorption and scattering properties of the various materials by (2.6), (2.7.), (3.6), (6.4) and (6.5). 1+X is defined in terms of the principal moderator dimensions and properties by (4.7) - (4.9) and may be read off the graphs of Figures 2-4. G_0 is defined in terms of the dimensions and "effective" properties of the lumps of fissile material by (5.9) - (5.14) and also may be read oft the graphs of Figures 2-4.
b) In the case that some thermal neutron sources are present outside the principal moderator, f is found by multiplying f_0 by the correction factor (1+δ) where δ is defined by (7.6). δ contains the ratios of densities of thermal neutron sources defined by (8.2), and in addition to quantities introduced previously contains Q defined by (6.6). A specialisation of the general results to the case of a water-cooled 1attice is discssed in section 9. The "levelling effect" contribution to the temperature coefficient of the reproduction factor k is discussed in section 10.

Comment: A useful compendium of results for plane, spherical and cylindrical geometries. Also including effects of cladding and an attempt at a shell void. Calculations are also given for temperature coefficients of reactivity. Many useful graphs. Theory now superseded but work is of historical interest, if only to see how they physically argued their way through a difficult problem.

MT-222 Efficiency of control rods as a function of their position in a cylindrical pile in the one-group picture
F.T. Adler (issued February 12th, 1947, re-issued as AECL-253 in February, 1956, 48 pp)

The efficiency of a single eccentric control rod and of a ring of N rods is determined as a function of their distance d from the centre of the pile. The eigenvalue problem for the critical lateral Laplacian β^2 is solved by means of the superposition method (section 2) and the eigenvalue condition for β^2 obtained in the form

$$\lambda_1(a) = -\frac{1}{\beta Y_1(\beta a)}\left\{Y_0(\beta a) + \sum_{n=2}^{N} Y_0(\beta r_{n1}) - N J_0^2(\beta d)\frac{Y_0(\beta R) - \beta\Lambda_1 Y_1(\beta R)}{J_0(\beta R) - \beta\Lambda_1 J_1(\beta R)}\right\}$$

The neutron density in the pile is given in section 3, as well as the lateral outward leakage and the total leakage into the control rods.

$$\frac{Lateral\ outward\ leakage}{No.of\ neutrons\ absorbed\ in\ the\ core\ per\ unit\ time} =$$

$$D\tau\beta^2 \frac{J_0(\beta d)}{J_0(\beta d) - J_0(\beta R) + \beta\Lambda_1 J_1(\beta R)}$$

$$\frac{Lateral\ leakage\ into\ N\ rods}{No.of\ neutrons\ absorbed\ in\ the\ core\ per\ unit\ time} =$$

$$D\tau\beta^2 \frac{-J_0(\beta R) + \beta\Lambda_1 J_1(\beta R)}{J_0(\beta d) - J_0(\beta R) + \beta\Lambda_1 J_1(\beta R)}$$

The validity of the approximation method is investigated (section 4) and the positive and negative interference (shadow) effect of 4 rods is discussed numerically as a function of the position of the rods.

Comment: The theory of a bank of control rods in a reactor was also solved by R. Scalettar and L.W. Nordheim of the Manhattan Project. The paper was entitled 'Theory of pile controls', MDDC-42 (1946). This was also published in Physical Review **70** (1946) 115. The date of MT-222 is February 12th, 1947, so it is likely that this work was done independently. The only relevant reference cited in MT-222 is 'Efficiency of control rods which absorb only thermal neutrons', CP-1461 , 24th February, 1944, by E.P. Wigner, A.M. Weinberg and R.R. Williamson.

MT-223 Fluctuations of the number of neutrons in a pile
E.D. Courant and P.R. Wallace (completed April, 1946, issued June, 1946, 10 pp)
(Physical Review, **72** (1947) 1037-1048)

Statistical fluctuations in the number of neutrons in a pile which is just under critical, and contains distributed neutron sources such as spontaneous fissions, $\alpha - n$ reactions, etc., are considered for the following two cases: (a) The delayed neutrons are taken into account, but the pile is assumed to be operating at a steady power, and (b), the power at which the pile operates is assumed to change periodically, but the delayed neutrons are neglected. For both cases the expression for the standard deviation of the number of neutrons is derived, and in case (a) the expression for the coefficient of correlation between the number of neutrons and the number of excited nuclei of each particular type, which lead to the formation of the delayed neutrons, is also given. The method used throughout the calculations is that of the probability generating function. For the case of a steadily operating pile, the effect of a finite resolving time of the recording instrument upon the observed value of the standard deviation of the number of neutrons is also determined through a study of the spectrum of the fluctuations.

Comment: This is a remarkable paper because it was the forerunner of a large body of work on random processes in nuclear reactors. It uses a probability balance equation which is essentially the forward form of the Chapman-Kolmogoroff equation and owes its general form to earlier work on cosmic rays. Full details of applications and the influence this paper had on future work may be found in 'Random Processes in Nuclear Reactors' by M.M.R. Williams (1974) Pergamon Press, Oxford.

MT-232 Influence of an air gap surrounding a small black sphere upon the linear extrapolation length of the neutron density in the surrounding medium
B. Davison (issued April, 1946, 21 pp)

In the present report we examine the neutron density in a uniform non-capturing, elastically and isotropically-scattering medium surrounding an arrangement consisting of a small black sphere and an air gap of a constant thickness separating the black sphere from the scattering medium, in the case when the neutron density at infinity tends to definite finite limit. "Small" sphere means small compared to the mean free path in the scattering medium. Thickness of the air gap is unrestricted.

It is shown that the effects of the small black sphere of the radius *a*, with an air gap of the thickness (*b*-*a*) upon the neutron density at large distances is the same as of a small black sphere of the radius

$$a' = a + \frac{a^2}{6}\left[1 - \frac{3}{2}\frac{a}{b+\sqrt{b^2-a^2}} + \frac{1}{2}\frac{a^3}{\left[b+\sqrt{b^2-a^2}\right]^3}\right] + O\left(a^3 \log^n a\right)$$

in the absence of an air gap. The linear extrapolation length at the surface of the black sphere for the asymptotic solution for neutron density in the surrounding medium λ_a is given by

$$\lambda_a = \frac{4}{3} - a\left[1 - \frac{2}{3}\frac{a}{b+\sqrt{b^2-a^2}} + \frac{2}{9}\frac{a^3}{\left[b+\sqrt{b^2-a^2}\right]^3}\right] + O\left(a^2 \log^n a\right)$$

In the above formulae the unit of length is taken to be equal to the mean free path in the scattering medium. The method of the solution is essentially the same as in MT-88.

Comment: Another example of Davison's mastery of the integral transport equation.

MT-240 Critical Laplacian and neutron densities in NRX pile
H.H. Clayton (issued May 18th, 1946, re-issued as AECL-376, November , 1956, 16 pp)

The conditions at the inner and outer boundaries of the core on ρ_{th1} and ρ_{f1}, the thermal and fast densities in the core on the two-group model can be put in the form

$$\rho'_{th1} = -a\rho_{th1} + b\frac{\rho_{f1}}{\mu_1}; \qquad \rho'_{f1} = -c\rho_{f1}$$

The natures of the reflector and tank wall in the cases of the outer boundary, and of the central thimble in that of the inner boundary, are all contained in the constants *a, b, c,* and μ_1 is the ratio of fast to thermal neutron density in those regions of the core which are removed by more than a migration length from the boundaries.

From these boundary conditions the conditions for the one-group density ϕ and the "transient" X are obtained as

$$\phi' = \pm\Lambda\phi; \qquad X = \frac{\gamma_1^2(c-\Lambda)}{c+\overline{\beta}_2}\phi$$

with

$$\Lambda = \frac{\overline{\beta}_2\left(a/\gamma_1^2 - b/\gamma_1^2 + c\right) + \left(1 + 1/\gamma_1^2\right)ac}{a + b/\gamma_1^2 + c/\gamma_1^2 + \left(1 + 1/\gamma_1^2\right)\overline{\beta}_2}$$

The first determines the one-group density ϕ and a critical value of the lateral Laplacian identical with that of the two-group model. The second determines the "transient" of the two-group model. In these $\gamma_1 = L_{s1} / L_1$ and $\overline{\beta}_2$ is the inverse relaxation length of the transient in the core, i.e.

$$\overline{\beta}_2^2 \approx 1 / L_{s1}^2 + 1 / L_1^2$$

The constants *a, b, c* for the outer boundary have been calculated for the case of an infinite reflector and a reflector containing a cylindrical shell absorbing thermal neutrons. Three types of shell are considered

A. A shell "black" to thermal neutrons.

B. A shell obtained by spreading out into a thin uniform shell the total material contained in the thorium rods of the N.R.X. pile.

C. A shell which absorbs as thermal neutrons a fraction T of the total neutron current entering the reflector.

The constants *a, b, c* for the inner boundary have been obtained for a central thimble absorbing thermal neutrons only with, and without, loss of neutrons due to longitudinal streaming in the central thimble. The height *h* to which the tank must be filled with moderator is calculated as a function of κ^2, the total Laplacian under the various conditions.

Comment: A competent two-group study of the criticality and flux distribution in the Canadian reactor NRX. All the details are neatly worked out and this report would be very instructive at the undergraduate level.

MT-241 Fate of neutrons in NRX pile and production rates of 49 and 23

H.H. Clayton (Appendix by J.M.G. Fell, issued May 11th, 1946, re-issued as AECL-377 in November, 1956, 14 pp)

Expressions are given for the rate of leakage and death rates of thermal and fast neutrons in the N.R.X. pile. For the case in which the thorium rods absorb 60% of the total neutron current entering the reflector (the thorium in the rods absorbs 53%) these are used to calculate the final fate of 100 thermal neutrons captured by 25 and the resulting production of 49 and 23. The fate of neutrons in the N.R.X. pile is shown schematically in Figs. 2 and 3. The estimated rates of production are 0.90 gms. of 49 and 0.056 gms. of 23 per Mwatt-day.

An appendix by J.M.G. Fell gives the calculation of the fraction T of the total neutron current entering the reflector subsequently captured as thermal neutrons by the thorium rods.

Comment: An extension of MT-240 with detailed calculations on reaction rates averaged over various annular zones in the core. Many numerical calculations to illustrate the problem.

MT-242 Fast fission in tubes: supplement to MT-199

M. Goldstein, M. Wales and A.S. Lodge (issued May 6th, 1946, 4 pp)

This report contains in both tabular and graphical form a few values of the collision probability $P\left(\kappa a, \kappa g\right)$ which is dealt with in MT-199, where

a = outer radius of the tube

g = inner radius of the tube

κ = inverse of mean free path

We have used these values of P to obtain values of the fast fission constant ε, where

$$\varepsilon - 1 = \frac{0.0948P}{1 - 0.521P}$$

The values of constants have been chosen for natural uranium.

MT-243 The temperature distribution in an infinite medium due to a spatially uniform plane source of heat

A.S. Lodge (issued May 10th, 1946, 8 pp)

An infinite medium whose thermal diffusivity is uniform and independent of its temperature is initially at zero temperature. Heat is generated at a rate $Q(t)$ heat units per unit area per unit time over the infinite plane at *x=0* in the medium.

In part I, the temperature $\theta(x,t)$ is expressed as a definite integral for an arbitrary function $Q(t)$. The rest of this report deals with a "triangular" heat pulse defined by the equations

$$\begin{aligned} Q(t) &= 0 && t < 0 \\ Q(t) &= Q_0 t / t_0 && 0 \le t \le t_0 \\ Q(t) &= Q_0 \left(2t_0 - t\right) / t_0 && t_0 \le t \le 2t_0 \\ Q(t) &= 0 && 2t_0 < t \end{aligned}$$

In part II, $\theta(x,t)$ is expressed in terms of tabulated functions, and the maximum value of $\theta(x,t)$ is found to be

$$\theta\left(0, 4t_0 / 3\right) = \frac{4}{3\sqrt{3\pi c\rho k}} Q_0 \sqrt{t_0}$$

where c, ρ, k are respectively the specific heat, density and thermal conductivity of the medium.

In part III, a numerical example is given. The medium is taken to be aluminium, the maximum temperature is specified as 250 C and the total duration of the pulse is $2t_0 = 0.01$ seconds. These data give the value of Q_0, and it is found that the energy generated during one pulse is

$$\int_0^{2t_0} Q(t) dt = 22.3 calories$$

This is equivalent to a power input, time-averaged over one pulse, of 8.67 megawatts per square foot. Two graphs are included which show, (1) the variation of $\theta(0,t)$ with *t* and (2), the variation of $\theta(x,t)$ with *x* for the three cases $t = 4t_0 / 5, 4t_0 / 3, 11t_0 / 5$.

Comment: This report deals with an idealised model which is an attempt to simulate a pulsed pile in which fissile material is sandwiched between two pieces of aluminium. It is a nice exercise in the application and solution of the time-dependent heat conduction equation.

MT-245 Linear extrapolation length for the neutron density at the surface of a large hollow cylindrical shaft

B. Davison (issued January 7th, 1947, 37 pp)

The purpose of this report is to obtain an expression for the linear extrapolation length of the neutron density at the surface of a cylindrical hollow shaft of circular cross section passing through an infinite homogeneous medium. The medium is slightly multiplying and an isotropic elastic scatterer of neutrons.

The neutron density is assumed to be a simple sinusoidal function of the coordinate parallel to the axis of the shaft and otherwise to depend only upon the distance from the shafts, i.e.

$$\psi_0(\vec{r}) = \cos\left(\frac{\pi z}{h}\right) n(r)$$

The thickness of the layer h, in which the neutron density is positive, and the diameter of the shaft $2a$ are assumed to be comparable to each other and both large compared to the mean free path ℓ. An approximate expression for the linear extrapolation length is determined and has the form

$$\frac{\lambda(a/h,C)}{\ell} = \frac{\frac{2}{3} + \frac{32}{3\pi}\int_1^\infty \frac{ydy}{\sqrt{y^2-1}}\int_0^\infty dt t^3 K_0\left(\sqrt{4(C+t)^2 y^2 + \Omega^2/y^2}\right)}{1 - \frac{16}{\pi}\int_1^\infty \frac{ydy}{\sqrt{y^2-1}}\int_0^\infty dt t^2 K_0\left(\sqrt{4(C+t)^2 y^2 + \Omega^2/y^2}\right)}$$

In this $\Omega = 2a\pi/h$, C characterises the absorption by the wall separating the hollow shaft from the surrounding medium [a beam of neutrons passing once normally through the wall is weakened by the factor exp(-C)] and

$$\lambda = \frac{n_{as}(a)}{n'_{as}(a)}$$

If the wall can be neglected, C = 0 and the expression above reduces to

$$\frac{\lambda(a/h)}{\ell} \cong \frac{\frac{2}{3} + \frac{4\Omega^2}{3\pi}\int_0^1 \frac{s^4 ds}{\sqrt{1-s^2}} K_2(\Omega s)}{1 - \int_0^1 \frac{sds}{\sqrt{1-s^2}} e^{-\Omega s}(1+\Omega s)}$$

If further, *a/h* is also small it reduces further to

$$\frac{\lambda(a/h)}{\ell} \cong \frac{h^2}{\pi^2 a^2}$$

If *a/h* or C, or both, tend to infinity (the Milne case) the above approximate expression for λ/ℓ tends to 2/3 instead of the correct value 0.71; for other cases the approximation should be expected to be still more satisfactory.

If the neutron density is not a simple sinusoidal function of z, the above linear extrapolation length could be used if we put the boundary conditions in the form

$$\frac{\int \psi_{0,as}(a,z)\cos(\pi z/h)dz}{\int \frac{\partial}{\partial r}\psi_{0,as}(a,z)\Big|_{r=a}\cos(\pi z/h)dz} = \lambda(a/h,C)$$

and a similar condition with $cos(\pi z/h)$ replaced by $sin(\pi z/h)$.

The above linear extrapolation length λ should be expected to be applicable to the case of a large cylindrical shaft in a slab of thickness *h* comparable with the diameter of the shaft, though it may lead in this case to a certain overestimate of the effect of the shaft.

In Appendix B another problem is considered, viz, a hollow wall-less cylindrical shaft of an arbitrary cross-section with its axis perpendicular to the free surface of a semi-infinite homogeneous non-multiplying and non-capturing medium with elastic isotropic scattering. It is shown that the excess number of neutrons, escaping from the system into the other half-space due to presence of the shaft is exactly equal to the excess flow of neutrons due to the presence of the shaft in a medium stretching to infinity in all directions.

Comment: This report contains some interesting arguments involving Fourier integrals to represent the flux in two-dimensions (r,z). It then goes on to discuss the internal boundary conditions for the hollow shaft. The corresponding integral equation is solved. The Appendix contains some useful integrals involving cylindrical functions and how to best treat them.

MT-249 Effect of the presence of fast neutrons on the utilisation of neutrons by absorbing rods around a pile
J.M.G. Fell (issued May 31st, 1946, 4 pp)

In MT-196 the fraction T of neutrons leaving a pile which is captured by absorbing rods embedded in the reflector was calculated on the assumption that all neutrons entering the reflector are thermal. In this report the two-group model is used to investigate the correction required to the result of MT-196 if the fact that some neutrons entering the reflector are fast is taken into account. It is found that the value of T given by the formula of MT-l96 must be multiplied by

$$1-\frac{\alpha}{\left(L/L_s\right)^2-1}\left(\frac{L}{L}e^{-\left(\frac{L}{L_s}-1\right)\frac{b}{L}}-1\right)$$

where

$$\alpha=\frac{current\ density\ of\ fast\ neutrons\ leaving\ the\ pile}{sum\ of\ current\ densities\ of\ fast\ and\ thermal\ neutrons\ leaving\ the\ pile}$$

L = diffusion length for thermal neutrons in the reflector
L_s = slowing down length in the reflector
b = distance from the pile boundary to the absorbing rods.
For the NRX pile the correction is less than 2.5 %.

Comment: This is an extension of some work carried out in report MT-196.

7. Early British Atomic Energy Reports on Reactor Theory

These reports are the records of work done, either before the Montreal Theory team was set up, or carried out in parallel with it in Britain. In general, the dates are consistent because Davison's work was done in 1943 and 1944 and he did not arrive in Montreal until late 1944. Similarly Pryce's work on criticality was done in 1943 and his name does not appear on Montreal reports until 1945. The other authors either went directly to Los Alamos (e.g. Klaus Fuchs) or remained in the UK (e.g. Dirac).

MS-1 On the possibility of a slow neutron chain reaction
R. Peierls (1940)

This describes some very early work on calculating the infinite medium multiplication factor in a homogeneous mixture of natural uranium and water. It employs the concept of thermal utilisation and resonance escape probability. At that time the number of neutrons emitted per fission was not known and Peierls gives values of the infinite medium multiplication factor for $\overline{\nu}=2$ up to 10. He concludes that the maximum value for k_∞, which he designates R, cannot exceed 0.84. He points out though that, by lumping the uranium, the multiplication can be significantly increased because of the reduction in resonance capture. He further adds that if graphite is used it may be possible to get a multiplication of 1.1. All this in 1940, before any significant data were available. A great deal of the background to this work is discussed in *'The Neutron and the Bomb'*, a biography of Sir James Chadwick by Andrew Brown.

There is a detailed list of these early reports available on the PRO website given earlier, which demonstrate the remarkable progress made in the understanding of these problems at a very early stage.

MS-P2A Critical conditions in neutron multiplication
M.H.L. Pryce (1943)

In his paper, Proceedings of the Cambridge Philosophical Society **35**, 610, 1939, Peierls has developed under the above title the theory of nuclear chain reactions arising from neutron multiplication. We propose to extend his results and in particular to make a more accurate calculation of conditions when the multiplication factor is neither very large nor very nearly unity. We follow Peierls in treating scattering as both elastic and isotropic and in considering a spherical mass of substance (uranium) of uniform density.

Comment: This is arguably the first use of a variational method to calculate a critical size. Full details may be found in 'Mathematical Methods in Particle Transport Theory', M.M.R. Williams, Butterworth, 1971.

MS-85 Effect of a scattering container on the critical radius and time constant
K. Fuchs (1943)

We consider in the following the critical radius and the time constant of a chain reaction in a sphere surrounded by a spherical container. We assume essentially that the mean free path is the same in the sphere and the container. For some purposes we specify further that the container only scatters, but does not absorb or create neutrons. The last assumption is not essential, but some assumption must be made for the purpose of interpreting the results and the assumption made represents the simplest possibility.

Comment: This also uses a variational method but the calculations are made more complex by the two-region nature of the problem.

MS-91A Reduction in neutron density caused by an absorbing disc
T.H.R. Skyrme (1944)

Editor's note: This report has no formal abstract, so we just note that it concerns the calculation of the corrections needed when an absorbing foil is used to measure neutron flux across a body. The integral equation is used and two cases are considered: (1) A disc of large radius and (2) a thin circular disc of radius comparable with a mean free path. The ideas introduced in this report are seminal and the author discusses a range of techniques for solving the integral transport equation.

MS-97 The critical radius and the time constant of a sphere embedded in a spherical scattering container
B. Davison and K. Fuchs (November, 1943)

In the present report we collect the data available for the critical radius and the time constant of a sphere embedded in a spherical container. These have been obtained by Peierls (Proc. Camb. Phil. Soc. 35, 610, 1939) and Fuchs (MS.85). Further data are obtained in some limiting cases.

Comment: Diffusion theory results are also presented in this report and extensive numerical results given for time constant vs critical size.

MS-100 Critical radius for a hemisphere for a one-sided infinite container
B. Davison (November 27, 1944)

One of the methods of assembling a large excess over the critical mass is to bring together two hemispheres each covered by a container over its curved surface, provided that the difficulties connected with the large critical distance can be overcome. Postponing the question of the determination of the critical distance, we shall limit ourselves for the present to the examination of the critical radius of a single hemisphere covered with a container over its curved surface, but having its plane surface bare.

Comment: This is a diffusion theory solution involving expansion of the Helmholtz equation in Legendre polynomials. Numerical calculations are carried out for the ratio M/Mo where Mo is the critical mass for a completely contained sphere and M for the semi-tamped case.

MS-102 The effect of small departures from the spherical shape upon the critical size and time constant of a sphere
A.H. Wilson (March, 1944)

One of the most important problems connected with bodies containing fissionable matter is the effect of the shape of the body upon the chain reaction. It is easy to see that, for a given mass of material, a chain reaction is most easily set up in a sphere, but it is difficult to obtain a quantitative estimate of how the time constant is affected by a change of shape except in certain simple cases. One especially simple case which has not so far been treated, but which nevertheless is of some interest, is when the body is nearly spherical. This case can be treated by various approximate methods, and the present report is concerned with the simplest of these, namely the diffusion method.

Comment: This report discusses the use of perturbation theory to study the effect on the time constant of small deviations from spherical symmetry.

MS-105A The general properties of the transport equation and its use in determining the multiplication in bodies having spherical symmetry
A.H. Wilson (January, 1944)

The author presents a study of neutron multiplication, in infinite homogeneous media and sundry spherically symmetric systems, based on the properties of the relevant transport equation. In particular, equations giving the critical radii and time constants of spherically symmetrical systems with homogeneous cores embedded in (either finite or infinite) homogeneous tampers are derived for the isotropic scattering, one-velocity model under the assumptions (i) that the net outward flux of neutrons is everywhere continuous, and (ii) that the flux of radially incoming neutrons is everywhere continuous [with, in particular, the value zero at the outer boundary (if any) of the system considered]. The numerical results for certain configurations are compared with the corresponding results obtained by other methods.

Comment: This is the report in which the 'Wilson' version of the famous 'Serber-Wilson' method is derived.

MS-106 The effect of inelastic scattering on the multiplication in a sphere.
A.H. Wilson (January, 1944)

In MS.105 a general method has been developed for obtaining approximate solutions for the neutron distribution in bodies containing fissionable matter. The method consists in obtaining exact solutions of the transport equation for the case in which the whole of space is filled with homogeneous matter, and then superposing these solutions so that the boundary conditions for a finite body are approximately satisfied. The discussion in MS.105 was confined to the case in which all the neutrons are supposed to have the same velocity and in which the scattering is isotropic. In the present report the method is extended to include the effect of inelastic scattering of the neutrons. The effect of anisotropic scattering will be considered in another report.

Comment: This report describes a very interesting way of dealing with a two-group transport theory problem and converting it, by linear combination of solutions, to a single group problem with effective parameters. It also describes the velocity dependent version of the Serber-Wilson and Feynman methods described in Davison's book, Neutron Transport theory.

MS-111 The critical size and time constant of a spheroid
H. Fairbrother (June, 1944)

The main object of the present report is to determine the critical size and time constant of a spheroid of uranium completely surrounded by an infinite container with same free path. When the central uranium mass is spherical, there are various methods available for solving the problem, but, for more general shapes, only the diffusion theory can be used without encountering very complicated mathematics, and the diffusion theory is therefore used in this report. As a preliminary to the discussion of the spheroid in the infinite container, the solution is given for the much simpler problem of a bare spheroid when the boundary condition is assumed to be that the density vanishes at the surface of the spheroid. Sections 1, 2 and 3 are concerned with the formulation of the problem and with the results of the calculations, while the detailed calculations are given in sections 4, 5 and 6.

Comment: This report is a *tour de force* of classical mathematics. It is a joy to read and it also introduces various useful expansions which make the solutions easier to use.

MS-112 Critical radius of a hemi-sphere completely surrounded by a container
P.D. Preston and B. Davison (July, 1944)

In MS-100 the author has determined under certain simplifying assumptions the critical radius for a hemi-sphere, covered by a container over its curved surface. That problem arose in connection with the following method of assembly: Two hemi-spheres each covered by a container over its curved surface are initially situated in such a position that their plane boundaries are bare. The hemi-spheres and their containers are then displaced so as to form a sphere completely surrounded by a container. The method of assembly more usually contemplated is to have the two hemi-spheres initially in such a position that the plane boundary of each hemi-sphere is covered by the plane boundary of the container of the other hemi-sphere. Our present purpose is to extend the calculations of MS-100 to the case of this latter method of assembly.

MS-115 A new method of determining the time constant of a sphere in a container
A.H. Wilson (August, 1944)

All the methods that have so far been used to determine the critical size and time constant of a uniform sphere of uranium give approximately the same numerical results, but there are still unexplained discrepancies for the numerical results for the time constant of a sphere in a container. (See MSS 97 and 105). It is therefore desirable to obtain results by as many different methods as possible. One such method was indicated in MS. 89. It consists in evaluating the variation integral for the eigenvalue of the problem using the eigenfunction given by diffusion theory, thus avoiding the necessity of knowing the boundary conditions to be used in conjunction with the diffusion theory. This method involves the use of the exponential integral with complex argument, tables of which are now available.

MS-D5 Approximate rate of neutron multiplication for a solid of arbitrary shape and uniform density, Parts I and II.
P.A.M. Dirac (1944)

Editor's note: These two reports have no formal abstract. They are important in that they introduce into reactor theory for the first time the concept of the chord distribution function, and the escape probability of a neutron from a uniform source in a finite body of arbitrary non-re-entrant shape. In part I, Dirac develops the method of chords and obtains the chord distribution function for some practically important shapes such as oblate and semi-oblate spheroids. In part II, with the collaboration of K. Fuchs, R. Peierls and P. Preston, Dirac further develops the method and presents extensive numerical results for the escape probability.

Comment: This method is developed and described further in the monograph 'Introduction to the Theory of Neutron Diffusion' by K.M. Case, F. de Hoffmann and G. Placzek, US Government Printing Office, 1953.

8. Professional personnel of the Montreal Laboratory before August 1945

This list is taken from the Appendix of the report by George Laurence cited below.

Canadians

W.J. Allan, C.A. Barnes, Mrs. D. Bate, A.H. Booth, T.W. Boyer, G.C. Butler, A. Cambron, H.M. Cave, H.H. Clayton, M. Cohen, L.G. Cook, D.S. Craig, A.J. Cruickshank, P. Demers, D.C. Douglas, D.M. Eisen, L.G.Elliott, S. Epstein, J.M.G. Fell, F.T. Fitch, C.M. Fraser, S.C. Fultz, P.E. Gishler, G.A.R. Graham, L.M. Grassie, W.E. Grummitt, E.W. Guptill, TJ. Hardwick, J.A. Harvey, E.P. Hincks, C.R.G. Holmes, D.G. Hurst, Miss M.E. Kennedy, Miss P. Kerr, D. Kirkwood, W.J. Knowles, S.A. Kushneriuk, Mrs. J. Laird, G.C. Laurence, Jeanne LeCaine (Agnew), W.R. Legge, M.W. Lister, J.G. Machutchin, S.N. Maldrott, J.C. Mark, J.H.L. Matheson, K.J. McCallum, L.A. McLeod, J.W. McKay, N. Miller, J.R. Mills, WA. Mohuzi, N. Morrow, G.B. Moses, A.M. Munn, N.J. Neimi, L. Nirenberg, J.W. Ozeroff, E.B. Paul, W.S. Peterson, E. Provost, D.S. Russell, B.W. Sargent, P.J. Sereda, C.H. Simpkinson, J.K.T. Spinks, E.W.R. Steacie, J.D. Stewart, B.M..Thall, A.L. Thompson, Miss A. Underhill, D. Van Patter, A. Vroom, G.M. Volkoff, Muriel Wales, P.R. Wallace, W.H. Walker, A.G. Ward, L. Yaffe.

The following Canadian scientists worked elsewhere on atomic energy problems in association with the Montreal Laboratory.

In the Chemistry department at the University of Toronto, under the direction of Professor F.E. Beamish; H.E. Bewick, J.E. Currah, and D.E. Ryan.

In the Chemistry department of McMaster University, under the direction of Professor H.G. Thode; G. Dean, H.E. Duckworth, R.L. Graham, A.L. Harkness, R.C. Hawkings, D.T. Roberts and S.R. Smith.

In the Metallurgy department at the University of Toronto, under the direction of Professor L.M. Pidgeon; W.A. Alexander and A.C. Topp.

In the Department of Mines and Resources - Fuel and Ore Laboratory, under the direction of Dr. G.S. Farnham; R. L. Cunningham, H.J. Nichols, G. Ensell and Miss A. McDowell.

From Other Countries

F.T. Adler, A.H. Allen, C.B. Amphlett, G.S. Anderson, W.J. Arrol, H.S. Arms, P. Auger, A.F. Barr, S.G. Bauer, D.V. Booker, W.E. Burcham, R. Callow, B. Carlson, H. Carmichael, P.E. Cavanagh, K.E. Chackett, J.D. Cockcroft, S.G. Cohen, G.B. Cook, E.D. Courant, R.J. Cox, T.E. Cranshaw, B.Davison, J. Diamond, J.V. Dunworth, J.Elsey, A.C. English, F.J.M. Farley, F.W. Fenning, G.J. Fergusson, B.H. Flowers, H.F. Freundlich, K.D. George, C.H. Gilbert, A.H.C.P. Gillison, D.W. Ginns, B.L. Goldschmidt, M. Goldstein, H.E. Gove, H. Greenwood, J.W.G. Gregory, J. Guéron, E.A. Guggenheim, H.H. Halban, R.G. Hanna, B.G. Harvey, H.G. Heal, H.G. Hereward, R.P.Hudson, J.D. Jackson, F.R. Jackson, J.B. Jelley, K.D.B. Johnson, N. Kemmer, B. Kinsey, L. Kowarski, P. Lamb, N.Q. Lawrence, C.E. Mackintosh, A.G. Maddock, R.E. Marshak, G.R. Martin, A. Nunn May, P.M. Milner, J.S. Mitchell, F. Morgan, W.K.R. Musgrave, R.E. Newell, H.R. Paneth, C.O. Peabody, G. Placzek, B. Pontecorvo, H. Preston-Thomas, M.H.L. Pryce, C. Reid, D.T. Roberts, H. Seligman, K. Smith, B.S. Smith, R. Spence, J.F. Steljes, F.Sterry, J. Sutton, J. Thewlis, H. Tongue, N.J. Veall, C.H. Westcott, J.B. Warren, C.N. Watson-Munro, D.West, W.J. Whitehouse, G. Wilkinson, R. Wilkinson, W.W. Young.

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P.R. Wallace, *Atomic Energy in Canada: personal recollections of the wartime years*, Physics in Canada, vol 56, No. 2, 2000, The Millenium Issue.
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Group photograph, Montreal Laboratory, 1943.

The photograph below shows some of the first members of the research staff of the Montreal Laboratory in 1943. It was provided by Atomic Energy of Canada Limited. The staff members are identified as follows, with a (C) to denote Canadian:

Standing, left to right: A.M. Munn (C), B. Goldschmidt, J.W. Ozeroff (C), B.W. Sargent (C), G.A. Graham (C), J. Gueron, H.F. Freundlich, H.H. Halban, R.E. Newell, F.R. Jackson, J.D. Cockroft (visiting), P. Auger, S.G. Bauer, N.Q. Lawrence, A. Nunn May.

Seated, left to right: W.J. Knowles (C), P. Demers (C), J.R. Leicester, H. Seligman, **E.D. Courant**, E.P. Hincks (C), F.W. Fenning, G.C. Laurence (C), B. Pontecorvo, **G.M. Volkoff (C)**, A. Weinberg (U.S. Liaison Officer), **G. Placzek**.

Three members of the Theory group are highlighted.

Bronze Plaque at The University of Montreal

To commemorate the scientific endeavours of the Canadian and Allied Atomic Energy Project, a bronze plaque was placed on the wall of the present day Medical Building. Reproduced below is a photograph of that plaque taken by Professor Robert Roy of the Ecole Polytechnique which is part of the University of Montreal. The photograph was taken under the most arduous conditions in sub-zero temperatures.

An English translation of the wording on the plaque is given below:

In Memory of the First
Canadian Nuclear Research Centre
HRH the Duke of Edinburgh
unveiled this plaque on 17th May 1962

From 1st March 1943 to the 30th June 1946 part of this building of Montreal University housed laboratories where more than 500 persons from Canada, the UK, France and elsewhere, pursued research and development on nuclear energy from fission.

The administration of this laboratory was the responsibility of the Chairman of the National Research Council, C.J. Mackenzie. Amongst the Canadians who took part in the work are:

E.W.R. Steacie, Deputy Director of the laboratory

C.C. Butler	D.G. Hurst	F.T. Rosser
A. Cambron	G.C. Laurence	B.W. Sargent
A. Cipriani	J.C. Mark	J.T.W. Spinks
H.H. Clayton	S.C. Mason	H.G. Thode
L.G. Cook	N. Miller	G.M. Volkoff
P. Demers	J.H.L. Matheson	P.R. Wallace
L.G. Elliott	J.F.W. Prevost	A.G. Ward
	L. Yaffe	

Amongst the scientists and engineers from other countries were:

H.H. Halban, first Director of this laboratory, J.D. Cockcroft, his successor

W.J. Arrol	B.L. Goldschmidt	G. Placzek
P. Auger	J. Gueron	B. Pontecorvo
S.G. Bauer	L. Kowarski	M.H.L. Pryce
H. Carmichael	J.S. Mitchell	H. Seligman
J.V. Dunworth	R.E. Newell	H. Tongue
D.W. Ginns	H.R. Paneth	C.N. Watson-Monro

It should be noted that not all personnel are listed here, quite why there are omissions is not clear.

Full list of Montreal Theory Reports

MT-1 G. Placzek
The Functions of $E_n(x) = \int_1^\infty e^{-xu} u^{-n} du$

MT-4 G. Placzek and G.M. Volkoff
Notes on Diffusion of Neutrons Without Change in Energy.

MT-5 G. Placzek and W.P. Seidel
Milne's Problem in Transport Theory.
(Physical Review, **72** (1947) 550-555)

MT-6 G. Placzek
The Angular Distribution of neutrons Emerging from a Plane Surface.
(Physical Review, **72**(1947)556-558)

MT-7 G. Placzek
Boundary Conditions in Elementary Diffusion Theory.

MT-12 P.R. Wallace and J. LeCaine
Elementary Approximation in the Theory of Neutron Diffusion
(Nucleonics 4(2),30-35, 4(3), 48-67, 1949)

MT-13 G. Placzek and G.M. Volkoff
A Theorem on Neutron Multiplication
(Canadian Journal of Research, **A25** (1947) 276-292)

MT-14 G.M. Volkoff
Analysis of Experimental Data on the Slowing Down and
Thermal Diffusion Lengths in Carbon.

MT-15 P.R. Wallace
Neutron Distribution in Adjoining Piles of Slightly Different Properties.

MT-16 G. Placzek
Neutron Density Near a Plane Surface, I.

MT-17 R.E. Marshak
On the Slowing-Down Length of Neutrons in Water.

MT-18 R.E.Marshak
On The Moments of the Distribution Function of
Neutrons Slowed Down in Heavy Elements.

MT-19 R.E. Marshak
On The Slowing Down Length of Neutrons in Mixtures.
(MT-17,18,19 in Rev. Mod. Phys. 19(1947)185-238)

MT-20 G. Placzek
Diffusion of Neutrons without Velocity Change. (*Not Issued)*

MT-21 G.M. Volkoff
Critical Conditions for a Multiplying Spherical Core with an Infinite
Reflector of the Same Multiplying Properties.

MT-26 J.C. Mark
Milne's Problem for Anisotropic Scattering.

MT-29 J. LeCaine
Critical Radius of a Strongly Multiplying Sphere Surrounded by a
Non-Multiplying Infinite Medium.

MT-30 J. LeCaine and G.M. Volkoff
Application of "Synthetic" Kernels to the Study of Critical Conditions in a Multiplying Sphere with an Infinite Reflector.

MT-34 P.R. Wallace
Boundary Conditions at Thin Absorbing Shells and Plates.

MT-35 P.R. Wallace
Neutron Distribution in a Multiplying Exponential Pile with a Plane Source.

MT-38 G.M. Volkoff
Critical Radius of a Multiplying Spherical Core Surrounded by a
non-Multplying Reflector of Finite Thickness

MT-40 E.D. Courant
Production & Consumption of Fissile Materials in One
Arrangement a of Producing Unit.

MT-49 R.E. Marshak and W.P. Seidel
Milne's Problem for a Sphere.

MT-50 J.C. Mark
The Neutron Density Near a Plane

MT-51 G. Placzek
Energy Conversion Factors and Nuclear Constants.

MT-52 R.E. Marshak
Black Utilization. (*Not Issued)*

MT-5 R.E. Marshak
A Rigorous formula for the slowing down
Length in an Element of Arbitrary Mass.

MT-54 R.E. Marshak
On the Slowing-Down Length of Neutrons in Water: Supplement to MT-17.
(MT-53 and MT-54 published in Rev. Mod. Phys**. 19**(1947)185-238)

MT-55 R.E. Marshak
The Application of Variational Theory to the Determination of Asymptotic Neutron Densities.

MT-56 J.C. Mark,
Constants & Expansions of Wiener-Hopf Method. *(Not Issued)*

MT-59 E.D. Courant
Measurements in Finite System of the Total Number of Neutrons in an Infinite System.

MT-63 P.R. Wallace
On the Thermal Utilization of Plates in the Presence of Linear Anisotropic Scattering.

MT-65 G. Placzek
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Milne's Problem with Capture. *(Not Issued)*

MT-47 E.D. Courant
Diffusion Equations & Critical Conditions in a Medium with Varying Mean Free Path.

MT-72 F.T. Adler
Theory of the Diffuse Reflection of Neutrons by a Plane Surface of a Semi-infinite Capturing Medium

MT-88 B. Davison
Influence of a Small Black Sphere Upon a Neutron Density In an Infinite Non- Capturing Medium.

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MT-97 J.C. Mark
The Spherical Harmonic Method, II. (Re-issued as CRT-338)

MT-106 P.R. Wallace
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(Canadian Journal of Research **A26**(1948)99-114)

MT-107 P.R. Wallace
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MT-119 J. LeCaine
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MT-124 B. Davison
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MT-131 J. LeCaine
A Table of Integrals Involving En(x)

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Neutron Density at the Centre of a Small Spherical Cavity.

MT-137 E.A. Guggenheim
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The Critical Size of a Multiplying system Surrounded by a Reflector of Different Scattering Properties.

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MT-243 A.S. Lodge
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MT-245 B. Davison
Linear extrapolation length for the neutron density at the surface of a large hollow cylindrical shaft

MT-249 J.M.G. Fell
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by Absorbing Rods Around A Pile.