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Technical Paper

The Los Alamos Computing Facility During the Manhattan Project

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Abstract — *This paper describes the history of the computing facility at Los Alamos during the Manhattan Project, 1944 to 1946. While the hand computations are briefly discussed, the paper's main focus is on the IBM Punch-Card Accounting Machines (PCAMs). During World War II, the Los Alamos facility was one of the most advanced PCAM facilities, both in the machines and in the problems being solved.*

Keywords — *PCAM, Los Alamos, computing, punch card.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

At Berkeley in the summer of 1942, future Los Alamos Laboratory director Robert Oppenheimer and future Los Alamos Laboratory nuclear theory group leader Robert Serber had Stanley Frankel, an Oppenheimer postdoc, and Eldred Nelson, an Ernest Lawrence postdoc, work out the neutronics integral theory to calculate the critical mass of a uranium bomb.[1–3] This work was pivotal at the July 1942 Berkeley conference where scientists concluded that a nuclear bomb was feasible.[2–4] As a result, Frankel and Nelson became very early staff members at Los Alamos. In retrospect, this was a crucial point for computing at Los Alamos because they led the development of the computing facility.

This paper focuses on the development and operation of the Los Alamos computing facility during World War II (WWII). For more information, see the companion papers regarding the development of the hydrodynamic algorithms[5] and the broader impact of the Los Alamos computing in this special issue.[6]

From a modern perspective, a computing facility encompasses much more than just the physical machines. There is general agreement that a computing facility includes the machines; the building that houses those machines, along with the power and cooling infrastructure; the supporting computing infrastructure of networks and storage; and the staff to program and operate the computers and infrastructure. Although not usually considered part of the facility, for scientific computing, the problems and equations to be solved must be identified, the numeric methods for solving the equations must be developed, computer programs to solve the numeric methods must be developed, and users to determine the problems, set them up, and interpret the solutions must exist.

Although not part of Oppenheimer's original plan for Los Alamos, between the fall of 1943 and April 1944, the complexity of the physics encountered while developing the bombs drove Los Alamos to develop all of these computing

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pieces. As will be described later, the idea of using the IBM Punch-Card Accounting Machines (PCAMs) for scientific computing was inspired by Wallace J. Eckert's laboratory at Columbia University.[3,7–9] The Los Alamos PCAMs were patterned after those of the Army Ballistics Research Laboratory (BRL) at Aberdeen, Maryland,[7] and the U.S. Naval Observatory Nautical Almanac in Washington, District of Columbia.[10] However, the Los Alamos problems in hydrodynamics and neutronics were unique, requiring new numerical methods, described in the companion papers regarding the first hydrodynamic code[5] and the most advanced IBM machines available, as described later.

This paper starts with an overview of the use of the IBM PCAMs for scientific computing. Section III gives a brief discussion of hand calculations using desk calculators. Section IV describes the initial PCAMs used at Los Alamos. Section V provides a brief description of the uses of the PCAMs at Los Alamos. Evolution of the computing facility during the war is discussed in Sec. VI, and Sec. VII describe some of the postwar impacts of the Los Alamos computing.

II. OVERVIEW OF SCIENTIFIC COMPUTING WITH PCAMS

Prior to WWII, there were three types of scientific computing machines. The most common were desk calculators used by human computers to manually solve equations, see Fig. 1. There were also a handful of analog differential analyzers. The most advanced differential analyzers were developed by Vannevar Bush at the Massachusetts Institute of Technology during the late 1930s and early 1940s (Ref. 7). These mechanical systems could solve second-order differential equations (see Ref. 7 for more information on the differential analyzers).

Fig. 1. Marchant calculator being operated by a human computer.

The third computing method was to adapt PCAMs to solve scientific equations.[7] Punch-card tabulating machines had been developed by Herman Hollerith for the 1890 census. His machines were very successful, but the business was not. This result led to a merger with two other companies in 1911 to create the Computing-Tabulating-Recording Company, which was renamed International Business Machines (IBM) in 1924 (Ref. 11). Originally the machines were tabulators that could add numbers and sort cards. Functionality was gradually added to make the machines more versatile for use in accounting and recordkeeping. The added functionality included subtraction, alphanumeric records, sorting options, collation, and removable control plug boards. The first IBM machine that could multiply, the type-601 multiplying punch, was released in 1931 (Ref. 12). The highly successful type-405 alphabetical accounting machine, the most advanced tabulator, was released in 1934 (Refs. 11 and 12). Eventually, a full suite of IBM machines would include a collator, an interpreter, a keypunch, a reproducer, a sorter, and a verifier in addition to the type-405 tabulator and type-601 multipler.[11] Descriptions of the eight types of IBM machines, which are discussed later in this paper, can be found in Refs. 8, 10, 11, and 13.

The IBM accounting machines caused a revolution in paperwork by automating many aspects of a business, such as sales, purchasing, production, shipping, personnel, and financial transactions.[11] An interesting example was the WWII Mobile Machine Record Units (MRUs) that had IBM accounting machines mounted on trucks to accompany Army headquarters.[14] The MRUs tabulated personnel status such as casualties and changes of units, supplies, prisoners, and bombing results.[14] By 1943, IBM was leasing 10000 tabulators, including 6400 type-405 and 2000 type-601 multipliers, 24500 keypunch machines, and 10250 type-080 sorters.[11] Operating together, the type-405 and type-601 machines would form the core of the WWII scientific computing facilities.

In 1928, astronomer Leslie Comrie at His Majesty's Nautical Almanac adapted the IBM Hollerith Tabulating punch-card machines to calculate tide tables based on the orbit of the moon. This adaption was the first use of the PCAMs for scientific computing; however, it was discontinued when Comrie left the Nautical Almanac in 1936 (Ref. 12).

During 1928, Benjamin Wood, head of the Bureau of Collegiate Educational Research at Columbia University in New York, persuaded Thomas J. Watson, Sr., president of IBM, to develop machines to automate the grading of exams.[12] IBM donated a set of PCAMs for Wood's use. These machines eventually became the mainstay of the Columbia University Statistical Bureau in June 1929 (Ref. 10). They were used to analyze test results and to interpolate astronomy tables.[10] Meanwhile, Wood worked with IBM engineers to develop a test scoring machine, resulting in the IBM 805 in 1937 (Ref. 10).

In 1933, Columbia University astronomer Wallace J. Eckert was inspired by the work of Comrie and Wood to propose to Watson Sr. the adaption of the new IBM type-601 multiplying punch-card machine for scientific calculations.[10,12] This resulted in IBM donating a type-601 machine that was modified to do "direct interpolation"[12] and related equipment to the Columbia University Astronomy Department in early 1934 (Refs. 10 and 12). This facility, variously named the Rutherford Laboratory, the Astronomical Laboratory, or the Hollerith Computing Bureau,[12] computed planetary orbits and carried out data reduction for star catalogs for Columbia and Yale.[10] In 1937, IBM, Columbia University, and the American Astronomical Society partnered to make the Columbia astronomy facility available to all astronomers, renaming it the Thomas J. Watson Astronomical Computing Bureau.[10,12] In 1940, to assist the many visitors to the Bureau, Eckert published what was probably the first programming book, "Punched Card Methods in Scientific Computing,"[15] which had wide influence on subsequent PCAM facilities.[7,8]

In 1940, Eckert moved to the U.S. Naval Observatory where he established a PCAM facility for the Nautical Almanac to calculate star navigation tables for aircraft and ships. In 1941, observing the success of the Naval Observatory, a PCAM facility was established at BRL at Aberdeen, Maryland, to calculate artillery ballistic tables.[7] During the course of WWII between 12 (Ref. 10) to 15 (Ref. 7) other government agencies and defense contractors established IBM PCAM facilities for scientific-type work. The author has been unable to find information on these facilities other than the two most prominent ones, the Los Alamos facility established in 1944 and the IBM Watson Scientific Computing Laboratory established at Columbia University in 1945. The IBM Watson Scientific Computing Laboratory started with equipment similar to BRL, but after the war, because of its status as IBM's research facility, it rapidly outclassed both BRL and Los Alamos.[8,12]

During WWII, the Astronomical Bureau, the Naval Observatory, and BRL served as patterns for the newer facilities. All three of these early facilities were built around one or two standard type-601 multipliers.[7,8,10,12] During the war, each facility was generally dedicated to a single type of problem—gun ballistics at the Astronomical Bureau and BRL, and star navigation charts at the Naval Observatory.[7,8,10,12] The new facilities were probably quite similar to BRL in the number and type of machines, one or two standard type-601 multipliers with supporting machines, and in dedication to a specific type of calculation.

The standard type-601 could multiple two numbers, but it could not divide. The BRL and Los Alamos facilities appear to have been the largest and most advanced PCAM installations during WWII. By November 1944, Los Alamos had four type-601s, three of which were specially modified by IBM to multiply three numbers and to do division. It is not clear how many standard type-601s BRL had, but in December 1944, two experimental IBM Pluggable Sequence Relay Calculators were delivered.[7,16] These "Aberdeen" machines could divide and were the fastest multipliers before ENIAC (Refs. 7 and 16).

The BRL machines were dedicated to ballistic calculations, although the renowned mathematician John von Neumann did use them for two hydrodynamic calculations in early 1944 (see the companion paper regarding the first hydrodynamic code).[5] The Los Alamos machines were used for a wide variety of problems in implosion hydrodynamics, neutron transport, equation of state, blast waves, and high explosives.

The Los Alamos implosion hydrodynamic problem was probably the most difficult problem being solved on the PCAM. The orbital mechanics problem that Eckert was solving was a set of linear and continuous, second-order, time-dependent, differential equations. The implosion hydrodynamics was a set of second-order, time-dependent, partial differential equations that were nonlinear because of the equation of state and discontinuous as a result of the shocks.[5] Today, ballistics problems can be solved on a phone, and orbital calculators can readily be found on the web. However, Los Alamos is still acquiring some of the world's largest supercomputers to solve the implosion hydrodynamic problem. During WWII, the Los Alamos computing facility was one of the most advanced PCAM facilities, both in the type of machines and in the breadth and complexity of problems being solved.

III. ELECTROMECHANICAL CALCULATORS

Frankel and Nelson, Figs. 2 and 3, had set up a "hand-computing activity to support development of

Fig. 2. Stanley P. Frankel.

the electromagnetic isotope separator and early critical-mass calculations" at Lawrence's Berkeley laboratory.[3,9] Frankel and Nelson arrived at Los Alamos in early 1943 to continue the critical mass work for the gun bombs. They were tasked to order electromechanical desk calculators for Los Alamos's "initial theoretical work."[9] To balance cost and capability, they chose a mix of high-speed, ten-digit Marchants and Fridens and economical, but slow, eight-digit Monroes.[9]

Some of these calculators were distributed to scientists who had the "most computing work,"[9] such as critical mass calculations. Others were used to set up the central computing pool, Group T-5, in the summer of 1943, which was led by Donald (Moll) Flanders[9,17] (Fig. 4) a mathematics professor at New York University.[12] The original human computers were the wives of the technical staff, who were eventually replaced by Women's Army Corps (WAC) staff.[18] Mary Frankel (Fig. 5) set up the problems for the human computers to calculate.[18] An example could be linear interpolation of a table, c = (a + b)/2. Frankel would set up a calculating sheet with a row telling where to get "a" and a space for its value, a row to get "b," a row that says do

Fig. 3. Eldred C. Nelson.

Fig. 4. Donald "Moll" Flanders.

Fig. 5. Mary P. Frankel.

Fig. 6. Dana P. Mitchell.

"a + b" with a space for the value, and finally a row to divide by 2, with a space for the final value. This level of detail was needed for every operation, with complicated operations handed off between different human computers.

Flanders soon decided to standardize the work by using the Marchant electromechanical calculators, the most powerful and fastest ones,[9,17] which were used extensively into the early 1950s for smaller numerical calculations. These electromechanical calculators were famously repaired by physicist Richard Feynman and Nicholas Metropolis.[17,18] The Group T-5 continued through all the reorganizations of T Division during the war (see the companion paper for further details on the electromechanical computing).[4,6]

IV. IBM PCAMS

During 1943, Los Alamos was focused on the gun bomb approach. A particularly vexing issue of the gun bomb design was calculating the critical mass of "odd-shaped bodies" resulting from firing the gun.[2,19] In the fall of 1943, it was clear that the hand calculators were struggling with this problem. During a Los Alamos Governing Board meeting, Dana Mitchell (Fig. 6), who had handled procurement for the Columbia University Physics Department before taking charge of Los Alamos equipment procurement, recommended to Hans Bethe that the IBM PCAMs should be used for the critical mass calculations.[3,9,19] Mitchell had seen Eckert's laboratory at Columbia University, which had pioneered the use of the PCAMs for astronomy calculations.[3,9,19] Bethe, the Theoretical Division leader, had also seen Eckert's computing facility and decided to order PCAMs for Los Alamos.[19]

Frankel and Nelson were assigned responsibility for determining how to use the IBM machines for the odd-shaped critical mass problem and for the specifications needed to order the machines.[2,3,9,17] In January 1944, Frankel visited the East Coast to get information about the suitability of the IBM machines for the odd-shaped criticality problem. Presumably, Frankel visited the Astronomical Bureau at Columbia University in New York, the Nautical Almanac at Washington, District of Columbia, and the BRL at Aberdeen, Maryland. After the visit, Frankel recommended proceeding with the PCAMs. These machines were to be similar to those in use by the BRL for calculating ballistics tables[7] and the Nautical Almanac for calculating navigation tables.[10]

The IBM PCAMs were delivered on April 4, 1944 (Ref. 2). Because of the classified nature of Los Alamos, IBM was not told where the machines were going and could not send a maintenance man to assemble them.

However, IBM identified their best PCAM maintenance man, John Johnston, who had been drafted and was then assigned to Los Alamos by the Army.[9] The PCAMs arrived at Los Alamos 3 days before Johnston, so Frankel, Nelson, and Feynman assembled the system, and Johnston carried out the final tuning.[3,9,18,19] The PCAMs were installed in Building E, see Fig. 7 (Ref. 17).

There is some uncertainty about all the components of the PCAM system that were used during the war, but all sources agree that there were eight core machines.[9,13,17] These eight machines are listed in the first part of Table I. They were operated as a combined system to carry out a calculation. This system was one of the largest PCAM installations in existence during the war.[7,8]

A very detailed description of the IBM PCAMs and the operation of the system was written in 1949 (Ref. 13). Figure 8 shows part of the Manhattan Project PCAM facility after the type-601s with a divide capability, discussed later, were delivered in November 1944. Note that Fig. 8 shows four type-601 multipliers, so at least one of the original standard type-601s was kept after the special type-601s were delivered.

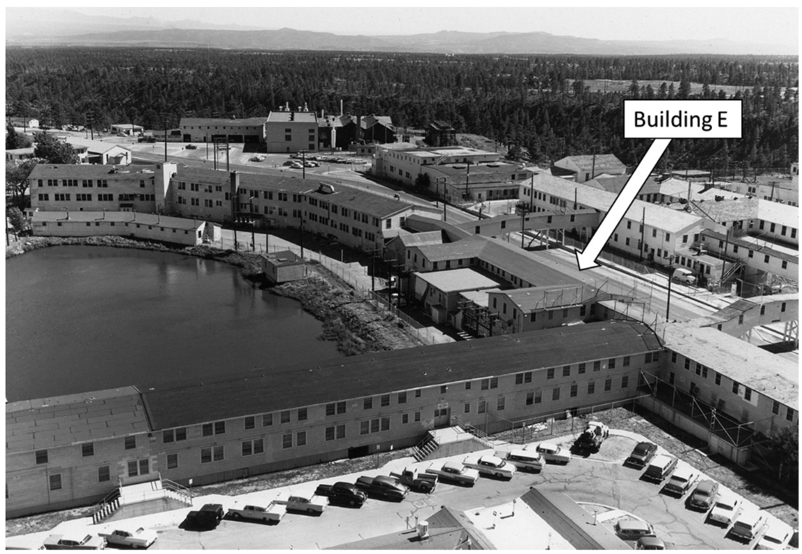

Fig. 7. Postwar photo of the Los Alamos technical area showing Building E, which housed both the hand calculators of Group T-5 and the IBM PCAMs of Group T-6.

TABLE I

The IBM PCAMs that Together Made the Los Alamos Computing Facility, 1944–1946*

Machine Type	Capability
Three 601 multipliers originally; four 601 by November 1944.	Multiply A × B, add, subtract, and print. Three had the unique A × B × C multiply capability, and two could also divide.
One 405 alphabetic accounting machine or tabulator	Add, subtract, and print
One 513 reproducing summary punch	Punch output cards and reproduce batches of cards.
One 031 alphabetic duplicating punch keypunch	Data entry keyboard that punched cards and could reproduce a single card.
One 075 card sorter	Sorting of cards by values of one column
One 077 collator	Sorting of cards by values of multiple columns
Possible Auxiliary Machines	
One 550 alphabetic interpreter (a 552 in 1949)	Copies punched information of one card onto another card and printed a human readable translation on the card.
One verifier	Retype a card to verify that it was originally typed correctly.

*References 9, 13, and 17.

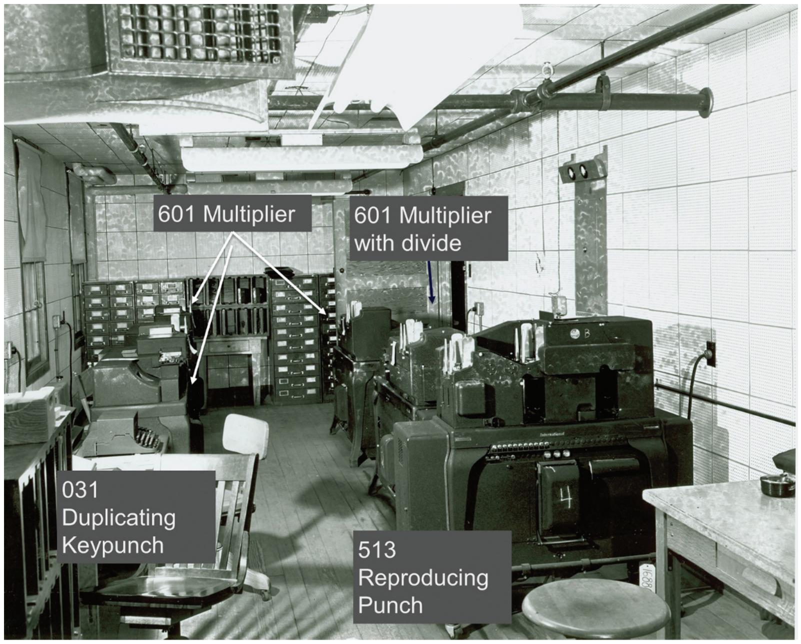

Fig. 8. Part of the IBM PCAM installation at Los Alamos during the Manhattan Project after November 1944. Right side, front to back: type-513 reproducer punch, type-601 multiplier with divide unit, type-601 multiplier without divide unit. Left side, front to back: type-031 duplicating keypunch, type-601 multiplier, type-601 multiplier.

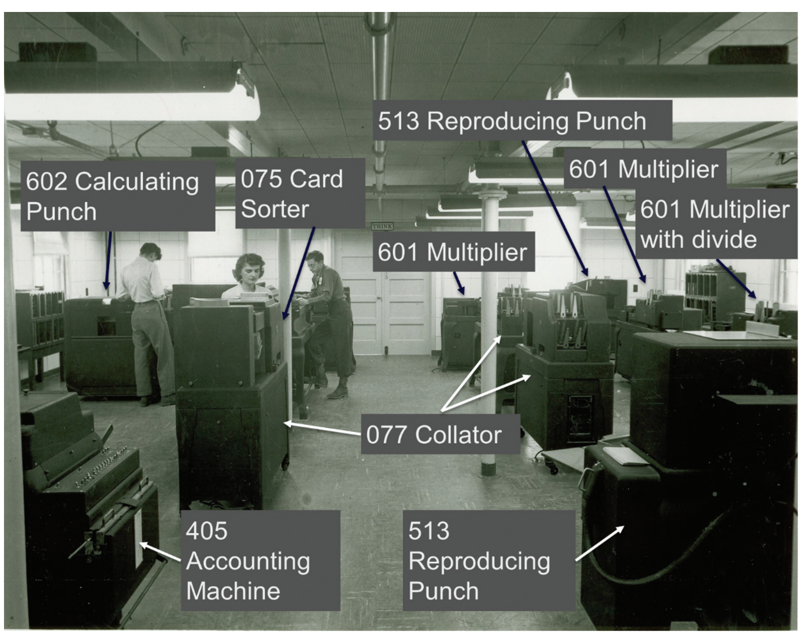

Fig. 9. Los Alamos IBM PCAM facility after the first type-602 was delivered sometime in 1947. This photo shows the 1945 equipment with the addition of two more type-077 collators, one more type-513 reproducing punch, and a type-602 calculating punch. The type-031 keypunch is not shown.

Figure 9 shows the Los Alamos PCAM facility after the first type-602 multiplier was delivered sometime in 1947. It has expanded somewhat, with three type-077 collators, two type-513 reproducing punches, and one of the new type-602 calculating punch machines. Otherwise, except for missing a type-031 duplicating keypunch, Fig. 9 shows the equipment used during the Manhattan Project.

There are two auxiliary machines in Table I that only appear on single lists. One, listed by Nelson, was a verifier of unknown model number.[9] On a verifier, an already-typed card was typed again to check that the original card was typed in correctly. The 1949 list[13] has a type-552 interpreter. This device was introduced in 1946, but was preceded by the type-550 interpreter. The interpreter duplicated a card with human readable annotation across the top. As a practical matter, Los Alamos must have had an interpreter. Another bit of evidence for the existence of these two machines is that Bethe mentioned that he ordered ten machines, not eight.[2]

V. USING THE PCAMS

Von Neumann became a consultant to Los Alamos after first visiting in September 1943. During that visit, he pushed Los Alamos to pursue the implosion method.[2] He also pushed to change the main use of the PCAM machines, which Los Alamos had already decided to order, from neutronics calculations to implosion hydrodynamic calculations.[20] During the winter of 1943–1944, Manhattan Project leadership became more interested in the implosion concept.

Fig. 10. Naomi M. Livesay.

Meanwhile, preparation for use of the PCAMs to calculate the gun bomb neutronics continued. Joseph Hirschfelder, a leader of the plutonium gun bomb effort, hired Naomi Livesay (Fig. 10) to assist with setting up gun bomb problems on the PCAMs. Livesay was uniquely qualified. She had a PhD in mathematics, and while working at Princeton University on government statistics, had attended a PCAM programming school and gained experienced programming PCAMs.

By February 1944, the implosion concept was rapidly increasing in importance and the decision was made to redirect the PCAMs to the implosion problem. The tasking of Frankel and Nelson was changed to the implosion calculation effort, and Livesay was assigned to assist them. Frankel, Nelson, and Livesay developed the first program for solving the set of hydrodynamic equations on the PCAMs during February and March 1944 (see the companion paper regarding the first hydrodynamic code).[5] When an implosion hydrodynamic problem was completed, it was used as the starting point of nuclear performance calculations by Serber's and Feynman's groups. By varying initial conditions, they could exam various design options.

Programming the PCAMs started with dividing the equations into IBM operations: add these two quantities, divide these two, sum, etc.[18] This type of programming is shown in detail in LA-1057 (Ref. 13) and LA-1058 (Ref. 21). To illustrate PCAM programming, a simple linear interpolation, $c = (a + b)/2$, from section 2.2-2 of LA-1057 (Ref. 13) is described. Linear interpolation was used to fill in the 1000 cards for the equation of state of each material, starting from a sparse grid calculated by hand calculators.

Figure 11 shows a typical 80-column punch card. The card is read by electrical brushes that contact through the holes punched into the card. Interpretation of punch cards is positional, in this case the card is from the 1970s with a FORTRAN "print" command in columns 1 through 11, and columns 15 and 16 have the argument to print to unit "40." Cards were manually typed on the type-031 keypunch, then retyped on a verifier to catch typing errors. Usually, cards generated by the PCAMs did not have the human readable label printed across the top of the card, as shown in Fig. 11. If this was needed, a card could be feed through the interpreter, which would read the card and print the label. As a practical matter, Los Alamos needed the verifier and interpreter listed in Table I.

The process to carry out the linear interpolation required using three PCAM machines, the type-513 reproducing punch, the type-075 card sorter, and the

 ANS

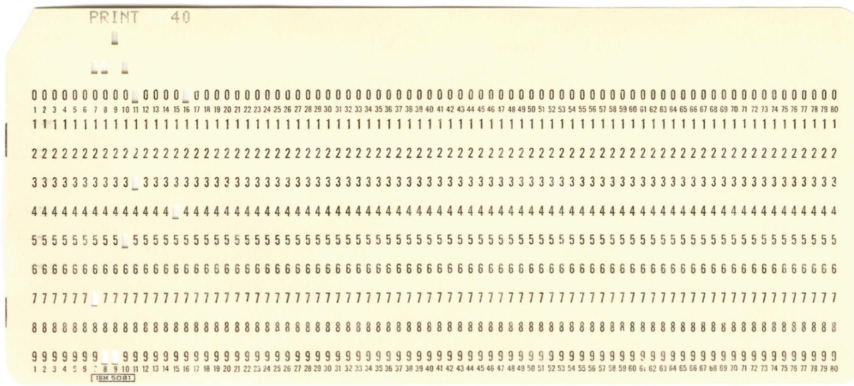

Fig. 11. IBM 80-column punch card.

TABLE II

PCAM Pseudo Flow Sheet for Linear Interpolation of C = (A + b)/2

	Operation	Card	Column
513 reproducer			
1	Read a	1	25 to 30
2	Read b	2	35 to 40
3	Write a, b, 5	3	25 to 30, 35 to 40, 80
075 sorter			
1	Merge card 3 into card deck that needs c	3	N/A[a]
601 multiplier			
1	Read card 3, a, b	3	25 to 30, 35 to 40
2	Add a + b	N/A	N/A[a]
3	Read 5	3	80
4	Shift 5 to 0.5	N/A	N/A
5	Multiply (a + b) · 0.5	N/A	N/A
6	Skip to next card	N/A	N/A
7	Punch c on new card	4	25 to 30

[a]N/A = not applicable.

type-601 multiplier. The programmers had to develop a flow sheet for the operators. A pseudo flow sheet for the linear interpolation is shown in Table II. There were 11 steps, as explicitly shown in Table II, but three more implicit operations were needed to manually move the cards between the reproducer, sorter, and multiplier. But how did the multiplier know what to do with card 3? Figure 12 shows the plug board for the type-601 multiplier that controlled the operation of the machine. The programmers had to develop a plug board wiring diagram to tell the operators how to wire the plug board. The wiring diagram for the linear interpolation is shown in Fig. 13. The bottom-left connection of "Brushes" 11 to "X-1" shows that if column 11, row 0 on the card is punched, then this plug board operation was activated. The top row [labeled "f(n)" and "f(n + 1)"] shows that argument "a" was on columns 25 to 30 and "b" was on columns 35 to 40. The wiring diagram then showed the process to carry out the rest of the operations, as shown in Table II. The operators received the flow diagram and wiring diagram, wired the machines, and then moved the cards between machines as required. This process obviously became a nontrivial choreography for solving the hydrodynamic equations.

The IBM PCAM operators were different than the human computers that operated the desktop calculators. The PCAM operators are listed in the Appendix. Some of the operators were from the 9812th Special Engineering Detachment (SED), some were WACs, and some were civilians. Nelson stated that "none of these persons had

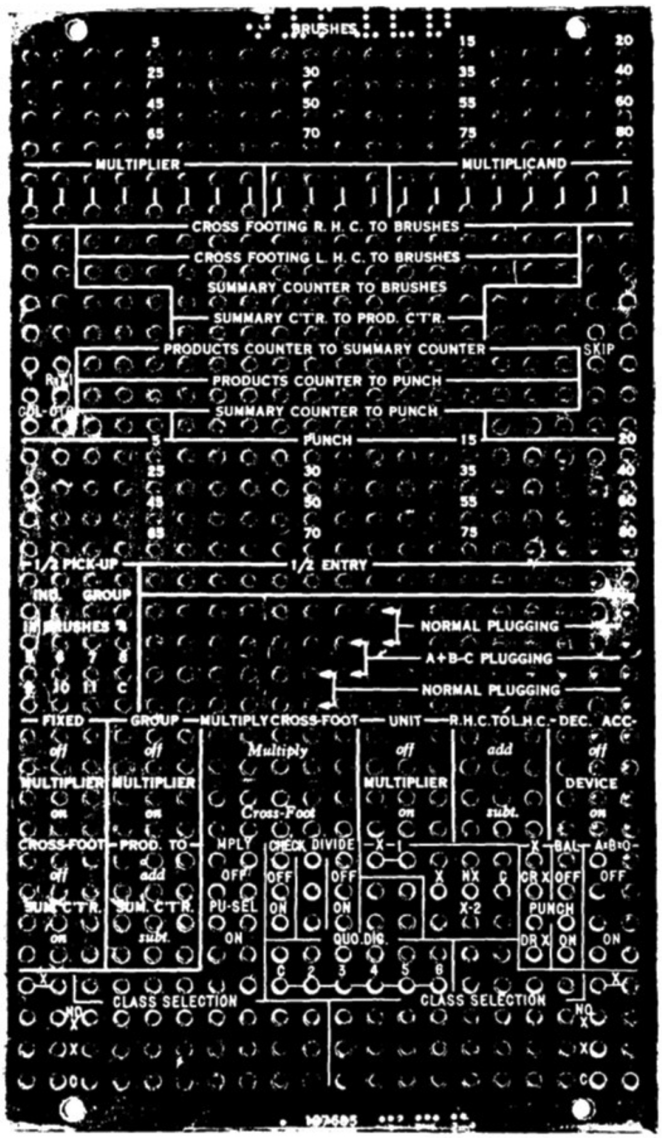

Fig. 12. Plug board for the IBM type-601 multiplier.

prior experience in punch-card machine operation. All had to be trained."[9] How the operators were selected is unknown, but members of the 9812 SED "were recruited through the Army specialized training program, at universities and colleges throughout the country, and the Roster of Scientific and Specialized Personnel"[22] compiled by the National Defense Research Committee. The result was that the 9812 SED had an average score on the Army General Classification Test of 133, the highest of any unit in the Army.[23]

In March 1944, before the PCAMs arrived, the hydrodynamic program was tested on the Marchant calculators with the assistance of Feynman. Each human computer was assigned one operation, passing the partial results from computer to computer in a specified order.[18]

The PCAMs started on the first hydrodynamic calculation "within a week of arrival"[2,9] under the direction of Frankel, Nelson, and Livesay. To check the PCAM results, Feynman arranged a competition between the computing pool and the PCAMs. The computing pool was as fast as the PCAMs for a couple of days, but tired out after that. The PCAMs gave the correct results, and completed the calculation in May 1944 (Ref. 18). Subsequently, Livesay supervised the PCAM operators.

By April 1944, Los Alamos had developed a scientific computing facility for solving nonlinear partial differential equations. This facility consisted of the IBM PCAMs, the building and infrastructure for the machines, the staff to operate the machines, the numeric methods for solving the equations, programmers, and the staff to set up the problems and interpret the solutions.

VI. FURTHER DEVELOPMENTS

The standard IBM type-601 could only multiply two numbers, A × B and could not divide. In May 1944, Johnston suggested that the calculations could be sped up by using a prototype multiplier he had seen at IBM (Ref. 9). They "decided to have IBM build triple-product multipliers and machines that could divide," machines that could do A × B × C and A/B.[9] In early June 1944, Nelson visited IBM Vice President John C. McPherson, convincing IBM to build the machines.[9] Los Alamos ordered three triple-product multipliers, two with the division capability. These machines were delivered in late 1944 (Ref. 9) and started being used in November 1944. Figures 8 and 9 both show at least one of the type-601s modified with a divide unit, as shown in LA-1057 (Ref. 13). With these unique machines, Los Alamos had one of the most powerful computing facilities in the United States.[8]

In September 1944, the IBM computations were removed from Group T-2, Serber's Diffusion Theory group, to form Group T-6, IBM Computations, led by Nelson and Frankel.[2,4] Nelson continued as the T-6 group leader until he left the Laboratory in January 1946 (Ref. 4).

As Feynman put it, "Mr. Frankel, who started this program, began to suffer from the computer disease."[18] The disease was that the machines were fun to experiment with. As a result, in January 1945 Frankel was moved to Edward Teller's thermonuclear group in F Division.[2,4] Frankel was replaced by Feynman (Fig. 14) in overseeing the PCAM calculations, with assistance from Metropolis (Fig. 15) reporting to

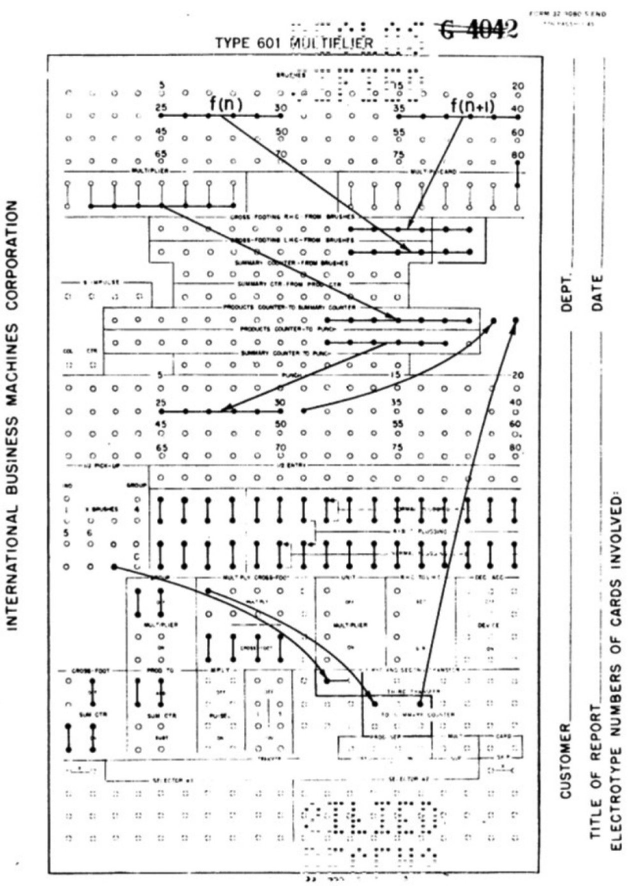

Fig. 13. Wiring diagram for a linear interpolation on the IBM type-601 multiplier.

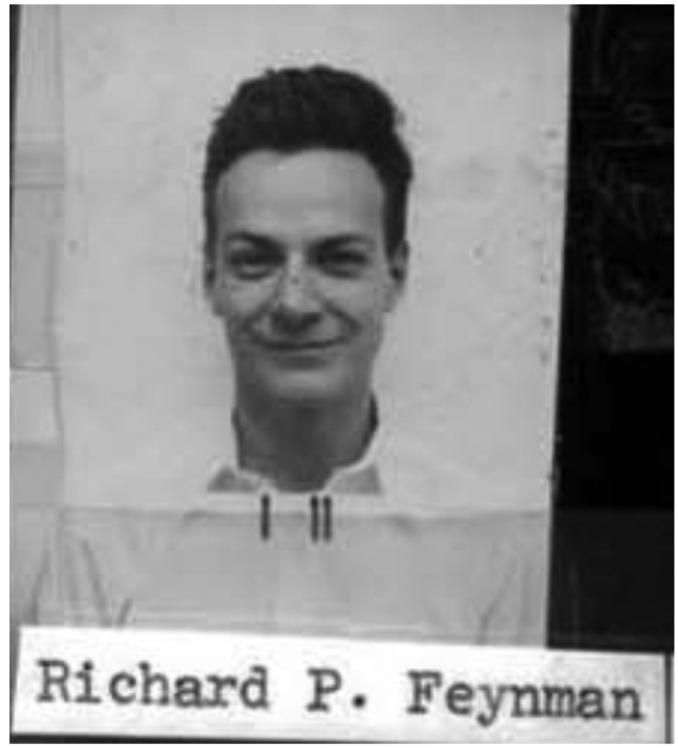

Fig. 14. Richard P. Feynman.

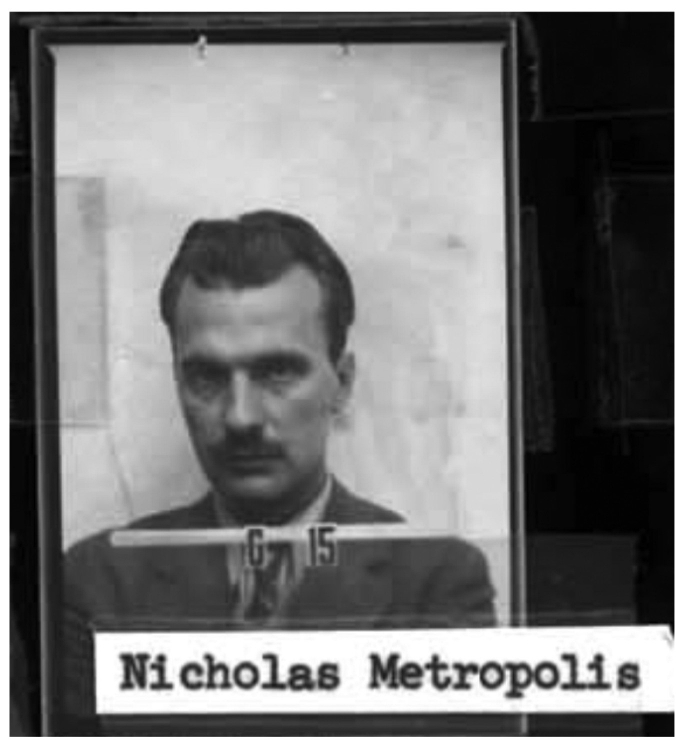

Fig. 15. Nicholas Metropolis.

Nelson.[9,18] Feynman was acting T-6 group leader during April and May 1945 while Nelson was hospitalized for a badly broken leg from a skiing accident.[9]

Feynman was able to motivate the staff operating the PCAMs by getting permission to tell them for the first time what they were working on.[18] This motivation was probably in April 1945 after no simulations were completed in March 1945. The operator staff, see the Appendix, then found ways to improve the PCAM efficiency[18] such that they went from doing less than one simulation per month to 12 problems in the next 4 months (April to July 1945). A major part of the speedup was taking advantage of idle machines as a problem ran through a cycle to run up to three problems at a time using different color cards for each problem.[17,18]

By late 1944, Los Alamos was trying to understand the radiation from the bombs.[24] However, the Los Alamos PCAM machines were overcommitted, so they reached out through von Neumann to IBM for help.[8,24] All the PCAM facilities were already committed to war work, so Watson Sr. decided to establish an IBM computing research facility at Columbia University to assist Los Alamos and to position the company for the coming peace time.[8,10] This facility, separate from the existing Astronomical Bureau, was the Watson Scientific Computing Laboratory, headed by Wallace Eckert, who returned from the Naval Observatory.[8,10] Using the Los Alamos procurement priority, it was quickly stood up in May 1945 (Ref. 8). Feynman visited and showed the IBM staff how to wire the machines for the Los Alamos calculations.[8] Other visitors included von Neumann, Bethe, radiation physicist Robert Marshak, and Maria and Joe Mayer.[8]

The Watson group solved two time steps per day, and the results were mailed to Los Alamos for analysis.[8] This effort was eventually stopped because it was slower than the analytical methods for solving the radiation equations.

VII. EPILOGUE

When Nelson left the laboratory in January 1946, he was replaced by mathematician R. W. Hamming, who had joined Los Alamos in April 1945 to assist with the programming of the PCAMs (Ref. 25). By December 1946, physicist Bengt Carlson was the group leader for both the Marchant and IBM Computations.[7] Carlson invented the discrete ordinates S_N method to solve the neutron transport equation in 1953 (Ref. 26), which is still extensively used.

The type-601 machines were supplemented with newer type-602 systems in 1947 and 1948 (Ref. 17). They were all replaced with the new IBM Card-Programmed Electronic Calculator (CPC) 604 machines in 1949 (Ref. 17). The last CPC was retired in 1956, replaced by the MANIAC and IBM 701 and 704 electronic computers.[17] The punch-card machines had quite a run at Los Alamos!

The Los Alamos experience showed the value of numerical computing for science. An example of this experience was reinforcing the belief in the value of scientific computing by Watson Sr. of IBM (Ref. 8). After the war, the Watson Computing Laboratory quickly surpassed the Los Alamos facility in size and advanced machines and attracted a large number of scientists in various disciplines.[8] In turn, this led Watson Sr. in 1946–1947 to direct the building of IBM's first electronic computer, the Selective Sequence Electronic Computer (SSEC), which was dedicated to scientific computing. IBM and Los Alamos had a long partnership from the 1940s into the 1960s developing scientific computers.

Probably the most important consequence of the Los Alamos computing facility was the experience gained by the staff. Frankel and Nelson formed one of the earliest computer consulting firms in California in 1947 and were heavily involved in starting the small computer industry on the West Coast. Von Neumann was a major figure in starting the large computer industry on the East Coast, defining the von Neumann computer architecture that is still fundamental today. Metropolis led the effort to build a von Neumann machine at Los Alamos, the MANIAC. John Kemeny, one of the SED PCAM operators, was a co-inventor of the BASIC programming language. Richard W. Hamming, who joined Group T-6 in April 1944, went on to Bell Laboratories, where he made many contributions to computing, including the first error-correcting code to fix parity errors.

The scientific managers were also taught the importance of computing. Oppenheimer, at the Princeton Institute of Advanced Study, was the patron of von Neumann's machine. Teller and von Neumann made sure computing was a core part of the new Livermore Laboratory in 1952. William Penney similarly acquired the use of a von Neumann machine for the United Kingdom nuclear weapons program, the first Ferranti Mark I computer installed at the University of Manchester in 1951, and acquired a Mark I* in 1954 (Ref. 27).

At Los Alamos, the wartime computing effort set the pattern for decades to come, and computing has always been a core part of the Los Alamos weapons program. Just as the Los Alamos triple multiple and divide PCAMs were among the most advanced IBM machines during WWII, the ever-increasing weapons modeling requirements have driven Los Alamos to stay on the forefront of computing. The thermonuclear weapons work in the 1950s drove Los Alamos's use of the first-generation computers, such as ENIAC, MANIAC, and the IBM SSEC. Since then, examples include the IBM Stretch 7030, CDC 6600 and 7600, the first Cray I, and today's massively parallel clusters, such as the IBM Roadrunner machine that first achieved one-petaflop performance. The PCAMs were used to calculate neutron diffusion, bombing tables, equation of state, and hydrodynamics. This was probably the broadest problem set of any of the PCAM installations during WWII. The types of problems Los Alamos needed to solve continued to expand after the war, leading to new physics methods and codes. Examples include developing the Monte Carlo method, the S_N neutronics method, and hydrodynamic methods such as particle in cell and arbitrary Lagrange-Eulerian.

The wartime computing at Los Alamos foreshadowed the growth of scientific computing, soon to be enabled by electronic computers, such as ENIAC and COLOSSUS, and had a wide and lasting impact on computing in general by showing that numerical computing could be of great value throughout science (see the companion paper on the impact of the Los Alamos computing facility on the broader computing community).[6]

APPENDIX

IBM OPERATORS

Usually overlooked are the actual operators of the IBM PCAMs. Below is a list, probably incomplete, of the IBM operators at Los Alamos during WWII. It was compiled by the author from lists in various reports on the IBM problems, LA-1057 (Ref. 13), and Nelson's recollections.[10] Not listed are Naomi Livesay and F. Eleanor Ewing, who supervised the operators. Livesay was hired in February 1944, and Ewing was hired by Livesay in the summer of 1944 as Livesay's assistant. The IBM PCAM operators included:

Robert Davis	T/5 Jerome Doppelt
J. Elliott	Pfc. Hazel Gensel
T/4 Samuel Goldberg	T/4 Alfred Heermans
T/5 Alex Heller	T/4 Daniel Hurwitz
T/3 John Johnston	T/3 John Johnston
T/4 John Kemeny	T/4 Joseph D. Kington
Harold Ninger	Frances E. Noah
Sgt. Warren Page	Pfc. B.W. Pierson
T/5 Angeline Sniegoski	Pfc Ethel Taylor
T/4 Alan Vorwald	Pvt. Edith Wright
T/3 W. Douglas Zimmerman.	

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