Engineers, Psychologists, and Administrators: Control Systems Research in Wartime, 1940-45

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World War II transformed American technology, creating new machinery, new organizations, and new ideas. Industry, government, and university research emerged in 1945 as a well-organized national innovation system tuned to government funding, national defense, and mission-oriented research on an unprecedented scale. Vannevar Bush led this transformation, along with the wartime scientific agencies he created: the National Defense Research Committee (NDRC) and its successor and umbrella organization, the Office of Scientific Research and Development (OSRD). The research these groups directed led to the atomic bomb, radar, operations research, and a host of other technologies that define our modern world.[1]

Curiously, however, outside of these famous efforts the NDRC's operations remain relatively unknown. Yet its work on fire control is of particular interest for the history of control systems and provides a unique window on the transforming relationships between industry, academia, and government. This article surveys the scope of the NDRC's research contracts in control systems and examines the more significant projects. Along with the knowledge, machinery, and experts they created, these projects contributed to a rich period of control engineering. Studying them also uncovers often overlooked aspects of the history of information systems and computing. Historians have discussed a few of the NDRC's control systems projects (particularly those of Norbert Wiener and George Stibitz), but not as part of an overall research program [2]. Seeing these projects in their organizational context places them in historical perspective and reveals the role of feedback, control, and human/machine interfaces in the development of automation and information processing.

From the beginning, Bush considered control systems for guns ("fire control") a central concern as he organized wartime research. In the spring of 1939, before Europe was at war, he grew alarmed about "the anti-aircraft problem." He wrote to his hero, the retired engineer-president Herbert Hoover, for help. As chairman of the National Advisory Committee on Aeronautics (NACA), Bush wrote that he saw the rapid progress aircraft were making toward higher speeds and greater altitudes. He also understood that such progress made them increasingly difficult, if not impossible, to hit with traditional gunnery methods. High-frequency radiation research at MIT and Stanford held promise as a way to detect and locate aircraft, he continued, but no one was coordinating the connection of such equipment into systems that could direct "the precise and rapid control of guns" [3]. Bush received no advice from Hoover, but he found support from other colleagues closer to home. He wrote to Frank Jewett, founder and president of Bell Labs, that his interest in national defense arose from both NACA work and "a private conviction that anti-aircraft is not receiving the attention it should have" [4].

With the outbreak of war in Europe in September 1939, international events dramatically demonstrated the airplane's central importance in modern warfare. In 1940, Bush proposed his idea for a council to coordinate defense research, much as the NACA coordinated aeronautics research. He wrote to President Roosevelt that, while the NACA "correlates military and civil research activities on aeronautical devices, no similar agency exists for other important fields, notably anti-aircraft devices" [5].

Initial Organization: Section D-2

On June 27, 1940, Roosevelt approved an order for the establishment of the NDRC and directed it to fund scientific research into military problems. The committee consisted of leaders in American science and engineering: Bush, Jewett (now also president of the National Academy of Sciences); James Conant, president of Harvard; Karl Taylor Compton, president of MIT; Conway P. Coe, Commissioner of Patents, Richard C. Tolman of Caltech, and one liaison each from the War and Navy departments, initially Maj. Gen. G.B. Strong and Rear Adm. Harold G. Bowen. This group tilted toward academia; NDRC work overall would heavily favor MIT. Jewett's Bell Labs, though the nation's top industrial laboratory at the time, also had a decidedly academic flavor. This bias would simultaneously be both the NDRC's strength and its weakness. Ph.D. scientists and engineers brought fresh ideas and a vigorous quantitative approach to military problems. But the professors and engineers were novices in fields in which many in the military and industry had already built careers. The eagerness of the NDRC's researchers could easily be taken as arrogance, both intellectual and organizational: Army and Navy laboratories, industrial contractors, and any number of government agencies sought to restrict their influence.[6]

Bush divided the NDRC into four divisions: Division A, armor and ordnance under Tolman; Division B, bombs, fuels, gases, and chemistry under Conant; Division C, communications and transportation under Jewett; and Division D, radar, fire control, and instruments under Compton. It also included the "Uranium Committee," which would later transfer to the Army and become the Manhattan Project. Division D divided into four sections: D-1 dealt with detection and radar, D-2 with fire control, D-3 with instruments, and D-4 with heat radiation.

Section D-2 took the lead on control systems [7]. To head it, Bush chose his colleague Warren Weaver. A mathematician and director of the Natural Sciences Division of the Rockefeller Foundation, Weaver was already funding the follow-on to Bush's differential analyzer at MIT (known as the "Rockefeller Differential Analyzer"). Weaver began in July 1940 and immediately invited Thornton C. Fry, Bell Labs' mathematical research director, and Samuel H. Caldwell to join as members of D-2. Caldwell, the head of MIT's center for analysis, had been Bush's graduate student and collaborated with him on the differential analyzer. Edward J. Poitras, another MIT engineer, had been working on naval fire control at the Ford Instrument company and joined as chief technical aide. The section held its first meeting in Hanover, NH, in September 1940, when the members were already in town for a meeting of the American Mathematical Society [8].

Section D-2 immediately began getting up to speed on fire control problems. The Navy had been developing its own fire control technology for several decades and had generated a set of industrial contractors and fire control officers (within the Bureau of Ordnance) as a secretive and closed technical community. Weaver and D-2, therefore, concentrated on the Army's problems of land-based anti-aircraft fire, especially for heavy anti-aircraft artillery. The Sperry Company had worked on mechanical computers for this purpose for 15 years, but their machines were only marginally satisfactory and the company was having difficulty with large-scale production [see this column, April 1995]. Weaver and the section members spent several months visiting military facilities, academic labs, and industrial facilities, including MIT, the Army's Aberdeen Proving Ground, the Coastal Artillery Board, the Naval Gun Factory, the Naval Research Lab, RCA, Bell Labs, the Sperry Company, and a host of others. They spoke to military users, academic scientists, and industrial engineers, trying to understand the problems of fire control and how scientific and engineering research might contribute solutions.

After several months of study, at an October meeting Weaver outlined critical areas and assigned responsibilities. Fry would coordinate systems, statistical analyses of errors, and research in servomechanisms. Caldwell and Poitras would investigate electrical analogs for mechanical computers and servomechanisms. The whole committee would look at problems of optical rangefinders, evaluate rangefinder operators, perform efficiency studies of manual procedures in loading guns, and improve instruction books for anti-aircraft systems. The individual members would not perform this work themselves, but rather let and supervise research contracts to other organizations.[9]

In November 1940, section D-2 began letting contracts for research in control. It was still more than a year before Pearl Harbor, but the country's scientists and engineers were already mobilizing. The shock of Dec. 7, 1941, is barely visible in the NDRC's working documents; by that point its members had been on a wartime footing for many months. Before the Japanese strike, few had questioned the need for anti-aircraft defenses, but few also had found it urgent. Afterward, the fear of air attack was etched into American consciousness.

Division 7 and Its Management Style

Within a year of its founding, the NDRC had spent more than $6 million (it would spend more than $500 million between 1941 and 1946), and had grown to such a size and complexity that it needed reorganization [10]. In June 1941, an executive order created the OSRD, which incorporated the NDRC along with a number of other committees, including one for medical research. NDRC's responsibilities expanded to include development of actual equipment (and pilot production in some cases) as opposed to only basic research, and it restructured into a number of different divisions. Later that year Section D-2 became Division 7, still responsible for fire control (other divisions included ballistics, missiles, subsurface warfare, and electrical communication). Weaver moved to head the newly-created Applied Mathematics Panel, which collected mathematicians to provide analysis services to the divisions.

Harold Hazen, head of the Electrical Engineering Department at MIT, former Bush graduate student, and author of two landmark 1934 papers on servomechanism theory, became the head of Division 7 [11]. Division 7 itself divided into a number of subsections. Their organization reflects how far the complexity and variety of fire control problems had come in the year since Weaver's initial assignments:

7.1 Ground-Based Anti-Aircraft Fire Control

7.2 Airborne Fire Control Systems

7.3 Servomechanisms and Data Transmission

7.4 Optical Range Finders

7.5 Fire Control Analysis (a connection to Weaver's Applied Mathematics Panel)

Late in the war, Section 7.6, Navy Fire Control with Radar, was added to serve as a liaison with the Radiation Laboratory [12]. The division membership expanded to include Preston R. Bassett, president of the Sperry Company, Duncan Stewart, president of the Barber Coleman Company, and Ivan Getting of MIT's Radiation Laboratory. Also associated with Division 7 in various capacities were Samuel Fernberger, University of Pennsylvania psychologist, Karl Wildes, MIT electrical engineering professor, George Stibitz, developer of relay computers at Bell Labs, George Philbrick of the Foxboro Company, Charles Stark Draper and Gordon Brown of MIT, and J.R. Ragazzini of Columbia, among many others [13].

For five years, D-2 and Division 7 supervised the research and development of control systems applied to wartime problems. Weaver, Hazen, and the group developed their own methods of operating distinct from those of other divisions. Division 14 (radar), for example, concentrated all its resources in a single institution, the MIT Radiation Lab (the most expensive NDRC project). Division 14 members served only as contract administrators; the technical work occurred exclusively at MIT and its subcontractors. In contrast, Division 7 took a more hands-on approach, acting in Hazen's words as "a closely knit group of experts ... studying, analyzing, and formulating service needs in terms of possible projects, then obtaining and directing contractors in the carrying out of such projects" [14]. Its members often took to the road supervising contracts, observing demonstrations, and meeting with military services. Every month or so the division would meet to discuss projects, report progress, solve problems, and discuss technical direction.

Division 7 projects originated in several ways. Sometimes the services requested work on a difficult problem. Sometimes they turned over existing research projects for the NDRC to administer. Others arose when committee discussions pointed to a promising or neglected path of inquiry. Sometimes contractors made proposals of their own. Often ideas came up informally, with preliminary arrangements made through personal contacts of members [15].

To foster innovation, Division 7 members also played an infrastructural role, transferring information, techniques, and equipment between the contractors, the services, and the other research groups. Yet the wartime climate constantly opposed technology diffusion. Division 7 often confronted military secrecy, proprietary industrial knowledge, and lack of cooperation between the Army and the Navy. These struggles could get rather heated, because despite their large budgets and frenetic activity, Division 7 and the NDRC controlled only a portion of wartime research in this country. Government laboratories and industrial firms carried on their own relationships with the services; companies and universities worked together as well; turf battles often ensued. The Sperry Company, for example, a prewar leader in military controls, made no contracts with Division 7—Sperry already had a relationship with the army and was funding research at MIT (by Draper and Brown) under a Navy project [16]. Even within the NDRC, Division 7 had to negotiate with other divisions for authority over radar control systems. Weaver wrote to Alfred Loomis, for example, director of Division 14 (responsible for the Radiation Lab), outlining his desire for "a reasonably definite understanding of the location of the fence between our two regions of activity [control systems and radar systems]," although "a wire fence, through which both sides can look and a fence with convenient and frequent gates" [17]. Relations with the Radiation Lab would constantly be strained by new projects.

Overview of Contracts

Among Bush's innovations as an administrator, the "research contract" may have had the greatest and longest-lasting impact. Where traditional government procurement practice dictated the delivery of some physical equipment or even piece of paper, "instead, the research contract assumed that the end item was research and development itself." NDRC contracts freed wartime research from the strictures of procurement and assured a free and flexible control of money. To safeguard this separate sphere, Bush consistently resisted requests from the military for the NDRC to produce the machines it designed (except for small, temporary, and urgent runs). Preferably NDRC contractors (companies or universities) would turn production blueprints over to another organization when research contracts finished. These arrangements also allowed scientists and engineers to remain in the employ of universities or companies rather than go into the military. Even more important, the government would pay the *full cost of research*, which included not only equipment and salaries, but also indirect costs, the now-famous factor of *overhead*. Thus contractors could sign on to government research with no additional financial burden, a system which remains the cornerstone of government-funded scientific research today. In historian Hunter Dupree's words, "the contract was the device by which the universities and industrial research laboratories were preserved as institutions even while their social role was temporarily but radically changed" [18].

During its tenure, D-2 and Division 7 let 80 contracts totaling a bit more than \$10 million [19]. Their character and distribution reveal much about the technological landscape of the time and how it shaped the development of control systems. Twenty-nine contracts went to academic institutions, the remaining 51 to industrial firms or laboratories. The largest contract cost \$1,273,000 (Bell Labs' gun director work) and the smallest \$2,000 (mostly support for Norbert Wiener's research assistant, Julian Bigelow), the mean being about \$145,000. The longest lasted nearly five years, the shortest four months, and the average about two years. More than half of Division 7's contracts went to institutions along the East Coast of the United States, the remainder being mostly concentrated in the Midwest and California. Most of the contracting organizations remain familiar today: Western Electric/Bell Labs, MIT, Caltech, Princeton, the Franklin Institute, Eastman Kodak, Polaroid, Foxboro, RCA, Bausch and Lomb, Bristol, and Leeds and Northrup, to name but a few.

The division tried to be scrupulous about only funding work that showed promise of demonstrable results before the end of the war or within five years. A number of these contracts produced significant results and were consistently extended. Others showed no promise and were unceremoniously terminated. Many completed their work successfully and ended. Several created important machines that went into production as fire control devices. More often contracts produced prototypes, pilot studies, and reports. A number of projects had been initiated redundantly as "insurance" against the failure of larger, more central efforts. When the primary approaches succeeded, the backup designs were not needed.

The Projects

A Systems Approach

"One must always remember that a fire-control system is more than the sum of component parts," wrote Harold Hazen. "It is an integrated whole with interrelated functioning of all its parts and one is safe in considering the parts separately only if one always keeps in mind their relation to the whole" [20]. In the years before the war, anti-aircraft fire control had been taking shape as a system, and the NDRC completed that formulation, taking a "systems approach" to organization, contracts, and engineering.

Anti-aircraft systems sought to shoot down attacking bombers, which required computing a "lead" based on the direction and velocity of the plane, adding the ballistics of the shell, and aiming the gun in azimuth and elevation. For close-in attack or airborne operations, simpler "lead computing sights" performed prediction for smaller guns. When the NDRC began operations, the components of the system had been fairly well defined (Fig. 1). Input devices, in the form of optical rangefinders and tracking telescopes, provided range, bearing, and elevation of the target. As the war progressed, radar took over these functions, at first just for rangefinding and later for actual active tracking. A central computer or "gun director" integrated these data with settings for wind,

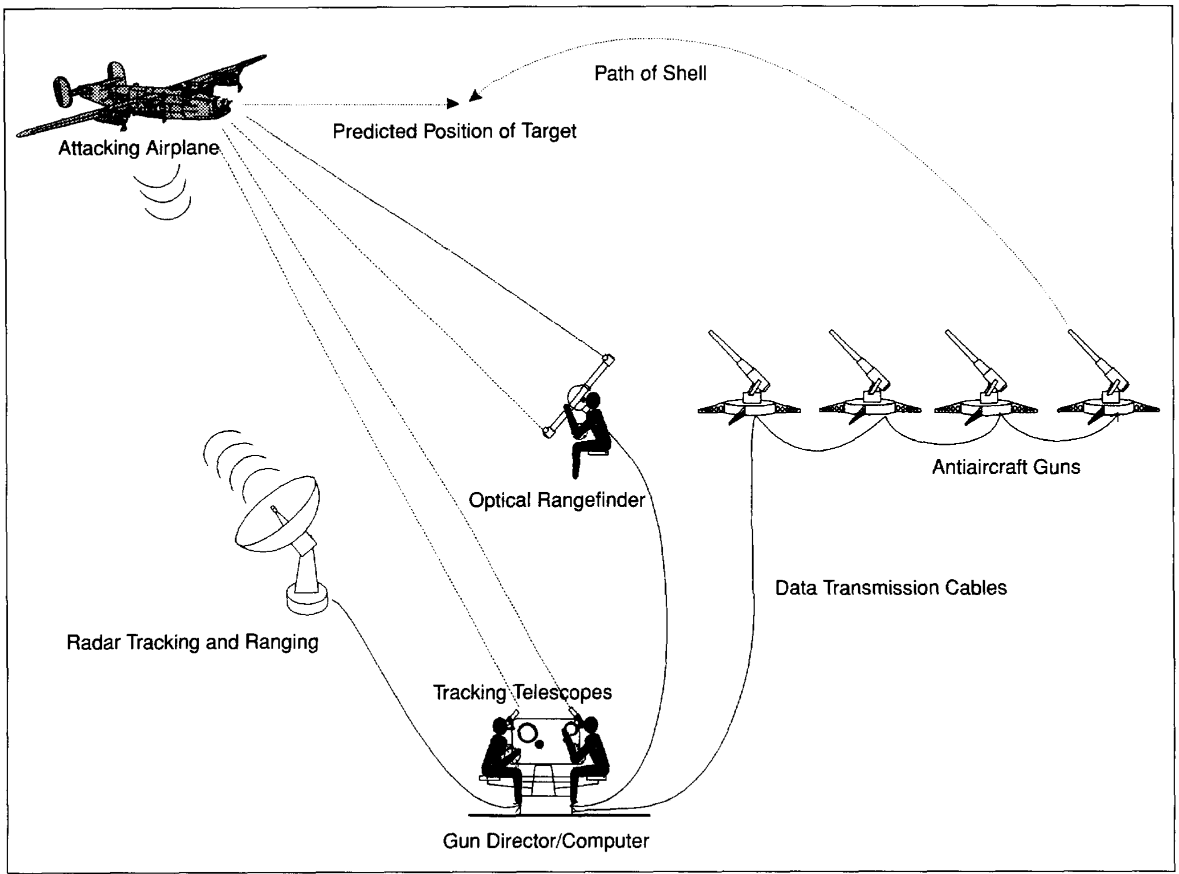

Fig. 1. Schematic representation of anti-aircraft system elements.

terrain, and predetermined ballistics, which depended on the particular gun and shell. The director predicted the future location of the target based on its speed and direction and calculated an output azimuth and elevation for aiming the guns as well as a fuze setting (the time after firing when the shell would explode). These data were transmitted to the guns, which pointed automatically with hydraulic or electric power controls or manually based on "follow-the-pointer" indicators.

Of the 80 projects D-2 and Division 7 funded, more than 60 addressed aspects of this type of anti-aircraft system. Some built individual components, some worked on interconnection, some studied the human operator, and some studied theory or performed "system engineering" (a term not used at the time). Most projects addressed the Army version of the problem; some added speed, pitch, and roll sensors to perform similar functions aboard Navy ships. The remaining projects concerned gun controls for airplanes, torpedo and rocket directors, regulators and governors, and bombing and bombsights (a bombsight is the reciprocal of an anti-aircraft computer), and guided bombs.

Input: Ranging and Tracking

On the input side, Division 7 put a great deal of effort into improving optical rangefinders. Eastman Kodak and Bausch and Lomb studied improved optics and geometries for ranging devices. Filling the devices with helium, for example, reduced the optics' susceptibility to temperature variations. Other sources of error included haze, camouflage on targets, low light levels, and misalignment and bad calibration. One company studied methods of combining rangefinding and tracking functions into a single device. Other studies considered optical design, reticule patterns, illuminated reticules, and eyepieces.

Of course radar effected the most important change in aircraft tracking. Bell Labs developed the SCR-547 radar for ranging, nicknamed "Mickey" because its separate parabolic antennas for send and receive gave it the look of mouse ears. This device determined range only, and needed to accompany telescope tracking. Later, full tracking radar (the Radiation Lab's SCR-584) would drive gun director inputs and supersede the range-only devices.

Operators and the Human/Machine Interface

Harold Hazen expanded his vision of the system to include the human operator. After observing an Army demonstration, he wrote, "The idea struck me more and more forcefully that we should know as much as possible of the dynamic characteristics of the human being as a servo and therefore his effect on the dynamic performance of the entire control system." While D-2 and others were studying some aspects of human performance already, they sought only training methods and personnel selection criteria. Hazen suggested studying the human operator "as an integral component of an automatic control system" during the development and design process [21]. His colleagues received this idea with enthusiasm, and it spawned seminal studies on what today we would call "human factors in automation."

This work put what had previously been an ad hoc informal process, namely matching the capabilities of the human to the characteristics of the machine, onto a solid scientific and psychological foundation. Psychologists at Brown University, Harvard, Ohio State, Tufts, and Princeton studied fire control for Division 7, part of a larger pattern of social scientists contributing to the war effort [22]. Seven contracts studied a broad array of psychological and physiological factors in rangefinding performance. Computer innovator John Atanasoff, for example, conducted experiments at Iowa State College. He proposed using small knobs instead of handwheels for tracking to achieve finer control with finger muscles than would be achievable with coarser hand and back movements. Studies at the Foxboro Company examined the effects of inertia, friction, and gear ratio on hand and foot controls, as well as the effectiveness of data displays. One battery of tests tried to determine the effects of diverse factors on operator performance including gender, exercise, practice, stereo acuity, pupil size, startle, bells and loud noises, electric shocks, and drugs. All except fatigue produced negative results, showing no effects on ranging or tracking. Some work sought standards for selection of rangefinder operators including height, vision, intelligence, mechanical ability, interpupillary distance, and coordination.

The strangest of these human performance studies gave new meaning to the concept of stability in a control system: psychologists searched for ways to determine if an individual would become "emotionally unstable" under fire. Division 7 brought five British seamen who operated fire control equipment to the United States. Two of these men had "broken up" in combat off Crete and the remainder had stayed at their positions under fire. Without being told who was who, researchers tried to develop tests to distinguish the "stable" and "excellent" men from the unreliable ones. Psychiatric evaluations, Rorschach ink-blot tests, ophthalmological exams, electric shocks, and a number of other scientific indignities all failed to detect which of the men had "broken" [23].

Output Devices and Servomechanisms

To improve the system's output, Division 7 let 16 contracts for investigations in servomechanisms. Harold Hazen had led the field in the '30s and his former student Gordon Brown, now on the faculty, was continuing his work at MIT. Among the first actions of D-2 was to ask Brown not to publish his paper "Behavior and Design of Servomechanisms." D-2 deemed it "confidential" instead and published it under the auspices of the committee, for controlled distribution only [24]. In recognition of Brown's leadership in the field, however, almost as a consolation for classifying his paper, D-2 let its first contract to MIT for the establishment of the "Servomechanisms Laboratory" under Brown. With this and subsequent contracts, the laboratory developed a number of important servos, including power drives for the Army's 37mm and 40mm guns. Brown finally published his paper at the end of the war, developed considerably further into a textbook. Division 7 supported other control theorists at MIT, including A.C. Hall and Herbert Harris. This work, along with that of Bell Labs, began to merge the servomechanism theory of electromechanical systems with the feedback amplifier theory of communications.

Computing and Systems Integration

The computer or "gun director" tied the individual fire control elements into a system, and much of D-2 and Division 7's effort went into computers for these machines. Whereas pre-war directors had been purely mechanical, Bell Labs built an electrical director, based on telephone feedback amplifiers and a novel set of custom potentiometers to solve equations. [This project will be the subject of another article in this series.] Initially, the Army liked electrical computers less for performance reasons than because they were easier to manufacture than mechanical devices and did not require scarce precision-machining production capacity. The Army accepted the device for production almost immediately, designating it M-9. When integrated with radar, hydraulic-controlled guns, and the proximity fuze, the M-9 formed the core of a fully automated anti-aircraft system. It proved particularly successful late in the war against the V-1 "buzz bombs," whose straight and level flight and lack of evasive action made them vulnerable to the M-9's linear prediction method. This little-known confrontation of automated weapons in 1944 prefigured the cybernetic battlefield envisaged during the Cold War (and as recently as the Gulf War). Under six Division 7 contracts, Bell Labs and other NDRC contractors designed and studied a number of successors to its M-9 based on alternate coordinate systems, different prediction methods, and new data-smoothing techniques.

But the first time a radar connected to a gun director the system nearly shook itself apart because of noise. Electrical systems required special attention to noisy signals, and to the problem of "smoothing," whether corrupted radar signals or jerky manual tracking inputs. Differentiating noisy tracking data to determine rates proved particularly difficult. Hazen described the electrical situation this way: "Imagine operating ... in a field service environment, microamp currents and megohm impedance levels, where a little moisture is fatal" [25]. Bell Labs researchers, especially Claude Shannon, Henrik Bode, and R.B. Blackman, viewed data smoothing as a problem in communications engineering, "since data smoothing is evidently a special case of the transmission, manipulation, and utilization of intelligence," thus sowing the seeds for information theory [26].

Furthermore, the problem of smoothing connected intimately to that of prediction. Most gun directors predicted the future position of the target by linearly extrapolating velocity. But when attacking pilots took evasive action, how could the machine lead the target? MIT's Norbert Wiener took a statistical approach to this problem, building a "prediction machine" as a demonstration and writing several important papers [27]. But Wiener's work was too theoretical to be of any use for the war: his optimal prediction scheme offered only slight advantage over techniques already in use [28]. Bell Labs' engineers recognized the value of Wiener's work but rejected its statistical approach in favor of "solutions couched entirely in electrical language" [29]. Still, Wiener's fire control research shaped his later work on cybernetics [30].

Testing and Computers

No aspect of the NDRC's work on fire control exemplified the systems approach more than testing. Earlier anti-aircraft technology programs had no means of quantitatively comparing the performance of different machines. A considerable amount of debate would surround any new device as to whether it worked better than older models, or even whether it worked at all. Understanding fire control as a system, however, meant seeing its components as "black boxes" with inputs that could be simulated and outputs that could be measured. NDRC researchers at the Barber Coleman Company built a "dynamic tester" that automatically controlled the inputs of a director, actually connecting servos to the handwheels, to determine the system's response. A set of machined cams programmed the tester, and changing the cams could program different flight profiles. The cams' motion simulated the input of ideal operator who perfectly tracked a target. A data logger recorded the output—allowing derivation of the system's transfer function. George Stibitz of Bell Labs thought to replace the cams with punched paper tapes which were less expensive and easier to program. He built the "Tape Dynamic Tester," otherwise known as the Model II Relay Computer, which generated servo outputs from flight profile tape inputs.

Creating the tapes themselves, however, required a significant amount of calculation. Stibitz designed another relay computer to ease this process, the "Relay Interpolator." Taking as input a few key points, this machine produced all the intermediate points on a tape for input to the tester. A third Stibitz machine, the "Ballistic Computer" (the Model III), created ideal outputs against which to compare the measured data. The latter two of these machines remained in government service until 1961 and 1958, respectively [31].

Testers allowed quantitative comparison of existing and new gun directors. These machines exposed fundamental flaws in several pre-war directors and provided a rigorous test for many new and complex computation schemes. They confirm historian Edward Constant's view of test rigs as often "themselves major technological achievements" [32]. While Stibitz's relay computers have been called milestones in computer history, their relationship to machine control has not been explored: programming machine movements by digital program tapes anticipated the development of numerically controlled machine tools. In 1941, in fact, Division 7 member Duncan Stewart asked Stibitz about the possibility of using his Tape Dynamic Tester to perform automatic milling for commercial applications, and the device was used to mill cams for later testers [33].

Paths Not Taken

In addition to the projects Division 7 undertook, we should also consider those it rejected, several of which offer insight into the NDRC's style of research. When the NDRC formed, television pioneer Vladimir Zworykin of RCA had been working with his colleague John Rajchman under a Navy contract to investigate electronic computing techniques for fire control [34]. They considered all types of electronic computing but were making progress in "computing devices in which variables are represented by discrete impulses," i.e., digital techniques [35]. In 1942, at the Navy's request, the NDRC took over funding this project. Zworykin and Rajchman concentrated their effort on "coders," or electromechanical analog-to-digital converters, and a "computron," a vacuum tube which incorporated elements for a 10-bit counter into a single tube. Warren Weaver, however, saw no immediate applications for digital electronic fire control computers. They promised greater accuracy than existing analog machines, but analog computers in development were already more accurate than the other parts of the system, including tracking equipment, power controls, and the guns themselves. Furthermore, practical digital machines did not seem likely by the end of the war. In 1942, then, the NDRC dropped RCA's digital computing project. Still, Weaver did recognize the scientific potential and importance of this work, writing to Zworykin of his "lively personal and scientific interest in seeing this computron project continued to its successful conclusion" [36]. Weaver and Hazen tried to find other NDRC divisions willing to support the project, but to no avail [37].

Another project Division 7 turned down became an important early computer. The Moore School of Electrical Engineering at the University of Pennsylvania had built a copy of Bush's differential analyzer in the 1930s. During the war, the Moore School operated the machine full-time under direct contract to the Ballistics Research Laboratory (BRL) at the Army's Aberdeen Proving Ground. Aberdeen's need for ballistics data was so great, and its computational facilities so pressed, that Division 7 let a contract to the school to refine its machine to increase throughput [38]. Based on this analog computing experience and some project work with MIT's radiation lab, the Moore School staff, including J. Presper Eckert and John W. Mauchly, put together a proposal for an "electronic numerical integrator and calculator" to do ballistics calculations [39]. This project would become famous as ENIAC, the first electronic digital computer (although not a stored program machine). Harold Hazen, however, did not think ENIAC could become operational before the end of the war (assumed to be within five years). Furthermore, the new Rockefeller Differential Analyzer was just coming on line at MIT and it would work full time to help BRL relieve its calculation burden [40]. Hazen, as an MIT professor and Bush disciple, had a clear institutional stake in the success of the Rockefeller machine. Division 7 decided not to fund the ENIAC project, which BRL then supported independently [41].

Some historians have argued that the conservatism of the NDRC leadership, combined with their devotion to analog computing, blinded them to the value of digital techniques [43]. But we should also see Division 7's interest (or lack thereof) in computing in the context of its overall work on fire control. Weaver and Hazen did not fund generic technology research; they rather explored all avenues that would get them closer to a pressing, immediate, and short-term goal. Division 7 routinely turned down promising projects with greater than five-year time horizons (indeed, ENIAC did not become operational until the war was over). Weaver and Hazen certainly saw the scientific and intellectual value of digital computing research; they expressed sincere regret at not funding the RCA project, and their efforts to find it another sponsor are well documented. But by 1943 fire control moved out of a period of radical innovation and into a period of refinement, incremental improvement, and system integration. The systems approach dictated that other elements in the system simply could not benefit from more accurate computing. Short-term military applications required reliability, ruggedness, and compactness, characteristics a decade away in digital computing. Such a view does not diminish but rather underscores the radical nature of the early proponents' faith in digital techniques, despite great difficulties in reliability, size, and complexity. These problems, however, made digital computing unsuitable for Division 7 support. The failure to pursue such work, despite recognition of its scientific importance, points to the limitations of the wartime research paradigm, focused on short-term results and practical devices rather than basic research [43]. Wartime research in control systems achieved success, but within, and perhaps because of, the narrow goals it defined for itself.

Division 7 Shuts Down

The NDRC was meant to be temporary, and with the close of the war it ceased operations. Research contracts terminated and closed out; only one survived, transferred to the Navy for completion. Each project concluded with a report. A three-volume synopsis is part of a 70-volume *Summary Technical Report of the NDRC* [44]. In addition, more than 350 papers from D-2 and Division 7 were published on microfilm.

Based on his work for Division 7, Wiener, in 1948, published *Cybernetics.* This famous book popularized what historian of science Peter Galison has called the "cybernetic vision" of human/machine integration [45]. Many also have noted Wiener's creation of this vision out of his prediction work and his interests in biology. But a broader view sees Wiener as part of a community of "cybernetic" thinkers who themselves built on earlier visions of human/machine interactions. Through their explorations of feedback, machine control, and human operators, this group shaped our conception of information and systems. Several NDRC control researchers went on to contribute their own "cybernetic visions" in ways parallel to but distinct from Wiener's own. Claude Shannon, for example, studied both fire control and cryptography at Bell Labs. He synthesized the two fields, machine control and messaging, in his 1948 paper "A Mathematical Theory of Communication" [46]. Bell Labs also incorporated the M-9 director's analog computing technology into its guided missile systems (including Nike-Ajax and Nike-Hercules), and other Cold War projects [47]. During the late '40s and early '50s, the Servomechanisms Lab at MIT built the real-time control computer Whirlwind, which grew into the SAGE air defense system, prototype of Cold War large-scale command and control systems. Jay Forrester, who was trained on NDRC projects in the Servo Lab, led this project and eventually introduced his own "cybernetic vision" into the social sciences in the form of Systems Dynamics. Others, including those at the Moore School, in the services, at Polaroid, Barber-Coleman, and Foxboro, similarly shaped their own worlds out of their wartime work in control, automation, and systems.

The NDRC's research program developed new methods of control engineering as it underwent a transformation in science and technology. D-2 and Division 7's systems approach included a conception of people as integral, dynamic elements of control systems, which paralleled a conception of technology as an integral, dynamic component of political and military power. Engineers, psychologists, and administrators explored and articulated the complex corollaries of systems thinking: the integration of humans and machinery, the linkage of institutional and technical systems, the interdependence of technology and government. These tense pairings became both more anxious and more critical in time of war.

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Notes

[1] James Phinney Baxter, *Scientists Against Time* (Boston: Little Brown and Co., 1946). Also see Henry Guerlac, *Radar in WWII* (New York: Tomash Publishers/American Institute of Physics, 1987). Richard Rhodes, *The Making of the Atomic Bomb* (New York: Simon and Schuster, 1988), Daniel J. Kevles, *The Physicists: The History of A Scientific Community in Modern America* (Cambridge, Mass.: Harvard University Press, 1971).

[2] See, for example, Peter Galison, "The Ontology of the Enemy: Norbert Wiener and the Cybernetic Vision," *Critical Inquiry* 21 (Autumn 1994), pp. 228-266. Paul Ceruzzi, *Reckoners: The Prehistory of the Digital Computer* (Westport, Conn.: Greenwood Press, 1983).

[3] Bush to Hoover, April 10, 1939, and April 29, 1939. Bush Papers, Library of Congress.

[4] Bush to Jewett, March 23, 1939. Jewett folder, Bush file, Carnegie Institution of Washington records, quoted in Carroll Pursell, "Science Agencies in World War II: The OSRD and Its Challengers," in Nathan Reingold, ed., *The Sciences in the American Context: New Perspectives* (Washington: Smithsonian Institution Press, 1979), 360.

[5] Draft Memorandum, n.d., Office of Scientific Research and Development papers, National Archives Record Group 227, Central Classified File, Organization, Washington, D.C.

[6] Pursell, "Science Agencies in World War II."

[7] For the official history of D-2 and Division 7, see Joseph C. Boyce, *New Weapons For Air Warfare: Fire-Control Equipment, Proximity Fuzes, and Guided Missiles* (Boston: Little Brown and Company, 1947), Chapters III-IX. The sources for these chapters are the personal histories written by the section members for Boyce in National Archives Record Group 227, Division 7 (hereafter referred to as OSRD7), General Project Files, History File.

[8] At this A.M.S. meeting, George Stibitz of Bell Labs demonstrated the remote operation of his relay computer over a telephone line to New York, credited as the first instance of telecomputing. Fry was Stibitz's research director for the project, and the demonstration was attended by Norbert Wiener and John Mauchly, among others, probably including the members of section D-2.

[9] Diary of Section D-2 meeting, October 16, 1940. OSRD7, General Project Files.

[10] Irvin Stewart, *Organizing Scientific Research for War: The Administrative History of the Office of Scientific Research and Development* (Boston: Little Brown and Co., 1948), 322.

[11] For Hazen's contributions to control systems, see Stuart Bennett, "Harold Hazen and the Theory and Design of Servomechanisms," Int. J. Control 42 (no. 5, 1985), 989-1012. Bennett's chapter, "Theory and Design of Servomechanisms" in A History of Control Engineering, 1930-1960 (London, IEE Press, 1993), presents a similar discussion.

[12] Stewart, *Organizing Scientific Research For War,* 12.

[13] For a full listing of Division 7 members, consultants, and technical aides, see United States Office of Scientific Research and Development National Defense Research Committee, Summary Technical Report of Division 7, NDRC Volume I: Gunfire Control, (Washington, DC: 1946), 168-169.

[14] Hazen to Stewart, Jan. 31, 1946. National Archives RG 227, Office files of Harold Hazen. This letter was Hazen's personal history of Division 7 for Stewart's Organizing Scientific Research for War.

[15] Ibid.

[16] Warren Weaver diary, Aug. 20, 1942. OSRD7, General Project Files.

[17] Weaver to Loomis, Dec. 10, 1940. OSRD7, General Project Files.

[18] A. Hunter Dupree, "The Great Instauration of 1940: The Organization of Scientific Research for War," in Gerald Holton, ed., *The Twentieth-Century Sciences: Studies in the Biography of Ideas* (New York: W.W. Norton and Co., 1970), 459. See also Stewart, *Organizing Scientific Research for War*, Chapter XIII.

[19] General information on Division 7 contracts comes from OSRD7, General Project Files. Financial information is from the NDRC index card file, National Archives Record Group 227, Index to Contracts.

[20] Harold Hazen, "Fire Control Activities of Division 7, NDRC" in United States Office of Scientific Research and Development National Defense Research Committee, *Summary Technical Report of Division 7, NDRC Volume I: Gunfire Control*, 4. Stuart Bennett has noted the "systems approach" in his comparison of British and American fire control work during the war in *A History of Control Engineering: 1930-1960*, 125.

[21] Harold Hazen memorandum to Warren Weaver, "The Human Being as a Fundamental Link in Automatic Control Systems," May 13, 1941. OSRD7, Office files of Warren Weaver.

[22] For an overall view of social sciences in World War II, see Peter S. Buck, "Adjusting to Military Life: The Social Sciences Go to War 1941-1950" in Merritt Roe Smith, ed., *Military Enterprise and Technological Change: Perspectives on the American Experience* (Cambridge: MIT Press, 1987) pp. 203-252.

[23] Report from Project 10 (Tufts College) to the NDRC, "Experiments with British Seamen," OSRD7, General Project Files. Also see *Summary Technical Report of Division 7, NDRC Volume III: Rangefinders and Tracking*, pp. 126-7.

[24] Gordon Brown, "Behavior and Design of Servomechanisms," OSRD 39, Report to the Services 2, The Massachusetts Institute of Technology, November, 1940.

[25] Harold Hazen interview with Marc Miller, March 2, 1977. "Computers at MIT" Oral History Collection, MIT Archives.

[26] R.B. Blackman, H.W. Bode, and C.E. Shannon, "Data Smoothing and Prediction in Fire-Control Systems," in *Summary Technical Report of Division 7, NDRC Volume I: Gunfire Control*, pp. 71-143.

[27] Norbert Wiener, "The Extrapolation, Interpolation, and Smoothing of Stationary Time Series with Engineering Applications," Division 7 Report to the Services No. 19, OSRD No. 370, Massachusetts Institute of Technology, Feb. 1, 1942.

[28] Stuart Bennett, "Norbert Wiener and Control of Anti-Aircraft Guns," *IEEE Control Systems Magazine* (December 1994), p. 61.

[29] Blackman, Bode, & Shannon, "Data Smoothing and Prediction," 73.

[30] Norbert Wiener, *Cybernetics or Control and Communication in the Animal and the Machine* (Cambridge: MIT Press, 1961), P. Masani and R.S. Phillips, "Anti-Aircraft Fire-Control and the Emergence of Cybernetics" in *Norbert Wiener: Collected Works with Commentaries*, ed. Masani, 4 vols. (Cambridge: MIT Press, 1985), 4:141-79.

[31] M.D. Fagan, ed., *A History of Engineering and Science in the Bell System: National Service in War and Peace (1925-1975)* (Bell Telephone Laboratories, 1978), 168-70.

[32] Edward W. Constant II, *The Origins of the Turbojet Revolution* (Baltimore: The Johns Hopkins University Press, 1980), 21.

[33] Stewart to Stibitz, June 18, 1941. OSRD7, Office Files of George Stibitz.

[34] J.A. Rajchman, G.A. Morton, and A.W. Vance, "Report on Electronic Predictors for Anti-Aircraft Control," April 1942 in Brian Randell, ed., The Origin of Digital Computers: Selected Papers (New York: Springer Verlag, 1982), pp. 345-348.

[35] "Recommendation for Appropriation," July 1, 1942. OSRD7, General Project Files.

[36] Weaver to Zworykin, Nov. 11, 1942. OSRD7, General Project Files.

[37] Hazen to Klopsteg, Feb. 6, 1943. OSRD7, General Project Files.

[38] Contract OEMsr-856, "Improvement of Differential Analyzers," Nov. 1, 1942. OSRD7, General Project Files.

[39] John G. Brainerd, "Genesis of the ENIAC," *Technology and Culture* 17 (no. 3) July 1976.

[40] Caldwell to Hazen, Oct. 23, 1943. OSRD7, Office Files of Harold Hazen.

[41] For a participant's account of ENIAC development, see H.H. Goldstine, *The Computer: From Pascal to von Neumann* (Princeton: Princeton University Press, 1972).

[42] Nancy Stern, "From ENIAC to UNIVAC," (Ph.D. dissertation, State University of New York at Stony Brook, 1978), pp. 45-54.

[43] It would take Vannevar Bush's 1945 report to the President, *Science: the Endless Frontier*, to add the crucial ingredient to the postwar research paradigm: government support of basic research.

[44] United States Office of Scientific Research and Development National Defense Research Committee, *Summary Technical Report.*

[45] Norbert Wiener, Cybernetics or Control and Communication in the Animal and the Machine (Cambridge: MIT Press, 1961). For the "cybernetic vision" see Galison, "The Ontology of the Enemy."

[46] C.E. Shannon, "A Mathematical Theory of Communication" *Bell System Technical Journal* 27 (July and Oct., 1948) 379-423, 623-656.

[47] Fagan, *A History of Engineering and Science in the Bell System*, 163.