NBER WORKING PAPER SERIES

THE WORLD WAR II CRISIS INNOVATION MODEL: WHAT WAS IT, AND WHERE DOES IT APPLY?

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Working Paper 27909
http://www.nber.org/papers/w27909

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
October 2020, Revised June 2022

We thank the editor (Paul Nightingale), four anonymous referees, Ashish Arora, Pierre Azoulay, Wes Cohen, and Scott Stern for helpful comments. We also thank participants at the 2020 NBER Summer Institute, 2021 NBER Entrepreneurship and Innovation Policy and the Economy workshop, and 2021 Strategy Science conference, and discussant Tarun Khanna. We are grateful to Harvard Business School and the NBER Innovation Policy grant (2016) for financial support. This material is based upon work supported by the National Science Foundation under Grant No. 1951470. All errors are our own. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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NBER Working Paper No. 27909
October 2020, Revised June 2022
JEL No. H12,H56,N42,N72,O31,O32,O38

ABSTRACT

World War II was one of the most acute emergencies in U.S. history, and the first where mobilizing science and technology was a major part of the government response. The U.S. Office of Scientific Research and Development (OSRD) led a far-ranging research effort to develop technologies and medical treatments that not only helped win the war, but also transformed civilian life, while laying the foundation for postwar innovation policy after it was dissolved. Scholars and policymakers have appealed to the wartime model as a template for other problems, often invoking the Manhattan Project rather than OSRD, which initiated and managed the broader effort of which atomic fission and dozens of other programs were a part. In this paper we bring OSRD into focus, describe how it worked, and explore what insights its experience offers today. We argue that several aspects of OSRD continue to be relevant, especially in crises, while also cautioning on the limits to generalizing from World War II to other settings.

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From war to disease to climate change, crises both natural and man-made have punctuated human history. Since crises present new problems, policymakers often turn to science and technology for solutions. The pressures of a crisis can be fertile ground for innovation, and few moments in history exemplify both the depth of crises and the power of science and technology more than World War II. Anticipating an eventual entry into the war, but fearing that the U.S. military was significantly behind the technological frontier of warfare, a group of prominent American scientists approached President Franklin Roosevelt in June 1940 with a proposal to create a National Defense Research Committee—later reorganized into the Office of Scientific Research and Development (OSRD)—to apply scientific research to military problems. Led by Vannevar Bush, OSRD quickly grew from a one-page proposal to a 1,500 person, multi-billion dollar federal agency engaging tens of thousands of scientists around the country in research to support the war effort.

OSRD developed a then-unprecedented approach to organizing crisis R&D, mobilizing American science and engineering to tackle problems that the wartime crisis presented, and produced major advances in technologies and medical treatments that not only helped win the war, but also transformed civilian life and innovation policy itself. In this paper, we examine how it did so, in an effort to identify the "OSRD model" of crisis R&D management and consider relevance for modern times. Although World War II has become the canonical reference for crisis innovation policy and other large, directed research projects, in these discussions it is often unclear precisely what features of the World War II model writers have in mind, or how they apply in other contexts. Moreover, that it is usually the Manhattan Project which is invoked as the wartime analogy (e.g., Alexander 2008, Navarro 2020), rather than OSRD more broadly, may reflect limited awareness of OSRD's role in the war or what lessons it may present for modern R&D policy.

A study of crisis R&D requires first understanding what a crisis is. Whether a given problem rises to the level of a 'crisis' is often subjective, but in our view, what makes crisis problems distinctive is their urgency.[1] In a crisis, losses can spiral out of control if a problem is not quickly contained. What also makes the World War II case distinctive, in our view, is the breadth of problems that needed research attention: far more than fission alone, it was that, plus other new weapons, remote detection (aircraft, ships, U-boats, rockets, torpedoes), electronic countermeasures, automatic fire control, radio communication, chemical engineering, reconnaissance photography, myriad military medical ailments and treatments, and dozens of other problems.

We begin the paper by reviewing how OSRD was organized and operated. In doing so, we distill several important features of the organization: its organizational design, including its organizational form and routines, which balanced structure with flexibility; and its operational approach to setting

[1] As we write in Gross and Sampat (2022a), crisis-driven R&D problems are "urgent, high-stakes, and often unanticipated." The most important feature for our purposes in this paper is urgency.

priorities, selecting researchers, providing incentives, coordinating across efforts and with end users, and translating research into practice. We bring these ideas to life with case studies of four specific OSRD research programs—radar, atomic fission, penicillin, and malaria—that illustrate the range of approaches OSRD adopted at the program level, while maintaining perspective on its role at the center of this portfolio. We then fuse features of the general model with specific insights from these examples to induce common principles and OSRD's underlying logic.

The crisis innovation agency, and its R&D management apparatus, was an invention of its own. When Roosevelt commissioned the NDRC (later OSRD) to undertake research on technological and medical problems to support national defense (Appendix Figure A.2), there was no precedent for large-scale government funding of research. The urgency of wartime problems forced resolutions to complex organizational problems, including the importance of speeding not only research but also downstream activities to get new technology into the field (Gross and Sampat 2021). As James B. Conant (President of Harvard, and a top OSRD administrator) wrote, "The basic problem of mobilizing science during World War II was [one] of setting up *rapidly* an organization or organizations which would connect effectively the laboratory, the pilot plant, and the factory with each other and with the battlefront" (Conant 1947). As we will see, this was far from straightforward, and OSRD's work grew to include not only R&D, but also diffusion.

OSRD faced a number of other challenges during its short existence, including battles between competing interests and occasional difficulties in its collaboration with the military branches, not all of which were successfully resolved. Yet on the whole, its effort is widely considered to have been successful, and its impact far-reaching. In the space of under five years, this effort produced major developments in a wide range of technologies including radar, computing, jet propulsion, optics, chemistry, and atomic fission, which later became the Manhattan Project. OSRD's Committee on Medical Research, the first serious government funding effort in the life sciences, helped support the mass production of penicillin, influenza and other vaccines, the malaria treatment chloroquine, new approaches to managing wartime hardships such as sleep and oxygen deprivation, cold temperatures, nutrient deficiencies, and psychological stress, and new techniques for treating injuries and wounds. Beyond its immediate impacts on the war and on science, OSRD also created the template for federal R&D procurement and laid the foundation for postwar science policy, and in recent research, we found that it also shaped the direction of U.S. innovation in the post-war period and catalyzed the growth of technology hubs around the country.

What can be learned from the OSRD approach to crisis R&D for modern problems? In *Science, The Endless Frontier*, Bush (1945) advocated an expansion of government support for basic research in peacetime, partly on the grounds that existing basic knowledge had been essential to OSRD's work, but he did not point out specific lessons from OSRD for crises or other large R&D problems, nor endorse the OSRD approach in other settings. Though many of Bush's recommendations were not adopted, a large set of research policy institutions subsequently blossomed. None quite mimics OSRD, despite Bush's claiming, shortly after the war, that it provided a "richly suggestive guide for other undertakings" (Bush, as quoted in Stewart 1948).

We use this opportunity to probe the relevance of OSRD's model in other settings. A basic point we emphasize is that despite the Manhattan Project being a common (though, per Mowery et al. 2010, often flawed) touchpoint for wartime approaches to big problems, OSRD is in some cases a better analogy, especially in its breadth. This is arguably true for the climate change R&D problem, though still it is different in key ways. We believe the OSRD approach may be most relevant to acute crises, a point which the COVID-19 pandemic brought into relief: when COVID emerged, dozens of new problems needed research. The U.S. government response, however, took a narrower approach focused on vaccine development, and though it was successful in its aims, we argue it may have benefited from a more sweeping attack, with a single OSRD-like organization managing a broader portfolio and correlating efforts from the center.

That being said, we also live in a different environment: the modern innovation system is far more developed today than it was in 1940. The decentralized approach to COVID problems may reflect where capabilities reside. Several of OSRD's key features have already been incorporated into the U.S. and global innovation system, in part due to its direct institutional legacies and in part to the influence of *Science, The Endless Frontier*. Yet it is also clear there is no OSRD-like agency in the current institutional arrangement, and if history is a guide, there are times when such an approach may be warranted, beyond a "new Manhattan Project" alone.

Our goal is thus to understand the history and explore its modern relevance and the limits thereto. In reconstructing OSRD's history we in part rely on narratives of people involved, whose accounts are on the one hand the most direct evidence available, yet on the other may not be fully objective due to the authors' own policy agendas in OSRD's memorialization (Kevles 1977a). Although we believe the available primary and secondary evidence enable us to synthesize the key features of the OSRD model, firsthand accounts warrant cautious reading.

We proceed as follows. Section 1 recounts OSRD's origins and provides a high-level summary of its work. Section 2 presents the details of how OSRD was organized and run, where we emphasize the organization over its individual programs. In Section 3 we use case studies of four programs to illustrate how its principles were applied in practice, and synthesize this evidence into key program design questions and what we perceive was OSRD's approach to them. In Section 4 we then reflect on specific lessons from OSRD's example—particularly through the lens of modern problems—and limits to its generality. Section 5 gives concluding remarks.

1 An Overview of OSRD

In 1940, the war in Europe (which began with Germany's invasion of Poland in September 1939) was merely a newspaper headline to most of the American public. However, recognizing that the country was at imminent risk of being drawn into the war after the failure of the Maginot line in France, and that the U.S. "was pathetically unprepared from the standpoint of new weapons" (Stewart 1948), a cadre of high-ranking scientists and science administrators approached President Roosevelt to propose that the U.S. put scientists to work on preparations for war. This outreach, led by Vannevar Bush (President of the Carnegie Institution of Washington and former Vice President and Dean of Engineering at MIT) with the support of Karl Compton (President of MIT), James Conant (President of Harvard), and Frank Jewett (President of the National Academy of Sciences and Bell Labs), resulted in a meeting with President Roosevelt on June 12, where he presented his proposal for a new National Defense Research Committee (NDRC) and got the go-ahead, and an order on June 27 formally creating the NDRC, with Bush as its chair.

Led by the aforementioned four scientists plus Richard Tolman (CalTech physicist), Conway Coe (the U.S. Patent Commissioner), and one representative from each of the Army and the Navy, NDRC was tasked to "coordinate, supervise, and conduct scientific research on the problems underlying the development, production, and use of mechanisms and devices of warfare," and was funded directly out of the President's discretionary budget. It was authorized to perform research as well as to contract with firms, individuals, and scientific institutions for research—and its work was to supplement (rather than supplant) that of the Armed Services and other agencies like the National Advisory Committee for Aeronautics (NACA).

NDRC began with a grand mission but only eight staff (the committee members themselves) and no precedent to follow. At its first meeting on July 2, 1940, the committee organized into five divisions by subject (Table 1), with subsections for individual military-scientific problems (Appendix Table A.1), and concurrently began recruiting other top scientists (largely from committee members' personal networks) to fill the new agency's ranks. It also made the decision that it would contract out research rather than performing it directly. For its time, this was a radical move. Although there had been previous attempts at large scale government support of research, tensions between scientists' desire for autonomy and taxpayers' need for accountability had stalled the idea (Geiger 1993), and the urgency of an impending war forced a resolution.

[Table 1 about here]

Over the next year, NDRC initiated over 200 contracts for research in radar, physics, optics, chemical engineering, and atomic fission, engaging many of the country's top academic and industrial institutions in its work.[2] But it was also limited by its emphasis on research, over engineering and development; its focus on instruments of warfare, versus other critical pursuits; and a lack of coordination with researchers at other agencies, including the military and NACA. Military medicine was a particularly important gap: Hoyt (2006), for example, notes that "In nearly every war prior to World War II, more men in the U.S. armed forced have died from disease than battle wounds." As such, the ability to outperform the enemy in treating common diseases such as malaria, influenza, and bacterial infection could provide major battlefield advantages.

NDRC's early successes persuaded Roosevelt to expand the organization, and on June 28, 1941, Executive Order 8807 created OSRD as the successor to NDRC to address these deficiencies and be the central agency organizing civilian science for war, with Vannevar Bush at the helm (Appendix Figure A.2 reproduces the executive order).[3] Now funded by Congressional appropriations, OSRD subsumed NDRC and added a Committee on Medical Research (CMR), which was also organized into divisions by subject matter, and led by scientific experts.[4] Whereas the role of the original NDRC (in 1940) was to "engage in research which would establish the practicability and usefulness" of new instruments of war and convey them to the military, which could then develop and manufacture them, OSRD was a combined research and development organization, with more resources devoted to development as the war progressed.

The NDRC branch of OSRD underwent a handful of changes over the course of the war, especially as the scope of its work grew. In December 1942, NDRC reorganized into 18 core divisions, two panels, and two special sections (S-1 and T); one more division and a handful of new committees were introduced over the next three years (see Table 2 for a list). These divisions covered a wide range of subjects and varied equally widely in scale. The two largest divisions were Radar (14) and Rocket Ordnance (3), with the majority of funding going to MIT and CalTech, respectively, to support major research labs such as MIT's Radiation Lab (the "Rad Lab"), which was the locus of radar research, employed over 4,000 people at its peak, and remains an institutional legend, or CalTech's Jet Propulsion Lab, which still exists today. NDRC also directed the atomic fission

[2] Atomic energy research was undertaken by NDRC at the explicit request of Roosevelt, who had been informed of its military potential. The atomic fission research program is described in depth in Section 3.

[3] It was not an inevitability that this research would happen within OSRD. In the early 1940s, various groups were politicking to be in charge of wartime medical research, and some had already started thinking about medical research funding before the war. Bush was initially reluctant to take on medical research (he observed in his autobiography that "medical men tend to have more feuds than the rest of the population"), and agreed only once assured he would have Roosevelt's backing in any inter-agency conflicts (Bush 1970).

[4] In addition to NDRC and CMR, OSRD included an Advisory Council, which coordinated research activities across the government. It later added an Administrative office (responsible for business operations, including contract management), a Scientific Personnel office (to manage personnel shared by OSRD and other government agencies, and to handle personnel issues for employees of OSRD and its contractors, especially draft deferments), an Office of Field Service (to create field offices, and deploy staff to study field problems and assist in ongoing training and the use of OSRD devices in combat operations), and a Liaison office (for coordinating research efforts and exchange of scientific information with research agencies of Allied countries), which we discuss below.

research program until it was transferred to the Army in mid-1943.

[Table 2 about here]

Despite having one-tenth the budget of NDRC, CMR was similarly important to the war effort. It was charged with mobilizing medical researchers and identifying "the need for and character of contracts to be entered into with universities, hospitals, and other agencies conducting medical research activities," and was equally radical for its time.[5] Though the National Institute of Health (NIH) had existed since 1930, its budget was small and mostly spent in its own labs. Private foundations had previously funded medical research through block grants, and later (after the Depression made these financially infeasible) through grants to specific researchers. But as we discuss below, these were different in important ways from the CMR model, including their focus on fundamental research. CMR also drove a major shift in emphasis in medical research, away from peacetime problems to specific wartime medical needs.

CMR piggybacked on a committee structure created by the National Research Council's Division on Medical Sciences (DMS) a year earlier in anticipation of war, organized around "problems with which the Services expected to be confronted" (Richards 1946). In cases where not much was known the NRC had hoped to launch investigations, but it never had a budget. Once CMR was funded, in worked closely with the DMS (under contract) to set priorities and evaluate proposals. CMR was chaired by A.N. Richards, a pharmacologist and administrator at the University of Pennsylvania, and its secretariat included three other civilian members—Lewis Weed (Johns Hopkins and the National Academy of Sciences), Alphonse Dochez (Columbia) and Baird Hastings (Harvard)—and representatives of the Army, Navy, and Public Health Service. Though there was some internal reorganization over the war, CMR's main divisions were General Medicine, Surgery, Aviation Medicine, Physiology, Chemistry, and Malaria.

The OSRD, including NDRC and CMR, grew to be a large agency, with 850 full-time paid employees and 1,500 total personnel at its peak (Stewart 1948). Table 2 lists its research divisions, along with total contract authorizations issued for the periods shown. These divisions operated relatively independently, and were effectively the operating units of OSRD. Each was led by a division chief and further comprised of subsections with section chiefs.[6]

In concurrent research (Gross and Sampat 2020), we have compiled data on all OSRD contracts from the agency's official records at the U.S. National Archives. In Table 3 we list the top industrial and

[5]Chester Keefer, the "penicillin czar", later described it as "a novel experiment in American medicine, for planned and coordinated medical research had never been essayed on such a scale" (Keefer 1969).

[6]Bush claimed that this hierarchy supported OSRD's efficient operation, and assisted him in his advisory role to President Roosevelt: by his own recounting, it allowed questions from Roosevelt to be transmitted down the OSRD chain of command and an answer returned (Bush 1970).

university contractors, where it is evident that OSRD funding was concentrated in a small number of firms and universities. Table 4 shows that the concentration was even greater across states, with ten states accounting for 90% of both NDRC and CMR spending.

[Tables 3 and 4 about here]

Though OSRD was established nearly six months before the attack on Pearl Harbor, once the U.S. was officially at war it embarked on a scientific sprint that lasted into the middle of 1945. OSRD's budget immediately grew many-fold, from $6.2 million in 1940-1941 to $39.6 in 1941-1942, and $142.5 million in 1942-1943. By the end of the 1945-1946 fiscal year, OSRD had spent over $536 million on R&D, across over 2,500 contracts—including 1,500 contracts let by NDRC, 570 by CMR, and roughly 100 for research on atomic fission before it was spun out into the Manhattan Project to develop an atomic weapon.[7] Figure 1 illustrates the collective focus of its work, using words in the titles of OSRD patents and CMR publications.

[Figure 1 about here]

The impacts of OSRD's work were significant, directly affecting not only the war itself, but also U.S. technological progress, scientific manpower, federal science policy, and the postwar economy. Its immediate impact was to support the Allied forces in bringing the war to a victorious ending, but it was also anticipated that its work would eventually permeate civilian life, outliving the war itself (Stewart 1948). In total, OSRD-funded research generated nearly 8,000 inventions, 3,000 patents, 2,500 scientific articles, and over 10,000 technical reports. Much of this work became foundational to post-war science and applied research in the fields OSRD supported. In concurrent research we find that it had long-lived effects on the direction of U.S. invention and the locations where it took place (Gross and Sampat 2020); the direction of biomedical research, drug development, and medical practice (Gross and Sampat 2022b); and the development of high-tech industry (Gross et al. 2022). The intense focus of the wartime experience also appears to have trained a generation of researchers and research managers, deepening U.S. scientific and administrative talent for the Cold War era. Its most important impact was arguably more general, laying a foundation for broad government support of research, including in peacetime.

2 The OSRD Model

Despite the complexity of this operation, we identify the key elements of OSRD which in our view represent the OSRD model of crisis R&D direction. These include:

[7] OSRD's total expenditure is equivalent to nearly $8 billion in 2020 dollars, and one to two orders of magnitude more than the U.S. government as a whole was previously investing in science.

Org { 1. Organizational design

Essential functions {
2. Priority-setting
3. Selecting researchers
4. Incentive mechanisms
5. Coordinating efforts
6. Translation to practice

In this section we describe how OSRD was organized and operated, and how it approached each of these essential functions. We focus on OSRD policy in the form it evolved into over the course of the war, and on what we understand (from contemporaries) to have been its general approach to funding and administering its expansive civilian research effort.

2.1 Organizational design

The structure of the organization was fundamental to how OSRD worked. From the initial kernel of four NDRC divisions and eight Committee members sprouted a sprawling, multidivisional agency, which managed a broad portfolio of research projects from the center and—as we will see below—engaged in a wide range of activities from research, to production, to deployment and field testing. Its organization chart, shown in Appendix Figure A.3, illustrates this structure and scope. The organization was staffed by civilians, and led at all levels by civilian scientists, many of whom had no prior experience in applied research—let alone R&D management—but were experts in their fields. Its hierarchy and chain of command helped information transmit efficiently throughout the organization, including up and down from its highest level (Bush).

The organization benefited from specific characteristics of its leadership. One seems to be a strong working relationship among its senior leaders, which was rooted in prior personal history and mutual trust. Another was Bush's past government and administrative experience, both as President of the Carnegie Institution of Washington and as a member and later Chairman of NACA—which Kevles (1977b) argues provided Bush with a "compelling model" in both form and function—as well as the relationships he had cultivated in Washington in the months before and after NDRC was created. His trust of, and direct access to, the President throughout the war—though used sparingly—likely afforded Bush more flexibility than other directors might have had.

Bush's experience and deftness as a statesman was particularly valuable in navigating institutional conflict and defending OSRD's turf. The proposal he brought to Roosevelt in June 1940 explicitly stated NDRC was "to aid and supplement, and not replace, activities of War and Navy departments," a point which Bush emphasized in his first meetings with the service secretaries to limit "bureaucratic jealousies" (Zachary 1997); as Pursell (1979) observes, NDRC had to make alliances. Though its relations with the Army were good, it was challenged by the Naval Research Laboratory, which viewed NDRC as a competitor. Bush met this challenge by lobbying other Naval offices to support its work, and ultimately prevailed, but research groups across the government would continue jockeying for influence and resources, most importantly manpower.

OSRD was, at its essence, a new experiment in research administration, pressed on by the urgency of war. Its entrepreneurial character helped it balance structure and organizational routines with the flexibility to adapt, and it repeatedly demonstrated an ability to make significant changes mid-stream, such as the reorganizations of NDRC and CMR, the subdivision of major programs (e.g., radar; see Section 3), or the expansion of field activities. Having an (effectively) unrestricted budget was a boon. Another was the lack of "red tape": with there being little precedent for its work, OSRD invented most of the tools, and guardrails, that it needed as it went. More generally, OSRD sought to minimize the transaction costs of research.

2.2 Priority setting

A basic question facing any R&D funding program is what research areas to fund, through which mechanisms, and at what stages of maturity (e.g., basic research, applied research, development, or even testing). NDRC and CMR took distinct approaches to identifying and funding specific research priorities, though they also had common features, such as their focus on applied research over basic science and collaboration with end users in the military.

At NDRC, ideas for research projects could come from within OSRD, the military services, or an Allied government. OSRD's individual sections would workshop these ideas and formulate a basic proposal, including a plan of action, possible contractors, and its expected cost and duration. These proposals were voted on by the committee at weekly meetings and forwarded to Bush, who made final decisions. Urgent requests could also be taken directly to Bush and authorized on the spot. According to Stewart (1948), this mix of autonomy and review gave NDRC's research divisions the flexibility to apply their imagination to military problems while also ensuring their ideas passed the scrutiny of other experts and aligned with the rest of the OSRD research agenda and the needs (and constraints) of the war effort overall. Bush later wrote, "most of the worthwhile programs ... originated at grass roots, in the sections where civilians who had specialized intensely met with military officers who knew the problem in the field" (Bush 1970).

CMR did things a bit differently, receiving proposals from individual laboratories, which were then evaluated by NRC committees in consultation with medical officers from the Army and Navy, and approved by Bush.[8] On occasion, CMR members also made "missions" to the front-line, which it viewed as helpful to identifying research priorities (Stewart 1948).

In both cases, research divisions staffed by leading civilian scientists determined research priorities, with input from military users. The committees would then assess scientific feasibility. For problems with high uncertainty, both NDRC and CMR funded multiple rivalrous approaches, organizing multi-front research programs. Within this portfolio they also ranked the priority of specific projects for allocating scarce resources such as elite scientists and materials, emphasizing radar, fission, and penicillin among others (Guerlac 1987). And in most cases, their focus was on applied research and development, small-batch production, and testing to meet military needs, not fundamental work. As Conant (1947) explained, the time for basic research is before a crisis, and urgency meant "the basic knowledge at hand had to be turned to good account."

2.3 Selecting researchers

The second question NDRC faced from the get-go was who would do the work. To build a roster of potential contractors, one of its first undertakings (in the summer of 1940) was to survey academic institutions to gather data on their facilities, research personnel, and ongoing research. This list proved to be an essential resource throughout the war—colloquially known as "the Bible" (Baxter 1946)—and was updated by OSRD's business office as new research facilities came to its attention. A similar survey of industrial facilities was made after Pearl Harbor, to be used especially for late-stage technology development in between laboratory trials and large-scale production (with the idea that the contractor might later double as manufacturer).

NDRC's research divisions were tasked with finding suitable contractors and placing contracts. In making these choices, the agency prioritized speed and quality over cost or distributional considerations, preferencing organizations needing the least new personnel, equipment, or facilities to do the work.[9] Once chosen, the division heads worked with contractors to develop formal proposals to be reviewed by the committee, which sought assurances that "the work would be well done" (Stewart 1948)—which could be founded in the strength of the proposal, the reputation of the researcher or institution, or both. Though NDRC's leadership (correctly) anticipated that the institutional and geographic concentration of its funding and cost of its programs might expose it to criticism (Stewart 1948), the urgency of the crisis made performance its top priority.

[8] When there were specific problems that needed research but for which it was not getting proposals, CMR members directly reached out to researchers "whom it regarded as most suitable" (Stewart 1948).

[9] Stewart (1948) writes of "a sense of urgency in the selection of contractors ... the need for speed hung like a sword over the head of the Committee and speed meant that problems should be assigned to those institutions with the facilities and manpower which promised the best results in the shortest possible time."

Because CMR solicited proposals rather than proposing the work itself, its process was necessarily different. Once received, these proposals were sent to the NRC Division of Medical Sciences, where over thirty committees (with hundreds of elite medical researchers) reviewed applications. Peer review was an "unprecedented approach" at the time, and CMR represented "the first sustained, large-scale exercise of the function in a biomedical context" (Mandel 1996). Based on the review feedback, the DMS gave each application a letter grade and submitted these reviews back to CMR. Typically, not always, CMR funded what the DMS recommended.

2.4 Incentive mechanisms

2.4.1 Inventing the federal R&D contract

OSRD was willing to fund projects with high upside but uncertain payoffs, with the intent of putting "the best scientific imaginations in the country" on problems of military importance. One of the organizational innovations of NDRC was the development of contractual terms that could balance the need to ensure researchers had the were focused on true military objectives without excessively constraining their ability to take risks and exercise judgment. No strong precedent existed for government R&D grants or contracts prior to World War II, but A. Hunter Dupree (1970) would later call OSRD's R&D contract "one of [ts] great inventions" and "the glue which held the whole system together." Broadly speaking, OSRD attempted to design contracts to limit "micro-managing" researchers, within broad constraints. Fox (1987) notes that although these were nominally contracts, they were "part contract and part grant," as it was research, not specific deliverables, that was being purchased. Though there was monitoring and feedback, once awarded principal investigators had considerable latitude, an approach Vannevar Bush called "giving a man his head." Bush further explained "this is more than a matter of scientific freedom ... it is entirely possible to give a man his head and yet to specify by agreement with him his objectives" (quoted in Hoyt 2006). Stewart (1948) described the performance clause as follows:

> [It] was a relatively simple provision. The contractor agreed to conduct studies and experimental investigations in connection with a given problem and to make a final report of his findings and conclusions to the Committee by a specified date. This clause was deliberately made flexible in order that the contractor would not be hampered in the details of the work which he was to perform. The objective was stated in general terms; no attempt was made to dictate the method of handling the problem.

Because rapid mobilization was a priority, the organization also tried to limit the lags caused by contract negotiation and execution. Bush (1970) reported "Once a project got batted into form which the section would approve, with object clearly defined, the research men selected, a location found ... and so on, prompt action followed." Projects could be reviewed within a week, and letters of intent could be sent out so work could begin.[10] Contracts were written for short periods (e.g., six months), with the "informal understanding that they would be extended if the progress of the work warranted." Even reimbursement of expenses was made easy.

2.4.2 Incentivizing participation

With the U.S. conscripting >10 million men into the military, nearly every scientist had friends or family deployed. The importance of helping U.S. servicemen survive in battle was thus more than an academic exercise: a sense of urgency and common purpose permeated American society, and it made available "the best scientific talent of the country" (Stewart 1948), working with intensity.[11] Nonetheless, OSRD needed to re-orient the research efforts of large swaths of scientists and engineers. This was disruptive, both to profit-oriented firms, and to scientists and universities, some of whom were wary of bureaucratic control. Its introduction of indirect cost recovery—novel for its time—was one way it did so, reimbursing contractors for overhead in addition to regular research expenses. A second was its precedent-setting patent policy.

The contract terms initially adopted by NDRC gave itself the sole power to decide whether to file patents on inventions arising from research it funded, as well as disposition of title. This reflected the principle that the public should own the fruits of publicly-funded research—but left contractors "completely subject to the judgment of the Government" (Stewart 1948), and several firms refused to sign contracts with this provision. Stewart (1948) explained:

> "[NDRC] was asking America's leading companies to take their best men off their own problems and put them (at cost) on problems selected by NDRC, and then leave it to NDRC to determine what rights, if any, the companies would get out of inventions made by their staff members ... These companies had acquired a great deal of 'know-how' as a result of years of effort and the expenditure of their own funds, often in large amounts. The research they were being asked to undertake was in many cases in line with their regular work ... and might result in some cases in inventions they might be expected to make at some future date at the appropriate place in their own programs. In some cases the Government contract involved minor adaptations of past inventions made by the contractors, and in such cases the contribution to the final product attributable to the work financed by the Government was relatively insignificant. But under the patent clause thus far offered by NDRC a company might be excluded from using its inventions under an NDRC contract in its own business, and might even find its competitors licensed by the Government while licenses were refused to it.

[10] Contractors "almost invariably started work under letters of intent which preceded the signing of contracts by weeks or months" (Stewart 1948), ensuring that negotiations would not slow progress.

[11] Conant (1947) later reflected, "human beings outdo themselves when their friends and relatives are facing battle." By October 1941, OSRD research had already involved 78 percent of America's top physicists and 52 percent of its top chemists, as measured in *American Men of Science* (Stewart 1948).

After extended negotiations, NDRC crafted new language which gave the contractor first rights to patent inventions produced under contract, and provided the government with an irrevocable, royalty-free license to make and use the invention for military, naval, and national defense purposes (notably, NDRC was unsuccessful at negotiating a license that extended to all government uses). Contractors were required to report all inventions to NDRC prior to contract settlement, and in the event that they elected not to file a patent application on any given invention, the government could do so, providing the contractor with a nonexclusive royalty-free license in return. Because of its lengthy terms, this language became known as the "long form" clause.

NDRC (later, OSRD) continued using its original patent clause—the "short form" clause—in specific categories of contracts, giving the government presumption of title where it supplied significant equipment, personnel, and training to support the work. This became standard for major OSRD-funded research programs hosted at academic institutions like radar (MIT), rocketry (CalTech), and submarine detection (Columbia). CMR contracts were also written under the short form clause. Research contracts in atomic fission were initially written with the long form clause but were converted to short form once it became clear that the research might result in an atomic bomb. These decisions were uncontroversial at the time, since in medicine there were strong norms militating against patenting, especially for public research, and in the other cases, the government's interest in controlling the IP rights was clear. Still, in exceptional cases, CMR would tailor its patent policy in order to motivate participation by qualified firms (see Section 3).

2.5 Coordinating research efforts

One of OSRD's explicit responsibilities was to coordinate research with other U.S. agencies and Allied governments. OSRD also coordinated across research it directly supported: for example, CMR organized meetings of investigators to facilitate their cooperation, circulated non-confidential progress reports, and (with the help of various NRC committees) monitored progress and identified which projects should be prioritized or terminated (Stewart 1948). NDRC divisions working on related problems could also share members, but for security reasons, information sharing across divisions was restricted to what was necessary to the work.

Coordinating research across U.S. government agencies was the job of OSRD's Advisory Council, which consisted of the Director of OSRD, the Chairmen of NDRC and CMR, the Chairman of NACA, and representatives from the Army and Navy. The Advisory Council was foremost a venue where these agencies could interact. In some cases, research programs begun by one agency might be transferred to another, the most notable being NDRC's atomic fission program being spun out into the Manhattan Project when it became a weapons development project. Concurrent with his appointment as OSRD Director, Bush also served as the Chairman of Joint Committee on New Weapons and Equipment at the Joint Chiefs of Staff, which advised the military on the use of new weapons and ensured that the scientific perspective would remain close to military strategy, and as a member of NACA, and all of Bush, Conant, and Tolman were active advisors to the Manhattan Project—strengthening OSRD's ties to these other agencies.

Close relations with the military were paramount to OSRD's research efforts. It worked with the military representatives in its leadership committee to pick research priorities, and with representatives on the OSRD Advisory Council to avoid duplication. Day-to-day coordination on individual research projects was performed by division-specific military liaison officers. These liaison officers supported the quick exchange of information, field tests, and at the late stages of development, the transition to manufacturing. Stewart (1948) explains that their job was "to speed the project from initiation to the final stage of large-scale Service procurement."

International coordination began shortly after NDRC was created. Scientific exchange between the American and British began in the fall of 1940 with a British mission to the U.S. led by Sir Henry Tizard, in which the British shared data, blueprints, and prototypes of a wide range of technologies being developed in England, in exchange for the same from the U.S. The most important technology was the cavity magnetron, which Baxter (1946) called "the most valuable cargo ever brought to our shores." This was the essential input to radar development, and the cornerstone of the U.S. radar program. Other exchanges related to the proximity fuze and the feasibility of an atomic weapon, both of which became important OSRD research programs.

From this point forward, international collaboration was a prominent feature of the research effort. OSRD established an office in London, whose staff was the conduit for information to flow between American and British researchers, and the British similarly established an office in Washington, DC. OSRD's London field office eventually evolved into a formal Liaison division, which managed cross-border scientist exchanges and information exchange.

That said, although OSRD created structures to support coordination, it was by no means seamless. Turf battles, and competition for scarce resources like manpower and materials, could complicate working relationships within OSRD and between it and its partners. Its research divisions at times wrestled over individual projects, especially those that spanned boundaries, like radar-driven fire control (Divisions 7 and 14; see Table 2). This was in at least one case resolved by creating an inter-division joint venture, and in another case by decree from Bush (Mindell 2002). Collaborating with the military on priorities and diffusion was made more challenging by frequent turnover of military attachés, which was partially relieved by having points of contact with the military at multiple levels of the OSRD hierarchy, but never fully resolved. International coordination, meanwhile, was at times challenged by competing priorities and security restrictions—though in general, defending

Britain was as high a priority as defeating Germany and Japan.

2.6 Getting the ideas into practice

The process of bringing new technology "into operation against the enemy," as Bush described it, proceeded in stages. "For a newly conceived device, these stages involve primary research, engineering development, initial production for extended field tests, and engineering for quantity production. For devices that have gone through these stages, as well as for older devices which are being adapted into new forms or for new uses, there are also the stages of production, installation, maintenance, development of tactics, training and use" (Baxter 1946).

Translation to practice thus involved several key steps, including initial production runs, field tests, and production at scale. Bush established an internal Engineering and Transition Office to bridge the divide between R&D and manufacturing. When a device being developed in the lab was ready for testing, it was the responsibility of this office to find a manufacturer which could produce enough units for a field test—which could range from a single unit (e.g., for radar) to thousands (e.g., for rockets). In doing so, it was necessary to ensure that manufacturers could match the specifications and performance of prototypes from the lab. Other basic considerations included the availability of facilities, supply of materials (especially given the materials shortages imposed by the war), and the ability to scale up manufacturing if the tests were successful.

Field tests were (quite literally) conducted in the field of battle. Without the support of experts, military testers frequently imposed self-designed tests, misused the device, or simply drew the wrong conclusions, and OSRD eventually found it necessary to have some scientists accompany OSRD technology into the field (Baxter 1946). This type of field testing was the initial purpose of OSRD's Office of Field Service, but the division later evolved to also support the deployment and proper use of finished OSRD technology in the theater of war—including (i) ensuring that technology was not distrusted by military users if it experienced bugs or was not properly deployed in their first attempt, and (ii) ensuring that it was not overextended (by being used in settings or jobs for which it was not designed and would not actually work).

CMR was also active in development, evaluation, and implementation. Even when there was initial evidence of the therapeutic benefits of new treatments from theory or animals, a key question was whether they worked in humans. Many of its contracts involved testing (e.g., of antimalarials, or an influenza vaccine), sometimes on prisoners and institutionalized populations—practices that would today not be permitted. Members of the Army and Navy also helped arrange field trials on soldiers and reported back results. This user perspective helped facilitate bi-directional feedback, and ultimately utilization. In some cases, CMR helped support manufacturing as well—most famously in the penicillin program, as we discuss in Section 3.

3 Example OSRD Research Programs

The organizational features and activities in Section 2 characterize OSRD as a research-directing agency and portfolio manager. It was at the program level where operating decisions were made—typically on shared principles, but differences in each problem and its context often necessitated distinct approaches. We use case studies of the radar, atomic fission, penicillin, and malaria programs to illustrate both. These programs shared an urgent military demand; questions over who would do the work, how to do it, and how to get results into the field; and a foundation in existing science. They also differed in organization and the division of labor, the pursuit of serial versus parallel research efforts, policies around patent rights and information sharing, and the end user. Table 5 provides an abridged summary of the following accounts.

[Table 5 about here]

3.1 Radar and radar countermeasures

When war broke out in Europe, Germany quickly established air supremacy in its invasions of Poland and France as well as the London Blitz. The results of these campaigns made it clear that defeating Germany would require breaking its hold of the skies. Radar—a technology for detecting fast-moving or distant objects not visible to the naked eye, including ships and aircraft obscured by fog or darkness—was thus a focus of OSRD's work from its inception. Much of the basic science of radar (namely: transmitting, reflecting, and receiving radio waves) was well known before the war broke out, though the technology was too primitive at ultra-high frequencies to be useful in military applications.[12] Section D-1 of NDRC, colloquially the Microwave Committee, was established with the specific objective to study the application of microwaves.

The Tizard mission and its cavity magnetron jump-started the radar program, which grew to be NDRC's largest in cost and scale. In late 1940, NDRC launched a new radar research laboratory at MIT, deliberately (mis)named the Radiation Laboratory (Rad Lab) to disguise its work. MIT was chosen for three reasons: the presence of a handful of scientists with experience in microwaves, its ability to attract more scientists to work on the radar problem, and its proximity to the ocean and Boston's Municipal Airport for testing. Research at MIT began on November 10, 1940, several

[12] Prior to the war, radar was an emergent technology, and much of the early experimentation in radio detection was done by the U.S. Naval Research Laboratory, the U.S. Army Signal Corps, and the the private laboratory of Alfred Lee Loomis, introduced below, in Tuxedo Park, New York.

months before a contract with the institute was finalized, under the direction of Lee A. DuBridge, a physicist from University of Rochester. The lab began with a kernel of ≈20 scientists but quickly staffed up, largely with physicists and electrical engineers, academic and industrial, faculty and students and recent graduates alike. The Rad Lab eventually grew to nearly 4,000 people, including numerous future Nobel laureates, most working on-site in one building with a continual sense of purpose and urgency in service to the U.S. and Allied war effort.

Baxter (1946) describes the Rad Lab embarking with a "feverish" pace. By January 1941 it was testing new radar sets from the roof of MIT buildings, and in February it was asked by the Army to make experimental sets for its planes, setting a precedent for limited "crash" production (though most production was both then and later done by industrial partners). By 1943, substantial progress had been made on the core technology, and though some fundamental research continued, much of its work shifted to engineering, production, and deployment.

Coordination was a prominent feature of the radar research effort. It had close relationships with industrial firms like Bell Labs, General Electric, RCA, Westinghouse, and Sperry Gyroscope from the beginning, who supplied the necessary components, collaborated on radar and radar-enabled technologies, and exchanged technical staff (Guerlac 1987). As the Rad Lab grew, OSRD began to contract select projects to other institutions when the work was sufficiently distinct, important, or sensitive, and it placed staff with these other contractors to be liaisons. It also placed staff in the field, and it was "at the [battle]front or at Army and Navy bases [that] the possible tactical uses of radar were explored, operating procedures were established, problems of installation and maintenance were met, and the training of operators and maintenance personnel went forward" (Baxter 1946). Collaboration with the British also persisted throughout the war, with the Rad Lab hosting a British liaison officer and running a branch in Britain. With multiple contractors as well as the military services working on radar, OSRD also organized a government radar patent program to exchange inventions and coordinate patent filing.

The Rad Lab's collaborations with manufacturers were just as notable. Although it was initially thought production would be relatively simple, with researchers handing off breadboard models to manufacturers to produce at scale, it was quickly proved to be more complex.[13] The arrangement that evolved typically had companies sending engineers to the Rad Lab to learn about the device they were to produce and prepare drawings, after which prototypes were made and tested before

[13] As (Guerlac 1987) explains, "there were very few companies with the facilities and experience" to produce radar components or systems, and these were tied up in other war production contracts. Moreover, there were hundreds of subcontractors across the country involved in the manufacture of parts, which needed to be coordinated. Guerlac continues: "All of these manufacturers had to be introduced to the problem; had to train their engineers to develop production methods; had to be supplied with detailed specifications and then necessary test equipment; had to be given initial educational orders in advance of larger Army or Navy orders; had to be assisted in the design of special tools; and often even had to develop new methods of packing and shipping."

production lines set up. Representatives from the manufacturer, the Rad Lab, and the Army or Navy "held frequent meetings to work out problems of general design, production schedules, choice of subcontractors, specifications for parts and performance, and [other] details," writes Guerlac (1987), who notes that in the last few years of the Rad Lab's operation, "manufacturers' engineers were often associated with a project throughout its course, and the [Rad Lab] research men followed it through the manufacturing design and production process."

As the war progressed, radar countermeasures (i.e., obfuscation and jamming of enemy radar) were proved to be nearly as valuable as radar itself. Shortly after Pearl Harbor, NDRC began work on countermeasures in collaboration with the Naval Research Laboratory and Army Signal Corps. The Rad Lab added a countermeasures division, led by Frederick Terman of Stanford, and due to its distinct objectives, staff, culture, and security requirements, it was soon moved to Harvard, christened the Radio Research Laboratory (RRL), and transferred to a new contract, under a new OSRD division (Division 15, "Radio Coordination"). Like the Rad Lab, RRL quickly added recruits from around the country, peaking at roughly 800 staff.

Between 1940 and 1945, radar developed into a profoundly important instrument of war, allowing soldiers to see enemy craft even when their eyes could not. Despite barely featuring in U.S. military strategy at the start of the war, by 1945 the military had procured over $3 billion of radar and $300 million of radar jamming equipment (>$45 billion today), and the Rad Lab supported R&D in over 100 distinct radar systems. Baxter (1946) attributes its performance to a "highly flexible and effective administration, extensive research in fundamentals, steady improvement of components, and close liaison with the Army and Navy, and the British."

3.2 Atomic Fission

The most widely-remembered scientific achievement of World War II is the harnessing of atomic energy to create a weapon of mass destruction. Yet the atomic bomb was the culmination of years of OSRD work on atomic fission which preceded the Manhattan Project and was transferred over only when the basic science was established, and the fission project converted into an all-out effort to produce enough fissile material for a bomb as quickly as possible.

OSRD's atomic fission research was rooted in the scientific breakthroughs of the 1930s, when the nuclear fission of uranium was first demonstrated, and the potential for chain reactions recognized. What made the discovery of fission remarkable was that the resulting fragments had less mass than the original uranium nucleus. By implication, the missing mass had transformed into energy. The finding electrified the physics community, presenting new possibilities in energy production. In the summer of 1939, urged by Leo Szilard and Albert Einstein, President Roosevelt appointed a special Advisory Committee on Uranium to study fission, led by Lyman A. Briggs, the director of the National Bureau of Standards. When NDRC was established in June 1940, this committee was folded in as one of its divisions. Briggs' first request to Bush was for an allotment to research the fundamental constants of nuclear fission, and contracts were let that fall with several universities and two federal agencies to support this work. Notably, NDRC's leadership itself was divided over the military relevance, and thus prudence, of this investment.

This internal dissension led NDRC to appoint an independent committee of physicists *not* deeply involved in atomic fission research to review the issue and provide a recommendation on whether atomic fission research held military promise, and whether or not this project should be prioritized. This committee recommended a "strongly intensified effort," but acknowledged that it would likely take years for this research to yield enough progress to be useful. Based on its report, Briggs requested to increase NDRC spending on atomic fission three-fold, writing over a dozen new contracts to study uranium isotope separation and nuclear chain reactions.

Even then, the scale of the program was relatively small, at a few hundred thousand dollars. But as both this work and parallel efforts in Great Britain made progress, American physicists involved in NDRC-funded research or close to the problem became increasingly convinced that an atomic weapon was feasible, and Bush decided that a course of action needed to be set by the President. In a meeting with Roosevelt in October 1941, Bush explained the state of the project, being conservative in his prediction of the feasibility of an atomic weapon by acknowledging it was based only on experimental laboratory data, and it was unknown if a full-fledged attempt at uranium separation would be successful. Roosevelt told Bush to proceed.

The uranium program was accordingly reorganized and accelerated: gaseous diffusion and centrifugal separation of U-235 was centered at Columbia under Harold C. Urey, electromagnetic separation at Berkeley under Ernest Lawrence, and chain reactions in unseparated uranium and its fissionable byproduct plutonium at Chicago under Arthur Compton. The United States' formal entry into the war following the attack on Pearl Harbor on December 7 triggered an "all-out attack on the uranium problem" (Baxter 1946). On December 16, the President urged Bush to "press as fast as possible on the fundamental physics and on the engineering planning."

Because it was unclear which method would be viable for large-scale production, OSRD invested in all approaches. As of May 1942, there were "five horses running neck and neck" (Baxter 1946): the centrifugal, diffusion, and electromagnetic methods of separating U-235, and the graphite and heavy-water pile methods of making plutonium from uranium. The military urged on this work on the grounds that Germany was likely also pursuing the bomb, and even brief delays could have catastrophic effects. Given this urgency, Briggs, Compton, Lawrence, and Urey proposed to begin building pilot plants for all five methods of producing fissionable material at scale before they were proven. This proposal was sent by Bush and Conant to the President, Vice President, and Secretary of War, suggesting the Army undertake the construction.

While the Army began building these plants, OSRD continued its work. A major breakthrough occurred on December 2, 1942—when the Chicago effort produced the first controlled chain reaction—but the experimental pile would have had to run for 70,000 years to produce enough plutonium for a bomb. Research on the five methods thus continued, though by the spring of 1943, centrifugal separation had been abandoned, and heavy-water was soon after.

This left the military with three viable paths to producing enough uranium or plutonium for a bomb. With the science of atomic fission understood and pilot plants running, OSRD transferred its work to the Army Corps of Engineers on May 1, 1943. Its contracts were subsumed into the recently-organized Manhattan Project, led by Brigadier General Leslie R. Groves, whose mission was to produce a functional atomic weapon, and several OSRD staff members were transferred into the project. In describing this hand-off, Hewlett (1976) explains Groves immediately converted the OSRD research groups into "an engineering and production effort" and recruited industrial contractors into the project as administrators of production sites. In all, OSRD wrote over 100 contracts to nearly 50 contractors for research on atomic fission, with total value of $19 million, comparable to the $28 million expended on radar through April 1943. Bush, Conant, and Tolman served in an advisory capacity until July 16, 1945, when all three were present at Alamogordo to witness the successful detonation of the first atomic weapon.

3.3 Penicillin

Infectious disease was the most important military medical problem in World War II. As with other wartime problems, there had been considerable but incomplete progress against infectious diseases in the decades before the war. Sulfa drugs, developed in Germany, were effective against a range of bacterial diseases, but had major toxicity issues and were not useful for many battlefield ailments. The best hope was in penicillin, which in 1929 the Scottish physician-scientist Alexander Fleming had found inhibited the growth of bacteria in the mold *Penicillium notatum*, where it was naturally grown. A decade later, in 1939, an Oxford University laboratory headed by Howard Florey and Ernest Chain was the first to purify the molecule, making it possible to conduct clinical tests. However, they were unable to produce enough for human testing, nor, in war-torn Britain, to engage British pharmaceutical companies to do so (Andrus 1948).

In 1941, Florey came to the U.S. for help. He was referred to the U.S. Department of Agriculture's (USDA) Northern Regional Research Laboratory (NRRL), which had experience growing mold at high yield, and also met with A.N. Richards at CMR. Though CMR's primary focus was research (rather than production), Richards assured Florey "he would see that everything possible was done to expedite production of penicillin" (FTC 1958). This commitment was made despite skepticism in certain quarters and considerable uncertainty about its feasibility. But it was buffered by CMR's decision to engage in a parallel effort to develop a synthetic penicillin.

CMR took sharply different approaches to the two R&D programs, which presented distinct problems. Research efforts focused on synthetic penicillin, where the key challenges were figuring out penicillin's molecular structure and finding a way to synthesize it. In deciding whether to concentrate resources in top firms or spread its bets, CMR ultimately chose organizations that had experience in or capabilities for synthesis, or an interest in penicillin more generally; this included nine firms, two universities, and the USDA (Swann 1983). Since several leading firms were already conducting research on synthesis, CMR issued token contracts with no funding, mainly to facilitate intellectual property licensing and information flow (Stewart 1948).

With natural penicillin, the problem was not research, but rather production. Here, CMR initially had a more limited coordinating role. In late 1941, it organized meetings between Bush, NRRL, and representatives of Merck, Squibb, Pfizer, and Lederle Labs, where it worked to persuade these (reluctant) firms to be involved (Neushul 1993). The NRRL was to work on techniques for increasing penicillin yields from mold, and the firms on production techniques.

This project presented several challenges. One was getting firms to invest in developing (unfunded) production capabilities, which CMR sought to assuage with evidence supporting proof of concept, and by brokering information among firms and negotiating waivers to avoid antitrust scrutiny that cooperative research sometimes attracted. CMR also worked with the War Production Board (WPB) to get the firms needed equipment, and connected them with academics who would evaluate production samples. In all cases, the firms provided their own funding, participating for patriotic, reputation, or competitive reasons—but since natural penicillin was a known molecule, there was no strong intellectual property to be had, save for process patents.

The synthetic program struggled to make headway, but by 1942, firms were producing 40 million units of natural penicillin per month, up from 10 million in 1941 (Baxter 1946).[14] Because quantity was initially scarce, the firms had agreed that clinical testing would be organized by CMR. Testing was organized in collaboration with the NRC Committee on Chemotherapeutic and Other Agents (COC). CMR acquired supply from the producers (initially for free; later at cost), and COC then distributed penicillin to hospitals free of charge, in return for detailed case reports. Initially the testing contracts went to recognized experts, but as supply of penicillin grew, more physicians could be involved. The COC received reports on over 10,000 patients, sending back its analyses to CMR periodically (FTC 1958). CMR also supported testing "in the field" on wounded soldiers, in

[14] Baxter (1946) notes that it takes about one million "units" of penicillin to treat one patient.

collaboration with the military (Andrus 1948). The positive results from these tests led to a desire for broad adoption by the military, and to civilian demand.

This meant there was a need to build large scale production facilities. The needs of massive scale-up were a distinct challenge, and one in which CMR was largely on the sidelines, as its expertise was in research and testing. At the encouragement of CMR, the WBP's Office of Production Research and Development (OPRD) provided material, and shared technical expertise and some funding, while the Defense Plant Corporation helped support construction (Baxter 1946). Even as WPB was working to convince firms to invest quickly in plants for scale-up, a lingering risk which allegedly slowed investment was the possibility that CMR might end up succeeding in a synthetic approach to penicillin production—illustrating a potential drawback to the parallel R&D strategy (Neushul 1993). WPB eventually recruited 20 firms into its production program.

The natural penicillin program succeeded. Monthly output grew to 425 million units in December 1943, 117.5 billion in June 1944, and nearly 650 billion in June 1945. The cost of producing 100,000 units fell from $20 to under $1 (Baxter 1946). By 1943 there was enough penicillin to treat U.S. and Allied troops and meet civilian demand. The synthesis problem, by contrast, proved more complex, despite initial enthusiasm and scientists who promised results in months. Once natural penicillin production was successful, the synthesis program was shut down. The causes of this "failure" have been examined elsewhere (Swann 1983), and include unexpected scientific difficulties, lack of information sharing among British and U.S. efforts, and difficulty getting enough penicillin for testing. But Swann (1983) also notes that lack of success during the war does not imply the program was a flop, since knowledge developed during the war "paved the way" for a number of clinically important semi-synthetic penicillins introduced in the 1950s.

3.4 Malaria

Malaria—an infectious disease caused by mosquito-borne, protozoan parasites of the *Plasmodium* group—has been a major contributor to global morbidity and mortality for centuries. In the U.S., malaria was on the road to elimination by the early 1930s. But much of World War II was fought in areas with high malaria risk, which posed a serious impediment to the Allied effort. Malaria could be treated with quinine—an extract from the bark of the Cinchona tree—and though its side effects (blurry vision, tinnitus, and nausea) were not ideal, it was effective. However, quinine supply routes were vulnerable, and after the Japanese seized Java in 1942, nearly all U.S. supply was cut off. As U.S. General Douglas MacArthur put it, "this will be a long war if for every division I have facing the enemy I must count on a second division in the hospital with malaria and a third division convalescing from this debilitating disease" (Slater 2009).

Some malaria research was conducted in the 1930s, much of it focused on finding or developing a quinine substitute. In the U.S. this was supported by the NRC and the Rockefeller Foundation, but this program was disorganized and not well funded. The Germans were also working on quinine substitutes during the interwar era, partly because their own stock had been cut off by the Allied blockade in World War I (Baxter 1946). Most of this work was conducted by the conglomerate I.G. Farben, which had sophisticated chemical synthesis capabilities. The German effort yielded several candidates, including a drug called atabrine (which had been marketed globally, including in the U.S. before World War II) and sontochin (which would be the German drug of choice during the war but was not widely known), among others. However, side effects of the U.S. produced version of atabrine (e.g., discoloration, gastrointestinal issues, and a loss of virility) made soldiers reluctant to take it, and generals reluctant to compel them to (Baxter 1946).

One of the first actions of CMR was to fund some of the efforts already underway, including the 1941 NRC Conference on Chemotherapy of Malaria (Baxter 1946) to outline and coordinate the needed research activities. This and other NRC and CMR efforts later morphed into the CMR's "Board for Co-ordination of Malaria Studies", which included representatives from CMR, NRC, and the Army and Navy, and whose function was to set priorities and coordinate research. According to Baxter (1946), "The presence of the service members enabled [the services] to follow developments in civilian laboratories and, through their knowledge of problems in the field, direct the attention of civilian research to particular problems that demanded solution."

CMR supported malaria research by firms and universities across the country in chemistry, biology, pharmacology, and clinical medicine on the disease, preventatives, and treatments. Much of this work was aimed at identifying, developing, and testing substitutes for quinine. Early work focused on atabrine: since the drug was being manufactured in the U.S. using slightly different materials and approaches, it was unclear if its adverse side effects were inherent or due to process. In addition to its research on atabrine, CMR simultaneously initiated a hunt for alternatives. This was a different type of problem than that facing the penicillin effort: CMR funded the synthesis and testing of *thousands* of antimalarial compounds, while managing the portfolio and shepherding compounds from synthesis to screening to testing (Slater 2009). It also worked with the military to conduct field trials on promising candidates, and Stewart (1948) argues that military involvement on the Malaria Board facilitated "prompt and adequate" clinical testing.

An important part of CMR's work was collecting, validating, and disseminating information among the many firms and labs involved in malaria research and development work. The Survey on Malarial Drugs, a "workhorse" of the program (Slater 2009), cataloged information on new compounds and prepared and distributed reports and bulletins (Baxter 1946). A key issue was how to get firms to contribute compounds, and CMR established categories of information allowing firms to do so in confidence in cases where they had proprietary interests. This was a balancing act, and a source of considerable controversy. In this program, more so than natural penicillin, the leader (William Mansfield Clark) was heavily focused on protecting firms' interests, even as Bush and Richards wanted broader sharing and disclosure. Importantly, many of the firms involved in the malaria program did not sign formal contracts, perhaps deterred by the "short form" patent provisions (Slater 2009). The final product, *A Survey of Antimalarial Drugs, 1941-1945*, included information on compounds from over 100 firms and institutions (Slater 2009).

In all, CMR supported research or testing of over 14,000 compounds in animals, and 80 in humans (Baxter 1946). One product of this effort was chloroquine, which—although it arrived too late to be useful during the war itself—became a revolutionary malaria treatment in the post-war period. Surprisingly, the drug that would eventually be used in the field was, in the end, atabrine. Once it was determined to be safe and effective in 1943, General MacArthur essentially decreed it be used (Condon-Rall 2000). By 1944, there was a sharp decrease in malaria incidence (Baxter 1946), making the other developments moot during the war itself.

3.5 Common principles and logic

Through these examples, we can observe the common dimensions over which OSRD had to make choices in each of these programs, and begin to discern the principles and logic that shaped these choices, which we characterize in Table 6. Following the structure of both Section 2 and Table 5, we organize these choices into five categories: research priorities, research performers, contracts and patent policy, coordination, and downstream activities.

[Table 6 about here]

Allocating limited resources between priorities—especially manpower, more than funding—required balancing military needs and technical feasibility. Bush's first condition for any project was that it would help win the war. This, for example, led to prioritizing the atomic bomb over rockets because it had "a better chance of being developed during this war" than advanced rocketry, which Bush saw as a weapon of future wars, not this one (Zachary 1997). Urgency thus drove its emphasis on applied research and technologies with short-run payoffs, though in cases like atomic fission where it saw a possibility of particularly high payoffs from advances in nascent fields, it supported fundamental research despite uncertain timetables and outcomes.

Within each of these projects, we see heterogeneity in the choice to invest in one approach or many. Parallel efforts of the flavor seen in the fission, malaria, and (to a point) penicillin projects, among others, prioritized speed and the probability of discovery over cost. A sequential approach, however, affords the opportunity to improve through iteration, and more aptly characterizes radar. That it followed such an approach may also reflect the more advanced state of its underlying science and that the problem was more one of applying and refining technique than of developing it wholesale, particularly after the cavity magnetron was provided by Britain.

In choosing how to organize and incentivize research efforts, we also observe common principles across OSRD's portfolio. Interdependencies within the R&D problem might suggest concentrating efforts at fewer institutions. Systems engineering problems, for example, were not easily divisible, and thus had this flavor: this was the case with radar, which was concentrated at MIT, and with fission—especially at the stage of bomb design and manufacture, which was sited at Los Alamos.[15] In contrast, penicillin was more mixed, and malaria diffuse—reflecting that discovery, synthesis, and testing of pharmaceutical treatments could be spread more widely across investigators. Setting patent policy was its own challenge, where OSRD faced the traditional tension between incentivizing its contractors and ensuring broad access in deciding whether the results of research it funded should belong to the public. The co-existence of two distinct patent clauses in OSRD contracts reflects the balance OSRD chose to strike, where with private contractors, it often allowed them right of first refusal to new patent applications, but in other cases it retained this right for itself or the armed services—especially where OSRD funded the creation of new labs (e.g., for radar) or provided other significant risk capital or if national security required it (fission).

Coordination was one of the most distinguishing, pervasive features of OSRD's approach to R&D administration relative to the status quo ante, or even today. Spillovers across research efforts made coordination across them desirable, especially when researchers were collaborating or competing for scarce inputs, and when one's successes and failures could benefit others. Though the military was in practice a large, bureaucratic, and diffuse customer, the scale of its needs made coordinating with military representatives on priorities, approaches, and outputs desirable. In other settings, absent these conditions, coordination may be less important, unproductive, or even detrimental, especially when time is short and managers are spread thin.

OSRD's involvement in production was also distinctive. Urgency may require the "telescoping of stages" (Baxter 1946) we see in the fission and penicillin programs, where manufacturing capacity was developed at risk or production at pilot plants began before any one approach was proven. The MIT Rad Lab too engaged in (limited) crash production of experimental radar, though it generally followed a more sequential path from development and testing to manufacturing and

[15]For example, as the Rad Lab grew, it was at one point suggested that "[it] was becoming too large for efficient operation and that it might be well to decentralize it by dividing the microwave radar work among various other universities," but NDRC determined that "to subdivide the Laboratory would impair its efficiency" and create difficulties in security and coordination (Guerlac 1987). Guerlac goes on to note that this "was not necessarily true for certain types of fundamental research which could be dispersed [more easily]."

distribution, reflecting the iterative nature of radar improvements. Also notable is how, and where, OSRD was or was not involved in diffusion. Whereas medicine and the atomic bomb were relatively straightforward to incorporate into existing warfighting and military medical practice, integrating radar into military strategy required broader changes, including a trained corps of radar operators. In this and similar cases, OSRD and its contractors (such as the Rad Lab) placed scientists in the field, who played a key role in supporting deployment.

4 Lessons and Limits

These examples help us distill the logic we believe OSRD used to operate individual programs. Yet OSRD was broader than these programs alone: as a research management organization, it managed a portfolio, and it developed a distinctive model for doing so. One question this accounting raises is where, and in what ways, it may be relevant to other problems—including modern ones. Vannevar Bush summarized the OSRD model at the end of the war, writing:

> "It was the function of [OSRD] to channelize and focus an amazing array of variegated activities, to co-ordinate them both with the military necessities which they were designed to help to meet and with the requirements of the powerful industrial structure on which their effective application relied... [OSRD] brought to being a pattern of administration which aptly met a new and unique need and which stands as a richly suggestive guide for other undertakings." (Bush, quoted in Stewart 1948)

It is unclear precisely what lessons, or undertakings, Bush had in mind. Near the end of the war, Roosevelt asked Bush to draw lessons from this "unique experiment", but for peacetime, not crises. Bush's response, *Science, The Endless Frontier*, famously made the case for government funding of "basic" research with scientific autonomy, on the grounds of its high returns for economic growth, national security, and public health. The 'Bush Report' drew mainly negative lessons from OSRD, emphasizing "we must proceed with caution in carrying over the methods which work in wartime to the very different conditions of peace." This emphasis reflected his own concerns (and those of his fellow conservatives) about government micro-management of science in peacetime and the appropriate roles of the state versus the market. Beyond the value of the prewar stock of "basic" science—e.g., in medicine or nuclear physics—to wartime R&D, the Bush Report did not delineate any specific lessons from OSRD for future crisis R&D efforts.

Much has been written on how World War II shaped postwar research policy (e.g., Kevles 1977b, Geiger 1993, Kleinman 1995, Greenberg 2001, among others). Though the Bush Report shaped the "rhetoric and tone" of these policy debates (Nelson 1997), many of the institutional features which Bush advocated were not adopted, most notably his call for a single agency (the National Research Foundation) focused on funding basic research (Kevles 1977b, Mowery 1995, Nelson 1997).

Instead, in the five years Congress spent debating aspects of this proposal, other agencies filled the vacuum that OSRD left behind. The Atomic Energy Commission took charge of nuclear research, the National Institutes of Health inherited CMR's portfolio, and the Army, Navy and Air Force (eventually the Department of Defense) weapons R&D. Unlike what Bush and his critics envisioned, these "mission" agencies came to dominate postwar funding (Mowery 1995, 2010). Though not specifically promoted by Bush, several features of OSRD contracts were incorporated into the postwar funding procedures of some of these agencies, including patent policies and indirect cost recovery. The report also helped shape the division of labor in the U.S. innovation system, with universities specializing in fundamental research (some of it oriented to uses; Stokes 1997) and firms in applied research, development, marketing, and diffusion.

In the seventy-five years since the Bush Report, the U.S. and global innovation system has grown massively in scale and scope. Whereas OSRD counted hundreds of firms and dozens of universities capable of performing funded research, today there are thousands of firms and nearly 300 active research universities in the U.S. alone, and many more globally. In the 1940s, only a handful of firms were qualified to be involved in CMR efforts; today, there is a large, diffuse global pharmaceutical industry. In general, R&D capabilities are much more dispersed globally than they were during the war (Nelson and Wright 1992). Science and technology have advanced considerably, as have tools for research, and collaboration, in most scientific fields.

These observations raise two questions. First, what are the lessons of OSRD for crisis R&D policy? And second, given the numerous changes in the innovation system since, does OSRD—a new, short-lived agency developed on the fly, for a crisis 75 years ago—have relevance today? Is it still the "suggestive guide" Bush hinted at, and if so in what ways?

4.1 OSRD beyond the Manhattan Project: relevance for Climate Change and other "Grand Challenges"

One part of OSRD's portfolio has attracted considerable attention: the Manhattan Project. Project Apollo, the War on Cancer, and recent calls for "mission-oriented" R&D, and R&D to address so-called "Grand Challenges", have each appealed to the Manhattan Project for inspiration, including in the context of climate change and the COVID-19 pandemic.

Such appeals have drawn some criticism. In an influential article in this journal, Mowery et al. (2010) argued that the Manhattan Project is not a particularly useful model for climate change. They also argue that the approach to Project Apollo—–itself inspired by the Manhattan Project—may not be applicable either. Whereas the Apollo and Manhattan projects were focused on a specific technological goal, with a single, government customer, climate R&D has to serve innumerable, heterogeneous users around the world, each with distinct needs. These users also have existing capital investments, such that diffusion faces the headwinds of replacement effects (Arrow 1962). Many of the implementers will be private sector firms. Whereas the Apollo and Manhattan projects were centralized, climate change research will likely need to be more dispersed, involving multiple governments and organizations and requiring mechanisms to identify needs, coordinate efforts, and allocate resources across problems and research performers.

Columns 1 and 3 of Figure 7 summarize these differences. We basically agree with the Mowery et al. (2010) argument. However, the Manhattan Project was but one part of OSRD. In some ways OSRD as a whole be a better fit for climate change, as a comparison of columns 2 and 3 suggests. Far from a singular, focused moonshot, OSRD was in fact many moonshots, pursued all at once. Its portfolio was multidimensional with many efforts and competing priorities, and it had not one customer but many, across the U.S. armed services and even Allied governments. It was centralized in direction but decentralized in performance. It hung close to its users, and provided significant coordination. Diffusion often had to overcome organizational inertia and required changes in military (customer) technology and practices. One insight from unpacking the OSRD model, then, is that it was more general than the Manhattan Project alone, and may be more relevant to some types of modern R&D challenges, especially those with diverse goals and consumers.

However, the table also illustrates that in several important ways, especially the role of the private sector as customer and implementer, climate change is different. The scale of global coordination required for climate change R&D would seem far more difficult than U.S.-Allied cooperation during World War II. The political economy of climate change is also more complex, with vested interests and widely heterogeneous impacts. This challenge thus seems more daunting now, even though the technologies for global coordination in R&D, especially in digital communication and dissemination, are much more advanced today than those relied on by OSRD.

One could thus conclude that was then, this is now, and although OSRD is interesting in its own right as a historical reference point, the OSRD model may not offer many non-obvious insights to policymakers today. While we recognize this argument, there are also aspects of the approach that we think are relevant to modern problems, and these can be particularly important in a crisis, as we discuss in the context of the COVID-19 pandemic below.

4.2 The OSRD model for crisis R&D: the case of COVID-19

The question of what rises to the level of a 'crisis' is subjective. Cancer, communism, and competitiveness crises have each driven major changes to U.S. R&D policy in the postwar era (e.g., Pavitt 2000), whereas malaria, poverty, and climate change have not. We opened this article by describing a crisis as a large, urgent problem which will be difficult to contain if not tackled quickly. When a crisis poses new challenges, technological and organizational innovation may be required to resolve them—which is why R&D can, in these contexts, be valuable.

Crisis R&D policy once again became relevant during the COVID-19 pandemic, which presented a wide range of urgent research problems, including vaccines, drugs treatments, diagnostic tests and contact tracing technology to limit its spread, models to understand disease epidemiology and design public health interventions, and organizational innovation to mitigate economic and social costs of social distancing, masking, and lockdowns at schools, restaurants, medical practices, and other venues. Prior to vaccines and treatments, front-line doctors and nurses needed non-pharmacological interventions to manage the COVID patients, including patient management techniques, hospital workflows, and more. In order to be effective, this innovation not only needed to be generated quickly; it also needed to diffuse broadly to the relevant users.

From early on, observers appealed to the wartime R&D model (Azoulay and Jones 2020, Lindee 2020). The U.S. vaccine development effort, Operation Warp Speed, was explicitly inspired by the Manhattan Project (Navarro 2020). Aspects of its approach, including public-private partnership, a heavy hand by the government in coordinating which technologies would be pursued, developing vaccine candidates and running trials in parallel, building production capacity at risk, and heavy funding indeed resembled the World War II fission project.

However, given the breadth of COVID-related problems, the policy response could have benefited from a more coordinated approach—a point we argue more fully in Gross and Sampat (2022a). In this sense, the COVID-19 challenge resembled OSRD's problem more closely than that of the Manhattan Project (Table 7). Yet as the table indicates, there were important differences as well, including—as with climate change—in the nature of the user and the role of the private sector in implementing solutions. And here again, the nature of the global coordination problem may have been more challenging for political and pragmatic reasons.

Even so, the gaps in the federal COVID-19 research portfolio, and the challenges faced by government funders in pivoting to COVID problems, raise questions about whether existing institutions are sufficiently flexible. Perhaps more than its specific policy choices, OSRD's organizational form may be useful for future crises. Bush and others noted that the fact that OSRD was a new agency, with clear lines of command and little red tape, allowed it to move quickly. During the COVID-19 crisis, agencies including the NIH were unable to pivot as quickly to focus on new problems (Balaguru et al. 2022), in part because of dominance of the investigator-initiated peer review model in biomedicine, but also due to the bureaucratic hurdles that are now associated with grantsmanship. In this light, the emergence of new funding agencies (like BARDA; see Sampat and Shadlen 2021, Gross and Sampat 2022a) and philanthropic approaches (like fast grants; see Collison et al. 2021) was extremely useful. Building in crisis R&D grant or contract mechanisms at existing agencies, or a special autonomous crisis R&D agency to be activated in a crisis, could be useful going forward. Such mechanisms would need to balance the need for urgent solutions against transparency and equity considerations, just as OSRD did.

4.3 Applications to non-crisis technology policy

Unlike Bush, some of his critics wanted aspects of OSRD to feature in peacetime, non-crisis R&D, including direct government steering of research to desired socio-economic ends and government involvement in (civilian) applied research. Since then, debates about the feasibility and desirability of targeting public R&D to specific goals, and the role of government in downstream R&D activities, have been perennial sources of tension in research policy. Many examples of "technology policy" at least facially resemble OSRD, such as fostering cooperative R&D, promoting diffusion, and using procurement contracts to facilitate development. Nelson (1997) argues that the Bush Report's characterization of the relationships between science and innovation hindered a useful conversation about civilian technology policy in the U.S. Without taking a stand in these contentious debates, we observe that much of what OSRD did would be called "technology policy" today (Mowery 1995), and the question of whether there is scope for more of it in non-crisis times remains as important now as it was 75 years ago.

5 Concluding Remarks

The OSRD represented the first serious government funding of extramural research in the U.S. and marked a major turning point in research policy globally. In this paper we described how it was organized and operated, identified the choices it faced and how it approached them both in general and in specific contexts, and distilled an approach for making program-level decisions. Importantly, however, OSRD was larger than any one of these programs alone: paraphrasing Bush, its role was to channel research efforts into a variegated array of wartime R&D problems and to coordinate them with both its industrial partners and military customers.

Beyond history "for its own sake", understanding the specifics of the OSRD model may contribute to improved policymaking in other settings. Historical analogies are commonplace in policy, especially in crises, and one role for academic history is to make sure that accurate analogies are being drawn (Eichengreen 2013). As we emphasized in the previous section, appeals to the Manhattan Project in particular may provide a distorted lens on the parallels between World War II and modern-day R&D challenges such as COVID-19 or climate change, and OSRD is a distinct analogy which in other contexts may be more (or less) useful for policy design.

In particular, as our discussion of these R&D problems suggests, there may be insights from the OSRD story that are relevant for modern crises. Working with users to identify key R&D problems, and explicitly coordinating public and private sector research activities (to avoid excess correlation and to plug holes in the portfolio), can be important in a crisis. The need for speed means that certain approaches may be more appropriate to R&D policy in crises than in "normal" times, including parallel R&D and a focus on downstream production and diffusion. New agencies (or mechanisms) may have benefits over established approaches in providing "air traffic control" across a portfolio of research programs and in getting things done at the pace required. Importantly, too, it may be easier to assemble coalitions and funding to accomplish such activities during crises than other times, because both the public and private sectors have interests in rapid crisis resolution, and—if successful—crisis R&D policies are temporally bounded.

With this paper we aimed to clarify (i) what the World War II crisis innovation model comprised; (ii) to what other problems it might apply; and (iii) how specific features of these problems govern its relevance in each context. While appeals to history are common in research and policy, there remains a need for more attention to the details of modern R&D challenges, and the specifics of historical approaches, to determine the extent to which historical policy models are useful guides.

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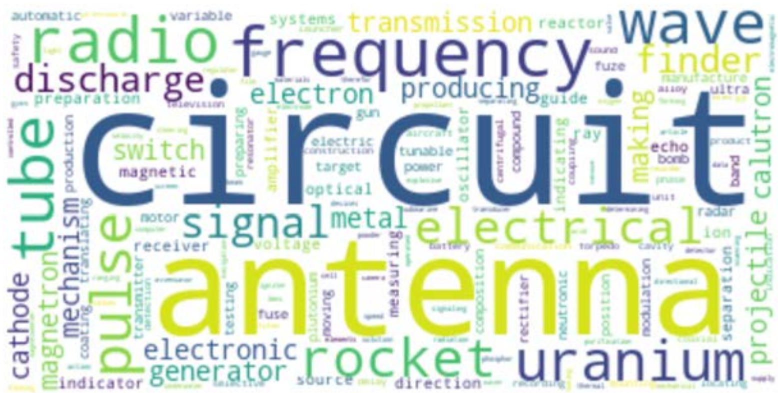
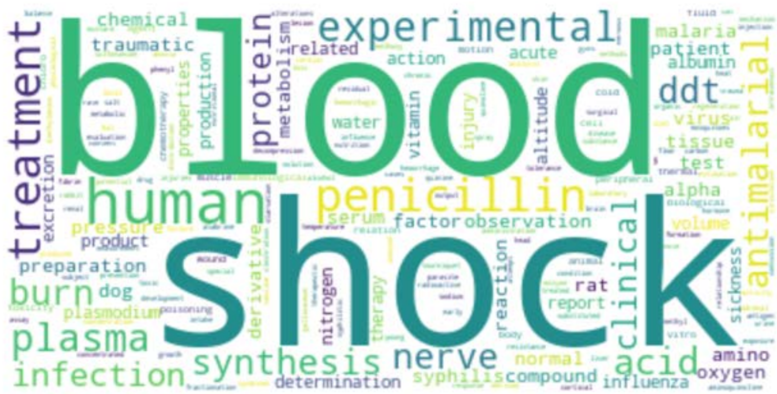
Figure 1: Common words in OSRD patent and publication titles

Panel (A): Words in patent titles



Panel (B): Words in publication titles



Notes: Figure illustrates the most common words appearing in the title of OSRD-supported patents and academic publications. Font size is proportional to number of occurrences, with larger words being more common. Patents primarily resulted from NDRC-supported technological R&D, and academic publications from CMR-supported medical research.

Table 1: NDRC Divisions (1940-1941)

NDRC Division	Director
A – Armor and Ordnance	Tolman
B – Bombs, Fuels, Gases, Chemical Problems	Conant
C – Communications and Transportation	Jewett
D – Detection, Controls, Instruments	Compton
E – Patents and Inventions	Coe
Committee on Uranium	Briggs*

*Lyman Briggs, Director of the National Bureau of Standards.

Table 2: OSRD Divisions, Panels, and Special Sections (1941-1947)

National Defense Research Committee (NDRC)		Contract Authorizations	
Division/Section	Name/Description	($, ’000s) (1943-1947)	
1	Ballistics	5,327.2	
2	Effects of Impact and Explosion	2,701.4	
3	Rocket Ordnance	85,196.5	
4	Ordnance Accessories	20,014.3	
5	New Missiles	12,881.2	
6	Subsurface Warfare	33,883.5	
7	Fire Control	7,711.7	
8	Explosives	11079.9	
9	Chemistry	4,698.2	
10	Absorbents and Aerosols	3,524.2	
11	Chemical Engineering	9,216.2	
12	Transportation Development	2,199.4	
13	Electrical Communication	2,073.9	
14	Radar	104,533.4	
15	Radio Coordination	26,343.0	
16	Optics	5,923.9	
17	Physics	7,655.3	
18	War Metallurgy	3,794.4	
19	Miscellaneous Weapons	2,416.1	*
AMP	Advanced Mathematics Panel	2,522.9	
APP	Applied Psychology Panel	1,542.5	*
COP	Committee on Propagation	453.0	*
TD	Tropical Deterioration	232.4	*
SD	Sensory Devices	272.5	*
S-1	Atomic Fission	18,138.2	*
T	Proximity Fuzes	26,400.0	*
Total		400,735.1	

Committee on Medical Research (CMR)		Contract Authorizations
Division	Name/Description	($, ’000s) (1941-1947)
1	Medicine	3,873.3
2	Surgery	2,847.6
3	Aviation Medicine	2,466.5
4	Physiology	3,981.5
5	Chemistry	2,383.9
6	Malaria	5,501.9
–	Miscellaneous	3,635.3
Total		24,689.9

Notes: NDRC authorizations from January 1, 1943 onwards, except where noted below. CMR authorizations reported for the entire history of CMR.
*Authorizations for Division 19 from April 1, 1943; APP, from September 18, 1943; COP, from January 22, 1944; TD, from May 18, 1944; SD, from November 1, 1945. Authorizations for Sections S-1 and T are from June 27, 1940 onwards, with Section S-1 terminating in September 1943.

Table 3: Top OSRD contractors, by contract obligations

Top 10 firms			Top 10 universities		
Contractor	Total oblg.	Percent	Contractor	Total oblg.	Percent
Western Electric Co.	$15.2 mil.	3.3%	Massachusetts Inst. of Tech.	$106.8 mil.	23.1%
General Electric Co.	$7.6	1.6%	California Inst. of Tech.	$76.6	16.6%
Radio Corp. of America	$6.0	1.3%	Harvard University	$29.1	6.3%
E. I. Dupont De Nemours & Co.	$5.4	1.2%	Columbia University	$27.1	5.9%
Monsanto Chemical Co.	$4.5	1.0%	University of California	$14.6	3.2%
Eastman Kodak Co.	$4.3	0.9%	Johns Hopkins University	$10.8	2.3%
Zenith Radio Corp.	$4.2	0.9%	George Washington University	$6.9	1.5%
Westinghouse Elect. & Mfg. Co.	$3.9	0.8%	University of Chicago	$5.7	1.2%
Remington Rand, Inc.	$3.7	0.8%	Princeton University	$3.6	0.8%
Sylvania Electric Products, Inc.	$3.1	0.7%	University of Pennsylvania	$2.9	0.6%
Total	$57.8	12.5%	Total	$284.0	61.5%

Notes: Table lists the top 10 firms and universities with OSRD contracts by total obligations. Percentages measure each contractor's percent of total OSRD research spending. The large university contractors were also the hosts of central laboratories for major research projects: 94% of MIT's funding was for radar research at the Radiation Laboratory, and 95% of Caltech's funding was for research on rockets and guided missiles at the Jet Propulsion Laboratory. Other institutions hosted a wider mix of projects.

Table 4: Top NDRC and CMR states, by contract obligations

Top 10 states for NDRC contracts			Top 10 states for CMR contracts		
Contractor	Total oblg.	Percent	Contractor	Total oblg.	Percent
Massachusetts	$143.4 mil.	32.6%	New York	$4.6 mil.	21.7%
California	$95.5	21.7%	Massachusetts	$4.3	20.1%
New York	$86.3	19.6%	Illinois	$2.5	11.5%
Illinois	$20.2	4.6%	California	$1.6	7.5%
District of Columbia	$15.7	3.6%	Pennsylvania	$1.3	6.1%
Pennsylvania	$13.3	3.0%	Maryland	$1.3	6.0%
New Jersey	$12.0	2.7%	District of Columbia	$1.3	6.0%
Maryland	$11.8	2.7%	Connecticut	$0.8	3.6%
Ohio	$8.0	1.8%	Ohio	$0.7	3.1%
Michigan	$6.2	1.4%	Michigan	$0.6	3.0%
Total	$412.4	93.8%	Total	$19.0	88.7%

Notes: Table lists the top 10 states with NDRC and CMR contracts by total obligations. Percentages measure each state's percent of the given division's total research spending.

Table 5: Summary of select OSRD research programs

Question/Issue	**Radar**	**Atomic fission**	**Penicillin**	**Malaria**
Research priorities	1. Develop a functional radar system at microwave frequencies; 2. Create (and refine) variants of radar for a wide variety of applications from land, sea, or air; 3. Assist manufacturers in production at scale; 4. Support military on installation and use.	1. Deepen science around nuclear fission; 2. Engineer a controlled nuclear chain reaction; 3. Identify a fissile material that could be produced in enough quantity to make an atomic bomb, before passing the reins to the Manhattan Project.	1a. *Natural*: Produce sufficient quantities of natural penicillin for research and clinical testing; 1b. *Synthetic*: Identify penicillin's molecular structure and how to synthesize it, 2. Conduct clinical tests; 3. Scale up penicillin production for military and civilian use.	Find an effective preventative or treatment for malaria, by: 1. Improving understanding of mechanisms; 2. Developing testing and screening protocols; and 3. Drug synthesis, production, and evaluation.
Research performers	MIT Radiation Laboratory: a newly-created "central laboratory" hosted at MIT, led by Lee A. DuBridge and employing thousands of scientists and engineers from around the U.S., was the locus of radar research. Specific projects sometimes subcontracted. Radar Countermeasures division spun out into the Harvard Radio Research Lab.	Basic research on fission contracted to several universities. Subsequent work on uranium separation and uranium piles was performed at UC Berkeley (led by Ernest Lawrence), U of Chicago (Arthur Compton); Columbia U (Harold Urey).	*Natural*: Initial work in fermentation, production, testing done by NRRL and pharmaceutical firms. CMR funded larger-scale clinical testing through contract to Mass Memorial Hospital. WPB and OPRD worked with firms to scale up production for military use. *Synthetic*: Contracts to pharmaceutical and chemical firms, universities.	Decentralized effort across many institutions, both industrial and academics. Firms typically not under formal contract.
Contracts and patents	Most work performed under the short-form patent clause, giving the government title. The Rad Lab and RRL had patent offices which prepared applications. OSRD led a Government Radar Patent Program which held monthly meetings where representatives from the radar research laboratories and the Armed Services shared new inventions on which they intended to file patents, resolved conflicts, and decided the scope of claims.	Early contracts used long-form patent clause, giving contractors title. As the work began to produce results and its consequences better understood, Roosevelt instructed Bush to arrange for the U.S. government to retain title. All contractors agreed to convert to the short-form clause, effective retroactively. Most nuclear patent applications were also issued secrecy orders by the USPTO (Gross 2021).	*Natural*: Most projects had short-form clause. Very little patenting, beyond a few USDA process patents. *Synthetic*: Short-form for university contracts. Contracts with firms typically didn't have any financial support, were to promote information exchange. Bush had control over any patent application decisions. OSRD had right to compel cross-licensing (subject to reasonable royalties) among the contractors, and retained a government license.	Most academic contracts were short-form. Firms retained patents and submitted information "in confidence" to NRC (though this was a source of tension between NRC and Bush-Richards throughout the war (Slater 2009)). After CMR added a malaria division late in the war, it brought new industrial contracts under short-form clauses (to protect the public interest) but this affected few contracts.
Coordination	Project began with the British Tizard mission to the U.S. (1940), which brought the cavity magnetron. Frequent international exchange thereafter. Both Rad Lab and RRL kept field offices near British radar research and hosted British researchers in U.S. Also hosted military liaison officers and worked with military to explore possible uses of radar, train operators, support installation and maintenance in the field.	Project initiated in 1940 at the request of President Roosevelt, with he and Bush communicating regularly on the viability of an atomic bomb. OSRD managed a multi-site research portfolio until a viable technology for producing fissionable material was found. Military built pilot plants while research was ongoing and later took over the project (under the Army Corps of Engineers' Manhattan Project) for weapons development.	*Natural*: CMR staff organized meetings among firms and agencies involved, including British research efforts, collected and shared progress reports, and brokered connections. *Synthetic*: Secured protection from antitrust regulation for firms collaborating on synthesis. *Both*: Worked with WPB to ensure contractors had the equipment and supplies needed. Promoted information flow across efforts.	CMR funded and participated in NRC-based efforts to share information across research projects, collect and report data. Unlike penicillin, an important goal was to distribute projects to different teams to avoid duplication. Developed and diffused standardized testing protocols. Coordinated civilian and military trials of chloroquine.
Downstream activities	Limited "crash production" of experimental radar sets at Rad Lab upon military request; production at scale provided by leading industrial firms (GE, RCA, Westinghouse, Western Electric). Rad Lab sent staff into the field to aid Allied installations of radar and learn about enemy radar.	Little OSRD downstream activity, which was made the Army's responsibility. OSRD supported pilot plant construction. After fission research transferred to the Army, OSRD leadership served as advisors to the Manhattan Project.	CMR primarily supported clinical testing of natural penicillin. After clinical testing, most downstream work was guided and funded by WPB and OPRD – not OSRD/CMR.	Funded researchers to overcome chloroqiune production bottlenecks, to generate enough drug for trials. Supported civilian and military trials of chloroquine.

Table 5: Summary of select OSRD research programs (cont'd)

Question	**Radar**	**Atomic fission**	**Penicillin**	**Malaria**
Number of OSRD contracts	183	100	*Natural:* 36 / *Synthetic:* 18	78
Total value	$156.9 mil.	$14.4 mil.	$2.4 mil. / $0.4 mil.	$4.8 mil.
Short form patent clause: pct. of obligations	86.21%	100.00%	100.00%	98.13%
Top five contractors	Massachusetts Inst. of Tech. (64.9%) Harvard University (10.0%) Research Construction Co. (8.2%) General Electric Co. (3.2%) Columbia University (2.3%)	University of California (30.4%) University of Chicago (19.6%) Columbia University (13.4%) Standard Oil Dev. Co. (6.7%) Princeton University (3.7%)	Mass. Mem. Hospital (66.6%) Cornell University (6.8%) Johns Hopkins University (4.7%) University of Michigan (4.1%) University of Pennsylvania (3.67%)	University of Chicago (15.8%) Columbia University (11.0%) New York University (9.7%) Johns Hopkins University (8.7%) Allied Chemical & Dye Corp. (5.2%)

Notes: Table summarizes the features of OSRD's radar, atomic fission, penicillin, and malaria research programs. Recall that the short form patent clause gave the government title to any patents on inventions produced under contract, unless the government chose not to file, in which case the contractor retained patent rights. Note that some atomic fission research contracts began under the long form clause but were later amended to the short form clause.

Table 6: Principles underlying OSRD choices

Category	Issue	Options	Determining factors
Research priorities	*How to select research priorities?*	Demand vs. feasibility	Value of a full solution Degree of urgency Expected timetables
	How many approaches to fund?	Serial vs. parallel	Solution uncertainty Degree of urgency Slope of learning curve
Research performers	*How to organize efforts?*	Concentrated vs. diffuse	R&D complexity
Contracts and patents	*Who owns the IP?*	R&D funder vs. performer	Contractor incentives Promoting diffusion Security risks R&D spillovers
Coordination	*Coordination of research efforts*	Hands-on vs. laissez-faire	Spillovers across efforts
	Coordination with users	Hands-on vs. laissez-faire	Size and number of users
Downstream activities	*When to begin production?*	During vs. after R&D	Degree of urgency + cost of scaling up production quickly
	Assist with deployment?	Yes vs. no	Difficulty of integration Training requirements

Notes: Table identifies common dimensions over which OSRD research programs made choices and characterizes the logic of those choices.

Table 7: Features of big R&D problems: A comparison

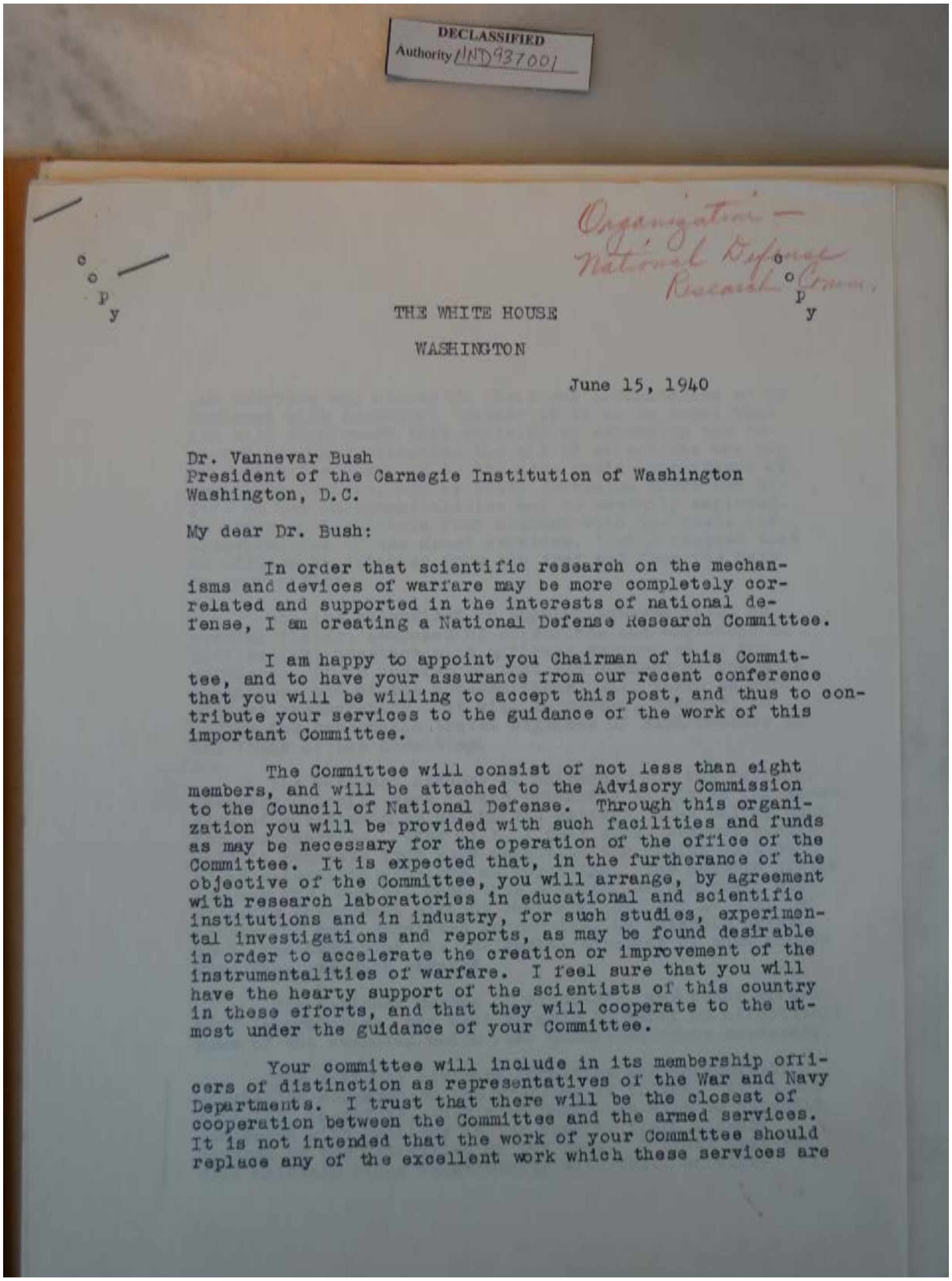
Question/Issue	**Apollo/Manhattan**	**OSRD**	**Climate Change**	**COVID-19**
Specific technological solution or system	Yes	No	No	No
Customer (implementers) concentrated or diffuse	Concentrated	Diffuse (within military)	Diffuse	Diffuse
Coordination with other agencies/countries valuable	Not much	Yes	Yes	Yes
Requires changes in user practices for adoption	No	Yes	Yes	Yes
Large private sector role in deployment of technology	No	No	Yes	In some areas
Existing capital stock to be upgraded or replaced	Small	Small	Large	Small

Notes: Table characterizes features of four “big” R&D problems, including OSRD’s problem as a point of comparison.

Web Appendix

A Historical Supplement

Figure A.1: Presidential approval of NDRC (June 15, 1940)



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Authority NND937001

Organization — National Defense Research Comm.

c o p y

THE WHITE HOUSE

WASHINGTON

June 15, 1940

Dr. Vannevar Bush
President of the Carnegie Institution of Washington
Washington, D.C.

My dear Dr. Bush:

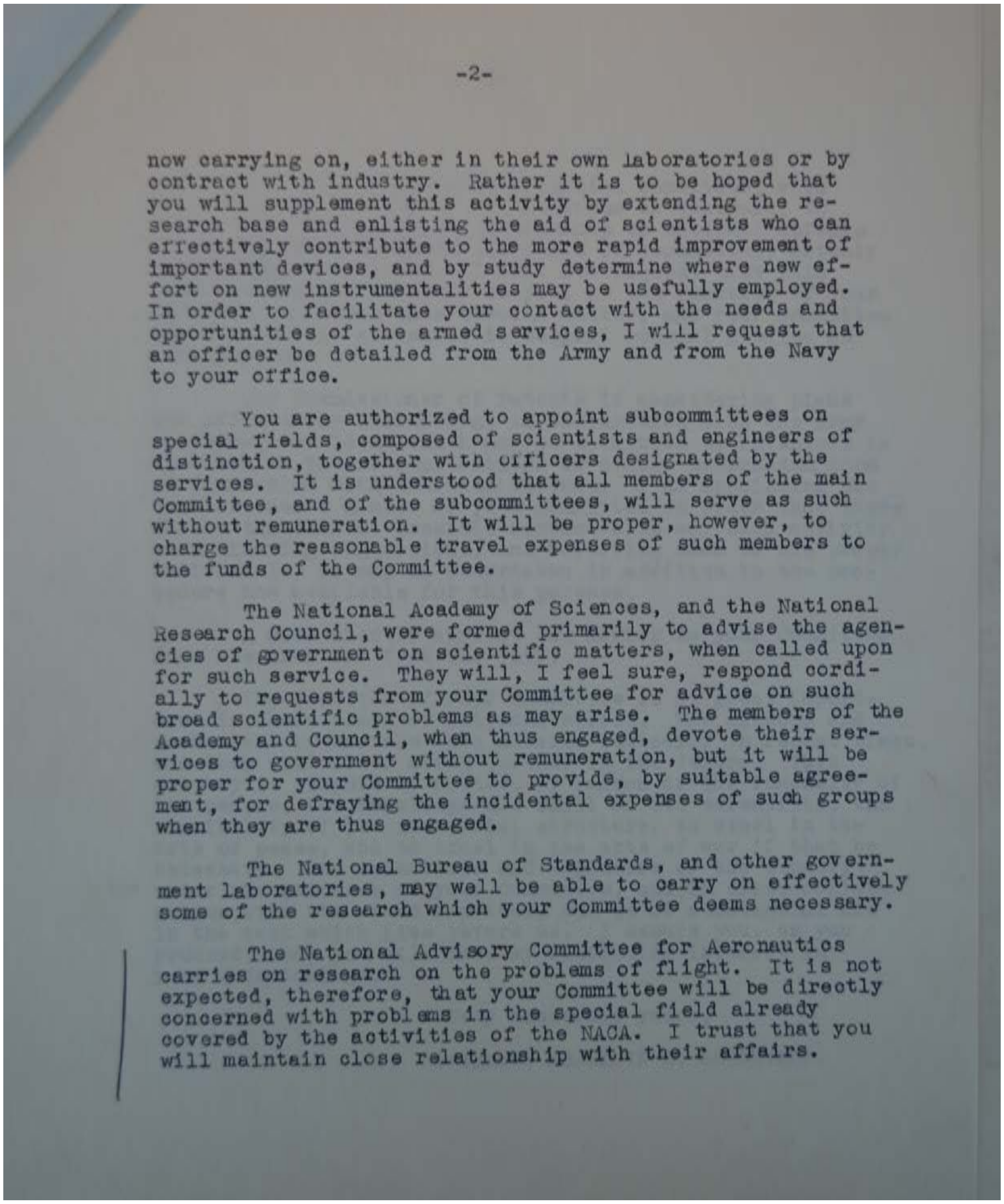
In order that scientific research on the mechanisms and devices of warfare may be more completely correlated and supported in the interests of national defense, I am creating a National Defense Research Committee.

I am happy to appoint you Chairman of this Committee, and to have your assurance from our recent conference that you will be willing to accept this post, and thus to contribute your services to the guidance of the work of this important Committee.

The Committee will consist of not less than eight members, and will be attached to the Advisory Commission to the Council of National Defense. Through this organization you will be provided with such facilities and funds as may be necessary for the operation of the office of the Committee. It is expected that, in the furtherance of the objective of the Committee, you will arrange, by agreement with research laboratories in educational and scientific institutions and in industry, for such studies, experimental investigations and reports, as may be found desirable in order to accelerate the creation or improvement of the instrumentalities of warfare. I feel sure that you will have the hearty support of the scientists of this country in these efforts, and that they will cooperate to the utmost under the guidance of your Committee.

Your committee will include in its membership officers of distinction as representatives of the War and Navy Departments. I trust that there will be the closest of cooperation between the Committee and the armed services. It is not intended that the work of your Committee should replace any of the excellent work which these services are

Figure A.1: Presidential approval of NDRC (June 15, 1940)



-2-

now carrying on, either in their own laboratories or by contract with industry. Rather it is to be hoped that you will supplement this activity by extending the research base and enlisting the aid of scientists who can effectively contribute to the more rapid improvement of important devices, and by study determine where new effort on new instrumentalities may be usefully employed. In order to facilitate your contact with the needs and opportunities of the armed services, I will request that an officer be detailed from the Army and from the Navy to your office.

You are authorized to appoint subcommittees on special fields, composed of scientists and engineers of distinction, together with officers designated by the services. It is understood that all members of the main Committee, and of the subcommittees, will serve as such without remuneration. It will be proper, however, to charge the reasonable travel expenses of such members to the funds of the Committee.

The National Academy of Sciences, and the National Research Council, were formed primarily to advise the agencies of government on scientific matters, when called upon for such service. They will, I feel sure, respond cordially to requests from your Committee for advice on such broad scientific problems as may arise. The members of the Academy and Council, when thus engaged, devote their services to government without remuneration, but it will be proper for your Committee to provide, by suitable agreement, for defraying the incidental expenses of such groups when they are thus engaged.

The National Bureau of Standards, and other government laboratories, may well be able to carry on effectively some of the research which your Committee deems necessary.

The National Advisory Committee for Aeronautics carries on research on the problems of flight. It is not expected, therefore, that your Committee will be directly concerned with problems in the special field already covered by the activities of the NACA. I trust that you will maintain close relationship with their affairs.

Figure A.1: Presidential approval of NDRC (June 15, 1940)

-3-

Recently I appointed a special committee, with Dr. Briggs of the Bureau of Standards as Chairman, to study into the possible relationship to national defense of recent discoveries in the field of atomistics, notably the fission of uranium. I will now request that this committee report directly to you, as the function of your Committee includes this special matter, and your Committee may consider it advisable to support special studies on this subject.

The Commissioner of Patents is considering plans for effectively evaluating, in cooperation with the Army and Navy, new ideas which may be submitted by inventors in the form of patent applications or simple memorandum form in connection with national defense. I am appointing the Commissioner a member of your Committee in order that there may be the closest possible contact with any such activity in evaluating suggestions, and referring them to the proper individuals, as may be undertaken in addition to the procedure now available for this purpose.

I will shortly appoint one member to your Committee from the Army and from the Navy.

The function of your Committee is of great importance in these times of national stress. The methods and mechanisms of warfare have altered radically in recent times, and they will alter still further in the future. This country is singularly fitted, by reason of the ingenuity of its people, the knowledge and skill of its scientists, the flexibility of its industrial structure, to excel in the arts of peace, and to excel in the arts of war if that be necessary. The scientists and engineers of the country, under the guidance of your Committee, and in close collaboration with the armed services, can be of substantial aid in the task which lies before us. I assure you, as you proceed, that you will have my continuing interest in your undertakings.

Very sincerely yours,

(signed) FRANKLIN D. ROOSEVELT.

Figure A.2: Executive Order 8807 creating OSRD (June 27, 1941)

EXECUTIVE ORDER NO. 8807

Establishing the Office of Scientific Research and Development in the Executive Office of the President

By virtue of the authority vested in me by the Constitution and the statutes of the United States, and in order to define further the functions and duties of the Office for Emergency Management with respect to the unlimited national emergency as declared by the President on May 27, 1941, for the purpose of assuring adequate provision for research on scientific and medical problems relating to the national defense, it is hereby ordered:

1. There shall be within the Office for Emergency Management of the Executive Office of the President the Office of Scientific Research and Development, at the head of which shall be a Director appointed by the President. The Director shall discharge and perform his responsibilities and duties under the direction and supervision of the President. The Director shall receive compensation at such rate as the President shall determine and, in addition, shall be entitled to actual and necessary transportation, subsistence, and other expenses incidental to the performance of his duties.

2. Subject to such policies, regulations, and directions as the President may from time to time prescribe, and with such advice and assistance as may be necessary from the other departments and agencies of the Federal Government, the Office of Scientific Research and Development shall:

a. Advise the President with regard to the status of scientific and medical research relating to national defense and the measures necessary to assure continued and increasing progress in this field.

b. Serve as the center for mobilization of the scientific personnel and resources of the Nation in order to assure maximum utilization of such personnel and resources in developing and applying the results of scientific research to defense purposes.

c. Co-ordinate, aid, and, where desirable, supplement the experimental and other scientific and medical research activities relating to national defense carried on by the Departments of War and Navy and other departments and agencies of the Federal Government.

d. Develop broad and co-ordinated plans for the conduct of scientific research in the defense program, in collaboration with representatives of the War and Navy Departments; review existing scientific research programs formulated by the departments of War and Navy and other Agencies of the Government, and advise them with respect to the relationship of their proposed activities to the total research program.

Figure A.2: Executive Order 8807 creating OSRD (June 27, 1941)

e. Initiate and support scientific research on the mechanisms and devices of warfare with the objective of creating, developing, and improving instrumentalities, methods, and materials required for national defense.

f. Initiate and support scientific research on medical problems affecting the national defense.

g. Initiate and support such scientific and medical research as may be requested by the government of any country whose defense the President deems vital to the defense of the United States under the terms of the Act of March 11, 1941, entitled "An Act to Promote the Defense of the United States"; and serve as the central liaison office for the conduct of such scientific and medical research for such countries.

h. Perform such other duties relating to scientific and medical research and development as the President may from time to time assign or delegate to it.

3. The Director may provide for the internal organization and management of the Office of Scientific Research and Development and may appoint such advisory committees as he finds necessary to the performance of his duties and responsibilities. The Director shall obtain the President's approval for the establishment of the principal subdivisions of the agency and the appointment of the heads thereof.

4. In carrying out its functions, the Office of Scientific Research and Development shall utilize the laboratories, equipment, and services of governmental agencies and institutions to the extent that such facilities are available for such purposes. Within the limits of funds appropriated or allocated for purposes encompassed by this Order, the Director may contract with and transfer funds to existing governmental agencies and institutions, and may enter into contracts and agreements with individuals, educational and scientific institutions (including the National Academy of Sciences and the National Research Council), industrial organizations, and other agencies, for studies, experimental investigations, and reports.

5. The Director is authorized to take over and carry out the provisions of any contracts which fall within the scope of this Order heretofore entered into by (1) the National Defense Research Committee, established by order of the Council of National Defense on June 27, 1940, (2) the Health and Medical Committee, established by order of the Council of National Defense on September 19, 1940, and (3) the Federal Security Administrator in his capacity of Co-ordinator of Health, Medical Welfare, Nutrition, Recreation, and other related activities as authorized by order of the Council of National Defense on November 28, 1940. The Director is further authorized to assume any obligations or responsibilities which have heretofore been undertaken by the above agencies for and on behalf of the Government of the United States and which fall within the scope of this Order.

6. There is created within the Office of Scientific Research and Development an Advisory Council consisting of the Director as Chairman, the Chairman of the National Advisory Committee for Aeronautics, the Chairman of the National Defense Research Committee (hereinafter described), the Chairman of the Com-

Figure A.2: Executive Order 8807 creating OSRD (June 27, 1941)

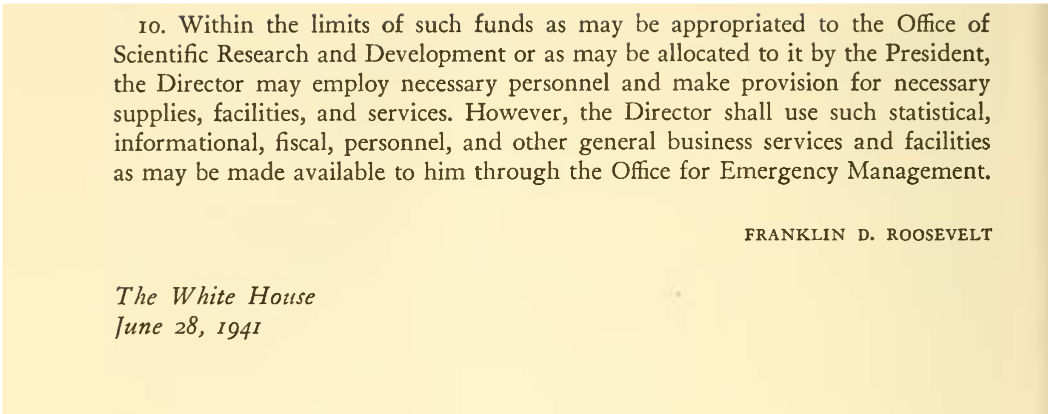
mittee on Medical Research (hereinafter described), one representative of the Army to be designated by the Secretary of War, and one representative of the Navy to be designated by the Secretary of the Navy. The Council shall advise and assist the Director with respect to the co-ordination of research activities carried on by private and governmental research groups and shall facilitate the interchange of information and data between such groups and agencies.

7. There shall be within the Office of Scientific Research and Development a National Defense Research Committee consisting of a Chairman and three other members appointed by the President, and in addition the President of the National Academy of Sciences, the Commissioner of Patents, one officer of the Army to be designated by the Secretary of War, one officer of the Navy to be designated by the Secretary of the Navy, and such other members as the President may subsequently appoint. The National Defense Research Committee shall advise and assist the Director in the performance of his scientific research duties with special reference to the mobilization of the scientific personnel and resources of the Nation. To this end it shall be the responsibility of the Committee to recommend to the Director the need for and character of contracts to be entered into with universities, research institutes, and industrial laboratories for research and development on instrumentalities of warfare to supplement such research and development activities of the Departments of War and the Navy. Furthermore, the Committee shall from time to time make findings, and submit recommendations to the Director with respect to the adequacy, progress, and results of research on scientific problems related to national defense.

8. There shall be within the Office of Scientific Research and Development a Committee on Medical Research consisting of a Chairman and three members to be appointed by the President, and three other members to be designated respectively by the Secretary of War, the Secretary of the Navy, and the Administrator of the Federal Security Agency. The members so designated by the Secretaries of War and the Navy and Federal Security Administrator shall be selected from the respective staffs of the Surgeons General and the Surgeon General of the Public Health Service with particular reference to their qualifications in the field of medical research. The Committee on Medical Research shall advise and assist the Director in the performance of his medical research duties with special reference to the mobilization of medical and scientific personnel of the nation. To this end it shall be the responsibility of the Committee to recommend to the Director the need for and character of contracts to be entered into with universities, hospitals, and other agencies conducting medical research activities for research and development in the field of the medical sciences. Furthermore, the Committee shall from time to time, on request by the Director, make findings and submit recommendations with respect to the adequacy, progress, and results of research on medical problems related to national defense.

9. The members of the Advisory Council, the National Defense Research Committee, the Committee on Medical Research, and such other committees and subcommittees as the Director may appoint with the approval of the President shall serve as such without compensation, but shall be entitled to necessary and actual transportation, subsistence, and other expenses incidental to the performance of their duties.

Figure A.2: Executive Order 8807 creating OSRD (June 27, 1941)



10. Within the limits of such funds as may be appropriated to the Office of Scientific Research and Development or as may be allocated to it by the President, the Director may employ necessary personnel and make provision for necessary supplies, facilities, and services. However, the Director shall use such statistical, informational, fiscal, personnel, and other general business services and facilities as may be made available to him through the Office for Emergency Management.

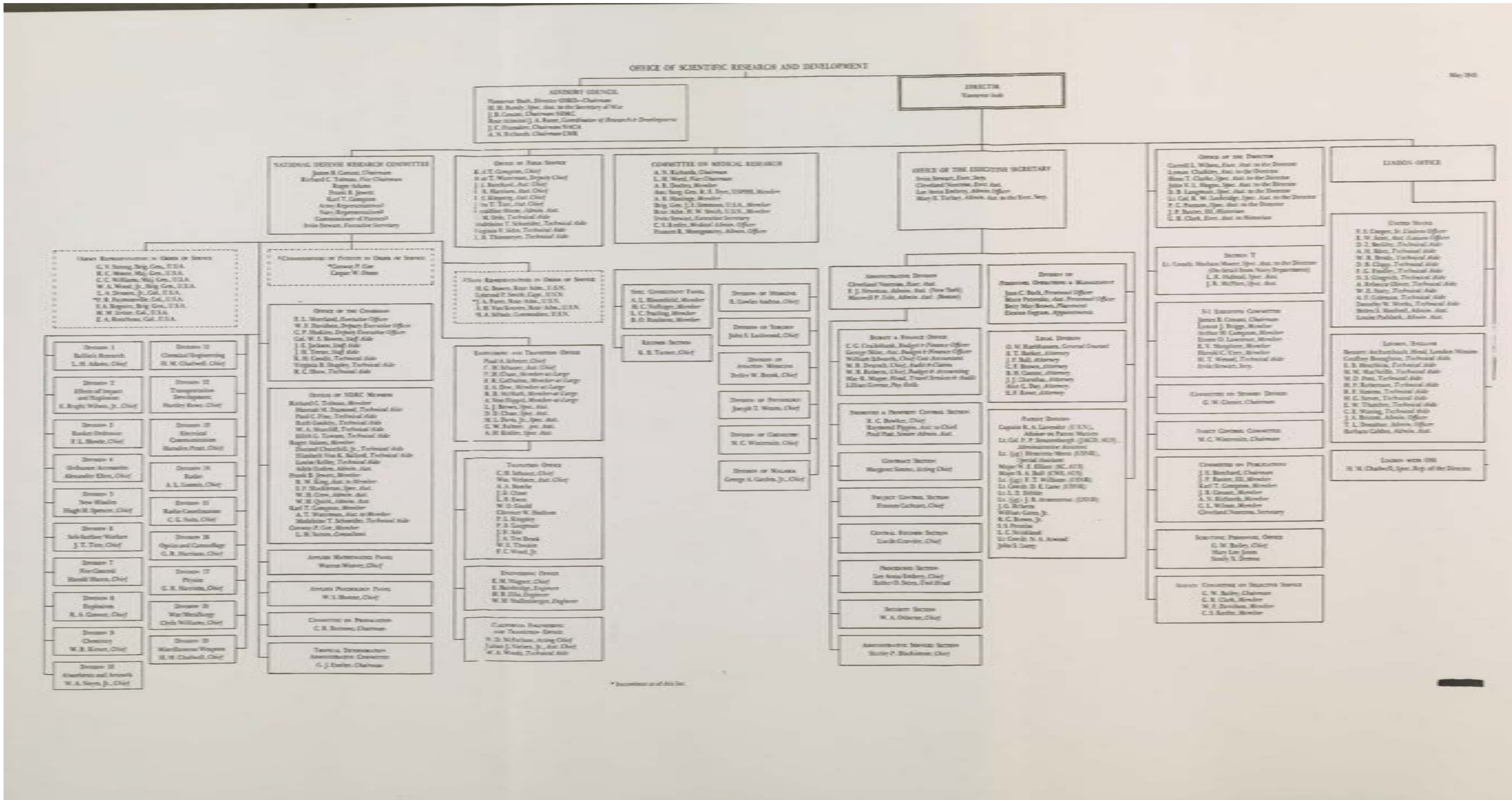
FRANKLIN D. ROOSEVELT

The White House
June 28, 1941

Table A.1: NDRC Divisions and Sections (1940-1941)

Division	Name/Description	Example Sections
A	Armor and Ordnance	Structural Defense; Propulsion; Ballistics; Proximity Fuzes for Shells; Guided Projectiles
B	Bombs, Fuels, Gases, Chemical Problems	Explosives; Detection of Persistent Agents; Aerosols; Absorbents; Protective Coatings; Exhaust Disposal
C	Communications and Transportation	Communications; Transportation; Mechanical and Electrical Equipment; Submarine Studies; Sound Sources
D	Detection, Controls, Instruments	Detection; Controls; Instruments; Heat Radiation

Figure A.3: OSRD Organizational Chart as of May 1945



Notes: Figure provides OSRD organizational chart. Source: *Summary Technical Report of NDRC: Master Subject Index* (1946).