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ORGANIZING CRISIS INNOVATION:
LESSONS FROM WORLD WAR II

Daniel P. Gross
Bhaven N. Sampat

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ABSTRACT

World War II was one of the most acute emergencies in U.S. history, and the first where the mobilization of science and technology was a major part of the government response. The U.S. Office of Scientific Research and Development (OSRD) led a major 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 science policy. Scholars and policymakers often make broad appeals to the World War II innovation model in other crises. In this essay we describe exactly how it worked. We do so first through a general overview of how OSRD approached several questions that may confront any crisis innovation effort: priority setting, selecting and engaging researchers, a funding mechanism, coordinating research efforts, and translation to practice. Next we present case studies of the radar, atomic fission, penicillin, and malaria research programs, illustrating how the principles applied in specific contexts, but also heterogeneity. We conclude by discussing lessons from OSRD, such as what makes crisis innovation policy different, how crisis innovation policy approaches may vary, and the limits to generalizing from World War II for contemporary crises.

Daniel P. Gross
Fuqua School of Business
Duke University
100 Fuqua Drive
Durham, NC 27708
and NBER
daniel.gross@duke.edu

Bhaven N. Sampat
Department of Health Policy and Management
Columbia University
722 W 168th Street, Room 486
New York, NY 10032
and NBER
bns3@columbia.edu

1 Introduction

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. Between 1940 and 1945, the OSRD 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.

Led by Vannevar Bush, the OSRD was an experiment then without precedent: large-scale funding of research by the U.S. government. Over the course of the war, the OSRD’s vast research effort produced major advances in technology and medical treatments to support the Allied forces. What made the OSRD’s problem distinctive from non-crisis research was its urgency, and the importance of speeding not only the research but also downstream activities to get new technology into the field. As James B. Conant (President of Harvard and one of the top OSRD administrators) 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 battlefield” (Conant 1947).

The first question OSRD faced was priority-setting, i.e., what to fund. The OSRD’s priorities were demand-driven, focused on solving specific military problems, and led by input from the Armed Services. The bulk of its work was applied in nature, and while basic studies were sometimes needed, the urgency of the crisis meant that it mostly had to take basic science as given and to put it to work. Its approach stands in sharp contrast to much of peacetime funding that followed at agencies such as NSF and NIH, where most of the research is investigator-initiated, often fundamental, and scientists have a more dominant role in shaping the agenda.

A second issue was finding and engaging the most capable researchers. To support this activity, the OSRD maintained a directory of potential contractors and took seriously the issue of making their involvement incentive compatible. To avoid disrupting universities by relocating their staff, much of the work was done using university facilities, offering indirect cost recovery on a nominally “no gain, no loss” basis. The leaders of the OSRD divisions themselves were typically volunteers,

but contemporary accounts suggest that participation in wartime research was generally through a spirit of volunteerism, powered by a belief in the need to defeat a common enemy. [Stewart \(1948\)](#) wrote that the wartime crisis atmosphere meant “the best scientific talent of the country was available,” and [Conant \(1947\)](#) also pointed to “the ordeal of battle” as a source of cohesion and cooperation above that normally possible in peacetime.

The decision to outsource research, rather than perform it directly, was precedent-setting. To do so, the OSRD invented the R&D contract, which balanced specificity with the flexibility to explore, accounted for the intrinsic uncertainty of research, and could be amended as the demands of the war evolved. In the end, it effectively procured research services, rather than any specific output. Because results from this work were often patentable, it also developed a novel, contractual patent policy that balanced private incentives with the public interest.

As the principal agency mobilizing research for war, the OSRD was also responsible for coordinating research efforts. In many cases—especially in medical research—OSRD funded multiple rivalrous approaches to the same problem. Parallel R&D, a portfolio approach, may have been particularly important where speed was an important consideration and solution uncertainty was high. But as (if not more) important was coordination with the military, other U.S. scientific agencies, and the broader Allied research effort. In cases where there were spillovers between research projects, OSRD facilitated information sharing. It also established field offices in Britain, and sent scientists to the battlefield to see military problems first-hand.

A final issue was translation to practice: the OSRD’s work needed to be advanced from laboratory prototypes to reliable, mass-produced units in the field. It had specific offices to assist in getting new technology from bench to battlefield, with small-batch initial production runs, field tests, and even battlefield deployment. Tight links between the researchers and users enabled rapid feedback and continual tweaking to ensure the technology met the needs in the field. Because the military was the main user, it was also easier to make changes to established practices to accommodate new technology than it may have been otherwise. And because of the way its contractual patent terms were written, there was no risk of technology transfer hold-ups.

In the space of five years, this effort produced major developments in a wide range of technologies including radar, electrical engineering, jet propulsion, optics, chemistry, and atomic fission—where the latter would eventually become the Manhattan Project. The 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, the 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 stimulated the growth of technology hubs around the country.

Vannevar Bush offered an overarching perspective of the OSRD’s work and achievements:

“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. In the contracting system which it developed, in the methods for safeguarding the public interest through sound patent policy which it created, in the means for effective and cordial liaison with co-operating agencies which it effected, and in a dozen other ways, the office 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](#))

Like Bush, scholars and policymakers have cited World War II as a model for crisis innovation (e.g., [Navarro 2020](#), [Markey and Slavin 2020](#), [Lindee 2020](#), [Azoulay and Jones 2020](#)). But what does this mean, beyond large amounts of R&D funding? In this paper we describe how the OSRD model worked, and assess the features of the model that may be generalizable, but also those that may have been idiosyncratic to the specific context in which it operated.

This paper proceeds as follows. Section 2 recounts the origins of the OSRD and provides a quantitative overview of the operation. Section 3 describes the challenges it faced as a crash innovation program, and its approach to solving them—the “OSRD model”. Section 4 provides case studies of specific OSRD research programs, which illustrate heterogeneity at the program level. In Section 5, we describe the OSRD’s immediate and long-run impacts—on the war, on scientists, and on science itself. Section 6 concludes by drawing lessons for future crises, discussing both the generalizable and distinctive features of the World War II era.

2 An Overview of the 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 Institute 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 of Bell Labs), resulted in a meeting with President Roosevelt in mid-June, a letter from Roosevelt on June 15 requesting Bush to be the head of a new National Defense Research Committee (NDRC), and an order on June 27, 1940 formally creating the NDRC.

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, the 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, the 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.¹ 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

¹Atomic energy research was undertaken by the 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 4.

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 forces 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.

The NDRC’s early successes persuaded Roosevelt to expand the organization, and on June 28, 1941, Executive Order 8807 created the OSRD as the successor to the NDRC to address these deficiencies and be the central agency organizing civilian science for war, with Vannevar Bush at the helm (Appendix Figure A.1 reproduces the executive order).² Now funded by Congressional appropriations, the OSRD subsumed the NDRC and added a Committee on Medical Research (CMR), which was also organized into divisions by subject matter, and led by scientific experts.³ 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, the 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, the 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. The NDRC also directed the atomic fission research program until it was transferred to the Army in mid-1943.

[Table 2 about here]

²It 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).

³In addition to NDRC and CMR, the 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 the 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 the exchange of scientific information with research agencies of Allied countries), which we discuss below.

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.⁴ 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. The CMR also drove a major shift in emphasis in medical research, away from problems of peacetime 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, it 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 the OSRD. Each was led by a division chief and further comprised of subsections with section chiefs.⁵

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 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.

⁴Chester 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).

⁵Bush claimed that this hierarchy supported the 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).

[Tables 3 and 4 about here]

Though the 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. The 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, the OSRD had spent over \$536 million on R&D, across over 2,500 contracts—including 1,500 contracts let by the NDRC, 570 by the CMR, and roughly 100 for research on atomic fission before it was spun out into the Manhattan Project to develop an atomic weapon.⁶ Figure 1 illustrates the collective focus of its work, using words in the titles of OSRD patents and publications.

[Figure 1 about here]

3 The OSRD Model

From its inception, the organization faced several of the core questions that any crash innovation program must address. What are specific problems that urgently need solving where R&D may be useful? What firms, institutions, and scientists should be put to work on solving them, and how? Should they be allowed to work from their home institutions, or organized into larger units? How (and how much) will they be paid? Who will own the intellectual property rights over their work? What will motivate top firms and scientists to contribute to the public cause? How should efforts be coordinated, and who will do the coordinating? How will research results progress to technology development, large-scale production, and ultimately deployment?

We aggregate these questions into following six categories:

1. Priority-setting (i.e., what to support?)
2. Selection of contractors (whom to support?)
3. A funding mechanism (how to support it?)
4. Incentives for participation
5. Coordination of research efforts
6. Translation to practice

⁶The 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.

The urgency of war necessitated careful, early decisions but also the flexibility to adapt, especially as the OSRD expanded and its research (and the war itself) progressed. Over the next several pages, we describe how OSRD approached each of these issues. 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. As we will see in Section 4, at a deeper level there was not one model but rather many, since different problems sometimes necessitated custom solutions.

3.1 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). The 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 the NDRC, ideas for research projects could come from within the OSRD, the military services, or an Allied government. It was the job of the OSRD’s individual sections to workshop these ideas and formulate a basic proposal, including a plan of action, potential contractors, and its anticipated cost and duration. These proposals were then voted on by the committee at weekly meetings, and its recommendations were forwarded to Bush, who made final funding 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 the NDRC’s research divisions the flexibility to use their imagination to dream up solutions to military problems—such as high-resolution aerial photography, electronic fire control, or infrared night vision goggles—while also ensuring their ideas passed the scrutiny of other experts and were consistent with the rest of the OSRD research agenda and the demands (and constraints) of the war effort overall. Bush later recalled “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.⁷ On occasion, CMR members also made “missions” to the front-line, which it viewed as helpful to identifying research priorities ([Stewart 1948](#)).

⁷When there were specific problems where it wanted research done but for which it was not getting proposals, CMR members actively reached out to researchers “whom it regarded as most suitable” directly ([Stewart 1948](#)). However, most CMR research was investigator-proposed, rather than internally proposed.

In both cases, research divisions staffed by leading civilian scientists determined research priorities, with input and in some cases collaboration from military users. The committees would then assess scientific feasibility. For problems with high solution uncertainty, both the NDRC and CMR funded multiple rivalrous approaches, such as in the atomic fission and penicillin research programs (see Section 4). 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 explained, the time for basic research is before a crisis, and since time was of the essence, “the basic knowledge at hand had to be turned to good account” (Conant 1947).⁸

3.2 Selection of contractors

The second question the 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 the 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).

The NDRC’s research divisions were tasked with finding suitable contractors and placing contracts. The agency followed four guidelines in selecting contractors: (i) prioritization of ability to deliver outstanding results as fast as possible – especially organizations requiring the least new personnel, equipment, or facilities to do the work; (ii) for devices which may later go into production, avoidance of contractors in local areas already overloaded with war production contracts or labor shortages; (iii) spreading work across contractors, as feasible; and (iv) all else equal, reducing cost.⁹ Once chosen, the division heads worked with contractors to develop formal proposals to be reviewed by

⁸Also worth noting is that Bush was deliberate in choosing what research problems the OSRD would *not* pursue. These choices were driven largely by Bush’s view of where the agency could have the most impact. For example, materials science was not a focus of OSRD research, and was instead relegated to the Office of Production Research and Development at the War Department. Bush similarly kept the OSRD out of what were primarily production problems, such as scaling up production of natural penicillin, instead focusing the OSRD’s efforts on synthesizing penicillin and running clinical trials for its application to specific diseases.

⁹Members of the NDRC specifically recognized the long lags in going from a kernel of an idea to its deployment in the battlefield, due to the research and development, mass production, delivery, and user training required, making speed of the essence. As Stewart (1948) writes: “The time interval between the inception of an idea and the use of the finished product upon the battlefield would normally run into several years. There was ever present in the minds of the Committee the possibility that the need would arise before the equipment could be completed. There was thus 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 the manpower which promised the best results in the shortest possible time.”

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 the NDRC’s leadership (correctly) predicted 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.

Because the 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 33 committees (with 221 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.

3.3 The contract mechanism

OSRD was willing to fund projects which it perceived to have high upside but uncertain payoffs, with the intent of putting “the best scientific imaginations in the country” on problems of military importance. There was also a desire to not impose excessive oversight that might interfere with scientists’ ability to take risks and exercise judgment. Yet it was also important to ensure that researchers remained focused on the true military objectives.

One of the organizational innovations of the NDRC was the development of contractual terms that could balance these needs. No strong precedent existed for government R&D grants or contracts prior to World War II, but A. Hunter Dupree (1970) would later call the R&D contract “one of the great inventions of the NDRC-OSRD” and “the glue which held the whole system together.” Broadly speaking, the 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.

In fields where military need could be divided into unrelated, discrete challenges (as in chemistry or medicine), contracts were drawn widely, including to individual scientists and their personal labs. However, when the need was for entire new systems (like radar or rockets), the OSRD often concentrated resources geographically and institutionally, including funding the creation of entire major research centers such as the Rad Lab. In still other cases (most prominently at the CMR, e.g., in the search for malaria drugs) OSRD played a coordinating role between efforts already underway in firms and universities, with limited formal contracting or funding.

3.4 Incentivizing participation

With the U.S. conscripting >10 million men into the military, nearly every scientist had friends and family members deployed. The importance of producing technology to help U.S. soldiers, sailors, and aviators survive in battle was thus much greater than an academic exercise. A sense of urgency, common purpose, and shared destiny permeated American society—especially among civilians supporting the war effort—and it made available “the best scientific talent of the country” ([Stewart 1948](#)), who were able to work long hours 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 indirect cost recovery policy and patent policy, each of which would be precedent-setting, were designed to help do so.

¹⁰Contractors “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](#)).

Overhead

Because the research was contracted out, it would use existing infrastructure at universities and firms. From its inception, contracts were written on a “no gain, no loss” basis, but the committee also recognized that in addition to regular research expenses, “there is a substantial indirect cost of a going concern which must be allocated as a part of the cost of a particular operation” (Stewart 1948). The NDRC decided to allow for “overhead” expenses amounting to 50% of labor costs for university contractors, and 100% for industrial contractors. These indirect cost rates were later amended to a sliding scale for universities, declining as more contracts were placed with a given institution. The OSRD likewise transitioned to a system of “direct” reimbursement of indirect costs at industrial contractors, whose cost accounting methods could explicitly specify the OSRD share of overhead. In a postwar review of overhead costs at the largest academic and industrial contractors, OSRD cost accountants determined that roughly 50% of contractors had received excess overhead payments, 10% were undercompensated, and 40% broke even.

Patents

The invention of the R&D contract introduced other novel challenges, especially in the assignment of intellectual property rights. The contract terms initially adopted by the NDRC gave itself the sole power to determine whether or not to file a patent application on inventions which resulted from the contracted research, and the power to determine disposition of title and any rights to use. This reflected the idea that the public should own the fruits of publicly-funded research. However, this left contractors “completely subject to the judgment of the Government as to the disposition of rights to inventions made under NDRC contracts” (Stewart 1948). Several firms refused to sign contracts with this provision. Stewart (1948) summarized the problem:

[The] 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.

After extended negotiations, the 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, the NDRC was unsuccessful at negotiating a license that extended to all government uses). Contractors were required to report all inventions to the 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 patent clause became known as the “long form” clause, and it was used with the overwhelming majority of industrial contractors.¹²

The NDRC (and later, OSRD) continued using a variant of its original patent clause—now called the “short form” clause—in specific categories of contracts, giving the government presumption of title where it supplied significant equipment, personnel, and even training to support the work. The short form clause became standard for major OSRD-funded laboratory research programs hosted at academic institutions, such as the research efforts in radar (MIT), rockets (CalTech), and submarine detection (Columbia). CMR contracts were also subject to the short form patent clause. Research contracts in the field of atomic energy were initially written under the long form clause but were converted to the short form clause after it became apparent that the research might result in the development of an atomic weapon. These decisions were uncontroversial at the time, since in medicine there were strong norms militating against patenting, especially patenting public research, and in the other cases, the government’s interest in controlling the intellectual property rights was clear. Still, in exceptional cases, CMR nevertheless tailored its patent policy in order to motivate participation by qualified firms (see Section 4).

3.5 Coordinating research efforts

One of the 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, the CMR organized meetings of investigators to facilitate their cooperation, duplicated and circulated

¹²There were also concerns about allowing firms to own patents resulting from publicly-funded research, especially among New Deal Democrats concerned with concentration of economic power. Bush acknowledged these concerns but argued that letting firms keep patents was important for ensuring their participation in the wartime effort, and the free government use license would be sufficient for wartime purposes. See [Sampat \(2020\)](#).

non-confidential progress reports among the community, and (with the help of the various NRC committees) monitored progress and identified which projects “should be prosecuted with vigor” versus “terminated or not recommended for renewal” (Stewart 1948). NDRC divisions working on related problems could also share members, but for security reasons, information sharing across divisions was restricted to that which was necessary to the work.

Coordinating research across U.S. government agencies was the job of the OSRD’s Advisory Council, which consisted of the Director of the OSRD, the Chairmen of the 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. When their work overlapped or bore conflicting demands, or when it seemed collaboration may be valuable, it convened ad-hoc expert committees to make recommendations on how to proceed. In some cases, research programs begun by one agency might be transferred to another, the most notable being the 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 the OSRD’s ties to these other agencies.

Close relations with the military were paramount to the 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. As Stewart (1948) describes it, their job was “to speed the project from initiation to the final stage of large-scale Service procurement.”

International coordination (primarily with Great Britain, but also other Commonwealth countries) began shortly after the NDRC was created. Scientific exchange between the American and British first took place in the fall of 1940 with a British mission to the U.S. led by Sir Henry Tizard (accompanied by representatives of the British and Canadian military, and the National Research Council of Canada), 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 event in the Tizard mission was the conveyance of 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 research program. Other exchanges

took place on the proximity fuze and the feasibility of an atomic weapon, both of which became important OSRD research programs. The Tizard mission, on its own, may have been the highest-impact scientific event for either country at any point in the war.

From this point forward, international collaboration was a prominent feature of the research effort. The OSRD established a “field 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. The OSRD’s London field office eventually evolved into a formal Liaison division, which managed scientist exchanges (U.S. scientists visiting England or vice versa) in addition to transmitting scientific reports. American radar research labs also established branches in England, near their British counterparts, putting American and foreign scientists in direct contact with each other and enabling them to coordinate their research programs.

3.6 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 the 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 the 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. In some cases, where it expected there could be pushback or negative publicity (e.g., testing of gonorrhea treatments on prisoners), CMR worked with contractors to develop protocols (Rothman 1991). 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 4.

4 Example OSRD Research Programs

Although the OSRD had a predominant model for identifying research priorities and supporting the work, there were also differences in how individual research programs were run. We illustrate the OSRD’s work with four case studies: radar (and radar countermeasures), atomic fission, malaria, and penicillin. What these projects had in common was (i) an urgent military demand, (ii) questions over who would do the work, how the work would be done, and how to get the results into the field, and (iii) a foundation in existing basic science. But they also differed in several ways, such as in the division of labor and organizational structures, the pursuit of serial versus parallel research efforts, and policies around patent rights and information sharing.

Table 5 summarizes these programs, where this heterogeneity can be seen. The table also shows, however, that although these programs were different in many ways, they all made clear choices in the categories of decisions we outlined above, choosing either to engage end-to-end or to outsource certain activities and functions to a partner organization.

4.1 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 the 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.¹³ Section D-1 of the NDRC, colloquially the Microwave Committee, was established with the specific objective to study the application of microwaves (radio waves <10 cm in length) to detection problems, guided by Alfred Lee Loomis (an independent inventor, physicist, and wealthy financier who was running a private experimental radar laboratory from his home prior to joining the NDRC), and staffed by academic and industrial scientists and engineers from various institutions with experience in the field of microwave radiation.

Concurrently with American efforts, British scientists were also investing in improving radar, for defense against German attack. When the Tizard mission demonstrated the cavity magnetron to U.S. researchers at Loomis’ Tuxedo Park laboratory in the fall of 1940, it jump-started what would grow to be the NDRC’s most significant research project.¹⁴ In October 1940, in light of the possibilities that radar presented and at the urging of the Tizard mission, the NDRC’s Microwave Committee voted to create a radar research laboratory at MIT. The institute was chosen over other contenders for four reasons: the presence of a handful of scientists with experience in the microwave field, its ability to attract more academic scientists to work on the radar problem, its proximity to the sea, and the possibility of using Boston’s Municipal Airport for testing. Research at MIT began on November 10, 1940, several months before the NDRC contract with the university was finalized, under direction of Lee A. DuBridge, a physicist from the University of Rochester. The lab was quickly staffed up with other scientists, largely physicists and electrical engineers, academic and industrial, faculty and students and recent graduates alike.

[Baxter \(1946\)](#) describes the Rad Lab embarking on its research mission with a “feverish” pace. By January 1941 it was testing new radar sets from the roof of MIT buildings, using it to track planes in the Boston area. In February, the Rad Lab was asked by the Army to make experimental radar sets for installation in planes, setting a precedent for limited “crash production” in addition to its crash innovation, though most production was both then and later done by industrial contractors like General Electric, RCA, AT&T, Westinghouse, or Raytheon.

¹³Prior 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.

¹⁴The significance of the cavity magnetron was its ability to generate enough power to make radar feasible at wavelengths of <50 cm, an achievement that had proved elusive. It sparked further innovation that brought wavelengths down to under 10 cm, and was the critical component in every radar set thereafter.

Throughout the war, radar development was centered at MIT, with parts procurement and various projects subcontracted out to other organizations, such as Bell Labs. The first two years of work at the Rad Lab focused on basic advances in microwave communication, growing from a kernel of perhaps 20 scientists to an organization of thousands, most on-site in a single, three-story building, all working long hours in service to the war effort—including numerous future Nobel laureates in physics. By 1943, substantial progress had been made on the core technology, and its work began shifting to engineering and production. It was in 1943, according to [Baxter \(1946\)](#), that the Rad Lab's operations expanded to “development, assistance to manufacturers, and field service.” To this end, the Rad Lab put staff members on detail at manufacturers, and manufacturers likewise sent personnel to Cambridge for collaboration on prototypes.

Coordination was a prominent feature of the research effort. As the Rad Lab grew, the 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 branches working on radar, the OSRD also organized a government radar patent program to exchange inventions and coordinate patent filing.

As the war progressed, radar countermeasures (i.e., obfuscation and jamming of enemy radar), and even counter-countermeasures, were proved to be nearly as valuable as radar itself. Shortly after the attack on Pearl Harbor, the NDRC was asked to begin work on countermeasures in collaboration with the Naval Research Laboratory and Signal Corps, and it added a countermeasures division to the Rad Lab, to be led by Frederick Terman of Stanford.

The countermeasures project had distinct objectives, staff, culture, and security requirements, and it was soon decided to move it to another institution—with Harvard being the natural choice due to its facilities and proximity. On March 20, 1942, the OSRD initiated a new division (Division 15, “Radio Coordination”) and a new contract with Harvard to fund the Radio Research Laboratory (RRL) for development of radar countermeasures. In July, Terman moved with his staff of then >100 people to Harvard. The lab quickly grew, with recruits piling in from around the country, including from firms like AT&T and CBS, and even re-training biologists and chemists into radar technicians, reaching a size of 800 staff members at its peak.

Between 1940 and 1945, radar developed into a profoundly important instrument of war, giving

soldiers the ability to see from land, sea, or air what their eyes could not. Despite hardly 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). The OSRD supported R&D in over 100 distinct radar systems for different applications (e.g., ground-, ship-, or air-based; stand-alone or integrated into firing devices; etc.). [Baxter \(1946\)](#) later described radar as “the most versatile instrument in modern warfare,” going on to attribute the Rad Lab’s success 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.” Though it was decommissioned at the end of the war, the Rad Lab lived on through its post-war descendants, MIT’s Research Laboratory for Electronics and Lincoln Laboratories. Fred Terman returned to Stanford as Dean of Engineering (later Provost), where he laid the foundation for the post-war ascendancy of the Silicon Valley area in electrical engineering, electronics, and microwave communications, earning a reputation as “the Father of Silicon Valley”.

4.2 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.

The OSRD’s atomic fission research was rooted in the scientific breakthroughs of Otto Hahn and Friedrich Strassmann, who in 1938 had produced barium after bombarding uranium with neutrons, and Lise Meitner and Otto Frisch, who discovered in a follow-up experiment in early 1939 that the result was achieved through atomic fission. What made the result remarkable was that the resulting fragments had less mass than the original uranium nucleus—and by implication, the missing matter had been transformed into energy, which Albert Einstein’s famous formula $E = mc^2$ implied would be very large relative to its mass. This finding alone was revolutionary, earning Hahn and Strassmann a Nobel prize in 1944, but the fact that the fission of uranium released additional neutrons suggested it may be possible to engineer chain reactions. The finding electrified the physics community, presenting new possibilities in the production of energy.

It was well known amongst the tightly-knit physics community in 1939 that U-235 was the isotope in which fission was achieved ([Baxter 1946](#)), and uranium was thus the focus of most early research on fission. At this time, only a handful of deposits had been discovered around the world, with

isotopes U-234, U-235, and U-238 comprising <0.01%, 0.7%, and 99.3% of material in naturally-occurring uranium. If only U-235 was reactive, scientists faced two possibilities: “One approach was to place unseparated uranium in a ‘pile’ with carbon or heavy water as a moderator or ‘slower down’ of neutrons to increase the chances of a chain reaction,” whereas the other was “to separate the isotopes and accumulate a stock of U-235” (Baxter 1946).

In the summer of 1939, at the urging of Leo Szilard and Albert Einstein, President Roosevelt appointed a special Advisory Committee on Uranium to initiate study of the fission of uranium, led by Lyman A. Briggs, the director of the National Bureau of Standards. When the NDRC was established in June 1940, this committee was folded in as one of its divisions (Table 1). Briggs’ first request to Bush was for an allotment to research the fundamental constants of nuclear fission, and contracts were let in the fall of 1940 with several universities and funds transferred to two federal agencies to support this work. Notably, the NDRC’s leadership itself was divided over the military relevance, and thus prudence, of this investment. As Baxter (1946) recounts:

To at least two members of NDRC these appropriations seemed questionable. The order creating the agency defined its objective as research and development of instrumentalities of war, and did not seem broad enough to include ... nuclear physics or the development of atomic energy for peacetime use. Eventually atomic power might be harnessed to propel battleships or submarines, but not for many years to come. In view of all the high-priority problems pressing for solution was it desirable to commit many of the limited group of first-rate physicists to the uranium job?

This internal dissension led Jewett (member of the 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 it “called for a radical expansion of our efforts” or a continuation of a modest, exploratory research program. This committee, which included Nobel laureates Arthur Compton and Ernest O. Lawrence, met twice in the spring of 1941 and recommended a “strongly intensified effort,” but acknowledged that it would likely take years for this research to yield enough progress to be of use in military applications. Based on this committee’s report, Briggs requested to increase NDRC expenditures on atomic fission three-fold, writing over a dozen new contracts for the study of “the possibility of a chain reaction and of full-scale equipment for the production of power,” as well as “continuation of work on the separation of uranium isotopes”, which was thought to be the only material conducive to a chain reaction in a mass small enough to be a bomb (Baxter 1946).

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 who were involved in the NDRC-funded research or close to the problem became increasingly convinced of the possibility of separating uranium isotopes and generating an explosive chain reaction, and Bush decided that a course of action needed to be set by the President. In a meeting with Roosevelt and Vice President Henry Wallace in October 1941, Bush explained the state of atomic fission research, 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 to accelerate its progress: gaseous diffusion and centrifugal separation of U-235 was headquartered at Columbia under the direction of Harold C. Urey, electromagnetic separation (through the use of a cyclotron) at Berkeley under the direction of Ernest Lawrence, and chain reactions in unseparated uranium and its (recently discovered) fissionable byproduct plutonium at Chicago under Arthur Compton.¹⁵ 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). At a December 16 meeting, the President urged Bush to "press as fast as possible on the fundamental physics and on the engineering planning, and particularly on the construction of pilot plants," with the understanding that when the program was ready for full-scale production, it would be transferred to the Army.

Because it was unclear which method of separation would be viable for large-scale production, the OSRD decided to continue investing in all approaches until any was successful or found infeasible. 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 the urgency of the project, Briggs, Compton, Lawrence, Urey, and Eger Murphree (a chemist from Standard Oil who was recruited to help manage the diffusion and centrifuge separation work) proposed to begin building pilot plants for all five methods of producing fissionable material at scale before the viability of any one had been proven. This proposal was then forwarded by Bush and Conant to the President, Vice President, and Secretary of War with a supplementary proposal that the Army undertake the construction of these pilot plants.¹⁶

¹⁵All Nobel laureates working with exceptional students and colleagues, including other past and future prize winners like Enrico Fermi, Glenn Seaborg, and Luis Alvarez (also of the MIT Rad Lab).

¹⁶Although R&D would normally precede pilot production, "Fear that the Germans would be the first in the field with atomic bombs led to a telescoping of stages, in which pilot plant work often overlapped research in the laboratory, and the design and construction of some of the huge production plants were carried out before lessons could be learned and obstacles surmounted in the pilot plant" (Baxter 1946). The Manhattan Project, under the guidance

While the Army began building these plants, the OSRD continued its work. A major breakthrough occurred on December 2, 1942—when Chicago’s Pile Number 1 produced the first controlled nuclear chain reaction, in effect becoming the world’s first nuclear reactor—but the experimental pile would have had to run for 70,000 years to produce enough plutonium for a bomb. Research on five methods of producing fissionable material thus continued, though by the spring of 1943, centrifugal separation was abandoned, and heavy-water soon thereafter.

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, the OSRD transferred its work to the Army on May 1, 1943. Its contracts were subsumed into the recently-organized Manhattan Project, whose mission was to produce a functional atomic weapon. In all, the 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. Several OSRD staff members were then transferred to the Manhattan Project, and 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.

4.3 Penicillin

Infectious disease was the most important medical problem facing soldiers during the war. 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, especially streptococcal infections. But they had major toxicity issues and were not useful for many other 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 (who later shared a Nobel Prize with Fleming) were first able to purify the molecule, making it possible to conduct clinical tests. However, the Oxford group was unable to produce enough of it for human testing, nor, in war-torn Britain, to engage British pharmaceutical companies to help do so.

In 1941, Florey came to the U.S. for help ([Baxter 1946](#)). He was referred to the U.S. Department of Agriculture’s Northern Regional Research Laboratory (NRRL) in Peoria, IL, which had experience growing mold at high yield, and also met with A.N. Richards at the CMR. Though CMR’s primary

of the military, engaged numerous industrial contractors to collaborate with the academic labs to build these plants at now-familiar sites: electromagnetic separation and gaseous diffusion plants were built at Oak Ridge, TN, and a plutonium plant at Hanford, WA. Work on the design of a bomb itself was moved to the newly established Los Alamos laboratory near Santa Fe, NM, for reasons of secrecy and safety.

focus was supporting research rather than production (Stewart 1948), Richards assured Florey “that he would see that everything possible was done to expedite the production of penicillin” (Federal Trade Commission 1958). This commitment was made despite the fact that the production program for natural penicillin was regarded as “chimerical” in certain quarters and there was considerable uncertainty about its feasibility (Federal Trade Commission 1958). But it was buffered by CMR’s decision to engage in a parallel effort to develop a synthetic penicillin, which had even greater appeal, as both Richards and Bush believed large scale production of a synthetic would be cheaper and more technically feasible than production of natural penicillin.

The CMR took sharply different approaches to the two R&D programs, which presented distinct problems. Its research efforts focused on synthetic penicillin, where the key questions were figuring out penicillin’s molecular structure and finding a way to chemically synthesize it. As with other OSRD research programs, the CMR had to decide whether to concentrate resources in the top firms, or spread its bets. Ultimately it decided to choose companies that had experience in or capabilities for synthesis, or interest in penicillin more generally. It included nine firms, two universities, and the U.S. Department of Agriculture in the synthetic penicillin program (Swann 1983). Under the terms of its contracts, Bush had the right to inspect contractors’ work and records, and contractors were required to provide progress updates through monthly reports. CMR could then share information from all contractors amongst the group, as useful (Swann 1983). Since several leading firms were already conducting research on synthesis, CMR issued “token” contracts with no funding, mainly to facilitate information flow. The principal terms of these contracts addressed patent rights of the participants: firms were allowed to take out patents, with Bush’s approval, but required to grant non-exclusive licenses to other contractors and the government, with reasonable royalties. This licensing policy was viewed as a substitute to presumptive government ownership.

In the natural penicillin case, the problem was not research; rather, it was production. Here, CMR initially had a more limited coordinating and recruiting role: beyond some funding to the NRRL, it did not fund much of the actual research. In late 1941, CMR organized meetings with Bush, the NRRL, and representatives from the pharmaceutical companies Merck, Squibb, Pfizer, and Lederle Labs, where it worked hard to persuade these (mostly reluctant) firms to be involved. The NRRL was to work on techniques for increasing penicillin yields from mold, and the firms on production techniques, and similar to the synthetic program, “their progress would be reported to CMR for such distribution as would advance the program” (Andrus 1948).

This undertaking presented several challenges. One was getting firms to invest in developing (unfunded) production capabilities. Merck and Pfizer were concerned about cross-over contamination of penicillin on other activities, and (early on) wanted more proof of concept from Peoria before

charging ahead—so CMR provided progress reports and other reassurances to assuage concerns (Federal Trade Commission 1958, Neushul 1993). It also served as a broker of information among these firms, and helped them get waivers to avoid antitrust scrutiny that cooperative research sometimes attracted. Finally, CMR helped the firms by working with the War Production Board (WPB) to get needed equipment to the firms, and connecting them with academics who would evaluate the samples they produced. In all cases, the firms provided their own funding, participating for patriotic, reputation, or other reasons. Since natural penicillin was a known molecule, there was no strong intellectual property to be had, save for process patents.

While the synthetic penicillin program struggled to make headway, by 1942, firms were producing 40 million units of natural penicillin per month, up from 10 million in 1941 (Baxter 1946)—enough for testing.¹⁷ Because quantity was initially scarce, the firms had agreed that all testing should be organized by CMR. Testing was done via contract in collaboration with the NRC Committee on Chemotherapeutic and Other Agents (COC), which would eventually be headed by CMR’s own Chester Keefer. CMR acquired supply from the producers (initially for free, but later at cost). The COC then distributed penicillin to hospitals free of charge, in return for detailed case reports (Federal Trade Commission 1958). 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 (Federal Trade Commission 1958). CMR also supported testing “in the field” on wounded soldiers, in collaboration with the military (Andrus 1948, Federal Trade Commission 1958). 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 for penicillin, beyond pilot plants. The needs of massive scale-up were a distinct technical challenge. On the encouragement of CMR, the Office of Production Research and Development (OPRD) of the WPB provided needed material, and shared technical expertise and some funding, while the Defense Plant Corporation helped support construction (Baxter 1946).¹⁸ Even as WPB tried to convince firms to invest quickly in plants for scale-up, a lingering risk which allegedly slowed investment was the possibility that the CMR might end up succeeding in a synthetic approach to penicillin production. Bush’s view, however, was that “Synthesis may make all this obsolete, but it may not, and the overall problem is so important that no leads should be neglected” (Neushul 1993).

WPB contacted 175 potential producers, and eventually included 20 in the program (Neushul 1993),

¹⁷Baxter (1946) notes that it takes about one million “units” of penicillin to treat one patient.

¹⁸Note that although the government supported plant construction, nearly 75 percent of the \$30 million spent on this came from private firms. The government provided authorization for rapid tax amortization of these investments to help defray these expenses (Swann 1983).

chosen based on experience with penicillin, fermentation, and biologic production in general, and the quality of staff. WPB spent a lot of time and energy trying to facilitate information sharing among the firms involved, which Richards later noted greatly increased productivity (Andrus 1948), while OPRD funded academic research to help solve technical bottlenecks in the scale-up process (Neushul 1993). In this effort, CMR was largely on the sidelines: its expertise was in research and testing, whereas military production was the domain of the WPB.

The natural penicillin program was successful. Monthly output grew from 425 million units in June 1943, to 117.5 billion in June 1944, to nearly 650 billion in June 1945. The cost of producing 100,000 units fell from \$20 to less than one dollar. By 1943, there was enough penicillin to treat U.S. and Allied troops and meet civilian demand. CMR was initially involved in rationing, but once civilian demand became large this was turned over to WPB. The government was the major buyer during the war, paying cost-plus prices of about \$20/dose (Achilladelis 1993).

The synthesis problem, in contrast, proved surprisingly 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 in getting enough penicillin for testing. But Swann (1983) also notes that lack of success during the war does not necessarily mean the program was a flop, since much of the knowledge developed during the war “paved the way” for a number of clinically important semi-synthetic penicillins introduced in the 1950s.

In *Science, The Endless Frontier*, Bush (1945) observed that “Penicillin reached our troops in time to save countless lives because the Government coordinated and supported the program of research and development on the drug.” As is well known, the drug would also have a major impact on civilian health as well providing treatment for a range of infectious diseases. Firms which participated in the natural and synthetic penicillin programs were also poised to be important players in the antibiotic revolution in the decades after the war. Achilladelis (1993) argues that “OSRD policies for the development of penicillin created a unique opportunity for the American Pharmaceutical Industry to gain experience in R&D and the manufacture of antibiotics which were the major market for pharmaceuticals in the following 25 years.”

4.4 Malaria

Malaria—caused by mosquito-borne, protozoan parasites of the *Plasmodium* group—has been one of the deadliest diseases in the world for centuries. In the U.S., malaria was on the road to elimination

by the early 1930s, reflecting urbanization and public health interventions such as mosquito control. But much of World War II was fought in areas with high malaria risk, especially in North Africa and the Pacific theater, and morbidity from malaria was 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 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 developing a quinine substitute. In the U.S. this was supported by the NRC and 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 during the Allied blockade in World War I. 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 many 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 similarly reluctant to compel them to do so (Baxter 1946).

In 1941 the NRC organized a Conference on Chemotherapy of Malaria (later called the Board for the Coordination of Malarial Studies) which CMR funded as one of its first activities. The Board would develop a coordinated approach to developing malaria preventatives and treatments. It included CMR representatives, NRC scientists, and representatives of the Army and Navy. 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.”

Much of the work supported by CMR was aimed at identifying a good substitute for quinine. The initial work focused on atabrine: since the drug was being made in the U.S. using slightly different materials and approaches, it was unclear if its adverse side effects were inherent or due to process. This work examined whether the U.S. variant was sufficiently pure and the actual incidence and severity of side effects, as well as testing and developing dosing guidelines. But CMR also supported synthesis and screening of other drugs in parallel (Slater 2009).

The hunt for other treatments began with basic research on parasitology in animal models (Baxter

1946, Slater 2009). Once testing capacity was widespread and there were good animal models, the bottleneck was rapid identification of new compounds. This was a different problem than penicillin, where only one or two compounds were studied: CMR funded synthesis and testing of *thousands* of antimalarial compounds, trying to find one better than atabrine. But in addition to funding, it also coordinated a decentralized, inter-disciplinary and cross-sector research network. Together with NRC, it helped share information across related efforts, and distributed research problems to different teams to avoid unnecessary duplication. The NRC Board for Malaria Studies (led by James Shannon, who would later become perhaps the most prominent head of the NIH) conducted trials of atabrine and other candidates—including in prisons and on other institutionalized populations, and, working with military liaison officers, on soldiers in the field.

The Survey on Malarial Drugs was the “workhorse” of the program (Slater 2009). This project 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’ proprietary interests, while 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). Despite all of these issues, by 1942 “research on the disease moved faster in one year than the previous ten” according to one account (Condon-Rall 2000). 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). Out of this effort came 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 on the field was none other than 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.

5 Impacts on Postwar U.S. Science and Science Policy

The impacts of the OSRD were significant, directly affecting not only the prosecution of the war, but also U.S. technological progress, scientific manpower, federal science policy, and the postwar

U.S. economy. Its immediate impact was to help protect Allied forces in battle and bring the war to swifter, victorious ending. Although we lack a counterfactual against which to measure its impact on the war, the view of contemporaries and historians is that the OSRD had a significant, multifaceted effect on its outcome (Bush 1945, Baxter 1946).¹⁹ It was also anticipated that the results of its work would permeate civilian life, outliving the war itself: as Stewart (1948) wrote, “its part in the winning of the war was its greatest contribution,” but its full impact would be realized later “as the civilian counterparts of its military developments begin to exert their influence upon life in the United States and in the world at large.”

We previously described the range of technological advances that the OSRD achieved in World War II. Yet many of these results would not have reached the public without a dissemination strategy, which the OSRD developed in the last year of the war.²⁰ The OSRD allowed individual researchers to write books and scientific articles, but until 1946 their publication required both OSRD and military approval. Technical reports were deposited with the military services, and other reports sent to the Department of Commerce, National Archives, and in select cases, to the Library of Congress for distribution to local libraries throughout the country.

When it was all over, OSRD-funded research had generated nearly 8,000 inventions, 3,000 patents, 2,500 scientific articles, and over 10,000 technical reports. According to Google Scholar, the *MIT Radiation Laboratory Series*, a 28-volume encyclopedic series sharing the engineering and technical details of all of the work of the Rad Lab, has over 12,000 citations at the time of writing. CMR publications have collectively been cited at least 70,000 times—an average of 40 per publication, for the 1,718 CMR publications we can link to Clarivate’s Web of Science. Moreover, the OSRD did more than simply advance the frontier of knowledge and state of the art in existing fields—it opened up entire new fields of research. Stewart (1948) wrote of the CMR: “The shift in emphasis and even in direction was enormous. Many subjects of minor importance in peacetime become of controlling importance in war,” and some were even “born of war.”

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. The MIT Rad Lab, for

¹⁹For example, radar was used to detect incoming enemy aircraft on land and at sea, and incoming rockets targeting the civilian population in London. It was also paired with electronic fire control systems for automatic, guided anti-aircraft fire, and was the critical component of the proximity fuze, which detonated explosive shells prior to impact to increase the probability of hitting a moving target and the damage inflicted.

²⁰Five years of “scientific silence” had left a gaping hole in the literature, and there were both obstacles and pitfalls to releasing all of this information at once—including concerns around security as well as the protection of government interest in patentable research—which necessitated a strategic approach. Even if the research were in publishable form and free of security classification, the sheer volume would flood journals, book publishers, and the scientific community beyond their capacity. The OSRD addressed these issues largely through pre-publication review. Interestingly, it also provided journals with list of candidate referees who, as of the end of the war, had the greatest experience or expertise in new fields in which it had sponsored research.

example, employed hundreds of recent college graduates, PhD students, and recent PhDs in physics, electrical engineering, and related fields—including future Nobel laureates—and anecdotally shaped many of their careers. Managing a sprawling research organization was itself a distinctive talent that grew more valuable after the war as many U.S. universities transformed into federally-funded research powerhouses, and many of the OSRD’s senior scientists and major lab directors went on to become university presidents, provosts, and deans after the war.

In a recent paper, we have also shown that the OSRD had a large, long-run impact on the direction of U.S. invention, the locations where it took place, and employment in related industries ([Gross and Sampat 2020](#)). World War II and the OSRD catapulted the U.S. electronics and microwave communications industries to the technology frontier, laying the groundwork for much of the innovation which took place in the subsequent decades, and setting in motion agglomeration forces which led to research activity increasingly concentrating in technology hubs around the country. The CMR may have had similar effects on medical research and the life sciences, though this remains an open question which has not yet been tested.

Several institutional innovations developed or refined during the war, including significant government funding of university research, remained features of the postwar era. Specific aspects of contract design—indirect cost recovery and patent rights on publicly funded research—evolved from the models developed during the war, and the debates on these issues in the postwar era echoed those in the 1940s ([Sampat 2020](#)). In medicine, the active CMR contracts were transferred to NIH after the war and formed the basis for its extramural program. The NIH “dual” peer review model itself was based on the CMR/DMS approach described above ([Mandel 1996](#)).

Its most important impact was more general, in laying the foundation for government support of research broadly. It was clear even before the war was over that the government would be an active funder of research in peacetime. In November 1944, President Roosevelt asked Bush to reflect on the lessons from OSRD for using research to promote peacetime goals of health, national security, and job creation ([Roosevelt 1944](#)).²¹ Bush’s response, *Science, The Endless Frontier* is sometimes considered the “blueprint” for postwar R&D policy.²² The “Bush Report” made the case for government funding of “basic” research at universities, with priority setting by scientists rather than politicians, and emphasized the need for scientific autonomy. This was a markedly different approach from how OSRD operated, and may reflect the difference between optimal innovation policy in crisis and non-crisis situations, a topic we turn to next.

²¹It is now well accepted that Bush composed the letter himself ([Kevles 1977](#), [Bush 1970](#)).

²²For alternative perspectives, however, see [Mowery \(1997, 2009\)](#).

6 Lessons and Limits

Policymakers often use war as a metaphor to motivate major R&D efforts.²³ Beyond large government expenditures in a short period of time, what does it take to mobilize science in an emergency? What lessons can we draw from World War II for future crises? Lacking a counterfactual, it is impossible to say with certainty exactly which features of the wartime effort were essential. Compounding this difficulty, we also must rely largely on accounts of individuals involved in the effort, who may lack perspective or objectivity in their assessments.

Even so, reflecting on the OSRD may inform innovation policy more generally. For one thing, the OSRD experience highlights that the innovation policy problems during a crisis are different from those in peacetime (or “non-crisis” times). The main difference is that in crises, speed is a primary objective. Because in crises the objective of R&D policy is not just to get research done, but also to get it deployed quickly, in various cases we discussed (e.g., atomic fission, penicillin, malaria) the OSRD, together with other government agencies, also supported parallel R&D efforts and production capacity “at risk.” Moreover, while non-crisis R&D policy worries about racing and overfishing (e.g., [Dasgupta and Maskin 1987](#)), in crisis contexts multiple shots on goal can be valuable, especially for problems where there is solution uncertainty ([Nelson 1961](#), [Scherer 2011](#)). The value of a solution is so great that large amounts of funding to increase probability and speed of success, even if much is ultimately wasted, can be cost-effective.

The need for speed in crisis R&D also may require a heavier hand, a tighter focus, and more explicit coordination than ordinary R&D problems. In contrast to the status quo ante, and also modern U.S. research policy, the OSRD chose to focus on applied research, involved users in priority setting, and had a heavy hand in coordination and implementation. [Hoyt \(2006\)](#) has called the wartime vaccine push “an integrated research model”—a term which would also apply to the rest of OSRD. The reason for the applied research focus and heavy government hand throughout—despite the fact that OSRD leaders generally supported scientific autonomy and limited government—was the urgency of the moment. For example, by and large there was no time for exploratory research: [Conant \(1947\)](#) recalled “Time set a limit to what could be done ... the basic knowledge at hand had to be turned to good account.” This, then, is another lesson from the OSRD model for crisis innovation: the need for clear objectives, tight focus, and active management of the R&D process, beyond simply correcting standard market failures in basic science.

The OSRD history also points to the choices policymakers have to make. A first choice is whether

²³According to Google searches, we need a Manhattan Project for cancer, AIDS, alternative energy, global warming, cybersecurity, nutritional supplements, and even for protecting Manhattan itself from rising sea levels ([Wellerstein 2013](#)), raising the question: what *don't* we need a Manhattan Project for?

to contract for research services or specific outputs. When choosing what to fund, research efforts can be serial or parallel. Contractors can be concentrated or diffuse. The funder can choose to retain patent rights or relinquish them to inventors. It can also actively coordinate across research efforts and with end users, or take a hand-off approach. Finally, it can invest in production at risk, or wait until a scientific solution (or feasibility) is known before scaling.

Though there was a general model, as the case studies suggest different problems called for different types of solutions. In Table 6, we try to characterize what seems to have been OSRD’s implicit framework for decision-making around these problems. These decision rules are a function of features of the problem (e.g., scientific uncertainty, divisibility of the R&D, and how hard it is to quickly scale up production), features of the contractors (e.g., their existing scientific capabilities, and their opportunity cost of being part of the crisis response), and features of the environment (e.g., who are the end users). We also characterize where our example OSRD research programs—radar, fission, penicillin, and malaria—came down on each.

OSRD leaders and historical scholarship have also pointed to other salient features of the organization that they viewed as important to its success. First, the OSRD benefited from the strong working relationship among its leadership, rooted in their prior personal history and mutual trust, and especially benefited from Bush’s keen judgment. The organization itself was staffed by exceptional scientists, with a clear chain of command that made it possible for questions, answers, and directions to transmit efficiently up and down the chain. Its ability to make significant changes mid-stream, such as with the reorganizations of the NDRC and CMR, was notable. It was willing to take risks, making big bets on uncertain but high-value research proposals. Having an (effectively) unrestricted budget was, in this sense, a boon. Another was the lack of “red tape”: having little precedent for its work, the OSRD invented most of the tools, and guardrails, that it needed as it went. One of these was the contract mechanism itself, which was simple and quick to execute.²⁴ More generally, the OSRD sought to minimize the transaction costs of research. It is important to recall that this was an era before formal grant and contract procedures were institutionalized at universities and in the federal government—and before IRBs, technology transfer offices and other gatekeepers in the research process were common. Though this is good for speeding results, research may have been too unrestricted: Rothman (1991), for example, has emphasized that in the medical context, the need for speed sometimes resulted in ethically questionable practices (e.g., experimentation on prisoners), even by the standards of the day.

²⁴Bush himself noted the fast pace of contracting in his memoir (Bush 1970): “Within a week [the] NDRC could review the project. The next day the director could authorize, the business office could send out a letter of intent, [and] the actual work could start.” Bush goes on to emphasize how “this swiftness in getting things started, [and] the flexible scheme of operations, was an important ingredient.”

The OSRD effort also benefited from some favorable conditions which are not guaranteed to recur in all crises. The U.S. economy was basically functioning and able to operate at high gear, unlike in Britain or Germany. The U.S. also had a head start: it knew the war was coming for several years and the OSRD pre-dated the formal U.S. entry into the war. As Bush would emphasize in *Science, The Endless Frontier*, for many of the problems facing the military there was a pre-existing stock of relevant fundamental understanding, developed through basic research before the war, allowing the OSRD to focus largely on development and application. Despite considerable controversy about whether the nation's "full" talent was being employed ([Kilgore 1943](#)), the R&D establishment was small and it was relatively easy for Bush and his network to identify the most capable individuals and institutions for each research program. Without these favorable conditions, it is possible the OSRD may not have succeeded. An additional lesson is thus the importance of strategically investing in science and technology in regular times, to draw on in crises. This may include investing in basic research and developing the scientific workforce, cataloguing top individuals and organizations to enlist for unplanned urgent research problems, and insuring supply chains.

The OSRD approach may also be more suitable to some problems over others. Its approach may be best suited to contexts where the government is the final purchaser and controls implementation, and the range of needed technologies and approaches can be clearly articulated. Defense applications are one example, but by no means the only one: others might include government-administered health care or education. However, in contexts where the users are diffuse and heterogeneous (e.g., climate change; see [Mowery et al. 2010](#)) or where significant behavioral change in the population is needed, the OSRD approach may not be sufficient.

Taking stock, the history of OSRD illustrates how crisis innovation policy is different, and suggests a framework for thinking about appropriate policy responses in different contexts. Yet the particulars of the OSRD model may only work for specific types of innovation problems, such that caution is warranted in appealing to the World War II model as a solution to all crises. These, in our view, are the main lessons from OSRD for organizing crisis innovation.

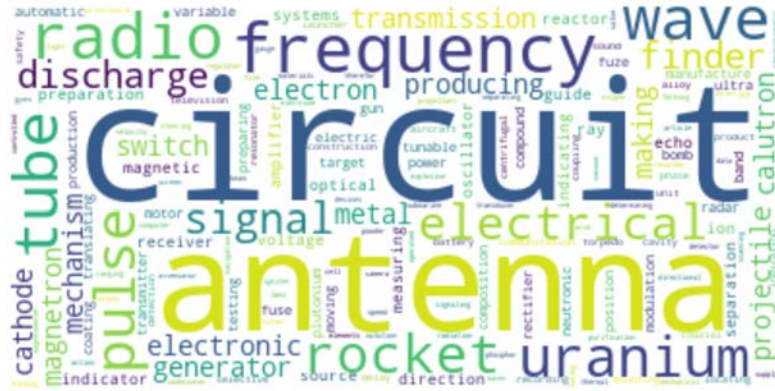
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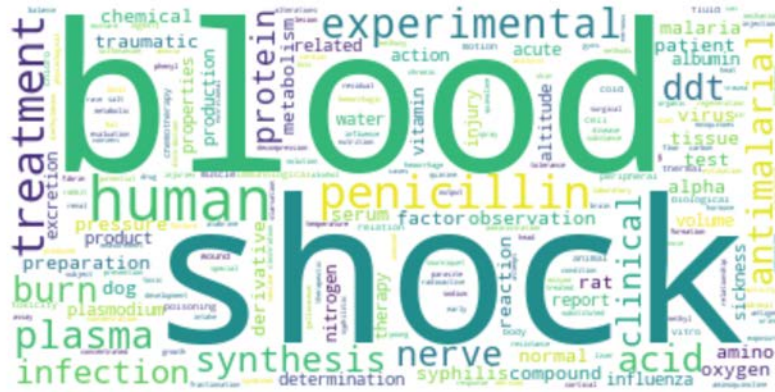
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Figure 1: Common words in OSRD patent and publication titles

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)

<i>National Defense Research Committee (NDRC)</i>		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 *
<i>Total</i>		400,735.1
<i>Committee on Medical Research (CMR)</i>		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
<i>Total</i>		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.

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	Radar	Atomic fission	Penicillin	Malaria
<i>What needed to be done?</i>	<p>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.</p>	<p>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.</p>	<p>1a. <i>Natural</i>: Produce sufficient quantities of natural penicillin for research and clinical testing; 1b. <i>Synthetic</i>: Identify penicillin's molecular structure and how to synthesize it; 2. Conduct clinical tests; 3. Scale up penicillin production for military and civilian use.</p>	<p>Find an effective preventative or treatment for malaria, by: 1. Improving understanding of mechanisms; 2. Developing high-throughput testing and screening protocols; and 3. Drug synthesis, production, and evaluation.</p>
<i>Who did the work?</i>	<p>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.</p>	<p>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).</p>	<p><i>Natural</i>: 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. <i>Synthetic</i>: Contracts to pharmaceutical and chemical firms, universities.</p>	<p>Decentralized effort across many institutions, both industrial and academics. Firms typically not under formal contract.</p>
<i>Contracts and patents</i>	<p>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.</p>	<p>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 2019).</p>	<p><i>Natural</i>: Most projects had short-form clause. Very little patenting, beyond a few USDA process patents. <i>Synthetic</i>: 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.</p>	<p>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.</p>
<i>Coordination efforts</i>	<p>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.</p>	<p>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.</p>	<p><i>Natural</i>: CMR staff organized meetings among firms and agencies involved, including British research efforts, collected and shared progress reports, and brokered connections. <i>Synthetic</i>: Secured protection from antitrust regulation for firms collaborating on synthesis. <i>Both</i>: Worked with WPB to ensure contractors had the equipment and supplies needed. Promoted information flow across efforts.</p>	<p>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.</p>
<i>Downstream activities</i>	<p>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.</p>	<p>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.</p>	<p>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.</p>	<p>Funded researchers to overcome chloroquine production bottlenecks, to generate enough drug for trials. Supported civilian and military trials of chloroquine.</p>

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

Question	Radar	Atomic fission	Penicillin	Malaria
<i>Number of OSRD contracts</i>	183	100	<i>Natural:</i> 36 / <i>Synthetic:</i> 18	78
<i>Total value</i>	\$156.9 mil.	\$14.4 mil.	\$2.4 mil. / \$0.4 mil.	\$4.8 mil.
<i>Short form patent clause: pct. of obligations</i>	86.21%	100.00%	100.00%	98.13%
<i>Top five contractors</i>	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 the 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: Organizing crisis innovation: A framework for key questions

Issue	Options	Depends on...	Explanation	OSRD approach			
				Radar	Fission	Penicillin	Malaria
<i>What needs to be done?</i>	Research vs. production	Stock of existing know-how	If solution unknown → fund research; if specifiable → contract for output	Both	Both	Primarily production	Primarily research
<i>How many approaches to fund?</i>	Serial vs. parallel	Solution uncertainty	High solution uncertainty → Multiple bets	Serial	Parallel	Parallel	Parallel
<i>How to organize research efforts?</i>	Concentrated vs. diffuse	R&D complexity	Complex R&D problems less divisible → greater concentration (e.g., systems engineering)	Concentrated	Concentrated	Mixed	Diffuse
<i>Who owns the IP?</i>	R&D funder vs. performer	Contractor incentives Security risks R&D spillovers Public interest	Contractors with pre-existing relevant assets, high opportunity cost, or large share of investment → allow contractor title to patents; Security concerns, benefits of knowledge sharing, or public interest → retain government title	Funder	Funder	Mixed	Mixed
<i>Coordination across efforts?</i>	Hands-on vs. laissez-faire	Spillovers across research efforts	High spillovers → coordinate research projects	Hands-on	Hands-on	Hands-on	Hands-on
<i>Coordination with users?</i>	Hands-on vs. laissez-faire	Size and number of end users	Large buyers → coordinate with end user	Hands-on	Hands-on	Hands-on	Hands-on
<i>When to begin production?</i>	During vs. after R&D	Immediate demand, cost of scaling up production quickly	If need is immediate and rapid production scaling difficult → Build production at risk	Ex-post	At risk	At risk	Ex-post

Web Appendix

A Historical Supplement

Figure A.1: Executive Order 8807 creating the OSRD (June 27, 1941)

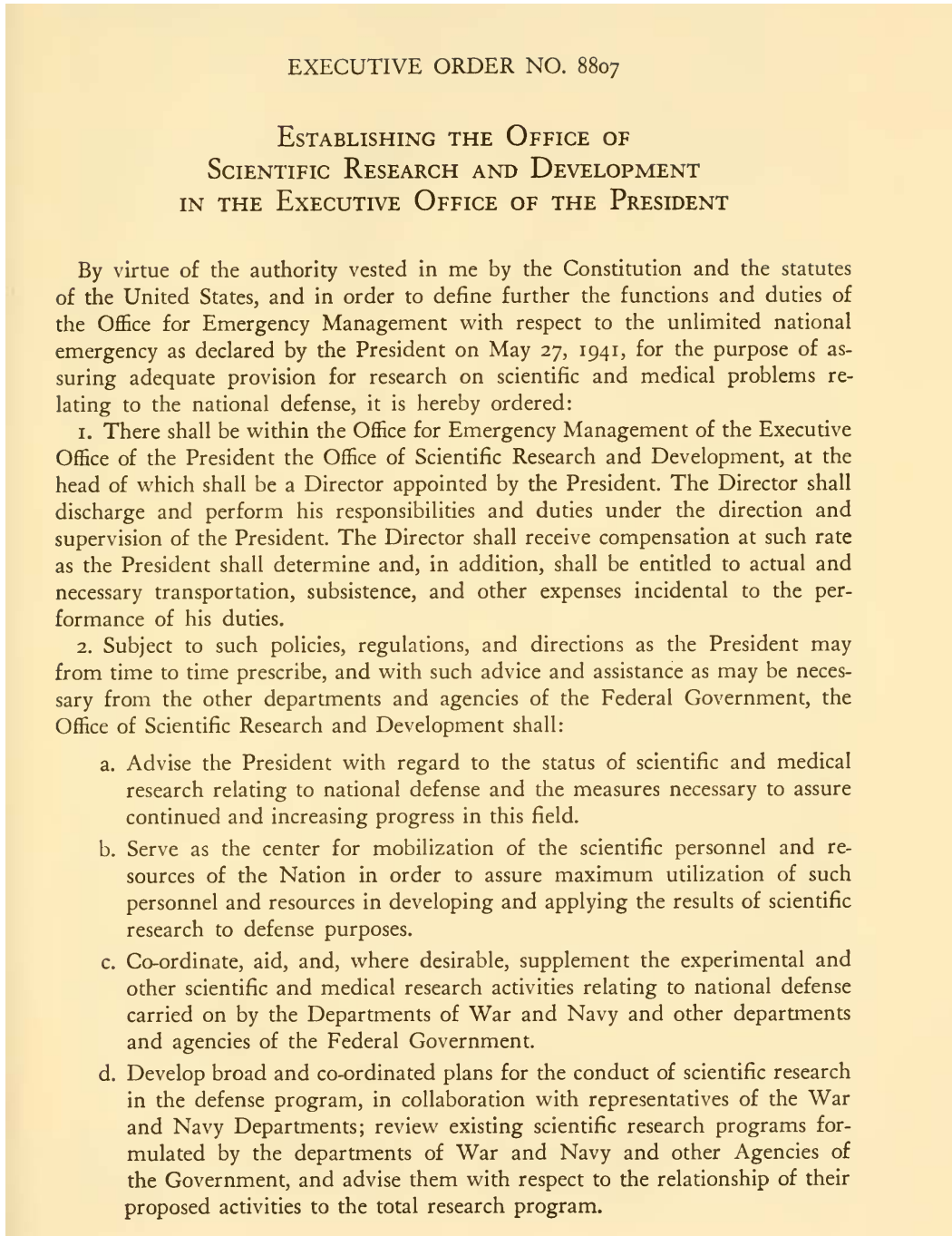


Figure A.1: Executive Order 8807 creating the OSRD (June 27, 1941)

- 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.1: Executive Order 8807 creating the 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.1: Executive Order 8807 creating the 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