United States Rocket Research and Development During World War II

Unidentified U.S. Navy LSM(R) (Landing Ship Medium (Rocket)) launching barrage rockets during a drill late in the Second World War. Image courtesy of the U.S. National Archives and Records Administration.

Over the course of the Second World War, rockets evolved from scientific and technical curiosities into practical weapons with specific battlefield applications. The Allied and Axis powers both pursued rocket research and development programs during the war. British and American rocket scientists and engineers (and their Japanese adversaries) mainly focused their efforts on tactical applications using solid-propellant rockets, while the Germans pursued a variety of strategic and tactical development programs primarily centered on liquid-propellant rockets. German Army researchers led by Wernher von Braun spent much of the war developing the A-4 (more popularly known as the V-2), a sophisticated long-range, liquid-fueled rocket that was employed to bombard London and Rotterdam late in the war. German Air Force investigators developed short-range rocket-powered bomber interceptor aircraft and jet-assisted takeoff (JATO) units for piston-powered attack fighters and bombers. Wartime American rocket research evolved along a number of similar and overlapping research trajectories. Both the U.S. Navy and Army (which included the Army Air Forces) developed rockets for ground bombardment purposes. The services also fielded aerial rockets for use by attack aircraft. The Navy worked on rocket-powered bombs for antisubmarine warfare, while the Army developed the handheld bazooka antitank rocket system. Lastly, both the Army and Navy conducted research into JATO units for use with bombers and seaplanes. Throughout the war, however, limited coordination between the armed services and federal wartime planning bodies hampered American rocket development efforts and led to duplicated research and competition amongst production facilities for scarce manpower and resources. Consequently, the war revealed the significant potential of rockets as a revolutionary military technology but also the shortcomings of the decentralized research and development efforts conducted by the armed services and the federal government during the conflict.

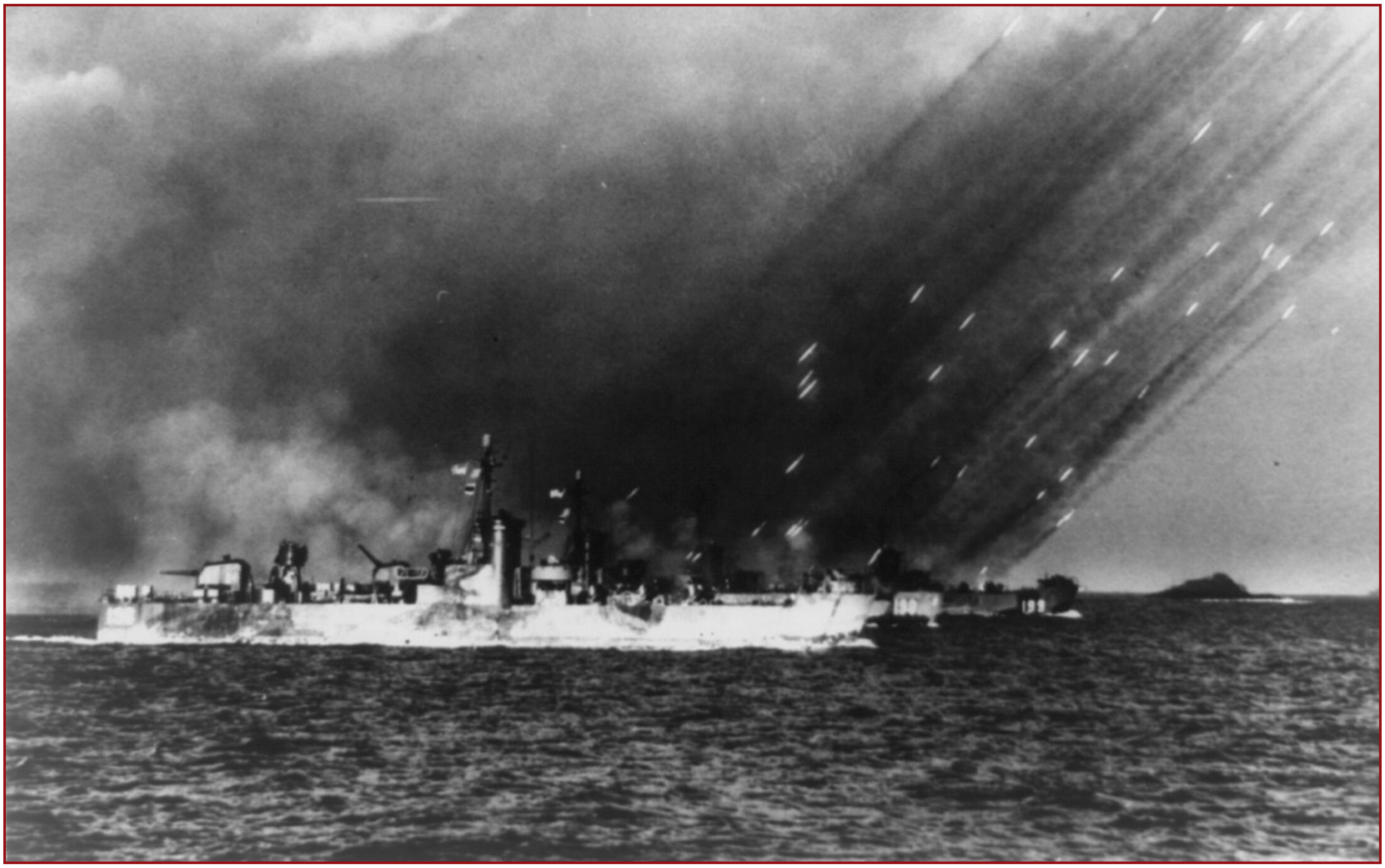
The Roots of American Wartime Rocket Research, 1940–1941

American military rocket research in the World War II era began under the auspices of the National Defense Research Committee (NDRC), which was established by the Council of National Defense (a body consisting of the secretaries of war, navy, interior, agriculture, commerce, and labor) with presidential approval on June 27, 1940.[1] NDRC leadership consisted of eight members, six civilian researchers, all of whom held senior posts in various government agencies and educational institutions, and two senior officers from the Army and Navy. Vannevar Bush, an electrical engineer and president of the Carnegie Institution of Washington, was selected as committee chair. Bush was an extremely capable administrator and served as chair for approximately a year until he was elevated to director of the newly created Office of Scientific Research and Development (OSRD) within the Office for Emergency Management. The NDRC became an advisory committee under the OSRD with primary responsibility for mobilizing "the scientific personnel and resources of the Nation" through collaboration 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 Navy."[2]

Prior to the formation of the OSRD in June of 1941, the NDRC oversaw research into a variety of advanced weapons technologies, including rocket propulsion. Rocket work initially fell under Division A (Armor and Ordnance), Section H (Investigation on Propulsion) of the NDRC, which was chaired by Clarence N. Hickman. Hickman was a physicist at Bell Telephone Laboratories who, as a graduate student, had worked briefly with Robert H. Goddard on solid-fuel rockets for the Army Signal Corps in World War I. Shortly after the creation of the NDRC, Hickman, with Goddard's approval, had written a letter to the head of Bell Labs, Frank B. Jewett, discussing the various military applications of rockets.[3] Jewett was also president of the National Academy of Sciences and a founding member of the NDRC. Hickman's advocacy helped to secure him a position as chairman for the NDRC's rocket propulsion section, which offered him great influence over rocket research and development work during the war. Ralph E. Gibson of the Carnegie Institution of Washington served as Hickman's vice chair.[4] Once the NDRC fell under OSRD oversight in mid-1941, some of the rocket work was subsumed under Division B, Section B-I-d (Unrotated Projectile Propellants).[5] A third reorganization of the NDRC research divisions took place in late 1942. Under this new arrangement, which remained in place until the end of the war, rocket ordnance fell under Division 3 (Special Projectiles, later Rocket Ordnance), Section H, with Hickman as chief and Gibson briefly serving as his deputy during 1943.[6]

NDRC division and section chiefs enjoyed statutory authority to draw up research contracts with universities, research institutes, and industrial laboratories based on suggestions or recommendations primarily originating from the Army Ordnance Department and Navy Bureau of Ordnance. Initially, these contracts were intended purely to advance scientific knowledge regarding specific subject areas. Following American entry into the war in December of 1941, however, NDRC/OSRD became involved with industrial procurement of specific advanced weapons and weapons components, though this was typically an outgrowth of existing research projects and treated as "crash procurement" by the armed services. In practice, NDRC was "highly decentralized" and the various division and section chiefs had great leeway with respect to contracting. Little effort was made to spread out research among the many colleges, universities, and public and private research facilities across the nation. Instead, a small number of elite East Coast and West Coast universities and research institutions received the bulk of the research work. This led to shortages of scientific labor at these institutions and concerns that too few researchers had too many critical research projects in their portfolios. Formal information sharing was also lacking, which led to duplication of research efforts and wasted time, energy, and money. While efforts were made throughout the war to address these issues, they were never completely resolved.[7]

In the case of rockets and rocket propulsion, initial work at the behest of the NDRC began in the early fall of 1940. Hickman's advocacy for new research on rockets as military weapons attracted little interest within the Army Ordnance Department and Navy Bureau of Ordnance with one exception: rocket-accelerated armor-piercing bombs. The Navy Bureau of Ordnance viewed rocket acceleration as a means for imparting aerial bombs with greater accuracy and penetration power.



Unidentified U.S. Navy LSM(R) launching barrage rockets at the shore near Pokishi Shima, near Okinawa, prior to American invasion in May of 1945. Image courtesy of the Library of Congress.

Naval staff believed that this would enhance the effectiveness of land- and carrier-based aircraft. The Bureau of Ordnance offered Hickman's NDRC-sponsored team research space at the Naval Proving Ground at Dahlgren, Va., along the bank of the Potomac River. The facilities at Dahlgren eventually proved insufficient, and in early 1941 the Navy moved the researchers to the Naval Powder Factory at Indian Head, Md., where they continued their solid-propellant research under the title of the Jet Propulsion Research Committee.[8]

Hickman's research team struggled to find a workable solid propellant for rocket testing. Double-base propellants, which contained both nitroglycerin and nitrocellulose, were deemed by the researchers to be the only propellants suitable for rockets. Hickman's team focused on ballistite, manufactured by the Hercules Powder Company, but at the time Hercules only produced ballistite in sheets for larger weapons and small grains for small arms, such as rifles. Neither suited the needs of the rocket researchers and they began to investigate purpose-made, double-base rocket propellants. The American process for extruding double-base propellants into grains involved suspending the powder in a solvent and "wet" extruding the resulting "dough" through dies. The ensuing grains had to be small or thin in order for the solvent to evaporate completely, which made them unsuitable for rockets that needed thicker and wider propellant grains. The British, on the other hand, employed dry extrusion of double-base propellants through rolling and pressure to produce larger powder grains much more suitable for rocket motors. Hickman's team encouraged Hercules to pursue the dry extrusion method in consultation with British powder manufacturers, but the American firm was hesitant to introduce the unfamiliar and potentially hazardous manufacturing practice to its existing powder mills.[9]

At the same time that the NDRC research team was beginning its investigations into rocket propulsion, a British delegation led by Sir Henry Tizard visited the U.S. to enlist the help of American researchers with a number of secret military technology development programs that the British had begun to pursue prior to the outbreak of war in Europe. While the U.S. was officially neutral at the time, the Roosevelt Administration and the armed services jumped at the opportunity to acquire information about British technical advances in exchange for American financial and research support. In addition to sharing research on radar, proximity fuses, jet engines, and atomic weapons, the British discussed the development of rockets as antiaircraft barrage weapons. This helped to spread interest in rocket technology and spurred the U.S. Army and Navy to commence work on new rocket-based weapons programs in conjunction with what eventually became Division 3, Section H, of the NDRC.[10]

By the summer of 1941, the Indian Head Jet Propulsion Research Committee had started to produce their own dry-extruded powder grains in a small homemade rig at the Indian Head research site. The Navy brass soon ended the experiment, however, due to the potential hazards of dry extruding double-base powders. Frustrated, the researchers organized a conference in July of 1941 with the Navy Bureau of Ordnance to address the powder production issue and chart a path forward for solid-propellant rocket research and development in coordination with the NDRC. The members of the Jet Propulsion Research Committee met with Ernest C. Watson, professor of physics at the California Institute of Technology (Caltech) in Pasadena, Calif., and the acting chairman of Division A (Armor and Ordnance) of the NDRC, and Ralph E. Gibson of the Carnegie Institute representing Section H (Investigations on Propulsion). The conference attendees discussed plans for Hercules Powder Company to begin manufacturing dry-extruded powder at a new facility under contract with the Army Ordnance Department. Samples would be provided to the Indian Head researchers to determine if they were suitable for use in rocket motors. Furthermore, attendees outlined a policy proposal for the Secretaries of War and the Navy that laid out the current status of rocket research for various military purposes and discussed specific applications that should be pursued by Army, Navy, and NDRC researchers.

Charles C. Lauritsen of Caltech, vice chair of Division A, summarized conference attendees' discussion in memorandum to Vannevar Bush on August 1, 1941. The report began by mentioning work in progress involving JATO development for the Army Air Forces and Navy. The Guggenheim Aeronautical Laboratories, California Institute of Technology (GALCIT), and the Navy Engineering Experiment Station at Annapolis, Md., both had research teams investigating solid- and liquid-propellant JATOs for the Army and Navy, respectively. The bulk of the report focused on solid-propellant rocket development work involving antiaircraft rockets and rocket-accelerated armor-piercing bombs. Lauritsen's report further discussed rockets of various sizes currently being produced in England and highlighted their shortcomings, particularly the lack of proximity fuses, as antiaircraft weapons. It also touched on other applications for the rocket motors currently being developed for aerial bomb acceleration, such as antisubmarine bomb projectors for warships. Lastly, it discussed how Section H, Division A, of the NDRC could contribute to this research and how the research could be coordinated by Army, Navy, and NDRC representatives in order to promote standardization of rocket components, including propellants, and manufacturing practices. The Lauritsen report was received favorably by the services, and the NDRC moved forward with expanding the activities of Section H, Division A (later renamed Division 3). This included issuing research contracts with General Electric and Western Electric for engineering services and with Caltech and later the George Washington University for material and personnel to support solid-propellant rocket research and development programs at Caltech and Indian Head (and later the Allegany Ballistics Laboratory).[11]

Wartime Solid-Propellant Rocket Research and Development

The Lauritsen report marked an important turning point in the institutional development of rocketry research and development capabilities in the U.S. Approximately four months before the U.S. entered the Second World War in December of 1941, an administrative framework had been established for rocket propulsion research and development that would help to direct wartime work on the West and East Coasts, respectively. Once the U.S. entered the conflict, Army and Navy needs and funding would dictate the evolution of research and development facilities and the growing specialization of rocketry experts as they worked to design, test, and manufacture solid- and liquid-propellant rockets for the armed services.

U.S. Army and Navy sponsorship of research into applications for solid-propellant rocket motors helped to dictate the structure of NDRC/OSRD-based research activities in the first six months after the U.S. joined the war. By mid-1942, significant work had begun on rocket-propelled antisubmarine weapons in order to counter the profound German submarine threat against Allied shipping in the Atlantic. Much of this work was conducted at Caltech under Navy oversight. Consequently, a new section of NDRC Division A—Section C (Antisubmarine Ordnance)—was established to encompass both rocket-propelled ordnance and underwater projectile properties. The new section was headed by John T.

Tate of the University of Minnesota. NDRC Division A, Section H (Investigation on Propulsion), led by Clarence N. Hickman (George Washington University), continued its prewar work on the East Coast at Indian Head but began to pursue projects primarily for the Army, which assisted with standardization of equipment, production issues, and procurement of auxiliary equipment.

In recognition of the new division of work between West Coast and East Coast research teams, the NDRC carried out a reorganization in December of 1942 that moved Sections C and H of Division A into a new division, designated Division 3 (Special Projectiles) with Tate as chair. Along with Hickman, Lauritsen, Ralph E. Gibson of George Washington University, and Earnest C. Watson of Caltech, the new Division's senior leadership included William N. Lacey of Caltech, George B. Kistiakowsky of Harvard University, Alexander Ellett of the University of Iowa, and Edwin P. Hubble of the Mt. Wilson Observatory and the Ballistics Division at Aberdeen Proving Ground, Md. Division 3 included two sections: Section H primarily under Army sponsorship oversaw activities on the East Coast and was headquartered variously in Washington, D.C., and New York City; Section L under Navy sponsorship focused on West Coast activities and was headquartered in Pasadena at Caltech. Tate later resigned as the head of Division 3 in order to focus on his work for Division 6 (Subsurface Warfare). Lauritsen stepped in briefly as acting chair and eventually Frederick L. Hovde of the University of Rochester took charge of Division 3 until the end of the war. Hovde also served as chair for Section L, while Hickman continued as chair for Section H.[12]

American soldier holding a bazooka, ca. 1943. Image courtesy of the Library of Congress.

Late in 1943, Section H relocated west from its research labs at Indian Head on the Chesapeake Bay to a new facility in the Appalachian foothills near Cumberland, Md. The Army provided space at the rural Allegany Ordnance Plant for rocket research and the new Allegany Ballistics Laboratory was founded. The facility was managed for Section H by the George Washington University and included laboratory buildings and a satellite firing range for long-distance rocket testing.

Section H

Section H researchers pursued a number of significant solid-propellant-based weapons projects during the war years. By mid-1941, the Navy concluded that development work on the rocket-accelerated aerial bombs that Hickman's research team had been working on for the past year was largely complete. Around the same time, the Army approached Section H about developing a rocket motor for a shaped-charge antitank projectile developed by the Ordnance Department. The Army hoped to field a handheld infantry weapon that could disable or destroy tanks at a range of 200 yards or more.[13] Such a weapon would help American soldiers counter German armored vehicles, which the German military had used effectively in blitzkrieg tactics that targeted the Polish and French militaries in 1939 and 1940, respectively. The Ordnance Department had originally intended to field the shaped-charge warhead as a rifle grenade, but the recoil at launch was far too strong for the average soldier to handle. Instead, Ordnance Department staff began to consider a recoilless concept using a rocket motor to propel the warhead out of a launching barrel. Eventually termed "the bazooka," the weapon could be fired from the shoulder like a rifle, and a quick-burning rocket motor ensured that the soldier firing the weapon would not be struck with rocket blast when the projectile cleared the barrel. Instead, the blast was vented out the back of the launch tube. NDRC Division 8 (Explosives) assisted Section H with the development of the rocket motor by creating faster-burning propellants that were less sensitive to temperature and produced significantly less blast when ignited. Once Section H had finalized the design of the bazooka, staff turned the plans over to the Army Ordnance Department, which handled contracting for the production of the weapon. Later in the war, Section H used the lessons learned from bazooka use in the field to create a "super bazooka" with a larger motor that offered the weapon longer range and more penetrating power. The new weapon did not see action, though, since production had not yet ramped up at war's end.[14]

At the same time that they were working on bazooka rocket motors, Section H researchers began building a 4.5-inch rocket motor to propel aircraft-launched rockets for Army Air Forces planes. Early tests of the motor proved encouraging and the Ordnance Department pressed ahead with standardizing the design. The first test launch from a plane took place in July of 1942. However, problems with the solid propellant used for the motors led to motor detonations and other ignition irregularities. Lighter-colored propellant samples, which had been developed to facilitate visual inspection of the propellant grains, proved to be more susceptible to ignition problems than darker-colored grains. Ultimately, darkening agents were employed during propellant production, to help eliminate ignition irregularities. The episode led to more fundamental research on propellant ignition properties, which Section H researchers conducted at Indian Head and also contracted out to researchers at the University of Wisconsin and the University of Minnesota.[15]

American soldier holding a rocket-powered bazooka round, ca. 1943. Image courtesy of the Library of Congress.

The 4.5-inch motor went through a series of iterative design improvements during 1942 and 1943. In late 1943, the Army Air Forces requested that the Ordnance Department and Section H develop a new 4.5-inch rocket motor with significantly more power, since use in the field had demonstrated that the existing aerial rockets were lacking in range and accuracy compared to 3.5-inch aerial rockets developed by Caltech for Navy aircraft. Section H staff began working on a "super" 4.5-inch motor. To meet Army demands, they decided to modify the solid propellant, Jet Propulsion Tubular, currently being produced for bazooka rocket motors. After testing validated the performance of the new propellant, they worked with Caltech staff to devise procedures for producing steel nozzles for the rocket motors. Finally, Section H and Division 8 staff worked together to design the warheads for the new rockets. The new super 4.5-inch aerial rocket design was standardized in December of 1944, but production remained extremely limited prior to the end of the war in August of 1945.[16]

Section H staff participated in a number of other solid-propellant rocket-related development projects during the war. In 1944, the Army Chemical Warfare Service asked the researchers to develop gas generators for two different experimental flamethrower projects. The first involved an aircraft-mounted flame gun in which solid-propellant grains would be ignited to produce gas that would drive a piston forward, ejecting the flaming fuel from the gun nozzle mounted on the aircraft wing. The resulting flamethrower worked well but was not deemed to be an improvement over the incendiary aerial bombs currently in use. A second project involved a single-shot lightweight flamethrower that employed a similar gas generation system to produce a seven-second blast of flame that could reach 50 yards. Section H staff completed work on the device but it was not put into production before the end of the war. A third gas generator project was intended to be used as a launcher for a self-guided aerial weapon similar to the German V-1 flying bomb. The propellant grains would be ignited, producing gas that would drive a cylinder forward to propel the jet-powered bomb into the air. Once again, field testing was successful but the device was not put into production prior to the war's end.[17]

Lastly, Section H researchers spent a number of years working on solid-propellant pusher rockets for a variety of purposes, including mine-clearing and demolition devices and JATOs. The mine-clearing Infantry Snake utilized a rocket motor attached to a series of overlapping metal plates containing explosives. The device would be launched at the edge of a minefield and would slide along the ground until a trip mechanism activated and the explosive detonated, clearing a path through the minefield. Another design involved a rocket motor attached to a high-explosive-filled cable for use in clearing battlefield obstacles. Section H's JATO work involved developing improved solid-propellant units that would produce less smoke and function consistently throughout a wide range of ambient temperatures. Early research and development work on solid-propellant JATOs had been conducted in the late 1930s and early 1940s by GALCIT in California and later the Aerojet Engineering Corporation, a commercial offshoot of the research laboratory. Units had been provided to the Army and Navy for use in the field. In late 1944, the Navy asked Section H research staff to develop an improved design based on their wartime experience with developing and utilizing solid propellants in rocket motor applications. Researchers devised a new slow-burning smokeless propellant that was temperature insensitive. When shaped into a cylinder, the resulting propellant stick could provide eight seconds of thrust, a significant accomplishment. Section H staff worked with GALCIT and Aerojet to complete the JATO unit, which was demonstrated successfully for Navy staff in the spring of 1945.[18]

Section L

Prior to the formation of Section L of NDRC Division 3 in December of 1942, researchers at Caltech pursued numerous solid-propellant rocket research projects for the military. In 1939, GALCIT received a $10,000 contract from the Army for JATO development. By 1941, research staff, including Theodore von Kármán, Frank Malina, and others, had devised a workable JATO unit for the Army fueled by asphalt and other solid-propellant materials. The Navy soon expressed interest in the GALCIT JATO units, and the GALCIT researchers established the Aerojet Engineering Corporation to produce the JATOs at an industrial scale.[19]

Caltech staff also focused on the key problem of developing a dry-extrusion press to produce double-base propellant grains suitable for rocket propulsion, since dry-extrusion grains were not readily available in the U.S. at the time. In the fall of 1941, they rigged up a press from spare parts, including a 30-ton hydraulic jack mounted on a trailer fashioned from the rear axle of an old Ford, that would produce a 15/16-inch stick of propellant from flat sheets of propellant. Given the danger of working with dry-extrusion propellants, they situated the rig in a canyon and utilized remote controls to operate it. After some trial and error, they were able to get the press working and quickly used up their supply of sheet propellant. Caltech staff soon built additional presses that could produce larger-diameter sticks of propellant for rocket motors. Simultaneously, research staff worked on developing target rockets for training antiaircraft gun crews and antiaircraft barrage rockets based on British designs. They also developed a bombardment rocket for the Chemical Warfare Service that could hold a variety of warheads and was intended for defensive purposes. All of these rocket designs used the propellant sticks produced at Caltech.[20]

Caltech staff operating under Section C-4 (Submarine Studies) of Division C (Communication and Transportation) began looking into rocket-propelled projectiles for antisubmarine warfare in the fall of 1941. The U.S. Navy was interested in the British Hedgehog spigot mortar system, but the weapon produced too much recoil to be used safely on small antisubmarine patrol craft. Researchers at Caltech began developing a rocket-launched system but were hampered by the lack of a suitable solid propellant. Eventually, with the success of the lab-built dry-extrusion propellant presses, staff devised a 2-inch rocket design based on the Hedgehog. Nicknamed the Mousetrap after the shape of the launcher, it was tested successfully in the spring of 1942. The Navy placed a large order for rockets and launchers in July of 1942, and Caltech staff oversaw the crash production of the rockets using local contractors in the Los Angeles area to build the rocket bodies and motors, with the propellant sticks being produced at Caltech. They also devised a subcaliber training round known as Minnie Mouse that helped to train Mousetrap crews without expending scarce supplies of Mousetrap rockets. Lastly, research staff developed a new fuse for the Mousetrap rockets since the fuses used in the Hedgehog rounds proved unsuitable. They eventually devised a design that employed both hydrostatic pressure and impact to detonate the fuse, which made the rockets highly effective in their antisubmarine role.[21]

The rocket motors that Caltech developed for the Mousetrap gradually evolved into a series of aerial- and ground-launched rockets employed by the Navy for its patrol and attack aircraft and for use against enemy beach installations during amphibious assaults. The first of these was a retrobomb designed for antisubmarine patrol aircraft. The bomb's 3-inch rocket motor fired backward when the plane passed over a submarine. By countering the plane's forward momentum, the bombs fell straight down onto the target as if the aircraft had been standing still when it released the bomb. Training began in early 1943, but by the time the weapons began to be fielded, German submarines had changed their tactics, rendering the weapon impractical.[22]

U.S. Navy sailor training with a launcher for 4.5-inch barrage rockets at the Amphibious Training Base, Fort Pierce, Fla., in April of 1944. Image courtesy of the U.S. National Archives and Records Administration.

A second outgrowth of the Mousetrap project was a 4.5-inch barrage rocket that could equip large amphibious landing craft. The rocket motor from the Mousetrap was employed essentially unmodified, and a new contact fuse was developed by institute staff. Tests in the summer of 1942 proved so successful that the Navy Bureau of Ordnance immediately ordered 3,000 rocket rounds and fuses and 50 launchers for delivery in 30 days. Given the short turnaround required for the project, Caltech, rather than the Navy, oversaw the production of the rockets and launchers, which were flown east as soon as they were completed for use in the North Africa landings in November. The rockets proved so successful that the Navy continued acquiring them for future amphibious landings. Industrial contractors took over rocket production, with the exception of the propellant grains, and Caltech researchers focused their attention on improvements to the rockets and launchers in order to make them more effective and to permit them to be mounted on a variety of boats and trucks.[23]

Lastly, Caltech staff began to focus on developing forward-firing aerial rockets for Navy and Marine Corps aircraft. Unlike the work done by Section H for the Army, in which aerial rockets were envisaged as general-purpose air-to-ground weapons, the work for the Navy was intended to provide naval patrol aircraft with a new antisubmarine weapon for use against submarines at or near the surface. By this point, institute activities had been reorganized as part of the creation of NDRC Division 3 with its East Coast and West Coast sections. Work began on the design in the summer of 1943. A 3.25-inch rocket motor originally developed for an antiaircraft rocket was employed in the new 3.5-inch rocket. The rocket warhead was a solid-steel penetrator, which allowed it to travel up to 50 feet underwater with enough momentum to damage the outer hull of a submarine. Section L staff collaborated with Division 6 (Subsurface Warfare) staff on the design of the warhead. The antisubmarine rocket soon evolved into a general-purpose weapon. The size of the rocket was increased to 5 inches in order to accommodate a larger high-explosive warhead, but the motor remained the 3.25-inch design developed for the antisubmarine rocket. Later, a newer 4.19-inch motor was developed, which gave the 5-inch rocket the same velocity as the 3.5-inch rocket. This was designated the 5-inch high-velocity aircraft rocket (HVAR). The success of the HVAR rocket led Caltech staff to suggest scaling up the design around a 12-inch rocket motor. This new rocket, nicknamed Tiny Tim and officially known as the 11.75-inch rocket, went into production in the fall of 1944 and saw service with both the Navy and the Army.[24]

Section L also began a program to develop spin-stabilized rockets that utilized existing motors. Eventually, 3.5-inch and 5-inch ground-launched models were

U.S. Marine Corps Vought F4U "Corsair" fighter launches aerial rockets during the Okinawa Campaign, ca. 1945. Image courtesy of the U.S. National Archives and Records Administration.

U.S. Navy Grumman TBF-1 "Avenger" torpedo bomber taking off from the USS Makassar Strait (CVE-91) using JATO units during training operations off Hawaii in January of 1945. Image courtesy of the U.S. National Archives and Records Administration.

developed. The 3.5-inch model was not used extensively, but the 5-inch design found use on light naval patrol craft. A 5-inch spin-stabilized barrage rocket was also developed for Navy use.[25]

Section L staff remained active at Caltech until war's end, but their primary efforts were directed toward improving existing rocket designs and helping to set up equipment at the Navy's new research and testing facility at China Lake, Calif. Some Section L staff were detailed to assist with research involving the Manhattan Project, while others participated in the transition of facilities at China Lake from Caltech to Navy management. Section L work formally ended in the fall of 1945.[26]

Liquid-Propellant Rocket Research and Development

American liquid-propellant rocket research and development were significantly more limited during World War II than solid-propellant research and development. As with solid propellants, the Army and Navy pursued parallel research and development programs with limited formal information sharing between the services. Most of the liquid-propellant work during the war went into the development of JATO units, although both the Army and Navy pursued missile development to a limited extent.

Army JATO work began with the 1939 GALCIT contract. The GALCIT staff led by Theodore von Kármán eventually founded the Aerojet Engineering Corporation in March of 1942 to manufacture JATO units for the Army Air Forces. A year later, they established the Jet Propulsion Laboratory (JPL) under Army sponsorship when the Ordnance Corps, responding to rumors of German rocket launches, asked them to conduct research into long-range missiles.[27]

The GALCIT research staffs' first efforts to develop a liquid-fueled JATO involved motors using red fuming nitric acid (RFNA) with an addition of dinitrogen tetroxide (N_2O_4) as the oxidizer and gasoline as the fuel.[28] Motors fueled by RFNA and gasoline did not run well and also had a nasty tendency to explode (i.e., "hard start") rather than to start smoothly. At the same time, Lieutenant Commander Robert C. Truax was pursuing JATO research for the Navy at the Annapolis Engineering Experiment Station. One of his staff discovered that aniline and RFNA ignited spontaneously upon contact and thus made an ideal fuel and oxidizer combination. Frank Malina of GALCIT learned of this discovery while visiting the Engineering Experiment Station in early 1942. He quickly informed his colleagues in California, and the GALCIT

Racks of barrage rockets on an unidentified U.S. Navy LSM(R), ca. 1945. Image courtesy of the U.S. National Archives and Records Administration.

team soon had a liquid-fueled motor running. By mid-April, they made their first test flight with it. Truax continued his Navy work and developed a motor that was flight tested on a seaplane successfully in early 1943. Aerojet/JPL researchers continued refining the rockets designed by GALCIT and eventually developed a JATO fueled by monoethylaniline (otherwise known as N-ethyl aniline) and mixed acid (a blend of nitric acid and oleum) as the oxidizer that went into production before the end of the war.[29]

Robert Goddard was also hard at work on a JATO at the Engineering Experiment Station in Annapolis. Goddard developed a unit that was flight tested in September of 1942 but it utilized liquid oxygen as the oxidizer and gasoline as the fuel. Thus, it was not well suited for field use. Researchers at Reaction Motors, Inc. (RMI), founded in New Jersey by members of the American Rocket Society, also worked on a JATO design for the Navy. Like Goddard's design, their motor employed liquid oxygen and gasoline, but the mixture burned too hot and destroyed their motors. They added a metering valve to drip water into the gasoline as it entered the combustion chamber. This lowered the combustion temperature enough to preserve the engine. They demonstrated their JATO for the Navy in 1943, but, as with Goddard's design, it was not ideal for use in the field.[30]

Army efforts to develop a long-range guided missile centered on JPL research and development with Aerojet-produced motors. Von Kármán and Malina began initial work on a solid-fueled, fin-stabilized Private rocket as a proof of concept in 1944. The Private rocket was powered by an Aerojet-manufactured JATO unit with four 4.5-inch solid rockets developed by Caltech as boosters. After numerous launches of the Private proved successful, Malina proposed a scaled-up intermediate rocket design known as the WAC Corporal. The unguided missile employed a liquid-fuel main stage motor based on an Aerojet JATO unit burning RFNA and aniline-furfuryl alcohol with a solid-fuel booster based on the 12-inch Tiny Tim solid rocket motor developed by Caltech. The first tests of the missile took place shortly after the war ended and provided valuable information that allowed JPL to eventually develop the full-size, liquid-fueled Corporal ballistic missile for the Army in the early 1950s.[31]

The Navy pursued its own liquid-fueled missile research. In response to the profound threat posed by kamikaze attacks on naval ships late in the war, the Navy issued a design contract for a liquid-fueled missile with a solid-fuel booster that would use radio homing to destroy incoming aircraft. Named the Lark, the guided surface-to-air missile used a motor developed by RMI that was fueled by monoethylaniline and mixed acid. However, the war ended before the missile could move beyond the prototype stage.[32]

Conclusion

Over the course of the Second World War, researchers working on behalf of NDRC/OSRD and the armed services developed and fielded numerous tactical rockets and JATOs that proved the value of rocket propulsion for military applications. Unfortunately, the decentralized nature of NDRC/OSRD, particularly with respect to research and contracting activities, and competition between the Army and Navy for resources and manpower led to duplication of research and development efforts by the rocket development teams. Other independent bodies such as the Propellant Panel of the Joint Army-Navy Committee on New Weapons and Equipment, itself part of the Joint Chiefs of Staff, worked with Division 3 staff to better understand the properties and performance of solid propellants utilized by the armed services during the war. Chaired by Ralph E. Gibson, who also oversaw Section H rocket work at the Allegany Ballistics Laboratory, the Propellant Panel sought information on all aspects of solid propellants, including characterization of specific propellants, safe storage and handling practices, ballistic performance, and other relevant data. However, frequent changes in military personnel assigned to the panel limited its ability to broadly disseminate propellant information to the armed services and NDRC researchers during the war. Ultimately, most of the coordination and information sharing between researchers regarding rocket propellants and motor designs occurred informally through social and professional contacts. As the U.S. transitioned into a new peacetime research and development regime after the end of World War II, it lacked formal structures for promoting new research and development into the rocket propellants that had proved so important during the conflict.[33]

References

1. Irvin Stewart, *Organizing Scientific Research for War. The Administrative History of the Office of Scientific Research and Development* (Boston: Little, Brown and Company, 1948), 7. Hereafter, Stewart, *Organizing Scientific Research for War*.

2. Stewart, O*rganizing Scientific Research for War*, 36-9.

3. John E. Burchard, ed. *Rockets, Guns and Targets. Rockets, Target Information, Erosion Information, and Hypervelocity Guns Developed during World War II by the Office of Scientific Research and Development* (Boston, Little Brown and Company, 1948), 17-18. Hereafter, Burchard, *Rockets, Guns and Targets*.

4. Alexander Kossiakoff, “Ralph Edward Gibson (1901-1983),” *Johns Hopkins APL Technical Digest* **4**(1) (1983): 42-4. Hereafter, Kossiakoff, “Gibson.” Joint Board on Scientific Information Policy, *U.S. Rocket Ordnance Development and Use in World War II* (Washington: U.S. Government Printing Office, 1946), 4. Hereafter, Joint Board, *U.S. Rocket Ordnance*.

5. Unrotated projectiles referred to projectiles that were not launched by guns with rifled barrels that imparted spin on the projectiles in order to improve accuracy. While spin stabilization eventually became common with rocket projectiles, early rockets did not employ this stabilization technique and were thus considered “unrotated.” Stewart, *Organizing Scientific Research for War*, 54.

6. Stewart, *Organizing Scientific Research for War*, 85-6. From 1943 through 1945, Gibson focused most of his attention on solid-propellant rocket research at the newly established Allegany Ballistics Laboratory. Kossiakoff, “Gibson,” 43.

7. Stewart, *Organizing Scientific Research for War*, 57-60.

8. Burchard, *Rockets, Guns and Targets*, 19-20.

9. Burchard, *Rockets, Guns and Targets*, 19-20.

10. Joint Board, *U.S. Rocket Ordnance, 10* and Burchard*, Rockets, Guns and Targets*, 19.

11. Burchard, *Rockets, Guns and Targets*, 23-30.

12. Burchard, *Rockets, Guns and Targets*, 23-35; Stewart, *Organizing Scientific Research for War*, 85-6. The head of Division 3 also served as a member of other NDRC divisions including Divisions 4 (Ordnance Accessories), 5 (New Missiles), and 19 (Miscellaneous Weapons). He also served as the NDRC representative to the Joint Chiefs of Staff Committee on New Weapons and Equipment and chaired its Rocket Subcommittee. Burchard, *Rockets, Guns and Targets*, 34.

13. Burchard, *Rockets, Guns and Targets*, 51.

14. Joint Board, *U.S. Rocket Ordnance*, 41-3; Burchard, *Rockets, Guns and Targets*, 54.

15. Burchard, *Rockets, Guns and Targets*, 56-7.

16. Burchard, *Rockets, Guns and Targets*, 62-2.

17. Burchard, *Rockets, Guns and Targets*, 72-5.

18. Burchard, *Rockets, Guns and Targets*, 77-82.

19. Chris Gainor, *To a Distant Day. The Rocket Pioneers* (Lincoln: University of Nebraska Press, 2008), 130-2. Hereafter, Gainor, *To a Distant Day*.

20. Burchard, *Rockets, Guns and Targets*, 83-94.

21. Burchard, *Rockets, Guns and Targets*, 95-106. Also see Buford Rowland and William B. Boyd, *U.S. Navy Bureau of Ordnance in World War II* (Washington: U.S. Government Printing Office, 1953), 298-302 and Joint Board, *U.S. Rocket Ordnance*, 15-17 for more information on Mousetrap production and use in the field.

22. Burchard, *Rockets, Guns and Targets*, 107-17.

U.S. 7th Fleet firing barrage rockets at Balikpapan Beach, Borneo, in July of 1945. Image courtesy of the Library of Congress.

[23]Burchard, *Rockets, Guns and Targets*, 118-34.

[24]Burchard, *Rockets, Guns and Targets*, 147-55.

[25]Burchard, *Rockets, Guns and Targets*, 191-7.

[26]Burchard, *Rockets, Guns and Targets*, 211-6.

[27]Gainor, *To a Distant Day*, 131-2 and John D. Clark, *Ignition! An Informal History of Liquid Rocket Propellants* (New Brunswick: Rutgers University Press, 1972), 19. Hereafter, Clark, *Ignition*.

[28]The Army wanted storable propellants, so cryogenic products such as liquid oxygen were out of consideration. Clark, *Ignition*, 19.

[29]Clark, *Ignition*, 19, 23. Aniline was highly toxic and had to be handled with protective gear. Thus, it was far from ideal as a fuel. Its main virtue, to quote John Clark, was "that it worked." Clark, *Ignition*, 21.

[30]Clark, *Ignition*, 20-1.

[31]Gainor, *To a Distant Day*, 131-2. The WAC Corporal also served as a research sounding rocket and provided the basis for the Aerobee sounding rocket developed jointly by Aerojet and the Johns Hopkins University Applied Physics Laboratory.

[32]Clark, *Ignition*, 23.

[33]Burchard, *Rockets, Guns and Targets*, 230-1.

Author Information

Benjamin Schwantes, Ph.D., is the Managing Editor of the *JANNAF Journal of Propulsion and Energetics* and the Editor of the *JANNAF News*. He received a Ph.D. in the history of technology from the University of Delaware and has been with the Johns Hopkins University Energetics Research Group since 2016. His study of the American railroad and telegraph industries in the 19th century, *The Train and the Telegraph: A Revisionist History*, was published by the Johns Hopkins University Press in 2019.