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A History of Rocket Motor Research and Development in the Caltech-NDRC- Navy Rocket Program, 1941-1946

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EATON CANYON: A History of Rocket Motor Research and Development in the Caltech-NDRC- Navy Rocket Program, 1941-1946

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PREFACE

In 1941, Eaton Canyon was a lonely place in the foothills of the San Gabriel Mountains, northeast of Pasadena, California. In the years 1942 to 1945, Eaton Canyon was transformed into a research, development, testing, and pilot production facility for rocket weapons used in World War II (WWII), a facility conceived, staffed, and operated by the California Institute of Technology (Caltech). I (EWP) was employed in that remarkable facility from December 1941 to mid-August 1944 and participated in the birth of the modern era of rocketry. Towards the end of this period the Eaton Canyon operation was gradually phased out as more complete and permanent facilities were built at China Lake, California. The Caltech team played an essential role in development of what is now called the Naval Air Weapons Center (NAWC) at China Lake, California, and I (EWP) went to the new center in October 1944 (and stayed until 1974).

In a meeting of the Solid Rockets Technical Committee of the AIAA in January 1998, I (EWP) was present at a discussion of potential papers for a proposed history session in a forthcoming meeting. Being acutely aware of the obscurity of this remarkable Caltech-Eaton Canyon contribution to rocket history, I asked if anybody on the committee had ever heard of "Eaton Canyon", and no one had. I offered to prepare a history for a meeting six months later. My resolve was reinforced in the following two days after asking several of my technical associates from China Lake if they had ever heard of Eaton Canyon and found they had not. I don't think any history of rocketry would be complete without the Caltech-Eaton Canyon-China Lake story. My co-authors and I make no claim to be historians and don't have enough time left to do a fully researched history. But we were participants, having some excellent historical references, and the aid of an informal Eaton Canyon Alumni Association that met recently with assistance of the Caltech Alumni Association. It is our hope that we can capture the spirit of this remarkable chapter in rocket history and put its achievements in the context of history. One of my sources is a paper in the Caltech Alumni Magazine by Conway W. Snyder entitled, "Caltech's Other Rocket Project", the title indicating that Caltech had two rocket projects during W.W.II, one of which later became the Jet Propulsion Lab, while Eaton Canyon gave birth to the Naval Ordnance Test Station, the original name of the NAWC. Another source is an unpublished manuscript by Carlton Horine on the subject of "Extrusion and Plant Operations". Some of the bunkers and magazines of Eaton Canyon are still there, now hidden in native overgrowth, surrounded by modern housing developments.

The Caltech rocket project functioned under Contract OEMsr-418 with the Office of Scientific Research and Development (OSRD). The program involved not only rocket propulsion under Section 5 of the project (centered at Eaton Canyon), but also the larger weapon development program as a whole (weapon concept, warhead and fuse development, motor case manufacturing, launcher design, external ballistics, range testing, and fleet support). Its output was designed for and used by the U.S. Navy; and at the end of the war the roster of navy rockets included 408 distinct models of rockets using 58 motors and 61 heads (payloads), all of which came out of this project. The main goal here is to describe the Eaton Canyon propulsion research and development (R & D). In the writing effort I have picked up some co-authors for sections of the narrative involving aspects of the R & D with which they are more knowledgeable than I.

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INTRODUCTION*

In 1940, the war in Europe was raging and the possible (or probable) active involvement of the United States was on everyone's minds. Many senior scientists (some of whom were science advisers to the War Department in W.W.I) recognized that technological advances would be decisive in W.W.II, and led initiatives to establish organized research and development (R&D) for new military technology (radar, nuclear weapons, proximity fuses, magnetic submarine detection, rocket weapons, etc.). These initiatives led to establishment of the National Defense Research Council (NDRC), headed by Vannevar Bush, in June 1940. The NDRC was divided into several divisions, which advised the President on different areas of military technology. These divisions were headed by dedicated scientists, many of whom emerged as leaders of major R&D programs. These programs were soon funded by an agency set up for that purpose, the Office of Scientific Research and Development (OSRD). This approach to guidance and sponsorship of military R&D would be unthinkable in 1998 (or any time after 1946), but was chosen in 1940, because the armed services were not staffed with in-house scientists, the scientific community came forth with a call to action, and a crisis existed. Many of the leading organizers who served as science advisors in World War I (Vannevar Bush, James Conant, Robert Millikan, Richard Tolman, and others), were experienced with military needs and conscious of the very limited scientific resources in the military. They also recognized the potential of the enemy in W.W.II to produce and use formidable new weapons that could determine the outcome of the war. The battle of technology was already unfolding in Europe, most notably in the air war and magnetic fusing for mines.

The two strongest leaders in the push for rocket development were Charles Lauritsen (California Institute of Technology or "Caltech"), and Clarence Hickman (Bell Telephone Lab). Hickman had his technical origin in the 1918 "Ballistics Institute" at Clark University, where he and another figure in this history (L.T.E. Thompson) were graduate students under Robert Goddard. Hickman worked with Goddard on development of an armor piercing (rocket accelerated) bomb in the 1920's. In 1940, he was working with a 1930's solid rocket pioneer, Lt. Leslie Skinner (U.S. Army), on experiments with rockets propelled with solvent-extruded double base propellants. Hickman became head of Division H of the NDRC, under which wartime development of Army rockets was carried out at Indian Head, Aberdeen Proving Ground, and the Allegany Ballistics Lab (the "East Coast Rocket Program"), coordinated through the George Washington University.

Charles Lauritsen was a physics professor at Caltech, and a close associate of Richard Tolman (Caltech physicist and head of the armor and ordnance division of the NDRC). In 1940, he was persuaded by Tolman to go to England to learn about the British progress with weapons technology. His reactions soon evolved into determination to pursue development of solid rockets using dry extruded double base propellants. His position as head of a section of the NDRC in Tolman's Armor and Ordnance Division evolved into leadership of the "West Coast Rocket Program." *

During the same period of time, another Caltech rocket program was well underway under separate auspices in the Guggenheim Aeronautical Lab (GALCIT), at a now much better known site, the Jet Propulsion Laboratory. The principal contribution by this group to wartime rocket propulsion was the invention of cast composite propellant and its application to Jet Assist Takeoff (JATO) motors for airplanes. The interaction between the two Caltech projects was minimal.

The success of the Caltech NDRC rockets was so great during the war that Caltech had to develop a 3000-man operation encompassing not only motor research and development, but also pilot production, warhead and fuse development, launchers, static and flight testing, and external ballistics and sighting tables. The demand for motors was so great that the "pilot plant" at Eaton Canyon operated 24 hours a day and produced a million or more rocket motors. This history is about the motor R&D program.

BEGINNINGS OF THE CALTECH ROCKET PROJECT

In 1941, Charles Lauritsen became increasingly convinced that a more vigorous rocket program was needed and that the initiatives and facilities of the Eastern rocket group could not meet those needs. In his position as associate head of Division A of the

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* This Section was based on Ref. 1-3.

* The drama of these very complex events deserves more full description, but is omitted here in order to get more quickly to Eaton Canyon. See references 1-3.

NRDC, he pressed this view energetically in the NRDC, the Navy, and the Army. These efforts are described in Reference 1, and reflected early on in an excerpt, shown in Appendix A, from his letter of April 1941 to his boss, Richard Tolman (Ref. 1, p. 106). About this time Lauritsen was asked to go to England for briefing on weapons programs and weapons in use there. After his return, Lauritsen made a strong case for a broadened rocket program, and received a positive response. After some discussions with Caltech, and with the Army regarding the use of their test ranges, Lauritsen prepared a letter (Appendix B) for Vannevar Bush, summarizing the present status of U.S. and British rocket weaponry, and proposing expanded U.S. efforts. This was delivered with arguments for a West Coast rocket program at Caltech. It was followed by an intensive discussion among NRDC personnel and Army and Navy ordnance officers. Out of these discussions there emerged decisions for several OSRD contracts, the largest of which were those to the George Washington University and Caltech (to support the "East Coast" rocket program and the "West Coast" rocket program). The stated objective of the Caltech contract was very broad, for "—studies and experimental investigations in connection with the development, adapting and testing of ordnance devices."

C. Lauritsen was appointed Principal Investigator of the project, and he returned to Caltech, bringing his associate, W.A. Fowler and his son Thomas Lauritsen with him. Another Caltech physics professor, Ernest C. Watson became the Project Administrator, handling the paper work and contractual relations with the government. The project was soon joined by three other faculty members to be in charge of propellant problems; Bruce H. Sage, Assistant Professor of Chemical Engineering, William N. Lacey, Professor of Chemical Engineering, and Donald S. Clark, Assistant Professor of Mechanical Engineering. Their activity during the next four years is the primary subject of this paper. The project was joined by many other faculty and graduate students - physicists, chemists, engineers, and astronomers. Work began on September 1, although formal approval and funding of the project did not arrive until the following February. The Caltech Board of Trustees immediately provided funding until the government action was complete.

While the Caltech team did not have any old-time "rocketeers" like Hickman and Skinner on the East Coast project, they consisted of extraordinarily able scientists and engineers, some familiar with the history and technology of rockets. They had a charter of remarkable latitude, and a sponsoring agency (NDRC) that was not cluttered with bureaucracy and historical bias about weaponry in warfare. The early start date reflects the Caltech commitment to energetic support of the country's military goals and trust in the dedication and skill of the technical team. Some had been involved as participants in East Coast projects in the preceding year, but now were on their own, "back home".

By the time the NDRC support became official, the new team had succeeded in dry-extruding trench mortar ballistite sheet propellant into 15/16 inch diameter tubes and machined them to desired length; and then fabricated 1.25 inch O.D motors which were loaded with propellant, supporting grid and improvised igniters. The propellant was first extruded on November 15, 1941 by "Tommie" Lauritsen in a jury-rigged press at Eaton Canyon (Figure 1). Propellant machining was done in the Kellogg Lab on campus. A sand bagged bunker was set up under the front steps of Throop Hall (the original Caltech administration building), with the necessary stands and instrumentation for static firing. For obvious reasons, tests were run only late at night. Data acquisition consisted of pressure-time records, and more often than not, post mortems on recovered hardware and propellant fragments resulting from unwanted pressure excesses. Meanwhile, Sage's crew had been busy designing and beginning construction of the permanent facilities for producing rocket propellants in Eaton Canyon - extrusion presses, motor assembly buildings, magazines, static-test facilities, etc.

In the light of modern knowledge about propellants, manufacturing, propellant combustion, gas flow, and internal ballistics, there was a great deal to be learned and very little time to learn. The team had gone ahead and shown that successful performance was within reach. It is safe to say that the brave approach in late 1941 and early 1942 was in part sustained by Charlie Lauritsen's knowledge of the British success with cordite propellant in the preceding three years.

A PERSPECTIVE ON ROCKETS AS WEAPONS IN 1941

Early ideas for use of rockets as weapons included barrage (e.g., Congreve rockets of the War of 1812), rocket-accelerated armor piercing bombs (promoted unsuccessfully to the military by Goddard for twenty years starting in 1918), and anti-aircraft rockets (used by the British in the late 1930s and early 1940s in World War II). Historically, acceptance or non-acceptance of rockets as weapons by the military was affected by several technical and tactical considerations that changed with time:

1. Guns were more accurate; but that changed as the need for accuracy decreased with advent of proximity fuses, and as rockets became more accurate (eventually more accurate than guns in later years with development of guidance systems).
2. Rockets have no recoil, allowing relatively large projectiles to be launched under conditions unsuitable for guns (most notable is launch from light ships and vehicles and from aircraft) and in far larger numbers than possible with gun firing (most notable in saturation bombing of dispersed targets such as in amphibious landings).
3. Military "requirements" changed rapidly during WWII, due not only to the emerging technical feasibility of rockets, but also due to the changing nature of delivery systems (ground vehicles, ships and aircraft) and changing nature of the priority targets (submarines, beachheads, tanks, aircraft, ships, antiaircraft guns, logistical systems, and bunkers).
4. The emergence of better solid propellant.

In later years (1960-present) rockets changed the strategy of warfare, but in WWII the rockets were tailored to compliment strategy, with the scientists often having to promote use of rockets to meet the military need. As the war progressed and the effectiveness of rocket weapons became more evident, the interchange of ideas and needs between the scientists and military strategists (so lacking in prewar days) became more dynamic.

THE CALTECH ROCKETS*

The Caltech scientists were involved in several early projects (1940-41) such as high altitude anti-aircraft rockets and target rockets, but the first service weapon was the 7.2 inch anti-submarine rocket (ASR) developed to help combat the disastrous Atlantic and Caribbean submarine attack on shipping. Original development occurred in March and April of 1942 and the first model was placed in service in May. The ASR was 35 inches long and weighed 65 lbs. The motor case was steel tube, 2.25 inches in diameter and 16 inches long. The propellant charge was designated the Mark 1 Mod A and was a 3-ridge extruded tube of ballistic (Figure 2a, 3a), 11.6 inches long, weighing 1.43 lbs.* The weapon could be launched from light craft and propelled its light depth bomb warhead 290 yards. It became known as the "Mousetrap" because of the appearance of its wooden shipping-crate launcher. The propellant charges and igniters were designed, manufactured, loaded in the motors, and static tested at Eaton Canyon; a sub-caliber training version called the "Minnie Mouse" was manufactured using the 1.25-in OD motor. It was during development of these motors that the lessons were learned about darkening the propellant and mitigation of combustion stability (see later).

Over the next few months in the first half of 1942, the 2.25-inch rocket motor was adapted and used for several different applications, and propellant charges were produced that varied from 0.6 to 1.8 lbs., and in lengths from 2.2 to 13.25 inches. The next service weapon using this motor was the 4.5-in Barrage Rocket (BR: Figure 4). This weapon has a range of 1000 to 1200 yards, and was intended for mass bombardment from landing craft prior to amphibious landings. A prototype of this rocket was tested on June 12, 1942 (within 12 days of verbal request for the weapon from Admiral Bowen, and the rocket was considered developed in August, at which time the Navy requested an immediate 30 day delivery of 3,000 rounds. The weapon was first used in the landings in Casablanca in November. The demands in 1943 were running around 20,000 per month and Eaton Canyon continued to support this with propellant charges and motor loading into 1944. Around 1.6 million were used during the war and adapted for use from light land vehicles as well as landing craft.

Another adaptation of the 2.25-in motor used it to fire a rocket to the rear from an aircraft. The speeds were matched, so the rocket actually fell vertically. This strategy was used with airborne magnetic submarine detection equipment that signaled when the search plane was over the submarine. The "retro rocket-fired bombs" (fired in salvos) would impact at the detection point, eliminating the need to make multiple passes, course

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* This section is based in part on Ref. 4.

* See Appendix C for an explanation of descriptors for motors and rocket weapons.

determinations and bomb trajectory calculations. The Caltech retro-rockets were the first air launched rockets of WWII. Several retro rocket motors were developed (including a 3.25-in motor) to give speeds to match several different aircraft. All used a three ridge tubular propellant charge configuration.

By the late spring of 1943, the German submariners changed their tactics regarding air attacks. They chose to surface (or remain surfaced) so they could defend themselves with anti-aircraft guns. In response to this, the British tried forward firing their 3.0-inch anti-aircraft rockets from their airplanes. The Caltech team was already working on a new higher performance 3.25-in motor, and quickly developed the 3.5 inch AR (Figure 5) which used a 3.25 in OD motor with a new 8.5-lb. external burning "cruciform" ballistite propellant charge (Figure 2b, 3b). With a speed of 1180 ft/sec (plus aircraft speed) and a steel warhead, the missile could easily penetrate a submarine hull, thus forcing it to remain surfaced until other air and naval forces could be brought up for attack. On July 7, 1943, Caltech received an official request from the Navy for adoption of its new 3.25-in motor to the new AR, and by August of 1943, the Navy asked Caltech to provide 10,000 of the new 3.5-in ARs a month for four to six months. Naval aircraft were rapidly equipped for this rocket and a follow-on version with a 5.0-in diameter explosive warhead, called the 5.0-in AR.

The heavier 5.0-in AR had a speed of 700 ft/sec. and was effective against all lightly armored targets, anti-aircraft emplacements, and light land and sea transports. In April 1944, the Commander-in-Chief of the Pacific requested 100,000 rockets per month. By this time, the extrusion presses at Eaton Canyon were producing some 8,700 lbs. of propellant charges a week and the design teams were working on design of a new, more powerful AR that would be effective against "harder" targets.

The new high performance AR was named the 5.0-in HVAR, or "Holy Moses" (so named at the scene of the first ground launch tests in December 1943). The HVAR had a 5-inch diameter motor, with a 24 pound cruciform shaped propellant charge. The warhead was the same as that of the 5.0 AR, but the velocity was 1,375 ft/sec., compared to the 700 ft/sec. 5.0 AR. This made the HVAR effective against harder targets. The weapon had been well tested by June 6 (D-Day), and the Army had called for HVAR's to use in its aircraft. In a few days, HVAR's were being air transported from Eaton Canyon to Europe, accompanied by Caltech advisors, Carl Anderson and W.A. Fowler (a Nobel Prize winner and a Nobel Prize winner-to-be). A squadron of P-47's was equipped with HVAR's, and had great success in attacking tanks, armored cars and pillboxes. The enthusiasm of the Army over these successes is reflected in messages reported in Reference 5, page 193:

> Lieutenant General Carl Spaatz, Commanding General of the U.S. Strategic Air Forces in Europe wrote, "The success of the equipment has resulted in a requirement from the Ninth Air Force to equip all of their P-47 fighter aircraft with rockets". Major General E.R. Quesada, Commander of the Ninth Air Force (in requesting thousands of the rockets by TWX), reportedly dictated, "We want Caltech rockets, repeat, we want Caltech rockets, not Army Ordnance". Also characteristic of the reaction was the statement by Major General B.E. Meyers of the Air Technical Service Command, who described the Holy Moses as the "best anti-tank weapon of the war".

However, according to Reference 5, p. 194, the initial successes was attained with a carefully trained squadron, and later use in Europe was less effective because of inadequate Army logistic and training support.

In the Pacific the use of rockets was supported by the close ties of the Navy to the Caltech team. Quoting further from Reference 5, p. 194:

> It was quite a different story in the Pacific. There, the war was essentially a naval war. The naval officers and the scientists associated with the Navy-sponsored rocket projects could carry their message to every level in the combat theaters, from the Commander-in-Chief, to the logistical support groups, and the sailors and marines loading the launchers. Once rockets had proven themselves in battle, the contacts between the operating forces in the Pacific and the Caltech scientists became a firm and fast relationship.
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> When W.A. Fowler toured the Pacific combat arenas in the spring of 1944, rockets were fast becoming major weapons of war. By the end of hostilities their use was extensive. The Army was procuring rockets

> to the tune of $150,000,000 a year. The Navy had 1,200 war plants in a program for turning out rockets at eight times this amount. The Navy's expenditure for rocket weapons in 1945 was $100,000,000 *per month*. From the standpoint of production and the rapid refinement of combat doctrine, it can be concluded that if Japan had been invaded, the rocket power released would have been phenomenal.

Roughly 2 million HVARs (Fig. 6, 7) were manufactured during WWII. After the war, the 5.0 HVAR remained the primary air-launched rocket of all services for the following five to ten years.

During the autumn of 1943, the Caltech team also started exploring the potential advantages of spin stabilized rockets. The most obvious advantage would be the absence of fins, facilitating more compact storage in or on launch vehicles and easy adaptability to automatic reloading of launchers. A 3.5-in SSR (Spin Stabilized Rocket) was developed as a barrage rocket by mid-1944, and test work was also done on a forward firing SSR from aircraft. However, the main product of this effort was the 5.0-in HVSR (high velocity spin stabilized rocket), which delivered a 19.1-lb. warhead 5,000 yards. This rocket used a 5.55-lb. tubular charge 9.1 inches long, in a 5-inch diameter motor. The round was guided in its initial motion by a guide-rail launcher, which was reloaded automatically by gravity feed from a 12-round rack, firing 12 rounds in sixty seconds. Landing craft and support craft were loaded with banks of these launchers (Figure 8), and the concentrated fire immobilized beach defenses in advance of amphibious landings. The 5.0 HVSR was used first in the landings on Iwo Jima in February 1945, where 12,000 HVSR's and 8,000 4.5-in BR's were used. The spectacles of the awesome beach barrages in 1945 are a familiar scene for viewers of the motion pictures of those landings.

It was inevitable that the success of the HVAR would lead to consideration of new and bigger aircraft rockets that could damage or destroy more well defended targets. In late 1943, the Caltech team was considering an 11.75-in diameter rocket for use with 11.75-inch diameter naval gun shells. The team at Eaton Canyon came up with a motor design and presented it to Bruce Sage as a Christmas present with the tongue-in-cheek name "Tiny Tim". A single-piece propellant charge would have been far too large for extrusion in any press, so a four piece charge using the cruciform configuration of the HVAR was chosen, with the individual pieces held in position by an X-shaped steel spacer. The propellant charge weighed 146 pounds and delivered 30,000-lbs. thrust. This motor was integrated with a 590-lb. warhead. The rocket was 10 feet long and weighed 1385 lbs. The first static firing at Eaton was successful but caused so much damage to the test facility that all-later firings were done at China Lake. The first firing from an airplane in flight was on June 22, 1944 (D-Day plus 16). To minimize blast damage to the aircraft, the first tests were done with a launcher design that displaced the rocket downward before firing (Fig. 9). However, it was found that, satisfactory air launch could be achieved by simply dropping the Tiny Tim from the aircraft and initiating firing with a lanyard. Tiny Tim was readied for fleet use and shipped to the Intrepid and Franklin in the Pacific in the summer of 1945, but did not see service because of the abrupt end of the war. The motors were used in early sled tests at Edwards AFB, and as boosters for a Jet Propulsion Lab WAC Corporal high altitude rocket that set altitude records of the time.

After the development of the 5.0-inch HVAR motor, the multiple piece charge was chosen for the 11.75-in AR because the extrusion presses were too small to extrude a one-piece charge. However, there is a penalty in cost and performance associated with the multiple piece charge and its support structure. Calculations indicated that an 8-in motor with a one-piece hexaform charge (Figure 2c), would make a formidable weapon, and the installation of the twelve inch press made such a charge possible. Some charges were produced and motors were built; and successful static firings were conducted. However, this investigation was halted at the end of the war and the work seems to be documented only in the minds of the investigators (Ref. 6).

Members of that part of the Caltech team who had moved to China Lake (still under Caltech direction) developed two other motors worthy of note. One of these developments, the 14.0-in. AR ("Big Richard") has been recorded in China Lake history (Ref. 5, p. 297). The other, the Caltech 5.0-in. Model 38 ("White Whizzer") embodied some important technical advances, but has been poorly documented (Ref. 7, 8). The "Big Richard" was a 14-inch diameter scale up of the "Tiny Tim", designed for use with a modified 14-in naval gun shell as a warhead. This scale-up was made possible by availability of the new 12-inch extrusion press; which was required for the scaled up cruciform propellant charges. The "Richard" was built in the spring of 1945. It was a 2000-lb. monster with a 1000-lb. warhead, a thrust of 60,000-lbs., and a 280-lb. propellant charge. The ground-launched flight testing was completed, but production and flight testing slowed after the end of the war, and were ended in January. 1947. The supply of motors was used at China Lake as boosters for sled tests and the Lark guided missile tests.

The "White Whizzer" embodied the first use of an all–internal burning star perforated charge design (Appendix D) with the outside periphery plastic wrapped to prevent burning, and carefully sized for close fit in the motor tube. This arrangement provided better support for the charge. These features permitted higher propellant loading and use of light weight aluminum motor tubes, resulting in much more performance potential than the 5.0-in HVAR. The 5.0 in. "Whizzer" motors were flight tested (ground launch) with light weight heads (around May 1946) and achieved then-record speeds for solid rockets, close to 3200 ft./sec. A stock of motors (CIT 5.0-in Model 38) was made and used for technology development (Ref. 8, 9), and the new design features (internal burning charge and aluminum motor tubes) were adopted in subsequent missiles such as the 5.0 inch diameter ZUNI and Sidewinder, and the 2.75-in FFAR (and most solid rockets since then).

A notable aspect of the Caltech-NDRC rocket program was the synergism among the propulsion team at Eaton Canyon, and the other Caltech teams responsible for warhead and fuse development, motor hardware design and production, launcher development and range operations. The level of interaction was almost daily, with some team members serving as needed on more than one team. The whole operation was guided by dedicated leaders such as Lauritsen (C.C. and son, Tommy), Fowler, and Sage. C.C. Lauritsen was the chief technical interface with the NDRC and the Navy, helping to identify Navy needs and promote Caltech rocket solutions. In most cases, development of a new rocket was already started before any Navy funding became available, such exploratory work being driven by team recognition of growing technical capability and familiarity with Navy needs. Lauritsen not only educated the Navy on the opportunities, but also followed through to service readiness and (with Fowler, Tommy Lauritsen, and others) into fleet operation to assist in problems and remedies in service use. This philosophy of operation resulted in maximum application of technical resources and innovation, very short development time of new weapons to meet growing and changing military needs, and expeditious introduction to fleet use. To the extent possible under new administrative constraints, this same philosophy was embodied in the mission statement and operation of the new Naval Weapons Center at China Lake and led to a generation of spectacular development successes such as the family of Sidewinder guided air-to-air missiles, a family of air-launched bombardment and anti-radar missiles, and ship-to-ship and air-defense missiles. With the construction of larger extrusion presses, many of these missiles used solventless extruded double base propellants similar to that in the Caltech rockets. One of this second generation of ballistite rockets (the 2.75 FFAR "Mighty Mouse") was developed in the early 1950's and has remained in service to the present day (most visible nowadays as pod-launched rockets from helicopter "gun ships"). Roughly 200 million have been produced for the US and NATO forces.

INTERNAL BALLISTICS

The central functions of Section 5 of the Caltech Rocket Team were design and production of rocket motors, centered at Eaton Canyon (metal components were manufactured elsewhere, primarily at the Caltech operated "Foothill Plant" in East Pasadena). The term "internal ballistics" refers to propellant characteristics, propellant combustion, charge design, internal gas flow, and their interaction to produce the desired pressure and thrust from the motor. R.N. Wimpress (Ref. 10) who summarizes the science and technology in a scholarly way in a book, prepared this as part of the close-out of the NDRC contract. Some of the highlights of progress on this then-obscure subject are reported here in the context of the overall rocket program.

Propellant Needs and Choices

The principal barrier to successful solid rocketry in the years prior to WWII was the lack of a suitable propellant. This is not surprising if one reflects on the many propellant requirements that are implied in the word "suitable". It is required that the propellant:

1. Burn with very large heat release and low molecular weight reaction products.

2. Burn inward from exposed surfaces at a uniform, predictable rate that is not too sensitive to pressure or temperature.
3. Be amenable to fabrication into solid structures of suitable configuration, with structural integrity sufficient to withstand substantial forces during motor firing.
4. Be safe during storage and fabrication, and preserve all properties over a substantial service life.
5. Be fairly inexpensive and available in sufficient quantities.

In the real world, these requirements tend to be mutually incompatible, and a practical propellant is a difficult compromise.

In 1940, ballistite, a colloid of roughly 50% nitrocellulose and 50% nitroglycerin, was the nearest candidate to a compromise of requirements 1-5. It was in mass production in the United States for use in guns and trench mortars. The most serious barrier to application in rockets was the need to fabricate propellant structures, one-piece charges.* The gun propellant was in small pieces somewhat like extruded macaroni, and the trench mortar propellant was in sheet form, manufactured by passing through a series of heated rollers. The gun propellant was mixed with a softening solvent to facilitate extrusion, and was subsequently dried to remove the solvent. The East Coast Project chose to use solvent extruded ballistite, a choice that forced them to work with multiple piece charges because large single charges took too long to dry and yielded poor dimensional control. The Caltech team, knowing of British success with dry extrusion, chose to go that route. This was not without risk, because the US ballistite was more energetic (less safe) and less plastic than the British "cordite" propellant. However, in retrospect, this was a decision crucial to the success of the Caltech rockets because it allowed larger, stronger propellant charges; more latitude for burning times; and higher propellant loading in the motor. But there was a lot of learning still required in February 1942 about propellant processing, charge design and propellant combustion.

Predicting Motor Performance

There were two choices for learning about how to design motors; a) build some and test them, and b) carry out the necessary theoretical developments. In the interest of time, both approaches were made from the outset. The propellant extrusion from Tommie Lauritsen's jury rigged press were static fired in improvised motors using educated guesses at appropriate nozzle thrust area. A suitable area was found by trial and error, and the results provided also the burning rate of the propellant (something that was needed, but would not be predictable from theoretical analyses). While this work was in progress in late 1941 and early 1942, Sage's team of chemical engineers were at work adapting one-dimensional steady state flow theory to the flow field in rocket motors, and solving the chemical equilibrium equations for the ballistite combustion reaction, steps needed to predict motor performance. In retrospect, it is "mind boggling" to imagine that complete enthalpy-entropy-temperature diagrams were computed using Marchant electro-mechanical calculators.

In even the simplest internal ballistics theory, prediction of motor performance depends on five equations.

$$F = C_F A_t p$$

Thrust = C_F *x* nozzle throat area *x* pressure

$$\dot{m}_d = C_d A_t p$$

Nozzle mass rate = C_d *x* nozzle throat area *x* pressure

$$\dot{m}_b = \rho_p S_c r$$

Mass burning rate = propellant density *x* burning surface area of the charge *x* linear regression rate of burning surface

$$\dot{m}_b = \dot{m}_d$$

Condition for steady operation

$$r = C \cdot p^n$$

Regression rate = *C x* pressure raised to the *n* power

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* In the early 1940s, the pieces of propellant were called "grains" (as in gun charges) and a suitable assemblage of grains was used to provide the "charge" for a motor. The term "grain" hung on in the literature for years, applied even to the larger one-piece solventless extruded charges. In modern times, with cast propellant charges weighing up to 1,000,000 lbs., the term "grain" is obsolete.

where:

C_F is determined by one-dimensional isentropic flow theory (and requires knowledge of the ratio of specific heats, γ, of the propellant gas).

C_d is determined by the same theory, but requires also the flame temperature of the propellant, T_f, and the molecular weight of the product gas, μ

C and n are parameters that had to be determined experimentally (with C being dependent on propellant temperature).

Systematic testing was done to determine burning rate from burning time of propellant charges, and the quantities η, μ, and T_f were determined from the thermochemical equilibrium calculations. The theoretical values of C_d and C_F were checked by determination from measured values of F, p, $\dot{m}_d$, and A_t.

By the time the NDRC contract came through in February 1942, the above-described internal ballistics work was well along. However, all was not well, because strange excursions in pressure were occurring during charge burning; seemingly the propellant was suddenly burning faster, for unknown reasons.

Combustion Instability

Unpredictable burning had been the undoing of solid rockets for the preceding 25 years, but it was not anticipated with the well consolidate, homogeneous extruded ballistite. The first clue to the cause was evident from fragments of propellant recovered after motor bursts. The tubular propellant charges had split longitudinally, as if from excessive pressure in the inner conduit. A device (a "partial burner") was built that allowed the propellant charge to be ejected into a barrel of water at a chosen time after ignition. The partial burning tests confirmed that the charges were splitting over a substantial length (not near the ends). The team did the obvious, i.e., drilled holes through the charge walls to relieve the excess internal pressure. This reduced the frequency and severity of pressure excursions, and became a standard feature of subsequent tubular propellant charges.

Calculations had indicated that "normal" burning would not give rise to a differential pressure between inner and outer flow channels large enough to crack the tube wall. This implied that there really was some kind of anomalous burning going on in the inner conduit that caused pressure excesses sufficient to crack the tube. This was confirmed by the partially burned samples that showed that the inner conduit had burned outward faster than the outer charge surface had burned inward. In addition, the surface of the inner conduit exhibited a curious "rippled" quality. These anomalies were present in a region centered midway between the ends of the charge, and not evident near the ends (undrilled charges). It was also noted that the number and spacing of radial holes for optimum smoothing of the pressure-time function of the motor was not clearly connected to relief of pressure excesses in the inner conduit. These various observations confirmed the suspicion that pressure excesses caused by anomalous fast burning in the inner conduit caused the cracking phenomenon. This was confirmed also in due course by observation that normal burning resulted when a solid rod was suspended in the inner conduit (something that would aggravate any normal pressure excess in the conduit that might exist in the presence of normal burning.

By mid 1943, it was suspected that some form of oscillatory gas flow-combustion interaction was involved in the excess pressure excursions, but direct evidence (measurements of pressure oscillations) was not possible with existing pressure detection systems (it has since been shown that the oscillations were around 35,000 Hz, and would not be detected even in conventional modern static firing facilities). It is worth noting that the East Coast rocket program had similar experiences with "combustion instability" with their solvent extruded ballistite multiple grain charges. The problem went away when the grains were strung on a wire support cage (introduced originally to retain the grains in position during burning). Later in the Eaton Canyon work it was found that the combustion instability problem was more severe with high energy, fast burning propellants like the JP ballistite used in the Caltech rockets.

In late 1943, the suspicion that the anomalous burning was due to oscillatory gas flow in the inner conduit of the charge led to the idea that a noncircular conduit might be less susceptible to the behavior. The 1.7 x 0.6 inch diameter charge for the ASR and BR rockets was modified by use of a 3-point star configuration (Fig. 2d). Charges with this configuration gave regular burning without use of radial holes (Ref.10, Ch.9). This finding came too late for adoption in most of the new Caltech rockets of the time, because of the change to cruciform-shaped charge cross sections. However, it was a factor in the decision in 1945 by the Caltech team at China Lake to develop the Caltech 5.0-inch Model 38 "White Whizzer" motor, the first to use a star perforation internal burning charge (all-inhibited outer surface, close-fitted to the motor wall). This charge design concept (which facilitated use of light weight aluminum motor tubes) soon became standard for the "industry", although it became clear that success in suppression of combustion instability depended on choice of details of shape of the conduit.

Worm Holes

During the time when combustion instability was plaguing the development of the charge for the 2.25 motor (for the ASR), the picture was complicated by another propellant problem. A new supply of ballistite was received, and new troubles with irregular pressure-time curves developed. Partial burning tests indicated that "worm holes" were developing in the propellant during burning, suggestive of subsurface ignition problems during burning. Unlike the original supply of black ballistite, the new supply was translucent. It was concluded that subsurface ignitions were occurring due to radiant heating at dark spots in the propellant interior. It was found that the propellant darkened with age, and that darkening could be accelerated by exposure to sunlight. The worm holing problem did not occur with sun darkened propellant, and later shipments were manufactured with darkening agents. However, a massive sun-irradiation activity had to be set up in order to continue production of charges until new propellant was received (see later section).

How Much Propellant Can You Stuff Into a Motor?

One key goal in rocket motor design is to maximize the amount of propellant, in order to maximize range and/or terminal velocity. The use of totally filled motors with end burning charges was not acceptable for the Caltech-Eaton Canyon rockets because short burning times were required. So side-burning charges were necessary. Then some of the interior space must be provided for gas flow to the nozzle, to avoid undue pressure forces on the propellant column. Unlike modern ordnance rockets, the propellant charges in the early Caltech motors gained little or no support from the walls of the motor case, and were susceptible to column buckling (typically late in burning) and to compression deformation (most notably at the downstream support, early in burning when low conduit area results in large pressure differences between fore and aft ends). Charge break-up leads to pressure peaks late in burning and possible nozzle blockage and motor bursts. Lateral deformation early in burning due to compression at the aft end blocks off needed flow conduit, causing the already low conduit area early in burning to be further reduced, with corresponding increase in pressure drop. This ultimately sets a limit on how much propellant can be safely used in the motor.

The above considerations were qualitatively "self-evident" from the outset, but quantitative calculations of charge deformation are fairly complex by 1942 standards and require better burning rate and propellant mechanical properties data than were available at the time. The limiting loading density is not hard to find. Above the limit the motor violently explodes immediately upon ignition! This was first experienced in the 1.25-in and 2.25-in motors when they were tested with long charges at elevated temperature, where the higher burning rate gives higher pressure differences in the motor (hence, higher compressive load) and the warmer propellant is less resistant to deformation. Initially, the problem was solved by limiting the length of the charge and using a better support "grid" for the aft end of the charge, and putting a relatively strong plastic end washer on the end of the charge. These practices became standard in all subsequent designs, but they did not make the problem of charge deformation go away completely when increased charge lengths were tried.

Calculations for later designs were made to predict charge deformation and the risk of experiencing mechanical failure, and designs were limited accordingly. However, the "proof of the pudding" was always found in high temperature flight test where the temperature-softened propellant experienced the added "setback" force of rocket acceleration. As noted in Wimpress's book (Ref. 10), the criterion for failure was not set by the ultimate strength or elastic limit of the propellant as first thought, but instead by the Young's modulus and Poisson's ratio of the propellant (properties that relate the cross sectional expansion of the propellant to the compressive load due to pressure difference between fore and aft ends). When insufficient gas flow area is provided, there is no equilibrium between charge deformation and pressure drop, so that port blockage will happen even if the propellant does not reach its ultimate stress limit. This mode of failure was describe by Wimpress (Ref. 10, Ch. 11) and used later by Price to characterize the loading limits of motors (Ref. 11). With the reduced risk of this kind of behavior in modern case bonded propellant charges, this mode of failure became less well recognized until the violent explosion of an early Titan 4 booster motor in the early 1990's.

Ignition

When a solid rocket motor is to be "fired," burning of the propellant surface is initiated by a fast-burning powder charge that heats the propellant surface and pressurizes the motor. In most of the Eaton Canyon motors, the igniter charge was "FFFG" black powder, which was initiated by a commercial DuPont electric squib. Both the powder and squib had been in production for many years, had been well characterized and yielded reproducible behavior. The problems were to choose optimum charge sizes, packaged so as to give a short, consistent ignition time and rapid pressure rise without excessive pressure peaks. In any given motor, the igniter had to achieve the performance over a wide range of temperatures, and even after years of storage and handling in all weathers.

The first experimental static firing motors (late 1941) were ignited with "cloth bag" igniters, with the grade of black powder and charge size chosen by trial, error, and interpolation. Bags were followed by copper cups, plastic cases, and crimped copper can igniters (Ref. 10, Ch. 10). FFFG grade black powder became standard, due first of all to its better safety and availability. It was found that more consistent behavior was obtained if slight compression (packing) of the powder was provided by a suitable assembly procedure of a rigid case. Most of the Caltech igniters used flat plastic cups (molded cellulose acetate), with screw-in plastic lids; the lids had molded extension tubes to hold the squib oriented to direct the flame centrally into the black powder. The case shape and size were chosen to fit snugly in the motor ahead of the propellant charge, with the squib tube and ignition wires on the aft side. These designs were developed in early 1942 and went in service with the 4.5-in ASR weapon.

Larger igniters were developed for larger motors, and the mechanical properties of the cases were tailored so the fragments would not be big enough to block nozzles or damage launchers in the exhaust (especially aircraft surfaces). Final designs had to be evaluated by extensive static and field firing of the motors over the whole service temperature range. The motors were of conservative design, and an appreciable ignition peak in high temperature firings was distinctly preferable to the misfires, hang firings, and intermittent "chuffing" that could happen at low temperature. So igniters tended to be designed with excess igniter charge somewhat like a margin of safety. This proved to be a fatal policy in the 11.75 AR, in which the effect of the exhaust blast on an aircraft control surface caused a fatal crash in one of the first flight tests (Ref. 5). After the accident investigation, it was concluded that this particular aircraft had an unnecessarily vulnerable design feature, and that the igniter charge in the motor was several times larger than necessary. Later motors used smaller charges. No further accidents occurred, and the weapon was sent to the Pacific Fleet for service.

Internal Ballistics as a Science

Because of the relatively low cost of trial-and-error development of the Caltech rockets and the urgency of the wartime situation, theoretical methods were sometimes back-of-the-envelope calculations. But from the start, a coherent body of theory and analysis was developed, starting with the very tedious thermo-chemical equilibrium calculations that were needed to predict motor performance. The body of theory is well described by Wimpress in Ref. 10, which remains unique in scope and clarity to this day.

DRY EXTRUSION OF BALLISTITE AND PILOT PLANT OPERATIONS[*]

Starting From Nothing

The Eaton Canyon site was started out as a place to conduct operations too hazardous to be conducted on the Caltech campus. Aside from propellant extrusion and static firing of motors, the scope and nature of operations could hardly have been foreseen in 1941. As it turned out, the rocket developments went from concept to construction and testing of experimental models to development of processing equipment and procedures to pilot plant production. Production grew to meet needs for static and range testing, and then to meet Navy needs for

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[*] This section is based substantially on Reference 12 by C.L. Horine who was the supervisor of plant operations at Eaton Canyon.

training programs. Because of time required for the Navy and Army to get the weapons into production, Caltech often had to operate its "pilot plant" facilities 24 hours a day, 7 days a week to provide ordnance for fleet operations. In retrospect, this was a good way to go because everything that was done was new. All processes had to be developed to the point of feasibility in production, including determination of product specifications, quality control and reliability in service operation. If the R & D team had not followed through to service use, none of the weapons would have seen service in World War II. Likewise, the job couldn't have been done if the design, manufacturing, testing and service qualification (which involved campus operations, flight test ranges and manufacturing operations off campus in addition to Eaton Canyon) had not been closely integrated by the Caltech team. But it just kept growing! At its peak the Caltech rocket project had an operating budget that was ten times the normal operating and research budget of Caltech. In Eaton Canyon alone there were 800 employees and special facilities designed and built for a whole range of processing operations, mostly involving hazardous materials.

The First Try at Extrusion of JP Ballistite

The beginning of the Eaton Canyon operations was in November 1941, when "Tommie" Lauritsen towed his jury-rigged extrusion press (Fig. 1) to the site to try out the dry extrusion of ballistite. Caltech had leased five acres and the site was remote enough for safety in case of an accident. The press was controlled from behind a sandbag shelter, from which the dials (pressure and temperature) were observed through a periscope. A decision had already been reached to build and install larger 3-inch and 5-inch presses and the project was already underway. The success of Lauritsen's early effort was crucial as a justification for that commitment, and crucial for the entire concept of the Caltech rocket program. The initial extrusions on November 15, 1941, yielded tubes with very rough surfaces, at which point it was realized that the air in the press cylinder needed to be evacuated before extrusion began. Having added this procedure, a very satisfactory product was obtained in the form of tubes 15/16 inch OD by 1/2 inch ID. This result was greeted with exultation by all and in the following few days all of the available 180 lbs. of propellant was extruded. Approximately 45 days later, the first permanent press designed by Section 5 came on line. This was the start of extrusion operations that culminated in multiple presses that extruded up to 8000 lbs. per day and a total of 4,700,000 lbs. by the end of the project in 1945. By then, the Eaton Canyon site had grown to 180 acres.

Extrusion of Ballistite

Propellant charges were made from various physical forms (rolls of sheet, lathe turnings cut up pieces of rejected extrusions) of ballistite material that were forced to flow through a forming die by compression of the material in a high pressure press. The charge was loaded in the barrel of the press, which had a piston at one end and the forming die at the other. As the piston moved in on the charge, a pressure around 3000 to 6000 psi was reached and maintained. The charge was often softened by preheating to about 120° F to aid in flow. The exact values of pressure and temperature were chosen to get useful extrusion rates with good consolidation and surface smoothness. The extrusion die was designed to give adequate shear working of the material. In order to do this, there was a required contraction ratio (barrel cross section-to charge cross section of the extruded charge). This requirement implies that large charges required large presses, including eventually the design of a twelve-inch press. The longitudinal perforation in the charge was made by a contoured rod suspended from a (typically) three-legged "spider" above the entrance of the die, and the material must flow around the legs of the spider and consolidate as it flows on through the contracting region of the die. A 100-lb. charge of ballistite contained in a high pressure press at 120°F (plus temperature rise during flow) is equivalent to a very powerful bomb. The presses were housed in reinforced concrete buildings designed to prevent escape of shrapnel in case of a press failure. One such failure occurred in a 8-inch press in 1943. The building was useless thereafter. The operator, Roger Wallace, was blown through the window of the control room, but fortunately was unhurt (Ref. 13). The wall between the press bay and the control room held up, but the blast wave had reflected around the building and in the side door of the control room.

In 1942, it was found that propellant sheet from Sunflower Ordnance Works, Kansas occasionally contained foreign objects like nails, stones, and bottle caps. Since such objects posed serious hazards during extrusion operations, careful inspection of press feed stock was instituted. The cause of the one press explosion was never determined. The sensitivity of the operation to ignition by foreign objects was inadvertently tested on one occasion when a gear tooth from a lathe was found in an extruded charge. In this press run the press charge had included lathe turnings from machining operations. A smear of metal from the tooth was visible on the surface of the charge, indicating a high degree of abrasion and yet the metal abrasion by the die did not cause ignition. Every effort was made to avoid repeat of such incidents. Some hazard existed in opening up, cleaning, and reassembling the press after a run. One of the pioneers of the Eaton Canyon project, Lee Carmichael, suffered a serious hand injury when an explosion occurred during a difficult press disassembly–assembly operation.

The credit for design of the extrusion dies goes primarily to Prof. Donald Clark, whose special expertise was in properties of materials and casting and extrusion of metals. Professors Sage and Lacey and their assistant, Lee Carmichael, had extensive experience in design of high pressure equipment, and their 3-inch, 5.5-inch, 8-inch, and 12-inch presses performed with few problems. Determination of optimum operating conditions was learned by experience, by plant supervisor C.L. Horine and his team. The collected "wisdom" was later shared with the Naval Ordnance Laboratory (Indian Head) and the Radford and Sunflower Ordnance Works when they got set up for large-scale production over the 1943-1945 period.

In spite of early fears that the American JP ballistite might be unsafe for dry extrusion, 4.7 million lbs. were extruded at Eaton Canyon during World War II, in propellant charges weighing up to 40 lbs. each. Extruded double base propellant was used in subsequent generations of Navy tactical rockets, even to the present. But it is not adaptable to modern large rockets, and it is not competitive with some very high-energy composite propellants that can be made by slurry mixing and casting. Its main advantage now is low cost, reasonable performance (specific impulse), and non-toxic, low smoke exhaust.

Other Plant Operations

While extrusion of ballistite was the crucial processing operation, it was only one of the steps leading to a loaded motor. The extruded charges were cut to length and radial holes were drilled in tubular charges. Early on, these machining operations were done in a room in Kellogg Laboratory on campus. One of two fatalities during the project, Mr. Raymond Robey, resulted from a fire in the machine room on March 27, 1942. After that all work with hazardous materials was carried out at Eaton Canyon. Facilities were built so that a minimum of propellant was present in the machining room, escape was easy, and roofs doubled as blow out panels to prevent pressure build up. Detailed handling procedures were established and fire retardant coveralls and safety glasses were standard.

Every motor requires an igniter. The primary requirements of igniters are that they fire only when desired, that they ignite the propellant fully and quickly even at very low temperature, and that they not over-pressure the motor or overload the propellant charge at high temperature. Because these are (in practice) contradictory demands, the final design (charge weight) had to be selected by trial and error. Once igniter design was chosen for a particular motor, it was then sometimes necessary to gear up to make thousands of them. This involved bonding the electric squibs in the closure lids of the igniter cases; weighing out the individual igniter charges; filling the igniter cases and sealing the lids in place, after which the assembled igniters were dipped in a material that provided weather proofing. The igniter leads were always kept twisted together (to avoid initiation by stray electrical stimuli). As the most sensitive part of the ignition sequence, it was crucial that no ignition stimulus reach the electric squib until motor firing was intended. A production line was set up and operated without serious incident, sometimes running lines for production of igniters for different motors at the same time.

When the first shipments of fresh translucent ballistite sheet started arriving in 1942, the plant requirements for press feed stock were more than 1000 lbs. per day. As soon as it was found that the propellant could be darkened by exposure to sunlight, a large array of wood and chicken wire racks was constructed and the sheet stock was "irradiated" in the sunlight until darkened. This operation was for a time a bottleneck in production, and the irradiated material was transferred as rapidly as it could be prepared directly to the extrusion area for ongoing processing. Later nigrosine dye and/or carbon black was incorporated in the new ballistite sheet as supplied, and the somewhat worrisome outdoor arrays of ballistite sheet were no longer needed. This was a blessing for plant personnel, who had been suffering from "nitroglycerin headaches" from handling the sheet and breathing the vapors. This ballistite irradiation operation is an example of an expediency that probably would not have been done except under the urgency of wartime. Without the irradiation operation, the plant would have been shut down for several weeks.

Another processing operation that became more important with the advent of cruciform charges for the 3.25 and 5.0-inch diameter motors for the aircraft rockets was inhibition of part of the propellant surface (Fig. 3b). Segments of plastic were bonded at intervals along the outer surface of the arms of the cruciform to provide centering and support in the motor and to provide constant overall surface area during burning. The bonding process was perfected, and special facilities were built. It was necessary to provide fume hoods over the charge-holding jigs because, otherwise, the solvent-nitroglycerin vapors made the operators ill.

Ovens were used to preheat press charges and for accelerated aging tests on charges. One problem encountered was condensation of propellant vapors on oven walls. Since the primary vapor that was expected was nitroglycerin, the condensate was carefully analyzed and fortunately found to contain 20% plasticizer, which was known to be enough to desensitize nitroglycerin, enough to allow safe cleanup by wiping. It was just one of those things you shouldn't take for granted when nitroglycerin is involved.

The endpoint of Eaton Canyon operations on motors was the loading of motors and static firing. The metal components were supplied by a Caltech operated plant in East Pasadena (the "Foothill Plant", managed by Trevor Gardiner). Loading involved insertion of support grids, propellant charges, and igniters. The igniter lead wires were strung from the front out through the nozzle (Fig. 6). Both ends of the motor were equipped with frangible weather seals, which left the motor non-propulsive until the warheads were screwed on in the field. Igniter leads were kept shorted to avoid accidental ignition. A major requirement was that the ordnance have a long "shelf life" under simulated service conditions; facilities had to be set up not only for surveillance testing, but also for temperature conditioning static firing motors at extended temperatures sometimes from -45° to .165°F. However, there were times during the war when aging was not a problem because the rockets were airlifted to the front as fast as the plant could turn them out. In hindsight, we could have anticipated the major offenses in Europe by the calls for 24 hour-a-day production and pick-ups for airlifting the plant output.

Static Firing

The initial firings of any experimental motor design are done with the motors mounted on an instrumented test stand (Fig. 10) that includes a threaded "receptacle" in place of a warhead. A hydraulic line in the receptacle was connected to a pressure recorder in the control room. The test bay was of reinforced concrete construction, open at the end for the rocket exhaust. The terrain sloped upward, providing a "catcher" for flying debris.

The burning time of the Caltech rockets ranged from 0.2 to 2.0 seconds. The pressure-time event during firing was the primary information needed from a test firing. No commercial systems were available that could measure and record such short events, so one had to be designed and built. The pressure detectors were bourdon tubes equipped with mirrors on the ends that reflected light beams on a rotating drum carrying photosensitive paper. A faster response system was also developed that utilized a tiny tube wrapped with wires that served as strain elements in a bridge circuit to produce an electrical output (which was recorded on a Miller galvanometer oscillograph). There were problems with stability of the calibration of the strain gages, but this system had a fast enough response to measure igniter peaks that the Bourdon system could not resolve accurately. As noted earlier, static testing included not only tests of experimental motors, but also proof testing of production lots of motors, including tests at temperature extremes. The rate of testing was so high that a second facility was established and the facility was rigged to fire three of the small motors at a time. According to Hugh Baird, who supervised the static testing operations, over 40,000 motors were static fired at Eaton Canyon. The most spectacular static firing test was the first firing of the "really big" Tiny Tim motor. While the test was successful, the damage to the test facility was so great that all subsequent firings were done at the new facilities at NOTS China Lake.

The Eaton Canyon Plant

The Eaton Canyon site was a moderately sloping alluvial fan at the entrance that narrowed and steepened further up the canyon. Small side canyons branched off and provided natural sites for separating hazardous facilities such as magazines and extrusion presses. Vehicles were continually shuttling between processing and storage sites, using commercial tractors with modifications to lift and carry boxes (the first fork lifts?). This busy and potentially hazardous transport operation was operated without mishap.

A major concern was the risk of causing, or being engulfed in brush fires. A small fire department was volunteered by the Pasadena Fire Department, who helped organize for fire prevention and control. Brush was cleared from critical sites, and no major incidents occurred. Much of the site is now occupied by the Kinneloa Estates, a part of modern suburbia. The remainder became overgrown with brush until 1993 when a brush fire burned through the area and revealed some remaining concrete structures.

CONCLUSION

By September 1945, the rocket work at Eaton Canyon was closed down, continuing rocket operations having been gradually shifted to NOTS China Lake. The Caltech team had played a primary role in selection of the site of NOTS and setting up the pilot plant and test ranges, and some of the Caltech team moved to China Lake and became a nucleus for the civilian staff. Prof. Fowler and Sage divided their time between Caltech and China Lake for some time. In effect, Fowler was the acting Technical Director at NOTS until all staff was converted to civil service and Dr. L.T.E. Thompson arrived as the first official Director. Professor Sage continued to commute between Caltech and China Lake until about 1949, as head of the China Lake Propulsion Lab, and earned the name of the "Great White Father". The rest of the Eaton Canyon staff returned to such diverse peace-time occupations as professors, students, housewives, realtors, a jockey, chemical engineers, cosmologist, etc.

In retrospect in 1998, the Caltech team and the NDRC showed the country how to build and operate a team that could carry weapon systems from concept to development to production and follow the weapons all the way into fleet service, at the lowest cost and in the shortest time possible. The operation also demonstrated an unprecedented interaction of civilian scientists and the military (especially the Navy Bureau of Ordnance and some truly dedicated Navy pilots). The freedom for the scientists to develop rocket science and technology under NDRC sponsorship (with minimal bureaucratic constraints) enabled the scientists to demonstrate the potential of rockets to the military, and the continual interaction of the senior scientists with the military created a mutual atmosphere of respect, trust, and cooperation that was embodied in the philosophy and original mission statement of the Naval Weapons Center at China Lake. Underlying it all was the dedication of people during wartime. Perhaps the same approach cannot be equaled in the modern era of complex missile systems, unwieldy bureaucratic management, corporate needs to maximize profit, and political differences regarding objectives. But the Caltech approach worked very well at China Lake for 30 years, and could work now if given a chance.

The Caltech team had written an unheralded chapter in Rocket History and set a model for concept-to-service development of rockets and weapons, that produced over one million rockets in World War II and that served as a model for the US Naval Weapons Center of the 1945-1985 era, a model for the effectiveness of which has yet to be matched elsewhere in modern times. A remarkable testimony to the effectiveness of the model is the statement in Ref. 14 in 1968 that "over 75% of the airborne weaponry in use by the free world today was developed at NWC" (China Lake).

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1998.

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FIGURES

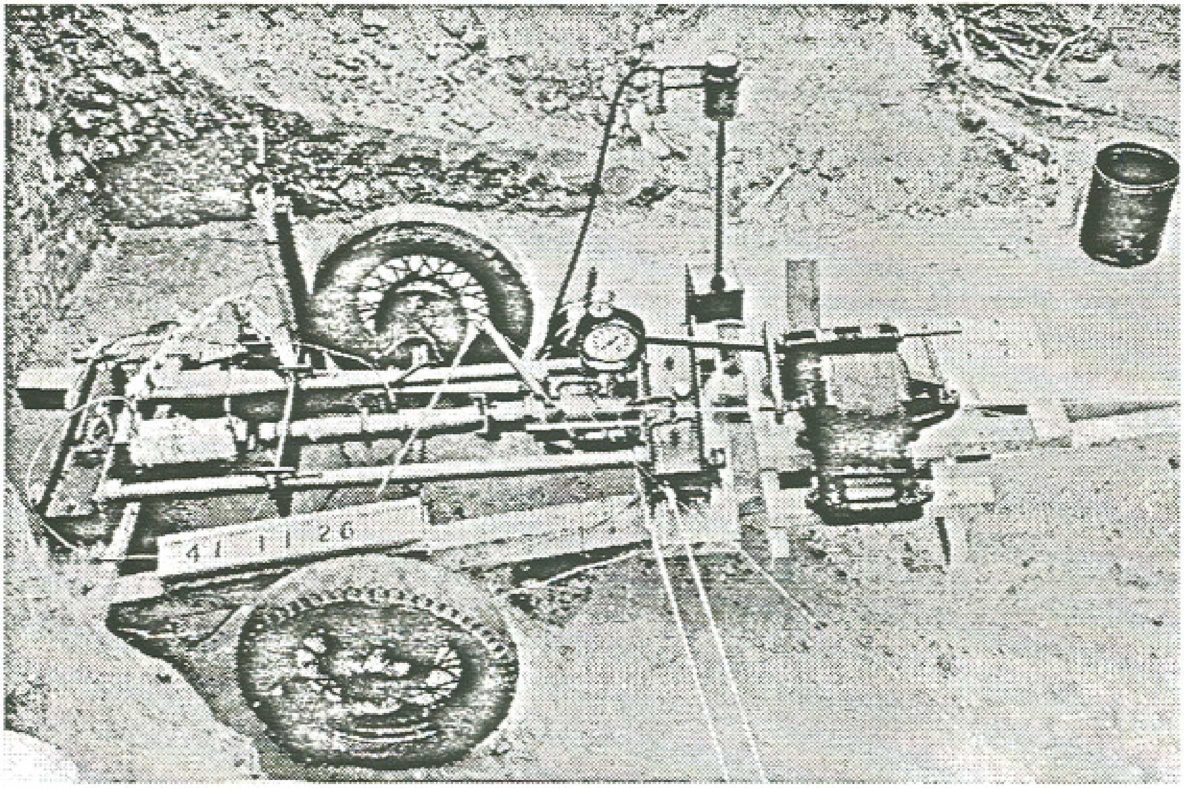
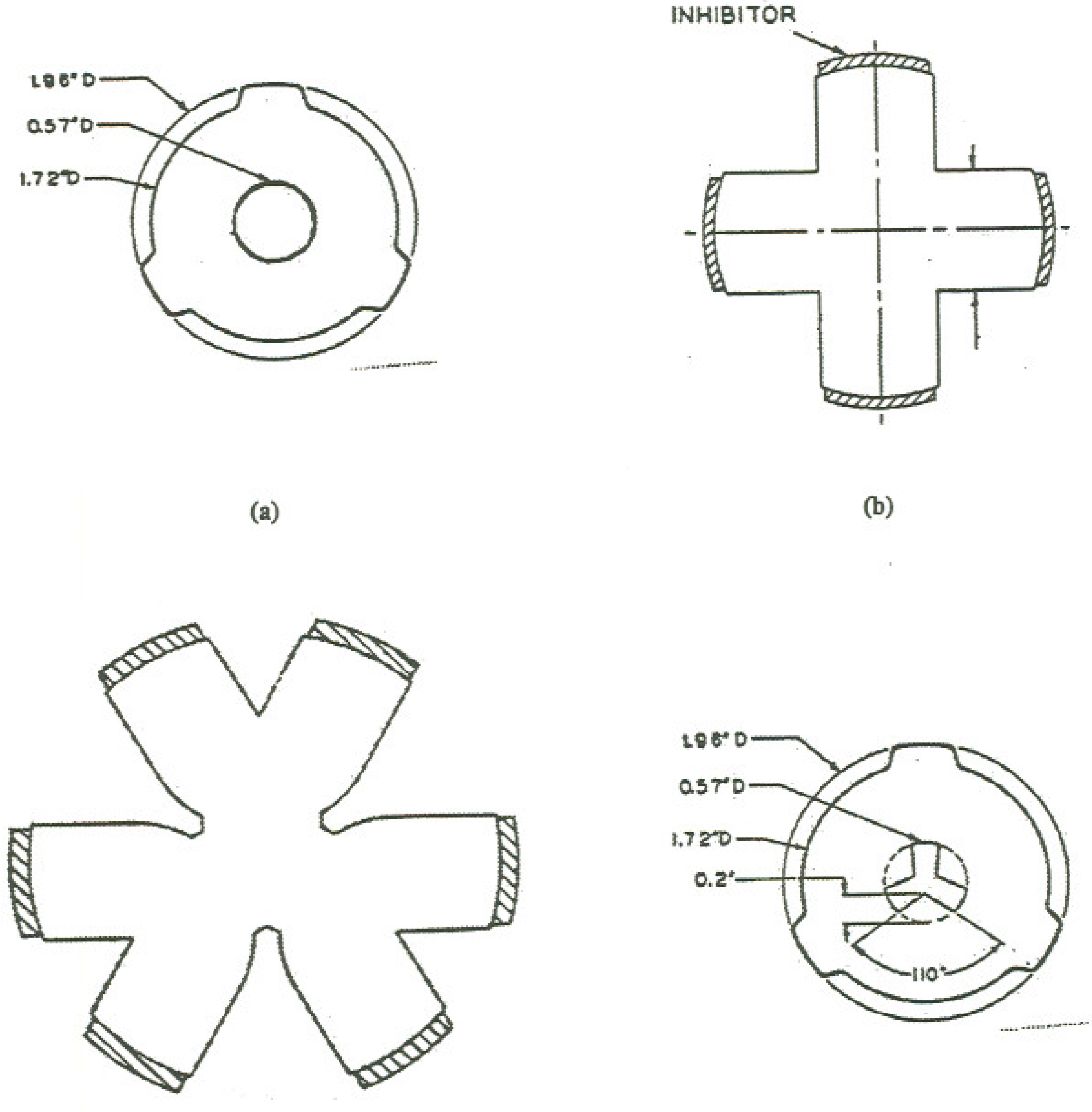


Figure 1. Jury rigged press used in first extrusion of JP ballistite at Eaton Canyon in Nov 1941 (the permanent press was in operation six weeks later).



(a)

(b)

(c)

(d)

Figure 2. Cross-sectional shapes of some extruded ballistite charges prepared at Eaton Canyon (figures from Ref. 10)

a) Three ridge tubular charge for 2.25-in. motors

b) Cruciform (external burning only) configuration used in 3.5 AR, 5.0 HVAR, 11.75 AR, 14.0 AR (4 in 11.75 and 14.0 AR's). Three different sizes

c) Hexaform (tested in 8.0-in. motor)

d) Same as (a) but with ridges in the perforation to suppress oscillatory combustion.

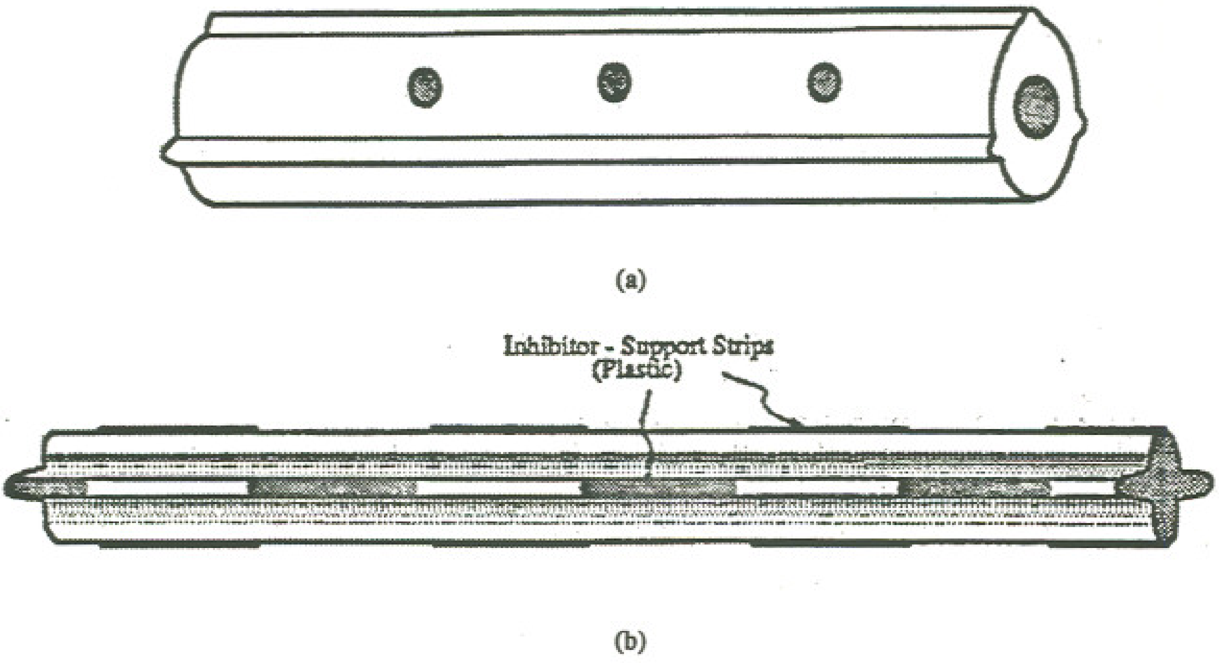


Figure 3. Sketches of propellant charges
a) Tubular internal-external burning charge (type used in 2.25-in motors for ASR, BR)
b) Inhibited cruciform charge (type used in 3.5-in. AR).

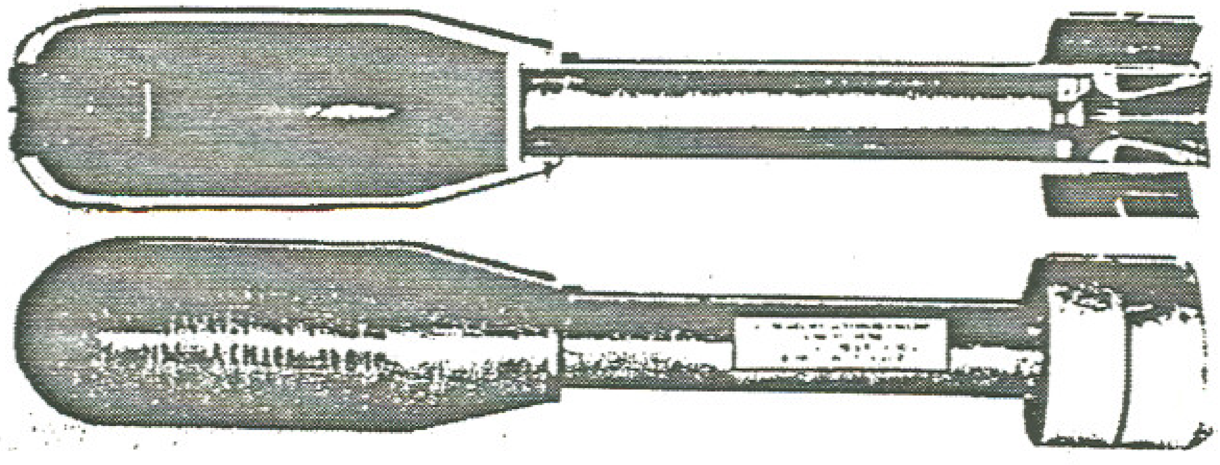


Figure 4. The 4.5-in. barrage rocket (in all landing operations in WWII starting with "Casa Blanca") (figure from Ref. 4).

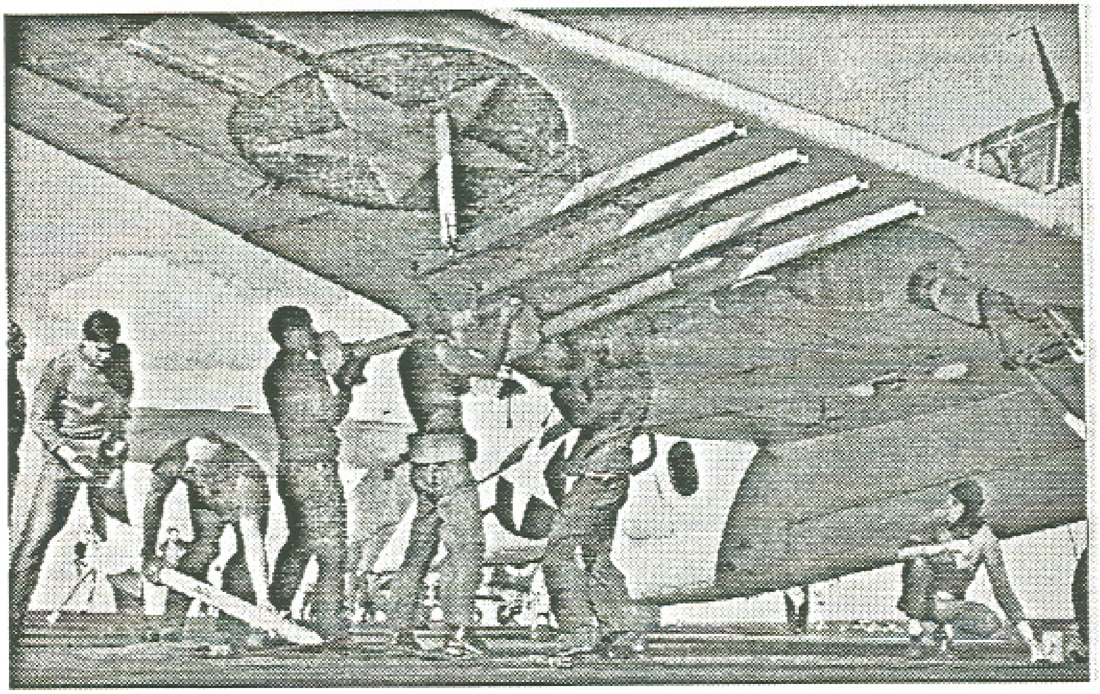


Figure 5. The 3.5-in. aircraft rocket (early model on rail launchers).

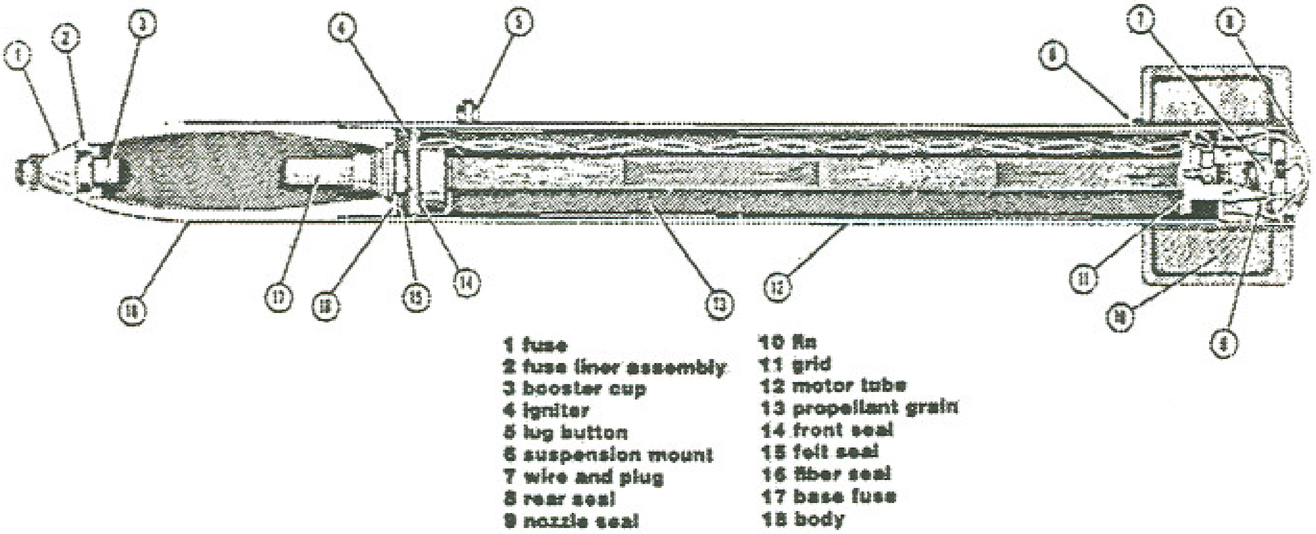


Figure 6. Diagram of the 5.0-in. HVAR (Holy Moses) (figure from Ref. 4).

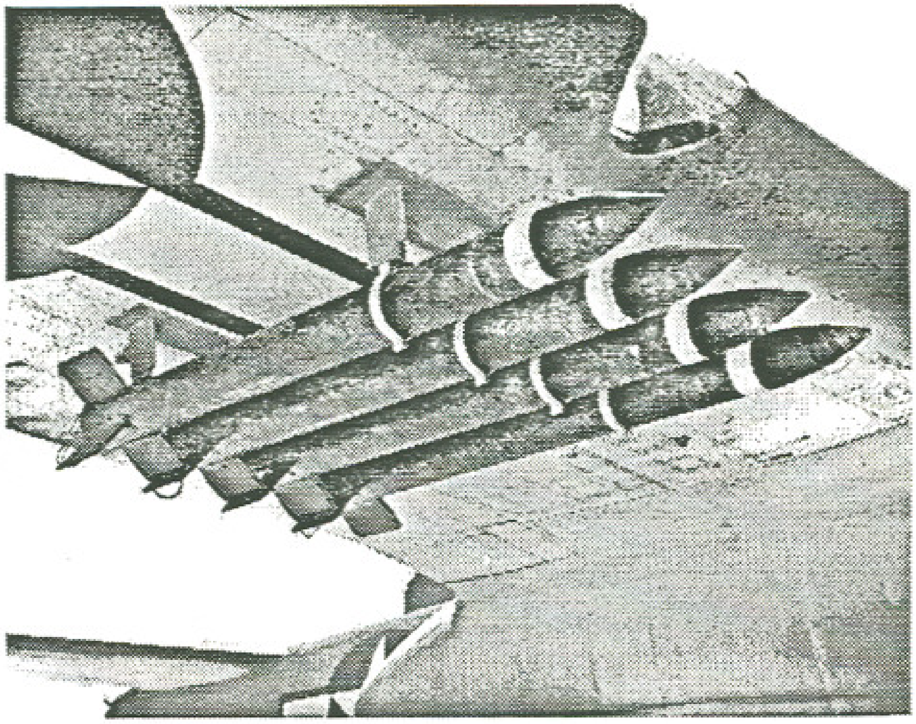


Figure 7. The 5.0-in HVAR (Holy Moses) on "zero length" launchers.

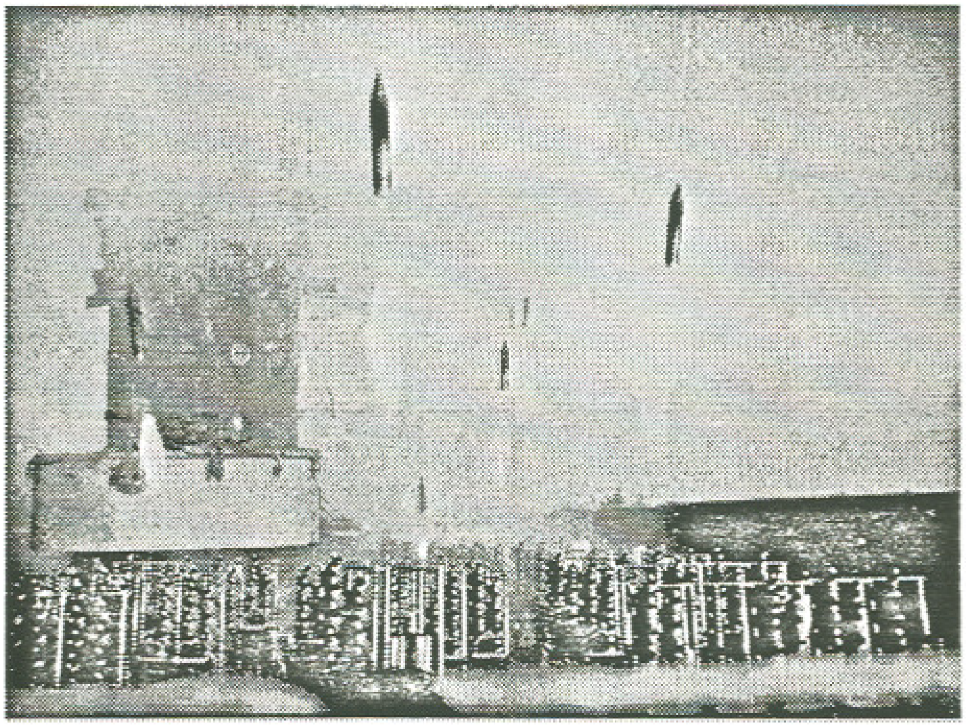


Figure 8. View of 5.0-in. HVSR (barrage rockets) in 12-round autoloading launchers aboard landing assault craft.

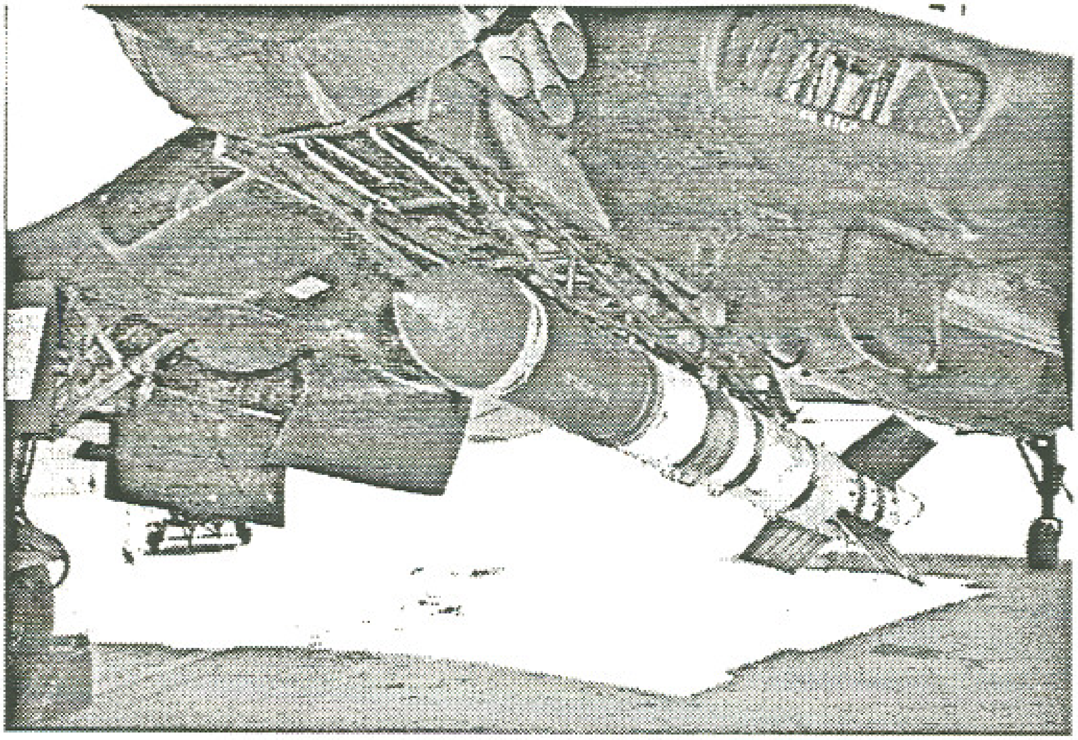


Figure 9. 11.75-in. AR shown in early displacement gear launcher on F-4U aircraft.

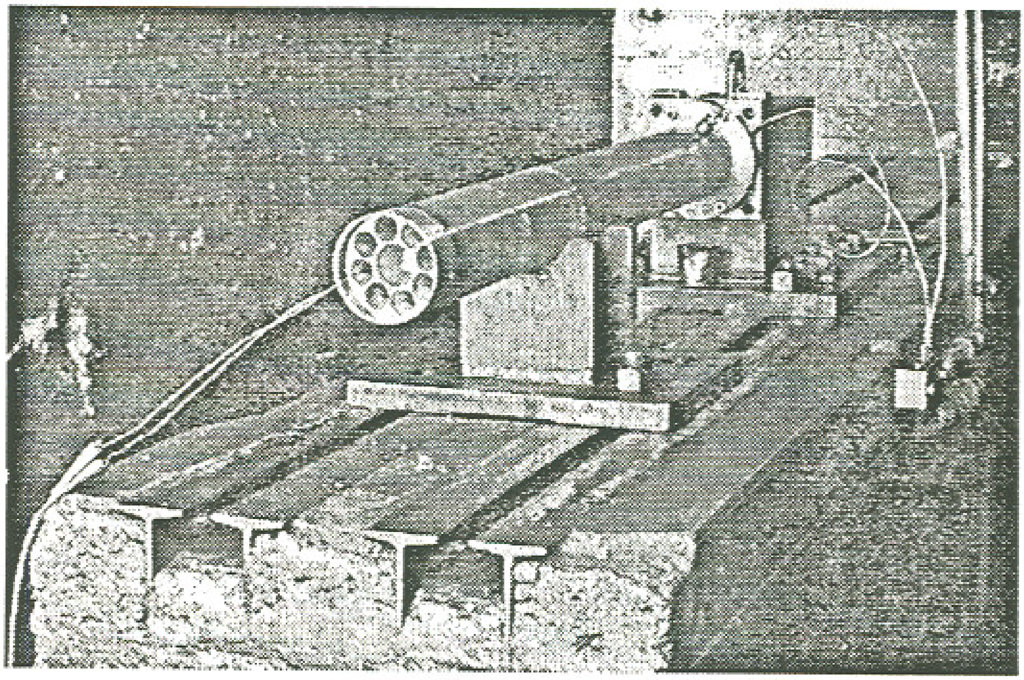


Figure 10. Open end of static firing bay at Eaton Canyon, with early version of 5.0-in. HVAR motor in place.

APPENDIX A

Excerpt from Reference 1 referring to early efforts by C.C. Lauritsen to get a rocket program started at Caltech.

In March 1941 Lauritsen discussed the need for expanding the rocket work with Hickman and Skinner, and following that discussion Lauritsen gave the first of several written proposals for the expansion of American rocket work. On April 1, 1941, he wrote Tolman:

> There is in my opinion an urgent need for a considerable expansion of the rocket program particularly as regards aircraft and anti-aircraft rockets. The British have had sufficient experience with the latter type of projectile to make it certain that we would be justified in developing such devices as rapidly as possible, and Major Skinner informs me that he and many officers in the Ordnance Department of the Army are convinced that a practical aircraft rocket can be developed and that such a project should be given a high priority rating.
>
> I am fully aware of the excellent progress that is being made by Skinner, Baker and Hickman at Indianhead [sic] and I think their work is further confirmation that an expanded program is now justified . . . This group should in my opinion be expanded as much as facilities at Indianhead will permit and in addition it would be very desirable to put one or more new groups to work on specific problems as soon as possible. . . .
>
> . . .
>
> I should like to recommend the following program to be started immediatelv and to be advanced as rapidly as possible:
>
> Project 1.
>
> Develop a 5-inch diameter aircraft rocket with proximity fuse and all necessary auxiliary apparatus for firing from a plane.
>
> . . .
>
> Project 2.
>
> Develop a 3-1/4-inch diameter AA rocket with proximity fuse and all necessary auxiliary apparatus.
>
> . . .
>
> In my opinion The California Institute of Technology is in a particularly favorable position for undertaking Project 1 . . .[84]

APPENDIX B

C.C. Lauritseen Summary of Status of Rocket Ordnance R&D as of August 1, 1941 (reproduced from Ref. 1)

OFFICE FOR EMERGENCY MANAGEMENT
NATIONAL DEFENSE RESEARCH COMMITTEE
OF THE
OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
1530 P STREET NW.
WASHINGTON, D. C.

JAMES B. CONANT, Chairman
RICHARD C. TOLMAN, Vice Chairman
ROGER ADAMS
CONWAY P. COE
KARL T. COMPTON
FRANK B. JEWETT
MAJ. GEN. R. C. MOORE
CAPT. LYBRAND P. SMITH

IRVIN STEWART, Executive Secretary

ADDRESS REPLY:
CARE NATIONAL RESEARCH COUNCIL
2101 CONSTITUTION AVENUE
WASHINGTON, D. C.

August 1, 1941

MEMORANDUM:
TO: Dr. Vannevar Bush
FROM: C. C. Lauritsen

Subject: Expansion of Program of Rocket Development

It has been my opinion for some time that there is an urgent need for a considerable expansion of the whole program of development of rockets for military purposes now under way in this country. This opinion became a firm conviction as a result of my investigation, while in England this spring, of the rocket work being done there. A large part of my time while in England was devoted to this problem and I came back more than ever convinced of its importance and urgency.

Before making specific recommendations it may be well to outline briefly (1) the work that is under way in this country and (2) the work that has been done in England.

(1) Official government work on rockets in this country is, I believe, limited practically to three fairly distinct projects. These are:

(a) Assisted take-off and accelerated flight for airplanes.—The NACA has a Special Committee on Jet Propulsion of which Doctor Durand is Chairman and a high priority has been given to this work by both the Army and the Navy. Research and development work is under way at the Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, California, and at the Engineering Laboratories, U. S. Naval Academy, Annapolis, Maryland. The former work is financed by an Army Air Corps contract and the latter by the Navy Bureau of Aeronautics. In addition, the Navy Department is having conversations with Dr. R. H. Goddard, with a view to using him as a consultant or to the authorization of a definite contract for the application of his methods and experience to the solution of this problem. Doctor Goddard has been working at Roswell, New Mexico, since 1930 under a grant from the Guggenheim Foundation of New York City.

(b) Rockets for plane-to-plane use.—Since the rocket action does not transmit recoil to the airplane that is doing the firing, it becomes possible to use large calibers.

(c) Armor piercing bombs.—Jet propulsion can be applied to accelerate armor piercing bombs in order to secure penetration of the decks of enemy ships even when the bombs are dropped from relatively low altitudes.

The two projects (b) and (c) have been the concern of Section H, Division A, NDRC. Since the establishment of our Joint Committee on Jet Propulsion with the Bureau of Ordnance, U. S. Navy, much of the work has been done with the help of facilities set up at the Naval Powder Factory, Indianhead, Maryland. Liaison with the Army has been maintained through an officer actively engaged in this development. This committee has recently been expanded to include an officer designated by Army Ordnance. It now consists of: Lt. Commander J. A. Snackenberg, U. S. Navy Bureau of Ordnance, Chairman; Major L. A. Skinner, U. S. Army Ordnance; Dr. L. T. E. Thompson of the Naval Proving Ground, Dahlgren; Dr. C. C. Lauritsen, Vice-Chairman, Division A, NDRC; Dr. C. N. Hickman, Chairman, Section H, Division A, NDRC; Dr. J. E. Henderson, Consultant, Division A, NDRC.

The study of these two applications of rockets, using model and full scale experimental rocket projectiles, has reached a stage of considerable success, but it is not yet at the point where final designs for production are warranted. Section H, Division A, NDRC, has also considered the possible development of high speed rockets for use against enemy aircraft and of rocket devices for setting up wire barrages similar to those used by the British or for sending up aerial mines as protection against enemy bombers. Both of these developments have been temporarily dropped, however, because of the lack both of proper facilities and of sufficient personnel at Indianhead. In fact the Indianhead group feels that it should concentrate upon the two aforementioned projects (b) and (c) to the exclusion of everything else until these problems have been solved. The knowledge gained from these two applications could then be applied to other rocket problems.

To obtain a satisfactory propellent powder for their work the Indianhead group has had to resort to the use of double base powder. Although the British employ a dry extrusion process to manufacture their rocket powder, American manufacturers undertake extrusion only with admixture of solvent. Unfortunately this American powder when made with the large web thicknesses required for most rocket applications retains too much solvent even after prolonged drying. At our instigation the Hercules Powder Company has begun work on the formation of sticks of cordite from the thin sheets of solventless powder now manufactured for use in trench mortars and is also considering the possibility of setting up, at Radford, experimental presses for duplicating the extrusion process used successfully by the British. Until this powder problem is successfully solved most of the rocket work under way in this country will be seriously curtailed.

(2) Although many millions of dollars have been expended in England upon the development and manufacture of rockets, to obtain a reliable evaluation of their importance as an antiaircraft weapon was exceedingly difficult. The proponents were optimistic, the most rabid of them claiming that rockets would soon replace antiaircraft guns; the critics complained that the results had not been commensurate with the efforts, that rockets would always be inaccurate weapons, although useful when guns are not available. However, all agreed that the rocket was an important development that must be continued at all cost.

Although the dispersion with antiaircraft rockets in their present stage of development certainly is at least five times that with guns under ideal conditions, in actual firing against a moving target this factor probably is more nearly two, owing to the fact that the tracking and prediction errors are large in both cases. Specific reasons can be cited for thinking that the dispersion is mainly due to poor performance of the present propellant and would be decreased if the internal ballistics could be improved. For example, slivers often are observed long after the acceleration; these sometimes burn in the chamber but often are ejected and burn in free space for several seconds, thus indicating a considerable loss of propellant. The remedy may be either an improved method of supporting the propellant or the development of a more suitable propellant.

Facilities in England are entirely inadequate for the manufacture of the propellant used at present in AA rockets—a solventless cordite extruded in the form of long hollow cylinders. A new plant at Bishopton has reached only 10 percent of its capacity, and the product is not as satisfactory as that from the older plants. Steps are being taken to improve the product but the results are still inconclusive. The best remedy obviously would be an improved propellant but this may be a long-time project. There is very keen interest among the ordnance authorities in England that some manufacture of cordite be started, for whatever reason, in America.

The following types of rockets are already in use in England:

(a) The 2-in. rocket.—The 2-in. rocket—the first weapon to be developed—is intended mainly for use on shipboard against dive bombers and low flying planes. For firing this rocket several types of projectors have been developed; the favorite seems to be a turret-like structure with open rails for firing 20 rounds simultaneously. There is talk of increasing this to 40 rounds. No predictor is used with this projector; it is operated by one man who occupies the turret.

The 2-in. rocket is economical and easy to handle. Although it appears attractive and convenient—especially for small merchant ships which cannot carry big guns and predictors—there is no evidence that it has been of practical use as yet. However, the interest of the Navy in this weapon may be judged from the fact that it has just placed an order for 4,500,000 of this type alone.

(b) The 3-in. rocket.—The 3-in. antiaircraft rocket is intended for use against dive bombers and high altitude planes. Its present ceiling is said to be 22,000 ft when used with a time-fuse, somewhat less with a photoelectric fuse and about 28,000 ft with a lighter load.

Although the projector now in service use is a light, mobile single unit, a double unit is under development. The plan is to have as many as 66 projectors operated from a single predictor and fired simultaneously. At present, 100 3-in. antiaircraft guns are being modified to accomodate [sic] rails for firing 9 rounds of 3-in. rockets; these units are intended for mobile use. There are few developmental problems in England on which so much money and effort is being spent as on the 3-in. antiaircraft rocket. Although still in the developmental stage, this rocket is already being produced in large quantities and is extensively used. In connection with this development there is a separate proving ground employing 300 men. A special regiment of the coast artillery consisting of three batteries is also assigned to this work and serves to train crews.

Doubtless this rocket is already a very useful weapon, but it would be much more useful if a better fuse were available. At present the only fuse in use is a powder train time-fuse which is initiated by the pressure in the nose. A photoelectric fuse is in production, but it is not yet entirely satisfactory. A radio proximity fuse is under development. The British antiaircraft command is much interested in this rocket and is most anxious to have the radio proximity fuse perfected. It also expressed the opinion that a continuously adjustable time-fuse would be a great improvement over the present pre-set fuse. The general in command is urging the development of faster and larger rockets with a ceiling of 40,000 ft. There is room for improvement in the ballistics, the mean deviation being about 1°, and there is every reason to believe that improvement can be made by relatively simple improvements in the propellant and its mounting in the rocket. There is also much room for improvement in the projectors, both single and multiple, as well as in the fire control apparatus. At the present state of development it is estimated that two 3-in. rockets are about as effective as a 3.7-in. shell. With a continuously adjusted time-fuse the rocket would probably be slightly better than the shell and with a reliable proximity fuse it would be more than five times as effective.

(c) Wire barrage rockets.—One of two existing types of wire barrage rockets consists of a 2-in. rocket that pulls a wire and bomb out of a stationary container; it is intended for laying a barrage from 2000 to 1000 ft. The other type is for much higher altitudes and consists of a 3-in. rocket with a special head that carries the parachutes, wire and bomb.

These devices function well mechanically, more than 90 percent of them opening properly and descending quite slowly. The claim is that such wire barrages have brought down or seriously damaged a number of German planes, and the Germans have equipped some planes with "wire cutters" and "fender wires" which are said to reduce the airplane speed by as much as 50 mi/hr.

(d) The 5-in. rocket.—The 5-in rocket is intended to carry a 30-lb bomb. It was designed originally for use with chemical bombs. Although the few that we have seen fired had square noses and tumbled badly, this defect doubtless can be corrected if desirable.

Work is in progress on an anti-submarine bomb that uses the same rocket. This bomb has a very blunt conical nose designed for proper entry into the water. It is intended for high-angle fire and is said to have good under-water ballistics.

This summarizes the rocket situation as it exists at the present time. What we desire to know at this time is whether the armed services think that further rocket work, and in particular work on the high altitude antiaircraft rocket, should be initiated at this time. As previously pointed out, no work on AA rockets has been done in this country so far. This is largely due to the fact that no suitable propellant has been available. It now appears that such propellants will be available shortly, at least in sufficient quantities for developmental work. Plans are under way for the construction of two extrusion presses of the British type for the production of this material in quantities sufficient for training purposes, and other methods of forming large sticks of cordite, initiated at Indianhead, are being developed by the Hercules Powder Company. The development of high altitude antiaircraft rockets can therefore be started at once, provided such a project is of sufficient interest to the armed services. However, it cannot be undertaken by the group at Indianhead without seriously interfering with the important work now in progress there. Furthermore, a considerably larger firing range will be required and the work should be carried out in the closest possible collaboration with antiaircraft units of the Coast Artillery. An arrangement similar to the one we now have at Dahlgren should be made with the Coast Artillery. The latter should provide targets, gliders, drones, etc., and should conduct the firing trials. A range, such as the Coast Artillery Range at Barstow, California, should be designated; there it is possible to fly every day. We have gone to Dahlgren again and again without being able to carry out scheduled tests because of unfavorable weather conditions.

Many of the objections which are now advanced against rockets can probably be met by improvements in the design, not only of the rockets themselves, but also of the propellant, the projectors and the fuses. Our photoelectric fuse is now quite satisfactory and can be placed in production on short notice if necessary. Its use is, however, limited to daylight and favorable light conditions. Our radio proximity fuse is very promising and several tests have been successful. It is reasonably certain now that this fuse will be the most satisfactory when it becomes available. Work has also been started on an electric time-fuse which can be continuously adjusted while in the projector either by hand or by a predictor.

If the armed services do not give the high altitude antiaircraft rocket a fairly high priority, then we should re-evaluate everything that is being done at the National Bureau of Standards on proximity fuses and much of the powder development we have under way can be postponed.

To be still more specific, we should like answers to the following questions:

1. Do the armed forces think that the rocket work already under way should be expanded?
2. What sort of priority will the armed forces give to the high altitude antiaircraft rocket?
3. Does the Army and Navy look to us to keep them posted on rocket developments and to make recommendations regarding promising developments or do they prefer to make such investigations themselves and suggest projects to us? The Indianhead Committee feels that it has no authority to suggest new projects. If they do not have this authority, who does? If it is the function of NDRC to recommend new developments to the Army and Navy, then we should recommend:
    (a) The development of a 2-in. rocket with contact fuse, similar to that of the British, followed by educational orders and experimental use by the services.
    (b) The development of a 3-in. rocket, similar to that of the British, but with urgently needed improvements, such as proximity fuses and continuously adjustable time-fuses.
    (c) The development of a 4.5- or 5-in. rocket for altitudes up to 40,000 ft.
    (d) The development of anti-submarine and chemical warfare rockets.
4. If the development of AA rockets is approved by the armed forces, should the projects be financed by NDRC or by the Coast Artillery?
5. Can the antiaircraft command of the Coast Artillery be authorized to cooperate with NDRC or its contractors in such a developmental

program in the same way in which the Naval Proving Ground at Dahlgren now cooperates in the development of proximity fuses?

6. Should a rocket committee composed of representatives of the Army, Navy, and NDRC (with perhaps a British representative) be set up to determine policies, make recommendations of new projects, evaluate priorities, standardize manufacture, etc.? There is a definite need for a standardization of American and British practice in regard to sizes of rockets manufactured and of all associated apparatus such as fuses, projectors and predictors.

[Signed] C. C. Lauritsen
Vice Chairman, Division A

APPENDIX C

Designations for Rockets and Motors

The Caltech rockets were distinguished by a specific style of designations, and often by popular nicknames. The primary descriptor indicates the diameter of the rocket, often of the warhead, which might be larger than the diameter of the motor. As an example, the original rocket was called the 4.5-inch BR, which in service acquired the name "Old Faithful". The motor was referred to as the 2.25-inch motor. These names are not unique, as 2.25-inch motors were used also in the 4.5-inch ASR (antisubmarine rocket) and 4.5-inch retrorocket. In this history the differences of these motors and warheads have not been detailed, but in official records each component was designated by mark numbers and "Mod" numbers. Such designators were assigned to every service igniter, propellant charge, assembled motor, warhead configuration, fuse, and launcher. In this history, the designators pertain to weapon diameter, or motor diameter, in combination with the letter abbreviation indicating the application, plus popular name when one was widely used. Primary examples are as follows (in historical order):

4.5-inch ASR (antisubmarine rocket) "Mousetrap with 2.25-inch ASR motor

4.5-inch BR (barrage rocket) "Old Faithful" with 2.25-inch BR motor

4.5-inch Retro-Rocket with 2.25-inch and 3.0-inch motors

3.0-inch AR (aircraft rocket) with 3.0-inch steel warhead and 3.0-inch motor

4.5-inch AR (aircraft rocket) with 3.0-inch motor

5.0-inch HVAR (high velocity aircraft rocket) "Holy Moses" with 5.0-inch motor

5.0-inch HVSR (high velocity spin stabilized rocket) with 5.0-inch "spinner" motor

11.75-inch AR (aircraft rocket) "Tiny Tim" with 11.75-inch motor

14.0-inch AR (aircraft rocket) "Big Richard" with 14.0-inch motor

5.0-inch (Caltech Model 38) "White Whizzer" a technology prototype motor

2.75-inch FFAR (folding fin aircraft rocket) "Mighty Mouse" one of China Lake-developed weapons with "White Whizzer" technology

APPENDIX D

Personal Recollection Illustrating the Spirit of "Getting Things Done" at Eaton Canyon

As a reflection on personalities and the spirit of making things happen, I would like to recount how the first tests of a "star perforated" propellant charge came about. Around January 1944, the 2.25-inch motors were using tubular propellant charges that had drilled radial holes (Fig. 3a) to stabilize combustion. We had begun to suspect that severe gas oscillations in the charge perforation were the real cause of the anomalous combustion, and that there might be better ways to solve the problem than drilling radial holes.

I proposed to my boss, R.N. Wimpress, that a few charges be pulled from current production before drilling radial holes, and be equipped with glued-in plastic strips in the perforation. Wimpress liked the idea, but found that his boss, Bruce Sage, did not. Wimpress offered to send three charges down to the static test facility for Sunday if I wanted to be there and glue the strips in place myself and load the motors. No sooner done, and Wimpress bootlegged the static firings. With the perfect pressure-time records in hand, Wimpress persuaded Sage to allocate funds for a new extrusion die to produce charges with extruded star perforations. I prepared illustrations of the successful test results for the report; illustrations that can now be seen in Wimpress, pioneering book on internal ballistics (Ref. 10). This first U.S. start with star perforated, stable burning charges didn't see application for a couple of years because the 2.25-inch motors were already in production with drilled charges and new motors in development called for "external burning" cruciform charges for the aircraft rockets. However, it provided the confidence to go ahead later with the all-internal-burning charges that were used in the "White Whizzer" in 1946 and became the standard thereafter.

EWP