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Chapter 15

Rocket History through an Artifact: American Rocket Society (ARS) Test Stand No. 2 (1938–1942)*

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Abstract

For more than 30 years, the American Rocket Society (ARS) Test Stand No. 2 was exhibited in the Rocketry and Space Flight Gallery of the National Air and Space Museum (NASM) in Washington, D.C., since the building opened in 1976. (This object is cataloged as Cat. No. 1968-0021 in the collections of the NASM.) But for most of that time the Stand had its back towards the wall, concealing its inner workings. In addition, the existing documentation on the object in the NASM's records was not very complete. However, in 2007, the Rocketry and Space Flight exhibit was closed and the Stand removed to the Museum's Storage and Restoration Facility. This provided the ideal opportunity to undertake a closer study of this artifact, which turned out to have a far more significant and interesting history than previously realized.

This paper is a summary of the 67-page long investigation report on this artifact by the author, which includes detailed examinations of the object, re-

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searches on its testing history using the early publications of the ARS and correspondence of early ARS members, extensive photo interpretations of extant photos of it throughout its operational life, and communications with a then, 93-year old former associate of the ARS who had played a role in its history.

In brief, the significance of ARS Test Stand No. 2 may be summed up as follows. ARS Test Stand No. 2 was used for static tests of experimental liquid-propellant rocket motors from 1938 to 1941, which was the main activity of the Society during those years. Most prominently, it tested and proved the effectiveness of the regeneratively-cooled liquid propellant rocket motor of ARS member James H. Wyld, the first successful regeneratively-cooled rocket motors in the United States.

This led directly to the formation, in December 1941, of Reaction Motors, Inc. (RMI), America's first commercial liquid-fuel rocket company, that marked the emergence of professional rocket engineering in the United States. In turn, RMI, which borrowed the Stand for their initial experiments, became an important pioneering company that developed, for example, the 6000C-4 rocket engine used in the Bell X-1 rocket research aircraft that became, in 1947, the first plane to break the sound barrier. Newly found early RMI photos also reveal that the Stand played a role in RMI's development of its first larger static test stands and contained features of the original ARS Test Stand No. 2.

Introduction

The rocket test stand is a fundamental tool of practically all rocket experimenters. It measures the performances of rocket motors, solid or liquid propellant, while fired in static (non-flying) ground tests. Yet, no history of this type of device presently exists. This paper focuses on Test Stand No. 2 of the American Rocket Society (ARS), used from 1938 to 1942, which appears to be the only extant stand of the 1930s, and perhaps of the world, from that period. Moreover, a closer study of this object reveals that it was far more significant historically than previously believed and has a colorful and complex history.

For more than 30 years, this object was on exhibit in the National Air and Space Museum (NASM) of the Smithsonian Institution in Washington, D.C., but its history and make-up were little known because for most of that time the Stand was mounted against a wall that prevented an examination of its interior, that contains many of its important parts. Also, the documentation on it was very poor. However, when the Gallery titled "Rocketry and Space Flight" was closed in 2007 to make way for a new exhibit, the Stand and other artifacts were removed. The opportunity was now presented to study the artifact more thoroughly. This study became a volunteer project for the author, the former Curator of Rocketry of the NASM who had retired that year. Consequently, a 67-page document was produced. This paper is a condensed version of that document.

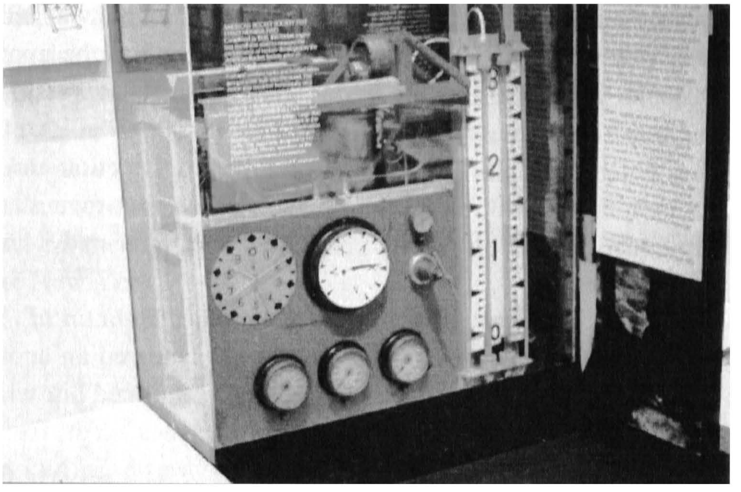


Figure 15–1: American Rocket Society Test Stand No. 2 as originally displayed in the National Air and Space Museum (NASM) from 1976 to 2007. Against a wall and covered by a plexiglass case, close curatorial examination of the Stand was not possible until the object was removed. Credit: Photo by Frank H. Winter, in Cat. # 1968-0021 file, NASM, courtesy Smithsonian Institution.

Background

ARS Test Stand No. 2 was designed and built by individual members of the American Rocket Society. It measured the thrust, duration of each run, propellant pressures, nitrogen pressure from the feed tank that forced in the propellants into the combustion chamber, and combustion chamber pressure. No temperature measurements were taken. The Stand had a thrust capacity up to 200 lb (90 kg) and the average duration of the test motors was a few seconds. This was a period when rocket technology was in its infancy, when everything was experimental and the hardware "home-made." Moreover, the ARS was an amateur group with only two or more professional engineers among its membership at the time, and with the funding for their projects from "out-of-pocket."

The group was originally founded in 1930 in New York City, mainly by idealistic space travel enthusiasts, and was known as the American Interplanetary Society. By the mid-1930s, they became more fascinated with the sheer engineering challenges and "fun" of rocketry as a "hobby," and began to experiment. As detailed in the author's *Prelude to the Space Age—The Rocket Societies: 1924–1940*, between 1932 and 1934, the ARS built only four rockets yet only two flights were made.[1]

In the latter year, they changed their name to the American Rocket Society, to attract more engineers and to distance themselves from what was still considered the fantasy side of the potential exploration of space and the upper atmosphere. At the same time, this was the period of the Great Depression and the members had almost no money at their disposal. They also concluded that a test stand was a far more practical way to learn about the construction and performance of rocket motors. But with no permanent testing station, their stand had to be portable, and cost as little as possible. Thus, when it appeared it was a very simple but effective stand.

However, some years earlier, in the mimeographed *Bulletin of the American Interplanetary Society* for September 1931, there appeared an anonymously written article titled "Preliminary Rocket Experiments Outlined" in which a test stand design is described and depicted with crude sketches.[2] Yet, for some unknown reason, a stand of this type was not adopted and was quickly forgotten. In the same years, Dr. Robert H. Goddard was the preeminent U.S. rocket experimenter and conducted his own rocket flights and static tests on stands, although he worked in secrecy and had no connection with the ARS.

History of ARS Test Stand No. 1

In the October–November 1934 issue of the Society's journal, now called *Astronautics*, it was first reported that: "...Tests will soon be commenced by the Experimental Committee of the American Rocket Society, with a light, portable proving stand of new design now under construction..."[3]. ARS Test Stand No. 1 no longer exists but surviving photos and write-ups in *Astronautics* provide sufficient information to describe it. The Stand was designed and largely built by member John Shesta and was constructed using "tanks, valves, and other parts" of his flight rocket, ARS No. 4. The Stand came in three separate units: the Stand proper, a wooden saw-horse with five dials on it, and a separate nitrogen tank for forcing in the propellants into the test motor. All these elements were linked by flexible hoses.

The Stand proper was a rectangular, vertically mounted steel framework bolted to a wooden base. Two cylindrical copper propellant tanks (oxidizer and fuel), each 3 in. (7.6 cm) in diameter, and 21.5 in. (54.6 cm) long, were fitted vertically within the framework, one opposite the other. Between the tanks was a single, much smaller diameter shaft that protruded beyond the top of the framework. On top of the shaft was secured the test rocket motor with its nozzle aimed skywards. The shaft served as the hydraulic plunger for measuring thrusts, a tube leading from the bottom of the plunger to a thrust gauge. (In those years, "thrust" was not a common term and the Society preferred the word "reaction.") Propellant feed tubes were connected from the motor to each propellant tank and also fitted with quick opening valves.

The gauges showed propellant tank pressures, thrust up to 100 lb (45 kg), combustion chamber pressures, and durations of test runs. The data was not recorded but was visually observed by the experimenters and filmed. From the data, thrust/time/pressure curves were drawn. The June 1935 issue of *Astronautics* reported on the results of the Stand's first runs on 21 April of that year at Crestwood, New York.[4]

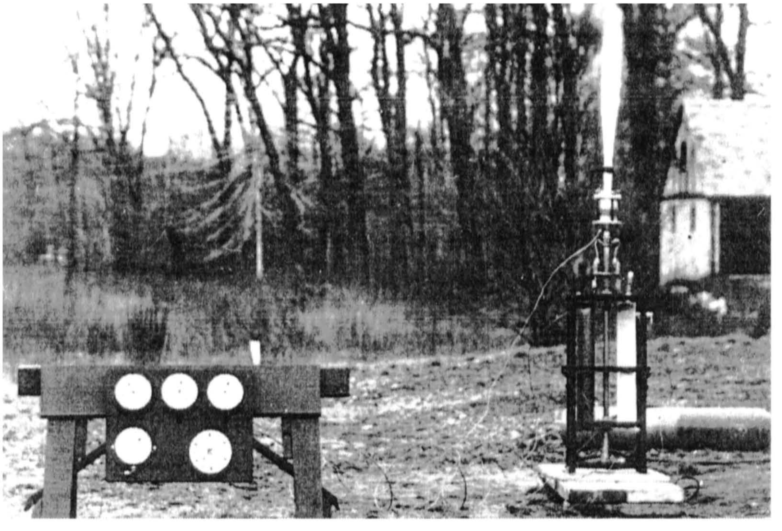


Figure 15–2: ARS Test Stand No. 1 during a static firing. Built in 1934, Test Stand No. 1 was used up to October 1935. It came in two sections: a wooden saw-horse with the dials, and the Stand proper, and showed thrusts up to 100 lb (45.3 kg). Credit: Smithsonian photo A-4559-C.

By photographing the dials simultaneously with a motion picture camera or a quick loading camera, the exact relations of these quantities throughout runs were permanently recorded. In addition, detailed records were kept on the types and amount of propellants used, motor dimensions, and other observed phenomena.[5]

One striking point brought out in the tests, was "the lack of a motor capable of withstanding the effects of firing for a sufficiently long time." In short, there was no adequate means of cooling the motors. (ARS Test Stand No. 2 was to play a critical role in finally solving this serious problem and led to a major breakthrough in U.S. rocket technology.)

Also in *Astronautics* for June 1935, it is pointed out that: "For some time the conviction has been growing amongst the Society's engineers and experimenters that we could learn much more about rockets—not by building and flying them—but by building rocket motors and putting them through exhaustive ground tests. Causes for failures or inefficiency could then be carefully observed and analyzed, in contrast to the difficulty of determining the causes of failure or success of a rocket in flight... Far more was learned in these trials than if each motor had been attached to a complete rocket and shot into the air, where its behavior would have been a matter of conjecture." This philosophy prevailed throughout the ARS's experimental period up to the end of its Test Stand No. 2 phase.[6]

The next series of tests with Stand No. 1 was conducted on 2 June 1935. Among the information sought was the "heat resisting value of Nichrome compared to aluminum for nozzle metal" and the "heat resisting value and strength of a carbon motor."[7] Nichrome, a nickel-chromium alloy with a high melting point of about 2,552 °F (1,400° C.), was found in the test to be "definitely superior to the aluminum..." From the calculations, the Society also used the measure of performance then termed "jet velocity," or what we call today exhaust velocity. The values for their first test motors ranged from 2,940 to 4,000 ft/sec (896–1,219 m/sec).[8]

They also discovered the "interesting phenomenon" of "waves of darker-colored flame, like nodes, up through the jet [exhaust]." These were diamond-shaped shock patterns throughout the exhaust. "It has been suggested," the report concludes, "that these are sound effects and may be used to determine the jet velocity." Africano confirmed they were "sound waves" and might "be utilized in some way to determine this velocity ... and making an ordinary phonograph recording of the sound of the jet, are certainly worth trying in a future test." But this was never done.[9]

Thus, while ARS Test Stand No. 1 and later No. 2, had no means of detecting temperatures, both stands were still highly useful in gathering fundamental information on the workability of certain materials and techniques in the make-up of basic liquid fuel rocket motors, while finding a reliable cooling means was the utmost goal.

Other tests were made on 25 August 1935. One objective at this time was to find out "the effect of using alcohol diluted with varying proportions of water." One lesson learned was that the alcohol-water mixture helped cool the motor although overheating still remained a problem.[10]

But the test on 20 October turned out to be the last for ARS Test Stand No. 1, although it is not recorded in *Astronautics*, perhaps because there was an accident in which one of the spectators, Miss Ramona Jennings, was injured from a motor that exploded. Her elbow was severed, leading the Society to solicit funds among the members to pay for her medical expenses, including an artificial elbow. The mishap was reported in the *New York Times* for 22 October 1935 and is the only known accident with both ARS Test Stands No. 1 and 2.[11]

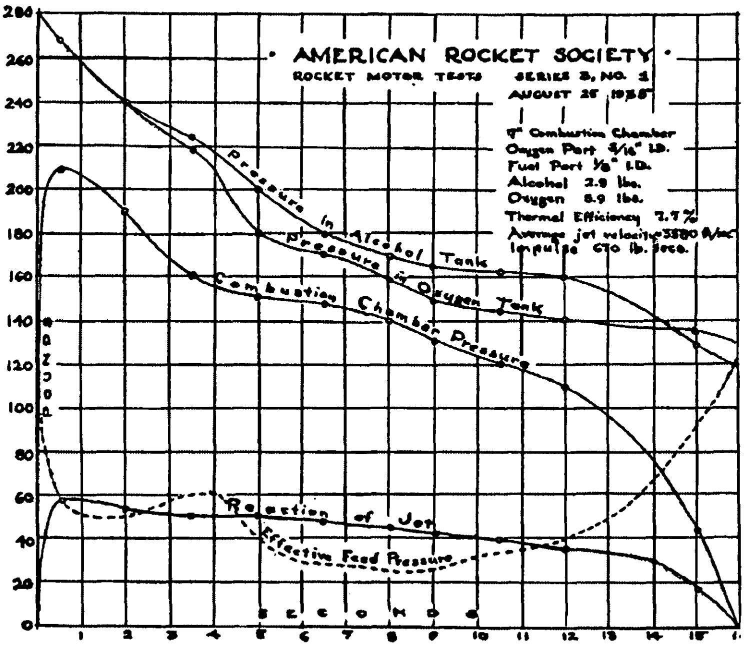


Figure 15–3: Performance charts of each test, like this one for 25 August 1935, were an important part of the histories of ARS Test Stands No. 1 and 2. The thrust, pressures, and duration (but not temperatures) of each run were carefully plotted on the charts. Credit: Smithsonian photo 92-14544.

Nonetheless, the overall data acquired from the tests of ARS Test Stand No. 1 "was sufficient" to enable Africano "to derive three new empirical rocket design formulas," although it was also felt by the Society that an improved and safer stand was now needed.[12]

Design and Introduction of ARS Test Stand No. 2

We cannot precisely date when work was started but, according to a postcard mailed to ARS members by Secretary Max Krauss in 1936, "The Annual

[ARS] Business Meeting will be held April 17th" and "Besides the election of the Board of Directors," there would be a talk by John Shesta on "The Design of a New Proving Stand." But it took about two years before the new stand was constructed due to unnamed "unavoidable delays."[13]

In 1938, Assistant Secretary of the ARS, James Rowlands, announced another Regular Meeting for 18 February of that year in which Shesta, "Chairman of the Experimental Committee[,] will describe the final design of the new A.R.S. proving stand that he and Mr. [Hugh F.] Pierce are building...".[14]

The Stand was first fully described in print in the April 1938 issue of *Astronautics*, and was "rapidly nearing completion...".[15] Pendray says Shesta was "aided by [James H.] Wyld, Alfred Africano, Peter Van Dresser, and others."[16] But the principal designers were Shesta and Pierce. Shesta, in his letter of 30 January 1978 to Winter clearly spells out who did what: "The test stand was assembled in Pierce's shop. He built the framework. I had designed and built all valves and other parts, tanks, regulators, etc., and brought it up piecemeal to Pierce's shop for assembly."[17] Shesta, one of the bonafide early engineers in the ARS, added that Pierce's "lathe work was a bit crude." Wyld confirms the Stand was completed "at the home shop of H. F. Pierce in the Bronx [at 1462 Leland Ave.]" and was to "embody several new features developed as a result of previous experience with the No. 1 Stand." Mainly, it was to "increase the scope and accuracy of [test] work," along with "increased safety and convenience of operation...".[18]

Similar data readings were obtained from ARS No. 2 compared with No. 1 and perhaps parts were taken from No. 1 and adapted for No. 2, although the principle difference is that No. 2 was a single unit, whereas No. 1 was more modularized. During the six month interval from April until October 1938, as reported in *Astronautics*, "many refinements were introduced ... particularly a pneumatic system for operating the fuel and oxygen valves." The latter could be "instantly opened or closed by nitrogen pressure controlled by a small pilot slide valve." In the same period, an initial "considerable difficulty" of transporting the Stand "of some 300 pounds" (136 kg) was overcome with construction of the "special trailer for road transportation..." although six men were required to take it on and off the trailer. A "water-flush system was also provided to cool the motor quickly after a run."[19]

On 13 September 1938, a month before the Stand became operational, member James H. Wyld took a series of detailed photos of it, front and back, as well as side views. Furthermore, he had almost completed the construction of his own regeneratively-cooled rocket motor and "fit checked" his motor on the Stand. But after taking the photos he did not develop the film. Somehow, years later, the negatives wound up in the National Air and Space Museum and about 2006—or, some 70 years after the pictures were taken, they were finally developed. The results were quite surprising. It turned out they offered wholly unexpected and fascinating "new" and invaluable details of both the Stand and motor when they were in "mint" condition, and also revealed that the Stand had been modified several times over the years.

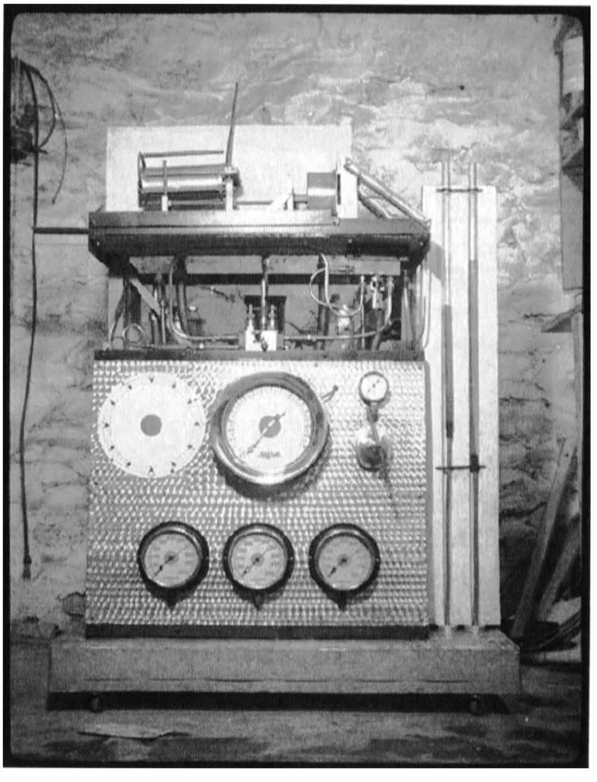
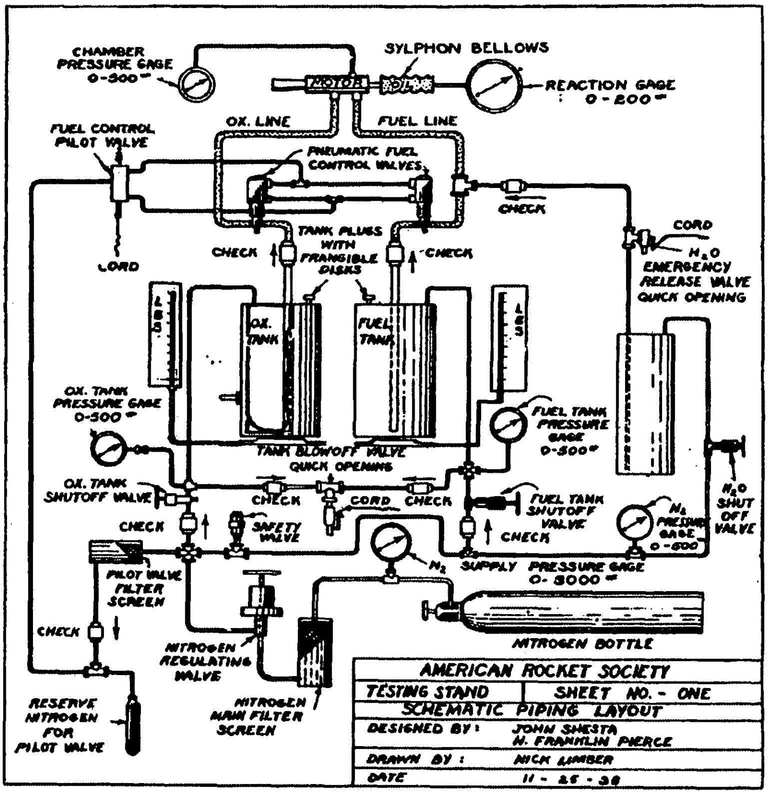


Figure 15–4: A rare photo, taken 13 September 1938 by American rocket pioneer James H. Wyld, showing his regeneratively-cooled rocket motor fit-checked on the then new ARS Test Stand No. 2. Note also, the hitherto unknown mottled finish on the front which was later repainted by the ARS in red finish. Motors were fired horizontally on this Stand. Credit: Smithsonian photo 9A05171.

At the Society's meeting of 16 September 1938 at the Engineering Societies Building in New York, Wyld ("in place of Shesta") announced that the Stand was finished, which drew applause.[20] He then described it in detail using (other) photos of the instrument board and motor carriage. Small photos were also made available to the members at 10¢ each. (However, these particular photos are no longer known to exist.) Later, the February 1939 issue of *Astronautics* featured on its cover, a schematic of the Stand drawn on 25 November 1938 by Nick (Nicholas J.) Limber of the Westchester Rocket Society, an affiliate of the ARS that participated in its tests.[21] Limber, at the time this paper was written, was age 93, and then recollected that he had "volunteered" to make the drawing when he spotted a request for this task in the ARS journal, although this has not been found in *Astronautics*. Nonetheless, he was an accomplished draftsman, well known in model aviation magazines for his airplane model designs, and simply used sketches made by Shesta to arrive at the schematic.[22]



Schematic Diagram of Proving Stand #2

Figure 15–5: Schematic drawing of Test Stand No. 2 by Nick Limber, 25 November 1938. During the course of the research on the Stand, Nick Limber, in his 90s, was located and was most helpful in the research. Credit: Smithsonian photo 75-10245.

This diagram is likewise helpful in identifying many of the original components in ARS No. 2, including the water quenching tank between the propellant tanks. As later recalled by Shesta: "The original version of the stand used a weighing system to gauge the propellant consumption. The tanks were flexibly supported and rested on diaphragms in water chambers, the hydrostatic pressure thus produced was registered by manometer tubes." But, he added, "The system was not satisfactory. The tanks were heavy, the propellants light and not enough precision was available in readings. Furthermore, when the tanks were pressurized, the flexible tubes stiffened up and affected the readings." The weighing system and flexible tubes were thus later eliminated, as was the water quenching tank.[23]

When used operationally and wheeled to a test site, then unloaded and placed on the right spot, the Stand "was carefully leveled" (perhaps using a hand-carried carpenter's level), then was secured by guy wires "to prevent the motor thrust from upsetting it." (Judging from photo interpretations, the guy wires were secured to existing holes on the Stand rather than using eye bolts.) According to Limber, the tests were "very informal" and there was no countdown. The participants merely said, "Let's go!," although another source indicates a hand signal was used, while a whistle was used for Test Stand No. 1 (and probably also for Stand No. 2) to move the observers to shelters and clear spectators. No instructions were written on how the Stand operated but everybody seemed to know what to do, Limber added.[24]

Testing History of ARS Test Stand No. 2

In its baptismal test on 22 October 1938 at New Rochelle, New York, a tubular Monel motor, built by Pierce, and different types of ignition means were tested, but the primary purpose was to "test the general operation of the stand." The problems encountered were failures in the rocket's own ignition systems, besides the sticking of the oxygen valve on the Stand. These were remedied before the next tests. As for the troublesome valve, it was removed and substituted by a new and large cylinder.[25]

In a postcard from Pierce to member Louis Goodman, dated 23 November 1938, he says: "The Chairman [Shesta] has asked me if I would go up to the new [test] location for the tests and see if it can be made in readiness this Sat., the 26th... There will be some repairs to be made on the Stand, and some brush to be cleared away for the tests." Hence, damage had occurred to the Stand during its first tests of 22 October, but we have no record of the nature the damage. It may have been the LOX valve, although the Stand may have simply been mishandled during its transport.[26]

In fact, buried elsewhere in the issue of February 1939 of *Astronautics* is a smaller, but poignant, item on the tribulations of transporting the less than "portable" new Stand for its operational debut: "The first field tests of Proving Stand No. 2 were described by ... Shesta at the November meeting ... the meeting was edified by a recital of the hardships encountered by the hardy experimenters, who had to wheel the proving stand two miles [3 km] by road and a quarter-mile [0.4 km] over rough ground, pull a car out of a ditch with the aid of stones lugged from a near-by well and a tow-rope composed of old auto chains, and live for two days on little but crackers and ham sandwiches... Such are the sacrifices of Science! [sic]."[27]

Among other early photos taken by Wyld are views of the Stand mounted on a large two-wheeled trailer (Figure 15–6). The trailer was hauled by a car "over rough [country] roads" in getting to the remote testing site and it seems likely that the Stand may well have suffered on account of the vibrations of the apparently iron-rimmed wheels over this terrain. For the same reasons, judging by photos of a 1941 test, the trailer was later replaced with a smaller one with automobile wheels and tires.

Figure 15–6: Another rare photo, taken by James Wyld in 1938, showing a specially-built cart for hauling ARS Test Stand No. 2 to its chosen test sites. The Stand was "portable" but still weighed some 300 lb (136 kg). Taken 21 October 1938 near the test site at New Rochelle, New York. Credit: Smithsonian photo 9A05175.

The second test series was made on 10 December 1938, also at New Rochelle, but at a different spot, within the abandoned foundations of house close to the home of Tucker Gugelman of the Westchester Rocket Society, so that direct A.C. electricity was available from Gugelman's house using a 200 ft (60 m) extension cord. For this reason, according to Shesta, et al., "the [spring-wound] clock of the old stand [perhaps from Stand No. 1] was replaced by an electric one especially constructed for the purpose, having two hands[,] one revolving once in ten seconds and the other in 100 seconds."[28]

Figure 15–7: Use of ARS Test Stand No. 2 at New Rochelle, New York, 10 December 1938, for testing the rocket motor of Hugh F. Pierce. From left to right: Picrce, unknown, Louis Goodman, and unknown. Credit: Smithsonian photo 9A07480.

This second series also turned out to be historic, as it marked the first time Wyld's regeneratively-cooled rocket motor was tested. Altogether, three motors were tried, all using LOX and alcohol. The first was Pierce's, modified since it was first fired in the 22 October test. The second was Wyld's, but "When ignited," according to the report, "a very large, diffuse sparkling, yellow flame was produced, but no reaction [thrust], showing that the combustion had failed to work back inside the motor from the fuse."[29]

It was therefore decided to give it a second chance later that day, after the next test on another regenerative tubular motor, submitted by Robert C. Truax, then a young midshipman studying at the Naval College at Annapolis, Maryland, who had begun his own experiments earlier in the year. However, in the ARS test, Truax's motor burned out. In the fourth test, the Wyld motor was tried again. This time, a thrust of 90 lb (40 kg) was reached and was "steadily maintained for about 13½ seconds..." until the "loxygen" (LOX) gave out. (Interestingly, at this point, Shesta yelled out "Water! Water," but the Stand's water flushing system, which then existed, had broken down. This is, however, confusing, as Wyld reported the next day that he himself had "vented the [propellant] tanks and turned on the water...".) In any event and more importantly, after the run "Examination of the motor showed that it was in good condition except for some melting and erosion of the head and liner..." In short, the Wyld regenerative motor design worked although it was seen that some parts needed to be made of more heat resistant materials. The resulting performance, including its maximum exhaust velocity of 6,870 ft/sec (2,094 m/sec) and thermal efficiency of 40% "represents a great advance on those obtained in former tests, and are among the highest ever recorded. The fact that they were reached without severe damage to the motor is especially encouraging and definitely proved the feasibility of the regenerative method of cooling", according to the report.[30]

The report further noted that: "A special recording camera is being constructed, using 35 mm film, since it ... proved difficult to read the 16 mm motion pictures separately." Also, "Certain parts of the Wyld motor, originally of aluminum, are being replaced by Monel, to resist the heat better."[31]

Despite the great promise of Wyld's motor and the general workability of the new Stand, it was not until a year and a half later, on 8 June 1941 in a "secluded valley outside Midvale, New Jersey," that the Stand and the motor were tried again. The delay, on Wyld's part, was due to his obtaining jobs in other cities, as well as not having his own workshop in which to continue work on the motor. We may also speculate that, rather than risk further damage to the Stand in being transported by the unsatisfactory cart, it took time for the members to build a new cart and to retrieve the Stand. Furthermore, the caption of a photo of Stand No. 2 in the April 1940 *Astronautics*, reads, in part, the Stand was "...soon to be modified for larger motors and longer runs" although no details are offered.[32]

By the 8 June 1941 tests, the Wyld motor was slightly modified with more heat resistant components, but otherwise retained its basic regeneratively-cooled configuration. It was one of two motors tested this day. The other was designed and built by Nathan Carver and Charles Piecewiez. (It was similar to ones made by Carver for the Greenwood Lake rocket mail flights of 23 February 1936, in which two small, unmanned rocket planes were fitted with mail in an experiment to send the planes in separate flights from the New York shore of Greenwood

Lake to Hewitt, New Jersey. However, only one plane, in an erratic flight, barely made it across the state line. That experiment was a minor, if colorful event in the early history of rocketry in the U.S. but had no connection with the ARS.)[33]

After a "practice run" in the 8 June series, Wyld's motor made its first official test. But instead of LOX (due to a shortage of oxygen), it used liquid air with alcohol. According to the report: "There occurred a series of chugging sounds and the fluctuations were visible in the exhaust flame. [But] ... this seemed to have little effect on the thrust intensity which hovered between 80 and 85 lb [36.2–38.5 kg] for the better part of the 26 second run." Overall, it was another great success for the Wyld motor and an exceptionally long run. After the test, "Examination of the motor revealed no damage to its internal parts."[34]

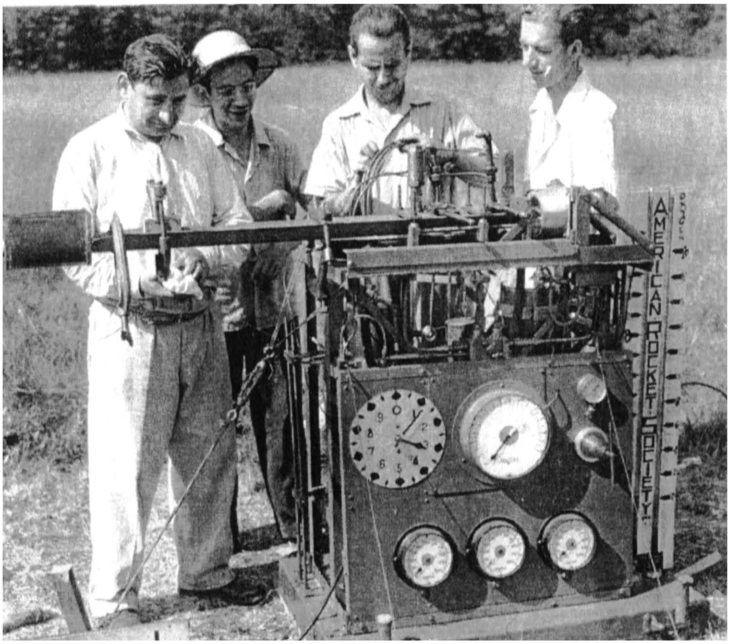


Figure 15–8: ARS Test Stand No. 2 at rocket tests of 22 June 1941 at Midvale, New Jersey. Note the repainted front and temporary addition of the extension of the rocket motor cradle, to accommodate a larger motor. Left to right are: Louis Goodman, unknown, Hugh F. Pierce and Kurt Fischer of the Westchester Rocket Club, the second affiliate of the ARS after the Yale Rocket Club. Credit: Smithsonian photo 87-1628.

On 22 June, the Stand was again taken to Midvale. This time, Wyld's motor was not tested. Rather, a refractory-lined motor of Alfred Africano, a small water-cooled motor, and a motor of Robertson Youngquist, a Massachusetts Institute of Technology (MIT) student and member of the newly formed M.I.T.

Rocket Club, were tried. Unfortunately, Youngquist's motor exploded at the end of its run, although prior to that moment, its brief, initial smooth running produced the now "classic" photo of ARS Test Stand No. 2 in action (Figure 15–9). In the case of Africano's motor, it was longer than usual and it appears from photos that an extension of the V-shaped trough to accommodate it was simply bolted on. This refractory-lined (heat-resistant) motor reached an estimated thrust of over 260 lb (118 kg)—then considered an ARS record—while another record of 48 seconds was achieved with the water-cooled motor. "The exact peak reaction [thrust] of this test [of the Africano motor] will never be known due to the limitation of the gauge," reads the report, "but it can safely be said that it exceeded 260 lb [118 kg] for about two seconds." That is, the pointer on the thrust dial reached the stop pin at 200 lb (or 90 kg), but the motor kept running and the maximum thrust was estimated. After the tests, says the report, the "reaction" gauge was "taken to the shop for overhauling" and "A new thrust gauge calibrated to 500 lb [226.8 kg] will shortly be installed on the test stand." This never came to be.[35]

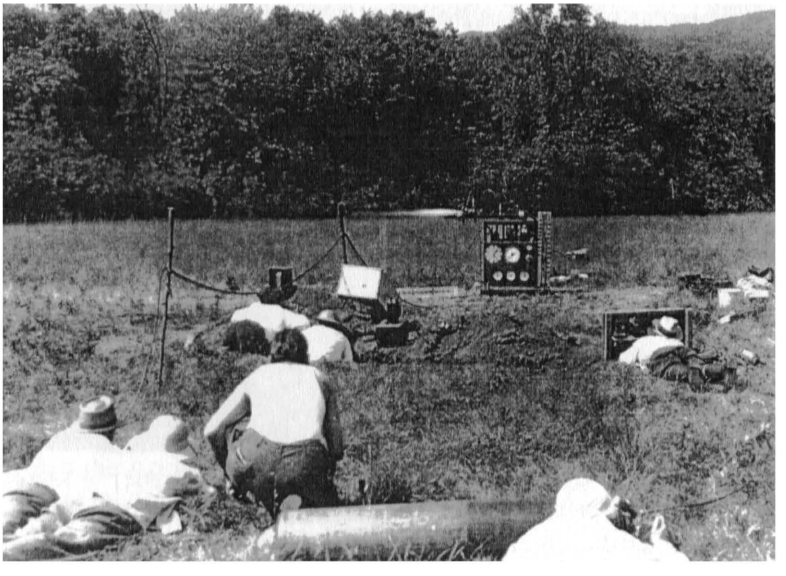


Figure 15–9: "Classic" view of Test Stand No. 2 in tests at Midvale on 22 June 1941. At front is the gaseous nitrogen tank to pressurize fuel into the motors. The motor tested was by Robertson Youngquist. But seconds later, it exploded, probably from overheating. Inadequate cooling was a major problem facing the experimenters. Credit: Smithsonian photo 75-11488.

On 1 August 1941, the Wyld motor was subject to yet three more tests, also at Midvale. The motor succeeded in all tests, in which the last one, "with a leaner mixture than previously used, lasted the surprising time of 45 seconds" while the thrust reached, at times, 135 lb (61 kg). There was no question now that the little Wyld motor and its reliable regenerative cooling was the breakthrough the experimenters had been seeking. It also turned out that these were the last known ARS tests on Test Stand No. 2.[36]

RMI Phase of the History of ARS Test Stand No. 2

On 18 December 1941, soon after the bombing of Pearl Harbor and the entry of the U.S. into World War II, Wyld, with Shesta, Pierce, and Lovell Lawrence, Jr., formed Reaction Motors, Inc. (RMI) for the sole purpose of developing liquid-fuel rocket motors for the U.S. military, based upon the Wyld regenerative principle. RMI thus became the first U.S. commercial liquid-fuel rocket company. Aerojet-General was founded four months later, on 19 March 1942. Together, these events marked the emergence of professional rocket engineering in the United States, in which the ARS Test Stand played a major part.[37]

Figure 15–10: Wyld's regeneratively-cooled motor, tested on Stand No 2 in 1938 and 1941, proved the efficacy of his technique. This led Wyld and three other ARS members—John Shesta, Hugh F. Pierce, and Lovell Lawrence, Jr.—to form Reaction Motors, Inc. (RMI) in December 1941, the U.S.'s first liquid-propellant rocket company. The ARS subsequently loaned the Stand to RMI for their first experiments. Credit: Smithsonian photo 78-12176.

RMI's first and main customer throughout its life until 1972, was the U.S. Navy. For the war, the Navy was primarily interested in the development of

JATO (Jet-Assisted-Take-Off) rockets up to 1,000 lb (453 kg) thrust, later increased to 3,000 lb (1,360 kg), for helping lift heavily-loaded seaplanes for the Pacific Theater campaigns, using islands with short runways. The first Navy contract to RMI stipulated that they first make a duplicate of Wyld's motor (known as Wyld motor serial No. 2), but burning LOX/gasoline rather than LOX/alcohol, and reliably produce a thrust of 100 lb (45 kg) over repeated runs. RMI was then to proceed with developing motors of much larger thrusts.[38]

Since RMI now served the benefit of national defense, and the ARS had ceased their experiments, the Board of Directors of the ARS voted, on 16 April 1942, to loan the Stand to RMI for their initial tests. Unfortunately, this phase is not well documented but it is clear from captioned and dated RMI photos that it was used up to at least September 1942, for not only proving Wyld's Serial No. 2 motor but also comparably sized follow-on motors, until RMI constructed its own larger, more sophisticated concrete-based test stands. House estimated that the Serial No. 2 motor was run by RMI as many as fifty times.[39] ARS Test Stand No. 2, with some RMI modifications, is thus the earliest known extant rocket performance measuring instrument used by a U.S. commercial liquid fuel rocket company.

Figure 15–11: RMI modified the Stand and continued using it to about September 1942. Shown here in a test of May 1942 of Wyld Motor Serial No. 2 are left to right: unidentified, John Shesta, and Lovell Lawrence. Note also, the new thrust dial (large dial in middle). Credit: Smithsonian photo 9A08129.

Through RMI photos in the NASM collections, we also know that Test Stand No. 2 led directly to what we may call RMI's Interim Test Stand of 300 lb (136 kg) thrust capacity by September 1942. This stand was either newly created, or a modified version of Stand No. 2; it looks similar and was portable. At the same time, RMI proceeded with designing and constructing a non-portable, permanent concrete and steel stand for larger thrusts. Interestingly, photos and existing films of RMI's larger stands further show that some features from their direct predecessor, Test Stand No. 2, were incorporated directly into RMI's follow-on stands, notably the vertically mounted glass tubes to show the propellant levels. Ultimately, RMI made its own giant pioneering milestones in aerospace history, notably the post-war development of the 6000C-4 rocket engine used in the Bell X-1 that became the first plane to fly faster than the speed of sound, in 1947.[40]

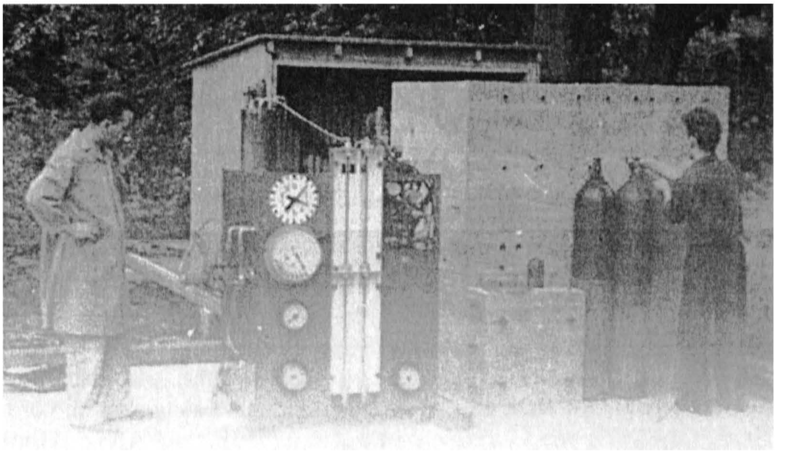


Figure 15–12: By September 1942, RMI modified the Stand, or built a new one, with equipment from Test Stand No. 2, for measuring thrusts up to 300 lb (136 kg). Here is a test of motor M15-G1, near RMI's plant at Pompton Plains, New Jersey. Credit: Smithsonian photo 9A07588.

In 1953, the Stand was donated outright to RMI by the ARS. According to Pendray, it was later one of the principal artifacts in "RMI's [own] historical museum."[41] Then, it was donated to the NASM and formally presented on 16 March 1967. In 1976, the Stand was placed on exhibit in the new National Air and Space Museum building, then was later removed from display in 2007. Recently, it was placed back on exhibit, in the "Pioneers of Flight" gallery which opened on 30 August 2010, fitted with a mockup of the Wyld motor.

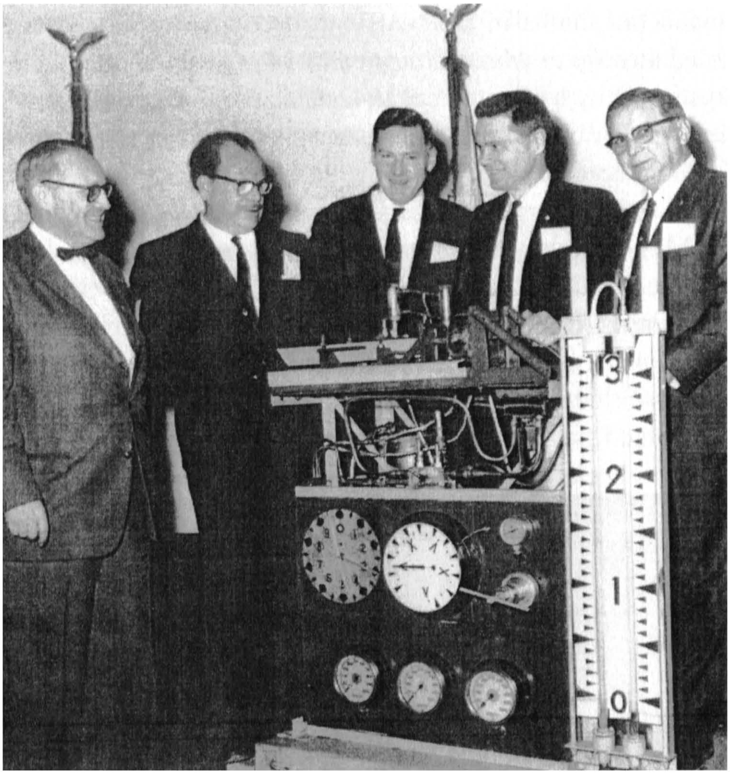


Figure 15–13: Presentation of Stand No. 2 to the NASM, 16 March 1967, by the Reaction Motors Division, Thiokol Chemical Corp. Left to right: Lovell Lawrence, Jr. (former President, RMI); Roy Healy, early ARS member who made test reports following early ARS tests with the Stand; Robertson Youngquist, motor tested on the Stand (1941); Robert C. Truax, motor tested (1938); and Alfred Africano, motor tested (1941). Credit: Smithsonian photo 82-14788.

Description of Existing ARS Test Stand No. 2

Overall

Test Stand No. 2 is a rectangular steel frame structure, mainly painted battleship gray. On one side (the "front," as was viewed by the ARS rocket experimenters crouched down at a safe distance) are the gauges, mounted on three adjoining steel plates bolted to the bottom of the frame and painted a flat, dark red.

There is literally a story behind the red paint, which was not the original finish of the Stand when it was first made, as mentioned earlier. Among the photos taken by Wyld in 1938 is a frontal view (Figure 15–4) showing the original dials, but these were mounted on steel plates with a mottled or "engine turning" finish. This kind of finish, usually done with a machine called a "rose engine" or "decoration lathe," most notably appears on the cowling of Lindbergh's famous Spirit of St. Louis airplane and was very popular in the 1920s and 1930s for aesthetic appearances only. However, in photos of Test Stand No. 2 taken in the 1941 tests, the engine turning finish has disappeared and the finish is, instead, of a flat dark, solid color, although these are black and white photos. But from an existing 1941 color movie of the Stand, apparently taken by Africano, and in the NASM collections, the Stand definitely shows up as red.

Hence, the ARS Experimental Committee most likely believed that the original "engine turning" finish gave the Stand a very attractive appearance but it was quickly found, during the real operations of the Stand, to be very troublesome to the eyesight, especially when looking at the dials from 50 feet (15 m) away. It may have also reflected sunlight, confusing viewers. The swirling pattern was thus soon substituted for the flat, hand-painted deep red that enhanced the appearance of the dials and made the Stand easier to look at from a distance. The change was probably made between early 1940 and mid-June of 1941.[42]

Today, upon close examination of the Stand, there are small areas of chipped-off paint, near the No. 5 pointer mark on the timing clock dial and elsewhere, that reveal evidence of the original swirling pattern underneath the present red paint. Therefore, the red paint applied over the original swirling finish was the most practical and economic way for the ARS experimenters to change the appearance of the plates.

Top

On the top of the Stand is a short V-shaped steel sliding trough, also called the "carriage." This is where the test motor was placed. The trough slides towards the right side on four roller skate wheels over grooved steel runners underneath each side of the trough. The motor was secured on the trough by two hold-down clamps as well as C-clamps. At the front end of the trough is bolted down an upright steel square plate, with a vertically cut groove with adjustable bolt in the middle. They are also for fitting in the rocket motor. At the end of the bolt is a protruding shaft tapered down to a blunt point. This point faces, but does not touch, the middle of a Sylphon bellows, although during the operation of the Stand, it did touch the bellows. During runs, when the thrust of the motor caused it to move forward, the point pressed on the bellows while the oil pressure within the bellows was transmitted by a copper tube (now broken off) to the "reaction" measuring gauge, or thrust gauge, on the bottom of the Stand. The Sylphon bellows on the Stand appears as a horizontally placed copper cylinder cut to form an open can-like fixture, with a recessed smaller open can nestled within a larger can; the smaller can is able to move freely within the larger one. Each motor had its own ignition system and therefore there is therefore no provision made on the Stand for ignition, which was usually an internal spark plug, or electrical hot wires, or electric squibs. Likewise, it was up to each motor designer to accommodate the feed-in pipe into the combustion chamber to read combustion chamber pressure; normally, the middle 500 psi (35.15 kg/cm^2) pressure dial was used. It had previously been used for the original water quenching system, which was later discarded, as mentioned above.

Front, Right Side, Vertical Gauges

On the front right of the Stand is a pair of almost identical vertically mounted steel gauges with hand-painted horizontal black scale marks, each in the form of a horizontal Greek letter Delta pointing towards the middle, between the two gauges. Between the gauges are painted, at equi-distances, reading from bottom to top, the numbers 0, 1, 2, and 3 in large format for ease in sighting by the experimenters at a distance. Running adjacent along the entire length of each vertical gauge is a corresponding glass tube. The purpose of the vertical gauges and tubes was for the experimenters to visually determine the levels of oxidizer (LOX) and fuel within the propellant tanks at the rear of the Stand. The black numbers may signify pints, while the smaller black marks represent divisions of each pint (e.g. 3.2 pints [1.51 liters], etc.) or volume, throughout a test run. Movie cameras (16 mm, and from the 10 December 1938 tests, a 35 mm camera) were used during the test runs and trained on these gauges.

Lower Front, Circular Dials

Mounted to the red plates are a series of six circular dials. The two large ones on top are the clock (at the left) and thrust dial (at the right), respectively. The much smaller dial at the top right shows the nitrogen pressure for forcing in the propellants into the test motor. This gauge, made by the Air Reduction Co., may have been furnished gratis or at reduced cost by the company via their Director of Research, Dr. George V. Slottman, who had donated LOX to the ARS since their earliest experiments. Beneath this gauge dial is a screw valve for regulating nitrogen pressure. The three identical medium-sized dials on the bottom row are commercially-manufactured pressure gauges, made by the Lonergan Co. of Philadelphia, for showing fuel, oxidizer, and chamber pressures.

However, the large thrust dial in the center has a curious arrangement of Roman numerals placed in odd positions, along with smaller Delta-shaped gradation marks. Offhand, it is difficult to interpret how the thrust could be read from this dial. Likewise, upon analysis of available photos of the Stand throughout its history, it is clear that the original dial was different and far simpler to read. (The original also had the word "Reaction" on it.)

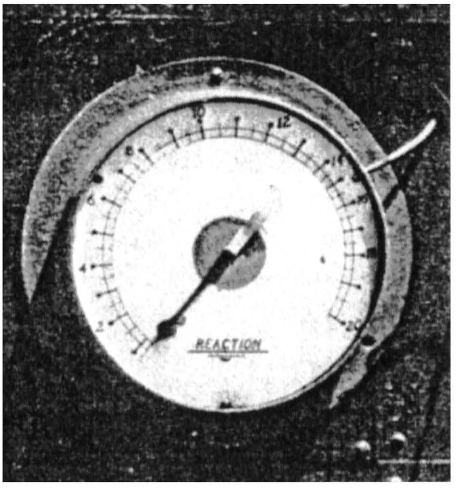


Figure 15–14: Close-up of original thrust, or "Reaction," gauge dial on Stand No. 2 (from Figure 15–4). This gauge was removed by RMI and in 1942 was replaced by a totally different gauge as seen in Figure 15–8. Credit: Close-up, Smithsonian photo 87-16287.

The tentative conclusion of this analysis is that the thrust dial change was made by the last user of the Stand, RMI, and dates to circa 1942. Furthermore, as explained by rocket historian George James, most likely the large, bold, Roman numerals were devised by RMI simply because they could be "read" far more easily in movies of test runs, compared with the standard but very feint Arabic numbers and (pound) unit lines on the previous dial. The Roman numerals were convenient starting or stopping points at any place around the dial.

Propellant Tanks and other Plumbing in Back

In the back of the Stand are two vertically mounted propellant tanks. The larger brass tank on the left, held the oxidizer (LOX). The smaller copper one held the fuel. A much smaller, apparently-copper tank, mounted at the lower left hand corner, may be the "Reserve nitrogen for pilot valve" tank in the schematic drawn by Nick Limber on 25 November 1938. Wyld's September 1938 photos show the water quenching tank in the middle, between the propellant tanks, but it is now not present. There are also pipes, mainly copper, leading from one component to another. These, of course, constitute the "plumbing" of the system which is described in greater detail in the full NASM document on this artifact (Cat. # 1968-0021) but can also be traced in the flow chart (Figure 15–18).

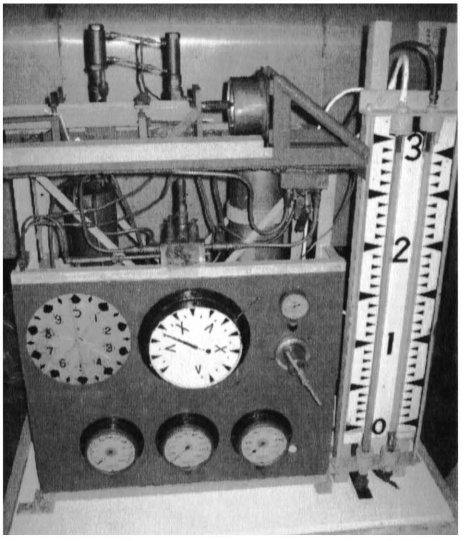


Figure 15–15: Present gauges on ARS Test Stand No. 2, including RMI's addition of a new thrust gauge (large dial at top right), with Roman numerals. The vertical glass scales at the right indicated the volume amount in the fuel and oxidizer tanks in the back of the Stand. Credit: Photo, in Cat. # 1968-0021 file, NASM, courtesy Smithsonian Institution.

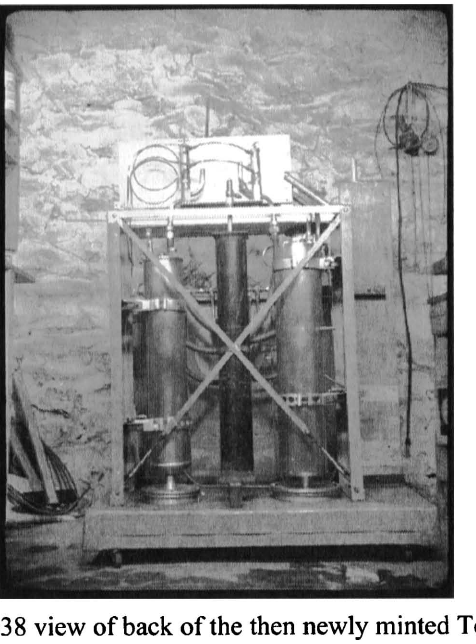


Figure 15–16: Rare 1938 view of back of the then newly minted Test Stand No. 2, taken by James H. Wyld that 13 September. At left is the oxidizer (usually LOX) and at right, the fuel tank. The tank in the middle was part of a built-in "water quenching system" in case of fires, but it was apparently not effective and was soon removed. Credit: Smithsonian photo 9A05167, courtesy Smithsonian Institution.

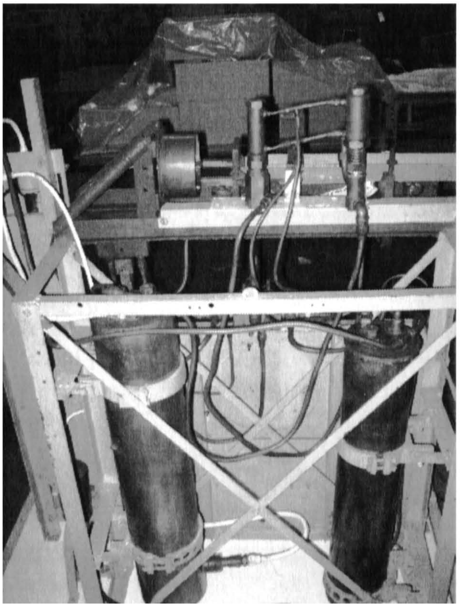
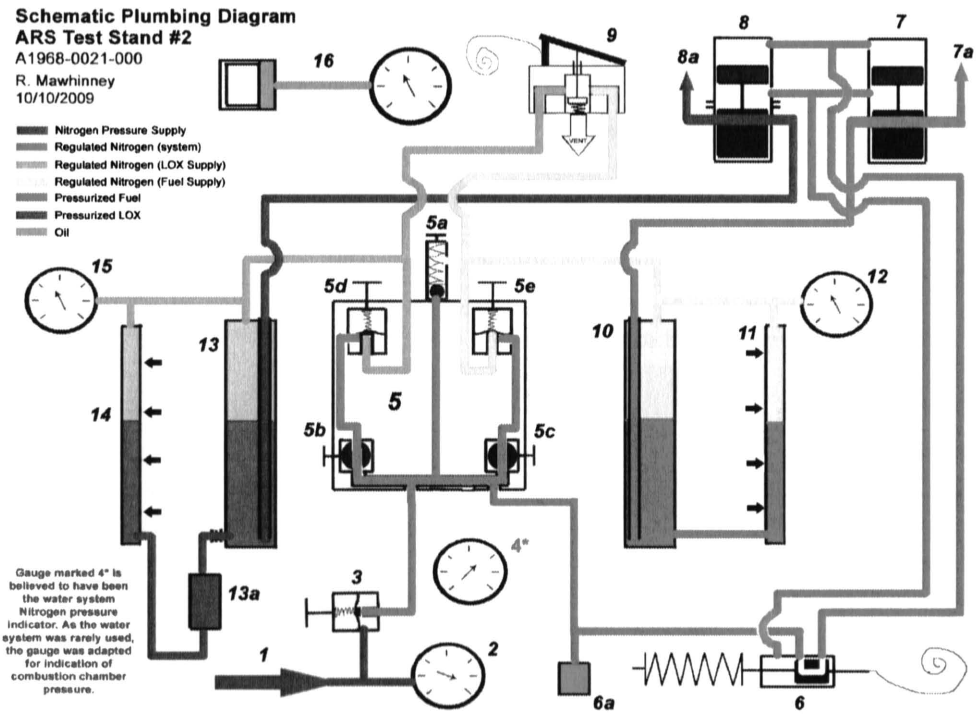


Figure 15–17: Back of Test Stand No. 2 today, showing that the middle tank was long-since removed. Credit: Photo by Gregory Bryant, A19680021 DOC 01, p. 4, NASM, courtesy Smithsonian Institution.

The whole assembly of the Stand is mounted on a flat white painted wooden rectangular base, although this is not the original base. Judging from earlier photos, it was originally on a thicker rectangular wood base to which were screwed on black carrying handles, not found on the present base. The handles made it easier to lift the 300 lb (136 kg) Stand by hand onto its cart, depicted in Figure 15–6.

Operation of the Stand

The operation of the Stand was fairly straightforward. As best as can be determined, it operated as follows. After the Stand was carefully leveled on the ground (possibly with a split level), the test rocket motor was installed and the nitrogen pressures were established. (The motor designer/builder had to agree with the ARS Experimental Committee, probably beforehand, on the desired nitrogen pressures for the fuel system and oxidizer system, as well as the maximum pressure for the entire system. Each system could be adjusted individually using regulators on the Stand.) The fuel and oxidizers were then poured in the tanks and an ignition system installed in the motor. The area was then cleared before the main nitrogen bottle pressurized the Stand's propellant tanks. With the nitrogen system pressurized, the clock was started. On the signal for firing, the pilot valve lanyard was pulled (and tension held) to start fuel and oxidizer flowing to the motor. The ignition system was then activated and ignition would occur, and be sustained, until the pilot valve cord was released at the end of the test run. Upon the completion of the test, the main nitrogen bottle was shut off and a second lanyard attached to the Stand's nitrogen system dump valve was pulled. This valve vented all the Stand's nitrogen pressure into the atmosphere, making the approach to the Stand as safe as possible.



Key to ARS Test Stand No. 2: 1. Nitrogen supply from bottle; 2. Nitrogen supply pressure gauge; 3. Nitrogen supply regulator; 4. Originally indicator for water system nitrogen pressure; later adapted for use as combustion chamber pressure indication; 5. Nitrogen control valve assembly; 5a. Pressure relief valve; 5b. LOX system nitrogen shutoff valve; 5c. Fuel system nitrogen shutoff valve; 5d. LOX system nitrogen regulator; 5e. Fuel system nitrogen regulator; 6. Pilot valve; 6a. Pilot valve nitrogen reservoir; 7. "Fast acting" valve for fuel; 7a. Fuel outlet from fast acting valve; 8. "Fast acting" valve for LOX; 8a. LOX outlet from fast acting valve; 9. Nitrogen system dump valve; 10. Fuel tank; 11. Fuel level sight tube; 12. Fuel system nitrogen pressure gauge 13. LOX tank; 13a. Unknown canister; 14. LOX level sight tube; 15. LOX system nitrogen pressure gauge; 16. Thrust measuring system.

Figure 15–18: Schematic diagram of present Test Stand No. 2, drawn by Robert Mawwhinney, Museum Specialist, NASM. Credit: Courtesy, Robert Mawhinney, Smithsonian Institution.

Comparative Test Stands, 1920s–circa 1940

At this point, it is very useful to briefly survey and compare other liquid fuel rocket test stands of the period in the U.S. to those of the ARS to more precisely determine the level of technology, efficiency, sophistication, and craftsmanship vis-à-vis these contemporary stands. However, the stands of Goddard and the GALCIT (Guggenheim Aeronautical Laboratory, California Institute of Technology) group were in a class by themselves, in that they were built by technically trained people: Goddard was a physicist, if not an engineer, while the GLACIT members were largely Ph.D. Engineering candidates. Moreover, Goddard and GALCIT were far better funded and/or had access to superior mechanical, electronic, or chemical equipment or supplies compared with other experimenters in this survey.

In this broad sense, considering that the 1930s were the embryonic years of modern U.S. rocket technology, Goddard and GALCIT may roughly be classed as "semi-professional," whereas the other groups and individuals, were in the "amateur" class. That said, Goddard had perhaps built the world's first liquid fuel rocket test stand far earlier, in the early 1920s, although its existence was unknown outside of his small circle of assistants. His stands evolved over the years although none are known to be extant.

By 1935, the same year the crude ARS Test Stand No. 1 appeared, Goddard's stand had some eight dials on it, including readings for fuel flows and temperatures besides voltmeters, galvanometers, and a built-in stopwatch; he also had thermocouples.[43] Malina mentions that when he visited Goddard in 1936, he then had "a 2,000 lb [907 kg] thrust static test stand" although he was not permitted to see it. Hence, during the 1930s to early 40s, Goddard's test stands were by far the most technologically sophisticated in the U.S.[44]

Harry W. Bull of Syracuse, New York, was perhaps the earliest U.S. "amateur" liquid fuel rocket experimenter. During 1928–1932, he conducted both solid and liquid fuel experiments with static test stands. At first, he had an "...apparatus for testing the recoil of different combinations of gases... Rolls of paper which were moved by clockwork recorded the duration and strength of the recoil. An electrical clutch permitted the apparatus to be operated from the next floor." By 1930 he tested vaporized gasoline and air, the thrusts measured on a simple spring scale.[45]

His main liquid fuel work dates from 1931. He made his own "recoil indicators," while the motor moved on roller bearings. Interestingly, Bull's stand was surrounded by a large tube, or "safety enclosure," mounted on tripod legs. Thrusts were registered on a spring scale, although the motors averaged thrusts of only two pounds (0.9 kg). Bull's stands were therefore modest but remarkable for the period.[46]

Independently, Lester D. Woodford of Ohio State University also conducted liquid fuel rocket experiments, from circa 1929, evidently using his own test stand, near Columbus, Ohio. But his records were apparently lost or destroyed and almost no details are known except that his motors reached thrusts of only about 10 lb (4.5 kg).[47]

From 1929–1932, Cleve F. Shaffer carried out private experiments with liquid propellant rocket motors at the U.S. Army's Marin County Reservation near San Francisco. He "tried both liquid and gaseous oxygen with gasoline, alcohol, butane, acetylene in many combinations of pressure, size...etc. ..." However, he concluded the data "was not sufficiently conclusive to publish as [a] scientific memoranda due to the rather rough apparatus for measurement." Thus, here too we may never know the details of his experiments, although in 1961 he donated to the NASM one of his motors, plus a standard spring fish scale used to record the thrusts (Cat. #s. 1961-0231 and 1961-0232, respectively). Judging that the motor is very large for the period (weighing 40 lb or 18 kg), but very basic in design, plus the accompanying fish scale of 400 lb (181 kg) capacity, Shaffer's test stand must have indeed been "rough," or rudimentary. (The thrusts of his motors were probably considerably less than that.) We have, at least, a partial photo of his stand of circa 1932, published in the 16 December 1957 issue of the *San Francisco Examiner* that shows a similar motor mounted horizontally but with only one dial in sight, although there may have been more.[48]

The GALCIT Rocket Research Project undertook gaseous and liquid fuel experimentation with a portable test stand from 1936. But this is well documented and we need not go into details except that it was fairly sophisticated for the time (but not as far along as Goddard's).[49]

In 1933, Ernst Loebell founded the Cleveland Rocket Society (CRS) and began liquid fuel rocketry experiments in 1934 at a "Proving Field Laboratory" at Kirtland, near Cleveland. It was not portable, but a multiple pipe structure 12 feet (3.6 m) high. However, it had a limited number of gauges, and a spring scale anchored in the concrete below. Thrusts were apparently less than 30 lb (13.6 kg), but even binoculars on hand were hardly powerful enough to permit the observers to adequately read the thrust scale. In fact, Tasher says the CRS "never managed to record any numerical data on combustion-chamber pressure or temperature, exhaust velocity, or thrust. The results of the CRS tests were really [only] determined by visual means... ."[50]

We know from photos in the NASM that, from about 1935 or 1936, ARS member Nathan Carver built his own amateur test stand, which he tried on the roof of his New York City home, although the details are unknown. In addition, he allegedly borrowed ARS Test Stand No. 1 for some of his experiments, although the latter was not recorded in *Astronautics*.

Finally, from 1936–1937, then Midshipman Robert C. Truax began building and testing liquid fuel rockets at the Navy's Experiment Station near Annapolis, Maryland. His first stand utilized Bourdon tube pressure gauges, an Eastman Kodak (photographic) timer, and a "stock-room [i.e., postal] scale" for recording thrusts: it was thus limited in capacity. He also noted that measurements were "undoubtedly highly inaccurate" and "...it was not accuracy, but the principle of the thing that counted at this stage of the game." Thrusts were around 10 lb (4.5 kg). Truax continued his tests which saw improvements in both his motors and stands.[51]

By 1938, he reconstructed his motor and "apparatus" "for accurate determination of fuel consumption, thrust, and consequently thermal efficiency." It had a "hydraulic weighing system, ignition circuit, combustion, chamber, valves, piping, and ... gauges ... to measure supply air pressure, air feed pressure, gasoline consumption, and time." Thus, his stand was comparable to ARS Test Stand No. 2, although his thrust capacity was much less.[52]

Less is known, as we saw, of the stands of Woodford, Shaffer, and Carver, but they were probably similar to the earlier, more basic ARS Test Stand No. 1. Hence, in the amateur category, ARS Test Stand No. 2 probably ranked first. It was smaller and portable compared with the giant fixed CRS stand. Yet, it had greater thrust capacity and was more efficient, with the experimenters able to observe and record the thrusts on film, both with motion picture and still cameras.

Conclusion

ARS Test Stand No. 2 is the largest and most significant extant artifact representing private rocket experimentation in the U.S. from the 1930s and 1940s, outside those of Goddard: it was the main focus of ARS activities of the time; it repeatedly proved the effectiveness of Wyld's breakthrough regeneratively-cooled motor; it played a key role in the start of professional rocket engineering in the U.S. in leading to the formation of Reaction Motors, Inc.; it is the earliest known testing device used by that company, with features incorporated into follow-up rocket stands, and therefore played a role in the evolution of commercial rocket test stands in the U.S.; and, it is an excellent gauge of the state-of-the-art of rocket technology in comparing the different experimenters of the period. From a broader perspective, the ARS Stand No. 2 also helps "humanize" the history of early U.S. rocket technology—in the ingenuity of its hand-made construction and the challenges faced by the early experimenters, some of whom (Shesta, Wyld, Africano, Youngquist, Truax, et al.) became amongst the first "professional" U.S. rocket engineers from World War II.

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[13] Louis Goodman Papers [includes notes, mailing cards of the American Rocket Society, ca. 1932–1939], Archives of American Art, Smithsonian Institution, Washington, DC, Microfilm number AAA 3690, p. 171; John Shesta, H. Franklin Pierce, and James H. Wyld, "Report on the 1938 Rocket Motor Tests," *Astronautics*, No. 42 (February 1939): p. 2.

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[21] Shesta, Pierce, and Wyld, "Report on the 1938 Rocket Motor Tests," front cover.

[22] Phone interview, Nick (Nicholas J.) Limber with Frank H. Winter, 6 December 2009; letter, Nick (Nicholas J.) Limber to Frank H. Winter, 5 December 2010. Thanks to the courtesy of my longtime friend, George James, it is now learned that Nick Limber passed away at his home at Palos Verdes Estates, California, on 19 August 2013.

[23] Letter, Shesta to Winter, 30 January 1978.

[24] Phone interview, Limber with Winter; letter, Limber to Winter; Shesta, Pierce, and Wyld, "Report on the 1938 Rocket Motor Tests," 3; "Pioneer Work with Rockets," *Scientific American*, Vol. 154, p. 89.

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