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Chapter 19

ROBERT H. GODDARD: ACCOMPLISHMENTS OF THE ROSWELL YEARS, 1930-1941*

Frederick C. Durant, III†

FOREWORD

It was my intention in this paper to go beyond the accomplishments and technical details of Dr. Goddard's work at Roswell, New Mexico. I'd planned to tell something of the personalities involved; to relate something of the many facets of this remarkable man--his love of painting, music, his quiet humor and love of nature. On performing detailed research, however, the magnitude of the effort, perseverance, invention and achievement of Goddard and his team, seemed the most important story to detail in this summary of his work at Roswell.

I am most grateful to Mrs. Robert H. Goddard. She generously assisted in comment on details and in providing archival photographs and motion pictures (shown during the presentation at the 7th History Symposium). It might be mentioned that Mrs. Goddard became an accomplished photographer in the course of taking hundreds of feet of motion pictures of her late husband's rockets tests. That such a remarkably detailed record of Dr. Goddard's research, inventions and tests was so carefully preserved since his death is a tribute to the care, judgment and dedication of his wife, Esther C. Goddard.

INTRODUCTION

Robert H. Goddard, while Professor of Physics at Clark University (Figure 1), conducted his early research on rocket propulsion at or near Worcester, Massachusetts. During the period 1917-1929 his research and test work was sponsored primarily by the Smithsonian Institution, Washington, D.C. The purpose of this research was to develop a rocket to carry meteorological instruments to altitudes above those achieved by balloons.

Four flights of liquid-propellant rockets were made near Worcester, 16 March and 3 April, 1926; 26 December, 1928 and 17 July, 1929. This fourth rocket launch-

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ing attracted much unsought public attention. Shortly thereafter, banker-financier Harry Guggenheim and Charles A. Lindbergh, the aviator, learned of Dr. Goddard in a newspaper account. Lindbergh had for some time been personally interested in the potential of rocket power for high-speed, high-altitude propulsion of aircraft and for emergency power in event of engine failure.

Figure 1 Dr. Robert Hutchings Goddard (1882-1945). NASA Photo No. 74-H-1250

At the urging of Guggenheim, Lindbergh discreetly checked on Goddard, told him of the much greater progress which could be made if full-time work were possible at a remote location. A proposal for a research program was requested and approved by a distinguished advisory committee, and a leave of absence was obtained from Clark University. In June 1930, Daniel Guggenheim, Harry's father, provided a grant of $25,000 of personal funds per year for two years with provision for another two years if the advisory committee "considers the results attained warrant further expenditure." Goddard and his wife Esther maintained a meticulous account of the funds which covered all moving costs, construction and materials, staff employment, travel, and a salary for Goddard of $5,000 per year.

A location near the town of Roswell, in east-central New Mexico was selected on the basis of terrain, climate and study of weather records. The Goddards motored to Roswell, arriving 25 July 1930. They were joined shortly after by Henry Sachs, Albert W. Kisk, Laurence C. and Charles W. Mansur, and their wives. Kisk and Sachs were instrument makers, Charles Mansur, a machinist; his brother Laurence, technical assistant. Nils T. Ljungquist, instrument maker, joined the staff the following spring. A large Spanish-style home, called Mescalero Ranch, was rented about three miles from the town of Roswell. Machine tools, equipment and materials arrived from Massachusetts.

Goddard laid out a machine shop of 9.2 m by 18.4 m (30 ft by 60 ft) floor space which was erected at the rear of the ranch house. Some 60 m (200 ft) away a 6 m (20 ft) tower was erected for small static firing tests. An 18 m (60 ft) launching tower was erected about 24 km (15 mi) away for flight tests. Observation and control shelters were built at distances of 15 m (50 ft) and 300 m (1000 ft). Orders for high-purity liquid oxygen and nitrogen gas were placed with the Linde Air Products Co. and obtained from Amarillo and El Paso, Texas. Shipment was initially in 15-liter metal dewar flasks. Gasoline fuel was commercial automobile quality and obtained locally. Availability of liquid oxygen was occasionally cause for delays and a problem, particularly in summer when the temperature sometimes soared to 40C (105F).

By the fall of 1930, static tests of liquid oxygen-gasoline motors commenced. Propellants were fed to the combustion chamber by gaseous oxygen generated by passing liquid oxygen around the motor nozzle. A cork float in the fuel (gasoline) tank provided minimal separation of potentially explosive vapors. The combustion chamber and nozzle were constructed of mild steel. A refractory cement coating was used in the vicinity of the propellant injectors in the upper cone section. The rocket motor, with flight-type tankage, was mounted on a spring-loaded test stand. Thrust was measured by a pencil stylus on a rotating paper-covered drum. Ignition was by electrically firing a small powder flare located below the nozzle. Four static firing tests were made in October-November 1930.

An 18-second run was obtained in the fourth test. Propellant supply pressure ranged from 14-17 atm (200-250 psi). Thrust averaged about 45 kg (100 lb). Valves were operated by control cords. Flow rates of fuel and oxidizer orifices were checked and calibrated with water flow.

In December 1930 a 3.4 m (11 ft) long rocket was assembled for flight. The object of the test was to determine if a simple gas-pressure tank might be sufficient for short flight tests. Oxygen gas, at normal temperature and 15.3 atm (225 psi) was used. the fuel, pressure, oxidizer tanks and rocket motor were fixed to longitudinal support rods. A four-fin tail provided aerodynamic stabilization. All tanks were cylindrical with conical ends. For insulation, the cones of the oxygen tank were covered with 1.3 cm (1/2 in.) felt to which was cemented aluminum foil. The cylindrical portion of the tank was enclosed by two halves of similar foil-covered felt. These half-sections were pulled off the tank at launch. A 1.8 m (6 ft) diameter silk parachute was contained in the nose cap. Deployment was actuated by airflow as the rocket descended. To determine if there was axial rotation in flight, one quadrant of the rocket was painted bright red. The rocket weighed 15.2 kg (33 lb) dry and carried about 6 kg (13 lb) of propellants. Static-tested, an attempted launch on 22 December failed when the rocket was pulled off the launcher guide rails.

On 30 December another flight attempt was made with this rocket. On ignition the rocket lifted between the two pipe guides against a stop. This brief motion, shown by coincidence of two white markers and observable by telescope from the control shelter, indicated greater thrust than rocket weight. Two release pins were pulled and the rocket lifted off--the first flight test in New Mexico.

A short white flame and grayish smoke trail were observed. Burning time was about 8.5 sec. A recording telescope, at a distance of 610 m (2000 ft), obtained flight data showing the rocket reached an altitude of 610 m (2000 ft) in seven seconds. The rocket landed about 300 m (1000 ft) from the launch tower. Little, if any, rotation about the longitudinal axis was noted. The parachute opened only partially, resulting in some damage on recovery.

For the next nine months ten static tests were performed on a series of rocket motor designs. Sheet nickel was used to construct cylindrical and spherical combustion chambers and nozzles. Different propellant injection systems at different flow rates and mixture ratios were tried. Refractory cement was used in portions of the combustion chamber and divergent nozzle. As might be expected, there were a number of burn-throughs and one explosion. About 5-6 kg (11-13 lb) oxidizer and 1.4-6.8 kg (3-15 lb) fuel were consumed in each of these tests. Oxidizer-to-fuel ratio varied from .75-4.3. Since operation on one side or the other of stoichiometric ratio resulted in lower combustion chamber temperatures, Goddard tried both oxidizer and fuel- rich mixture ratios.

By May 1931 Goddard had obtained an average thrust of 77 kg (170 lb) during a 19-second run. In this motor design, oxygen entered at the cone-shaped head of the combustion chamber and impinged upon a nickel rotor having eight blades. Fuel entered the chamber near the top of the cylindrical portion of the chamber two tangential orifices. Calculated exhaust jet velocity was 975 m/sec (3200 ft/sec).

On 29 September 1931, a flight was made with this motor. The rocket was fitted with a streamline casing of thin duralumin sheet. the recovery parachute was carried between the propellant tanks. Release was activated by a timing mechanism constructed from a small watch. When the timer contact was closed, a battery-powered explosive bolt freed half of the case surrounding the parachute compartment. A launch-sequence timing system was developed for this rocket. In the previous flight three men had been required to pull on ten cords upon observation and command in order to operate valves, igniter, pressure hose removal, vehicle release, etc. The new system was automatic so that closing a single electric circuit at the 300 m (1000 ft) shelter started a nine-second series of events. A slowly dropping weight in a dashpot of kerosene served for timing of events. Blasting caps caused weights to fall sequentially applying propellant supply pressure, removing hoses and controls and operating releases. The rocket was 3 m (9 ft 11 in) long, 30.5 cm (12 in) diameter. Dry weight was 16.8 kg (37 lb). Propellants were 22.6 kg (50 lb) bringing launch weight to 39.4 kg (87.2 lb) (Figure 2).

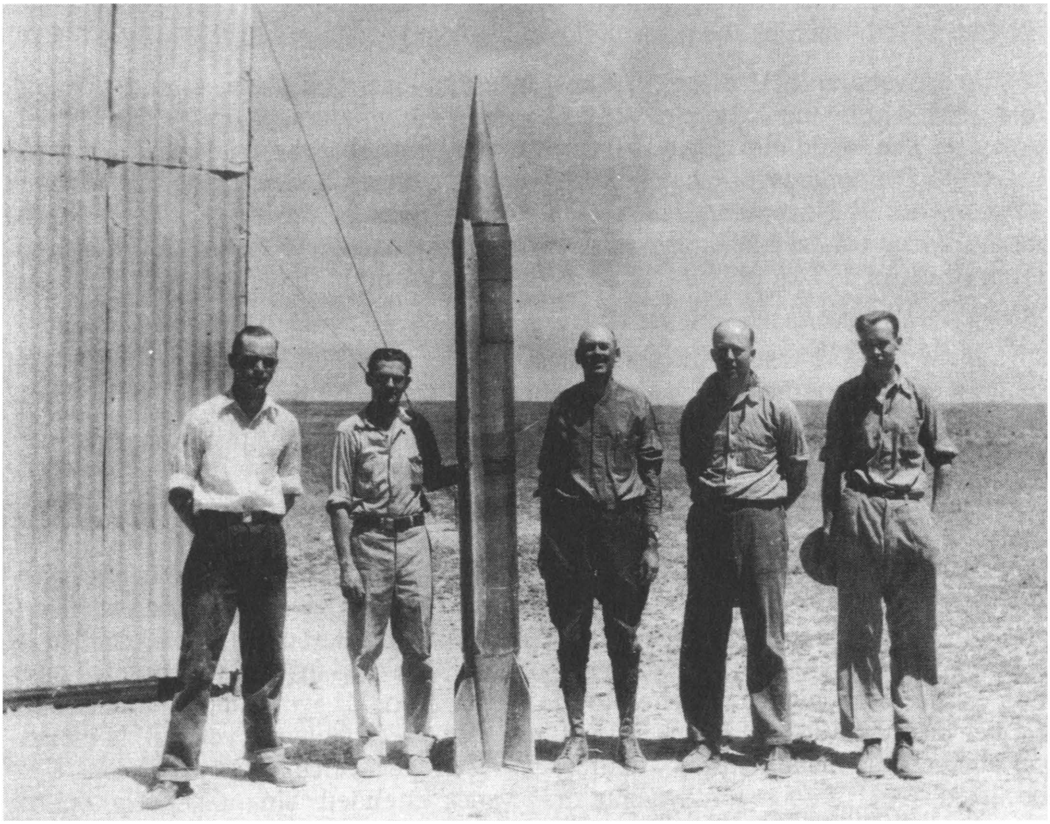

Figure 2 This rocket was used in Dr. Robert H. Goddard's New Mexico test of September 29, 1931. Shown with the rocket is the group that took part in the flight. Left to right are: N. Ljungquist, L. Mansur, Dr. Goddard, A. Kisk, and C. Mansur. NASA Photo No. 74-H-1202.

On this flight the automatic launch system operated flawlessly. The vehicle lifted off smoothly but rose slowly to about 60 m (180 ft) only, losing thrust and descending.

About two weeks later (13 October 1931) another flight was made with a similar rocket but with some changes in injector head and fuel tank design. This time the motor fired for 13 seconds and an observed altitude of 520 m (1700 ft) was reached. At this point the fuel tank exploded.

In three weeks (27 October) another flight was made with changes to fuel injector and a device to close the fuel valve on sufficient fall of supply pressure gas. A gas pressure/time recorder was carried on board to obtain data for post-flight analysis. A metal bellows moved a pencil stylus recording pressure on a rotating disc operated by a watch mechanism. An altitude of 406 m (1330 ft) was reached before the fuel tank exploded once again. The data recorded showed that pressure supply had fallen almost fifty percent. There was clear indication of flash-back into the fuel tank containing the pressurizing oxygen vapor.

In November 1931 a series of new investigations took place. Liquid nitrogen, in a tank within the oxygen tank, was used for nonflammable propellant supply pressure. The liquid nitrogen was flashed to gas by passing through a series of tubes brazed to the combustion chamber. Other design changes were made but a launch attempt, on 18 November, resulted in an explosion of the motor. Later in the month a new oxidizer injector was tested. A 24-second static test achieved a maximum thrust of 123 kg (270 lb) at an oxidizer/fuel ratio of .58. Exhaust velocity was calculated to 1550 m/sec (5090 ft/sec).

Early in 1932 tests were made of a positive displacement bellows pump and bellows engine operated by vaporizing liquid nitrogen. Static test runs of up to 32 seconds and 87.6 kg (193 lb) thrust were obtained on a rocket motor using this pressurizing system.

During February 1932 Goddard and his team of four or five assistants made a major advance in rocket-powered vehicle design. Gyro-stabilization was added. Goddard understood and appreciated the potential capability of a spinning gyroscope as a two-axis table of motion reference. He had been considering their application back in Massachusetts a few years before. Mounted in the rocket with its spin axis along the rocket's longitudinal axis, a gyro would maintain its original position as the rocket tilted. Attached to the inner and outer gyro gimbal mounts were copper brushes. When the rocket was tilted 13 degrees from the vertical an electrical contact was made, closing a battery-powered electric circuit. Two actions then occurred. One of four aerodynamic drag vanes extended. Simultaneously, one of four metal deflector vanes was inserted into the rocket exhaust. Both actions would cause a correction of the flight path of the rocket, returning it to the vertical. Mechanical motion of these vanes was obtained by pneumatic bellows operated from a 3.7 atm (55 psi) gas pressure source, controlled by electromagnetic valves. Gas to operate the bellows was obtained from the high pressure nitrogen through a reducing valve. Dry-cell storage batteries provided electric power.

The gyroscope was mounted at the aft end between the oxidizer tank and the rocket motor. The 10 cm (4 in.) gyro rotor was of brass, mounted on a steel spindle.

A further use of the gyro was to trigger parachute deployment when the rocket tipped to 130 from the vertical. Since center of pressure air resistance of the rocket was below the center of gravity, the rocket would always tip over and head downward after propulsion had ceased and upward velocity reached zero. Just prior to launching, the gyro was spun by four light-weight fish-lines, 112 cm (3 ft 8 in.) long. To each line was attached a 2.3 kg (5 lb) weight. These weights were sufficient to spin the gyro for 6-7 minutes without appreciable loss of velocity.

On 19 April 1932, the gyro-stabilized rocket was ready for flight. It was 3.3 m (10 ft 9 in.) long, 30.5 cm (12 in.) in diameter. Dry weight of the vehicle was 41.5 kg (91 lb).

The firing sequence was automatic. Here, in the words of Goddard's test report, is how it operated:

> . . . . pressing the first key freed the gyro for spinning. When one of the 5-lb weights for spinning the gyro finally dropped, it struck a platform that closed a switch, thus firing the igniter. The heat of the igniter melted a 0.010-in. iron wire, which allowed a weight to drop and close a switch, thus freeing a kerosene dashpot weight, which turned on the gasoline. The final motion of this dashpot weight freed a lever that operated the gas-generating tank, at the same time closing the vent valves on the oxygen and nitrogen tanks, together with a safety valve on the gas-generating tank, which had previously been held open.
>
> Rise of pressure of 205 psi closed an electrical circuit that freed the main releasing lever. This lever served to pull off the pressure hose to the rocket, freed the gyro for turning, removed the control cord to the gasoline valve by which the latter could be shut off in case of a poor start, allowed the doors in the casing to close, and freed the clock of the pressure-timer recorder. It also freed a clockwork timer on the tower, which fired the two explosive links that held the rocket, after a delay of 3.5 seconds, the time required for the (bellows) pump and engine to restore the pressure to 200 psi after the pressure hose had been removed.

The above may seem complicated but the straightforward use of physical principles applied through ingenious devices is impressive.

In this flight test the automatic sequencing started by closing the firing circuit (actually a telegraph key). The rocket ignited and rose smoothly from the tower but only for about 40 m (135 ft). Thrust fell and, still firing, the rocket struck the ground. Immediate inspection showed that the two exhaust deflectors were warm, indicating that the automatic guidance system had operated. It was deduced, however, that in full deflection position, the rocket exhaust was sufficiently blocked to reduce thrust appreciably. This obstruction, moreover, was found to have increased combustion chamber pressure and the upper cone of the chamber was considerably bulged (Figure 3).

A new rocket was constructed with numerous improvements in components, including the gyro control system. On attempting a flight on 20 May 1932, however, the motor burned through before launch.

A progress report on the first two years of the Guggenheim-supported research at Roswell was reviewed by the scientific advisory committee, which unanimously recommended continuation of the program for another two years. Daniel Guggenheim, however, had died earlier, in October 1930. Moreover, the United States--and the world--was in the throes of an economic depression. Harry Guggenheim and Mrs. Daniel Guggenheim decided, reluctantly, that they could not finance further research at that time; perhaps later. This was in May 1932.

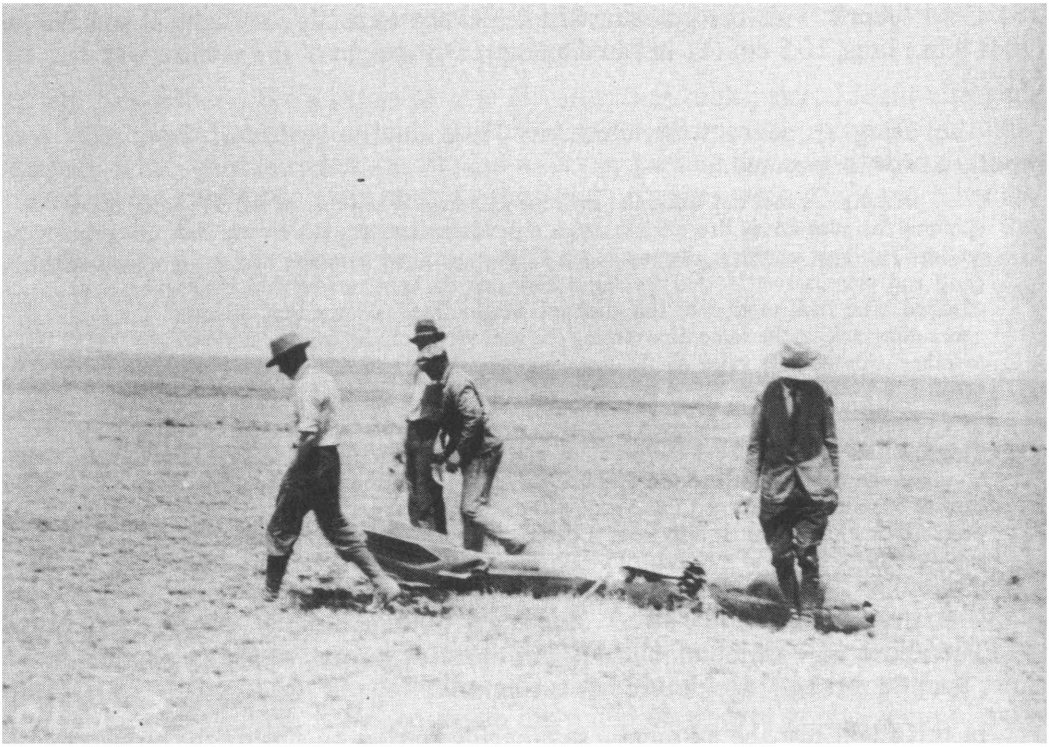

Figure 3 Dr. Robert H. Goddard's rocket after flight, April 19, 1932. Left to right are: N. T. Ljungquist, C. Mansur, A. Kisk, and Dr. Goddard. NASA Photo No. 74-H-1204.

During the next two months the shop and test facilities at Roswell were "mothballed." Many parts were scrapped and buried. Crates were packed and the Goddards returned to Worcester. Resuming his post as head of the Physics Department at Clark University, Goddard taught and carried on small-scale research, aided by a small sum from the Smithsonian Institution. Among his investigations were:

> .... comparisons of various heat insulators, an exploration of better ways to make strong bolted joints, studies of methods of making welded joints without affecting the strength of heat-treated metal, methods of balancing gyroscopes, improvements in bellows-type pumps, preliminary investigation of centrifugal and other pumps for rocket propellants and engines for driving them....

In the summer of 1934, the Daniel and Florence Guggenheim Foundation, headed by Harry Guggenheim as President, resumed financial sponsorship of Goddard's research. The Goddards, together with Ljungquist, Kisk, and C. W. Mansur returned to Roswell, New Mexico, in September.

Work began on a large, light-weight, gyro-stabilized model. Initial flight tests, however, were conducted with a small 23 cm (9 in.) diameter, A-Series, model with stored nitrogen gas pressurization. Dry weight of this series of rockets ranged from 26-38.6 kg (58-85 lb); the lengths varied from 4-4.7 m (13.5-15.3 ft). The cylindrical combustion chamber was 14.6 cm (5.8 in.) in diameter. Construction was of thin sheet nickel. This smaller model permitted changes in controls and reconstruction after flights at less time and cost. One change in design applied a pressure gas jet to spin the gyro. Tests A-1 and A-2 did not fire because of gas pressure valve problems. A short parachute-recovered flight was made by A-3 on 16 February 1935.

Three weeks later (8 March 1935), A-4 was launched. A simple pendulum device was tried as a substitute for the more expensive and delicate gyro control. Corrective signals were given at a 10-degree deviation from the vertical. Burning time was 12 seconds and an estimated flight velocity of 1125 km/hr (700 mph) was achieved. A 3 m (10 ft) diameter parachute deployed but was ripped loose because of the high velocity.

On 28 March 1935, A-5 with gyro-control and redesigned jet deflector vanes reached an altitude of 1460 m (4,800 ft) 15.5 seconds after lift-off. Successive correction of flight deviation, back and forth (like a fish swimming), was observed. Further improvements were made in A-6, but in an attempted flight, on 19 April, the rocket motor fired but the release mechanism did not operate, resulting in a static test. On Test A-7 the motor produced insufficient thrust for flight because of low oxidizer tank pressure (Figure 4).

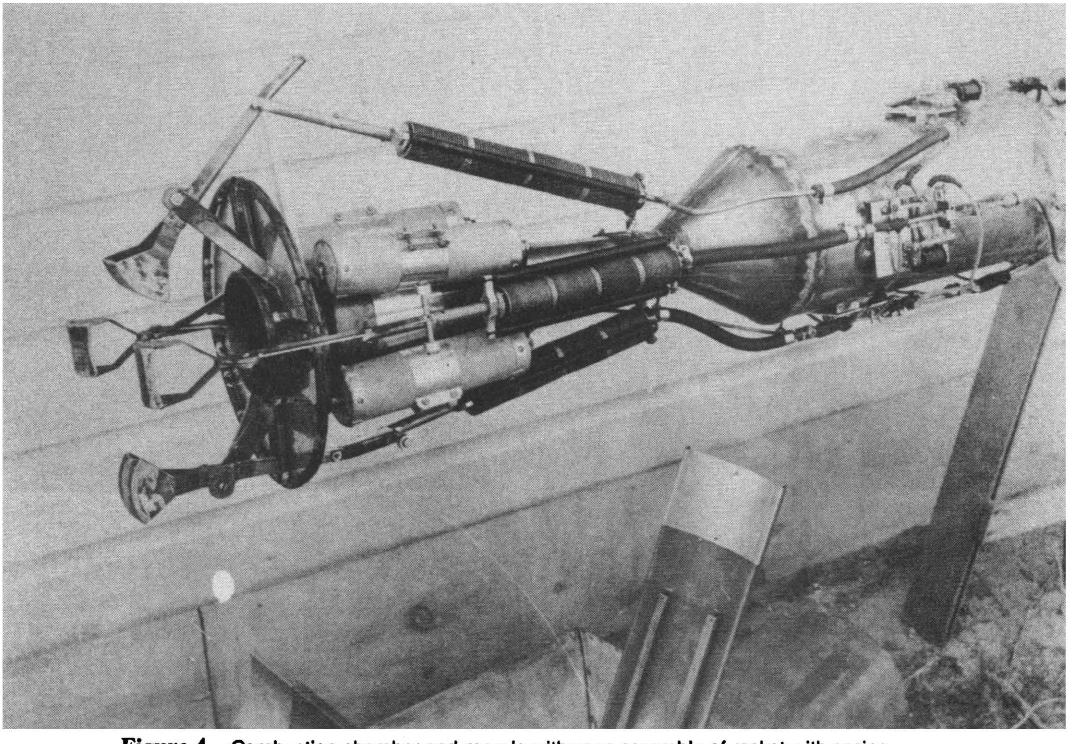

Figure 4 Combustion chamber and mozzle with vane assembly of rocket with casing removed. This picture of Dr. Robert H. Goddard's rocket was taken in 1935. NASA Photo No. 74-H-1212.

On 31 May 1935, A-8 reached 2290 m (7500 ft) altitude, the motor firing for 14 seconds and successive flight corrections were observed. A-9 made a short flight but was unable to correct sufficiently the effect of a strong wind. A-10, launched on

12 July, had stronger and thicker aerodynamic drag vanes. Stabilization was noted, and the rocket was tracked to 2015 m (6600 ft) altitude.

Following a series of unsuccessful flights caused by injector problems, A-14 was launched on 29 October. A burning time of 14 seconds resulted in an altitude of 1220 m (4000 ft). This concluded the A-Series of tests (Figure 5).

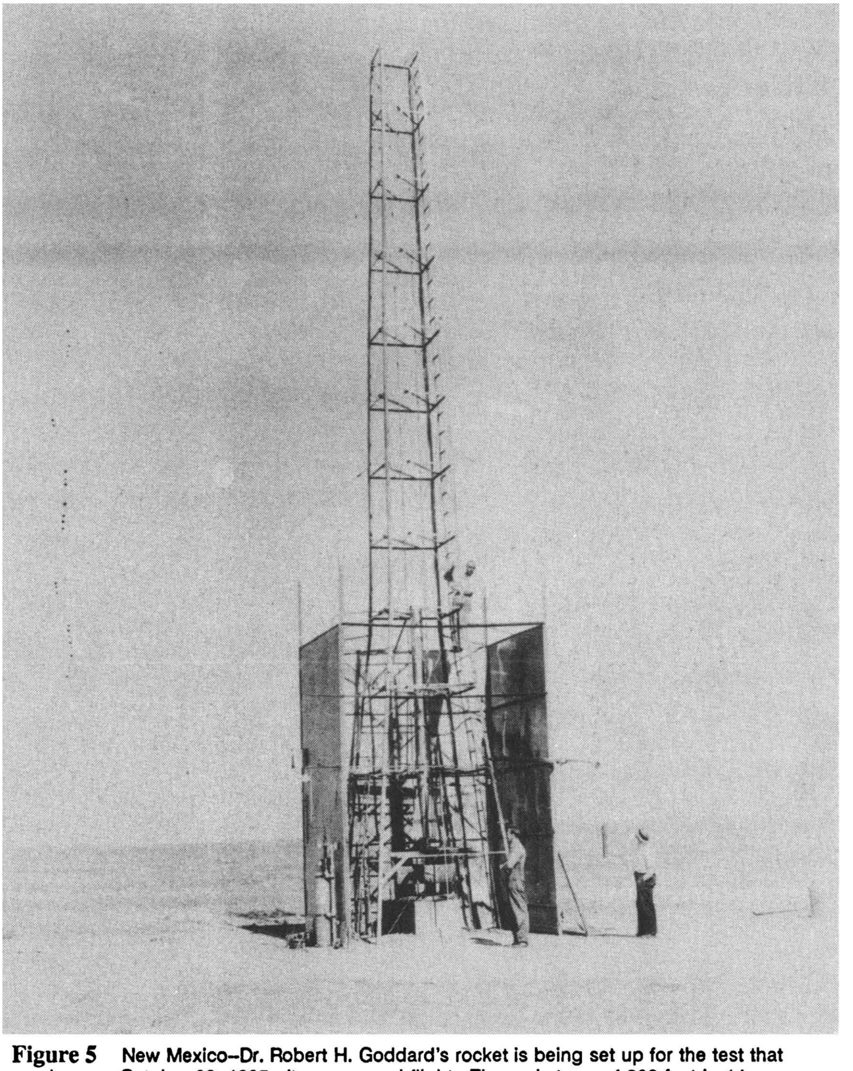

Figure 5 New Mexico--Dr. Robert H. Goddard's rocket is being set up for the test that place on October 29, 1935. It was a good flight. The rocket rose 4,000 feet in 14 seconds. NASA Photo No. 74-H-1219.

Goddard now concentrated on a larger, 25.4 cm (10 in.) diameter motor. The 10 tests in this series were conducted at the launch site for safety reasons. Instrumentation was increased. Thermocouples on the combustion chamber and exhaust nozzle were added. Hydraulic gauges measured thrust level, combustion chamber and nitrogen supply tank pressures. These gauges were mounted on a display board with a stop-watch. A 35-mm motion picture camera took photographs every three seconds. The camera view included also the rocket motor so that characteristics of the rocket exhaust jet could be recorded. Control was from the 300 m (1000 ft) distant shelter. Duplicate large pressure gauges on the tower showing thrust and combustion chamber pressure were observed by telescope. The rocket was observed also through slit openings in a barricade at a distance of 38 m (125 ft) (Figure 6).

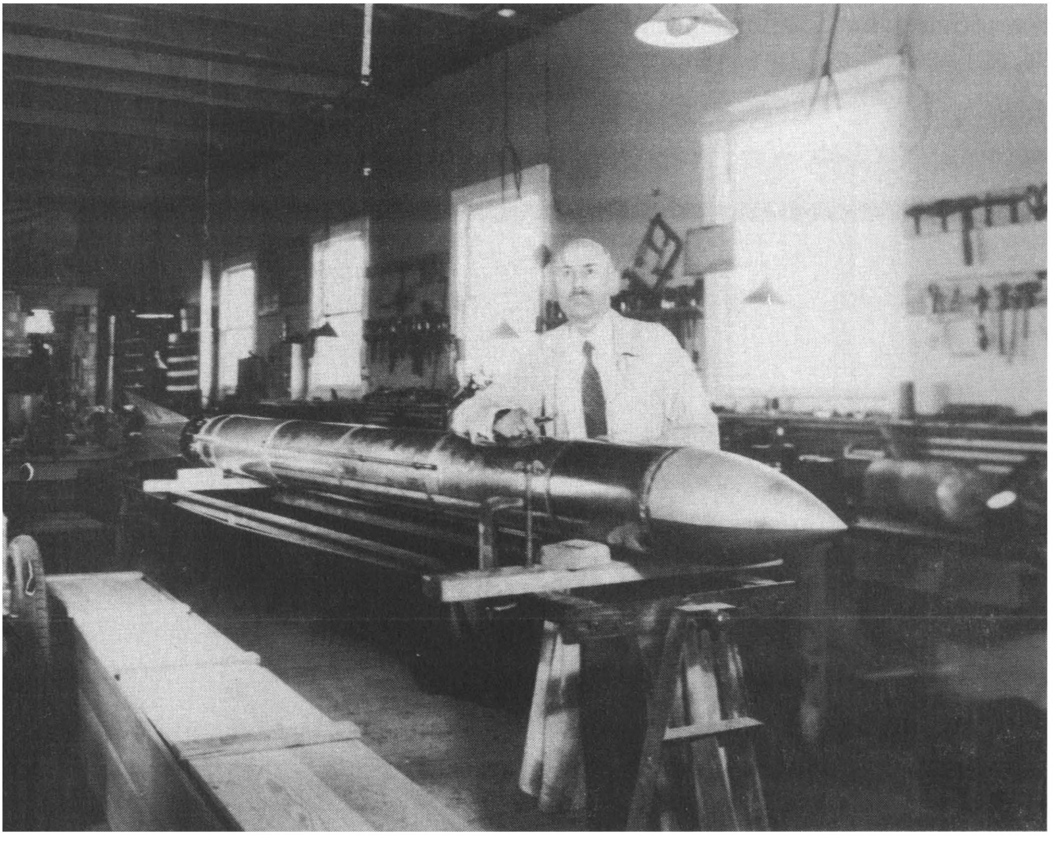

Figure 6 Dr. Robert H. Goddard with his rocket in his workshop at Roswell, New Mexico, October 1935. NASA Photo No. 74-H-1220.

The initial K-1 motor design was a 25.4 cm (10 in.) diameter cylinder, 38.1 cm (15 in) long. The upper cone was 45. Through the cone's vertex liquid oxygen was injected against a stainless steel deflector which caused the oxidizer to spray backwards against another smaller inverted 45^o cone inside the chamber. Refractory cement was applied to this lower cone. The lower cone was perforated to equalize pressure in the upper end of the chamber above. The gasoline fuel was injected through two tangential orifices on opposite sides of the chamber just below the commencement of the cylindrical portion. At the lower end of the cylindrical section of the chamber was the convergent portion of the nozzle, a 60^o cone. The nozzle throat was 6.2 cm (2.4 in.) in diameter and 61 cm (24 in.) long. The nozzle exit diameter was 13.9 cm (5.5 in.). The motor weighed 8.2 kg (18 lb).

When K-1 was tested on 22 November 1935, an average thrust of 204 kg (450 lb) was obtained during a 15-second run. Jet exhaust velocity was calculated at 1040 m/sec (3420 ft/sec). In the succeeding nine tests, numerous changes were made, including injector designs, flow-rates and nozzle throat diameter. Thrusts ranged to a high of 350 kg (770 lb); jet velocity of 1325 m/sec (4340 ft/sec). In Test K-6, and thereafter the rocket nozzle was jacketed with water and the water temperature rise measured. Table 1 shows a comparison of K-6, K-8 and K-10 tests in which the propellant flow rates and ratios were equivalent. Measurements shown were made two seconds after ignition. Specific impulse (thrust/mass flow/sec) in these tests was 96, 111 and 135 seconds, respectively (Figure 7).

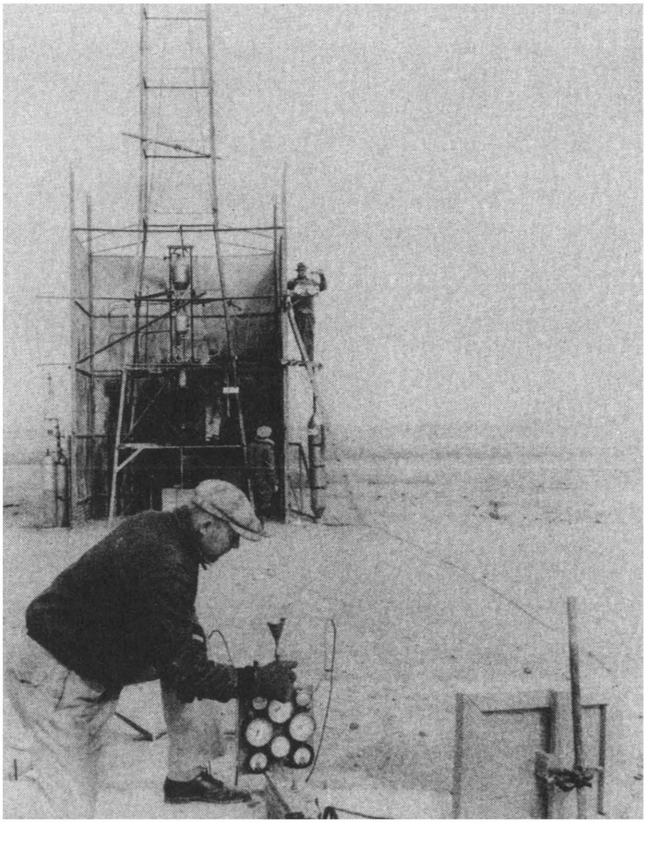

Figure 7 New Mexico–The lift-recorder line is being filled with fluid for Dr. Robert H. Goddard's static test, November 1935. A model for one of the series of static tests is in the tower. NASA Photo No. 74-H-1222.

Goddard tried three different propellant injector methods which he termed "double oxygen sprays," "focusing method" (propellants impinged, and mixed, on an annular unit) and "impact spray." Analyses were made comparing injector spray velocities, mixture ratios, exhaust jet velocities and nozzle thrust diameter (Figure 8).

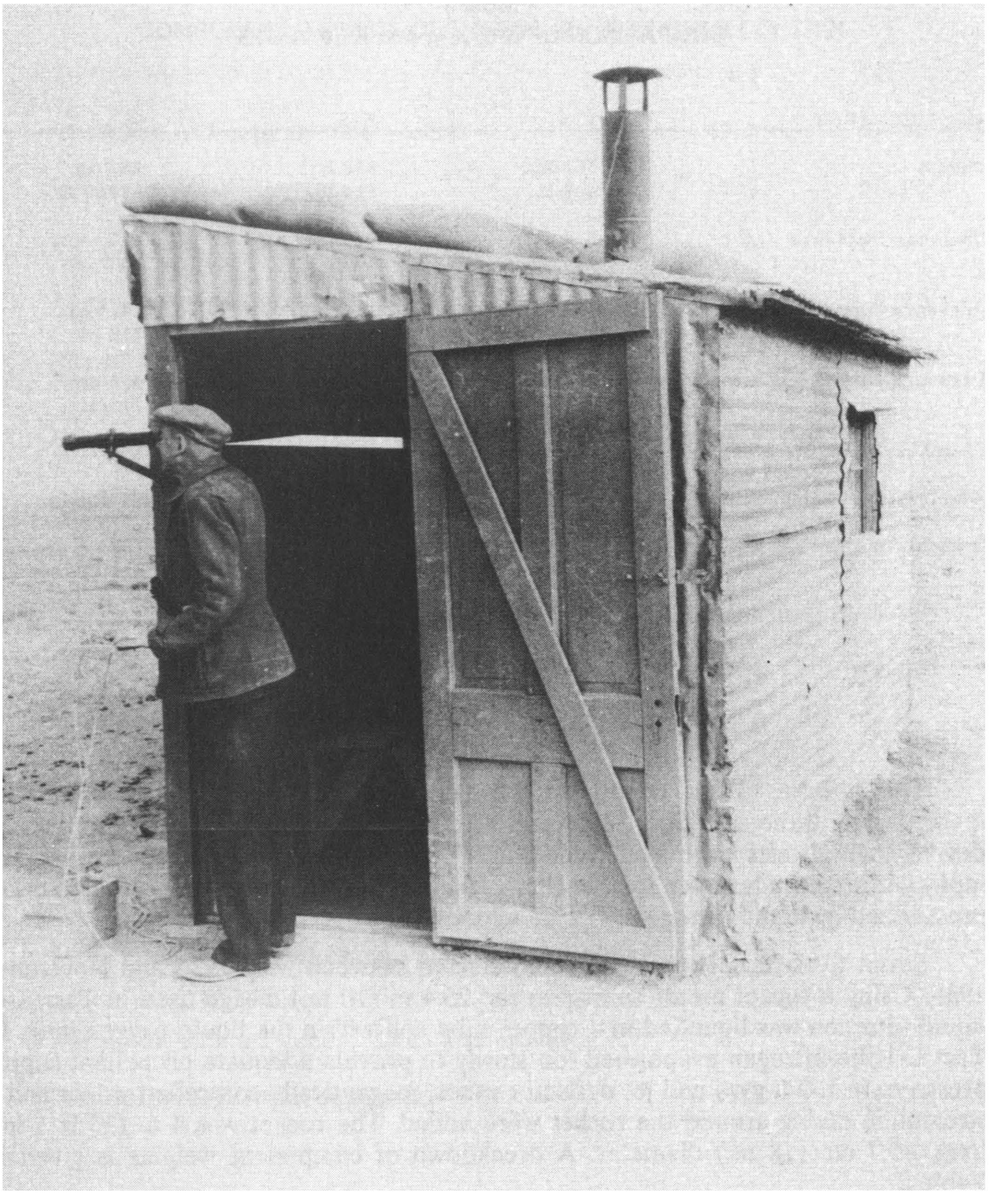

Figure 8 March 16, 1936--Rocket controls being operated by Dr. Robert H. Goddard, to fire, release, or stop test if firing unsatisfactory. The sandbags on the roof provided protection against possible accident. NASA Photo No. 74-H-1223.

Table 1
COMPARISON OF K-6, K-8, and K-10 TESTS

MEASUREMENT	K-6	K-8	K-10
Thrust	201 kg. 442 lb.	233 kg. 514 lb.	283 kg. 623.5 lb.
Chamber Pressure	8.4 atm. 124 psi	9.3 atm. 137 psi	9.7 atm. 142 psi
Pressure Supply	13.3 atm. 196 psi	13.1 atm. 192.5 psi	14.5 atm. 213 psi
Pressure Difference	4.9 atm. 72 psi	3.7 atm. 55 psi	4.8 atm. 71 psi
Chamber Temp. Rise	130°C,	170°C.	150°C.
Nozzle-jacket Temp. Rise	55°C.	20°C.	15°C.
Exhaust Velocity	930 m/sec 3060 ft/sec	1086 m/sec 3560 ft/sec	1324 m/sec 4340 ft/sec
Flow rates (calibrated with water): Liquid Oxygen at 1.4 atm. (20 psi)		482 gm/sec 17 oz/sec	
Gasoline		624 gm/sec 22 oz/sec	

The L-Series Tests, conducted between May 1936 and August 1938, were divided into three sections, A, B and C. During this period of 14 months, 30 developmental tests were made including 17 flights at velocities of 800 km/hr (500 mph) and to altitudes over 2500 m (8250 ft). The aim was to develop a flight rocket pressurized by liquid nitrogen.

Seven tests in Section A, were conducted between May 1936 and November 1936. Using a rocket motor similar to the 25.4 m (10 in.) design used in Test K-6, liquid nitrogen was liquefied in a copper tube coil within the liquid oxygen tank. In Test L-1 the nitrogen evaporated too slowly to provide adequate propellant supply pressure. In L-2 a gyro and jet deflector vanes, magnetically-controlled valves and a streamline casing around the rocket were added. The rocket was 4 m (13 ft 1 in.) long, 45.7 cm (18 in.) diameter. A breakdown of component weights is given in Table 2.

Anticipated thrust was the same as in the K-6 static test, 200 kg (440 lb). Unfortunately, the motor burned through shortly after ignition. In L-2, propellant fuel rates of oxidizer and fuel were increased 29% and 15% respectively. The motor burned through again. Changes were made in the oxidizer feed and a 28-second static test run was made in L-3. Thrust averaged 250 kg (550 lb); maximum reading was 272 kg (599 lb). Tests L-5 and L-6 both achieved short flights of about 60 m (200 ft).

Table 2

COMPONENT WEIGHTS OF L-2 ROCKET WITH GYRO CONTROL

	Kg	Lb
Chamber and copper-tube jacket	10.2	22.25
Gasoline tank	13.2	29.00
Oxygen tank	7.5	16.50
Liquid-nitrogen tank	3.9	8.50
Three 2-in. tube supports between tanks	1.5	3.25
Valves (regulator, oxygen- and gasoline-tank safety) and pressure recorder	2.7	6.00
Gyro and box, complete	1.5	3.37
Two magnet-valve boxes, complete	2.3	5.13
Battery, consisting of 27 dry cells	2.3	5.27
Cap, complete, less large parachute	3.6	8.00
Large parachute	0.7	1.50
Two half-cylinder casings	3.2	7.00
Door, for hoses and control wires	1.4	3.00
Steel ring, four steel arms, and blast vanes	1.3	2.92
Steel ring, four steel arms, blast and movable air vanes	2.1	4.62
Tailpiece with all vanes, fixed and movable	5.1	11.25
Tubing, braces, and supports	37.6	83.00
Dry weight of assembled rocket	88.0	194
Weight of liquid oxygen	35.4	78
Gasoline	38.1	84
Liquid nitrogen	1.8	4
Total	163.3	360

The L-6 rocket was 9 cm (3 in.) longer but did not carry a streamline casing and weighed (dry) 68.8 kg (151.5 lb); about 19 kg (42 lb) less than L-2. This 22% reduction was due largely to refinement in design in the continual struggle to reduce weight. For flight, 18 kg (40 lb) oxidizer, 21 kg (46 lb) fuel and 1.8 kg (4 lb) liquid nitrogen were loaded.

Test L-7 was a unique design in which a cluster of 4 motors, each 14.6 cm (5-3/4 in.) in diameter, replaced the single 25.4 cm (10 in.) diameter motor. The motor design was essentially the same as those in the A-Series tests. Propellant flow rates of each motor, using water at 1.4 atm (20 psi), were oxidizer, 181 gm/sec (6.4 oz/sec); fuel, 149 gm/sec (5 oz/sec).

The cluster of four motors weighed about twice the weight of the single motor. Dry weight of L-7 was 68.7 kg (151.5 lb). L-7 ignited and reached about 60 m (200 ft) before one of the motors burned through. Goddard noted, however, that the rocket flight was stable and commented that vehicle guidance might be accomplished without air or jet vanes by individually controlling thrust of the motors.

Section B of L-Series comprised 10 tests between November 1936 and August 1937. In the interest of obtaining a high-altitude flight soon, Goddard returned to the 14.6 cm (5-3/4 in.) diameter motor. In Test L-8 the three undamaged motors from the previous tests were used in comparative static tests of fuels. Regular gasoline, the usual fuel, was compared with lower-density aviation gasoline and with naphtha. Finding no significant advantage with the other fuels, Goddard modified the motor in L-9 to increase the oxygen flow rate 20%. The motor burned through.

In L-10, Goddard returned to the L-7 and L-8 propellant flow rates and a nitrogen gas pressure tank. The rocket was 4.5 m (14 ft 7 in.) long, streamlined and weighed 35.4 kg (78 lb) dry. Propellants were estimated at 8.6 kg (19 lb) oxygen and 12.7 kg (28 lb) gasoline. The rocket left the tower but tilted sharply. This was attributed to modification made in the spring-loaded, roller guides which traveled with the rocket up the launch tower. The rocket landed some 610 m (2000 ft) from the tower.

In L-11 the tail section was fitted with jet deflector and air drag vanes connected in tandem, on opposite sides, by a cross-bar. Thus, on control gyro command, a jet deflector dipped into the rocket exhaust at the same time extending aerodynamic drag vane on the opposite side. The rocket reached an altitude of 570 m (1870 ft) according to the recording telescope trace at the 305 m (1000 ft) observation point (Figure 9).

The cylindrical tanks in L-12 were redesigned, increasing the diameter and using hemispherical instead of conical heads. The r of 570 m (1870 ft) according to the recording telescope trace at the 305 m (1000 ft) observation point (Figure 10).

The cylindrical tanks in L-12 were redesigned, increasing the diameter and using hemispherical instead of conical heads. The rocket was observed to correct trajectory more than once in flight. Recorded data showed an altitude of 456 m (1500 ft) was reached.

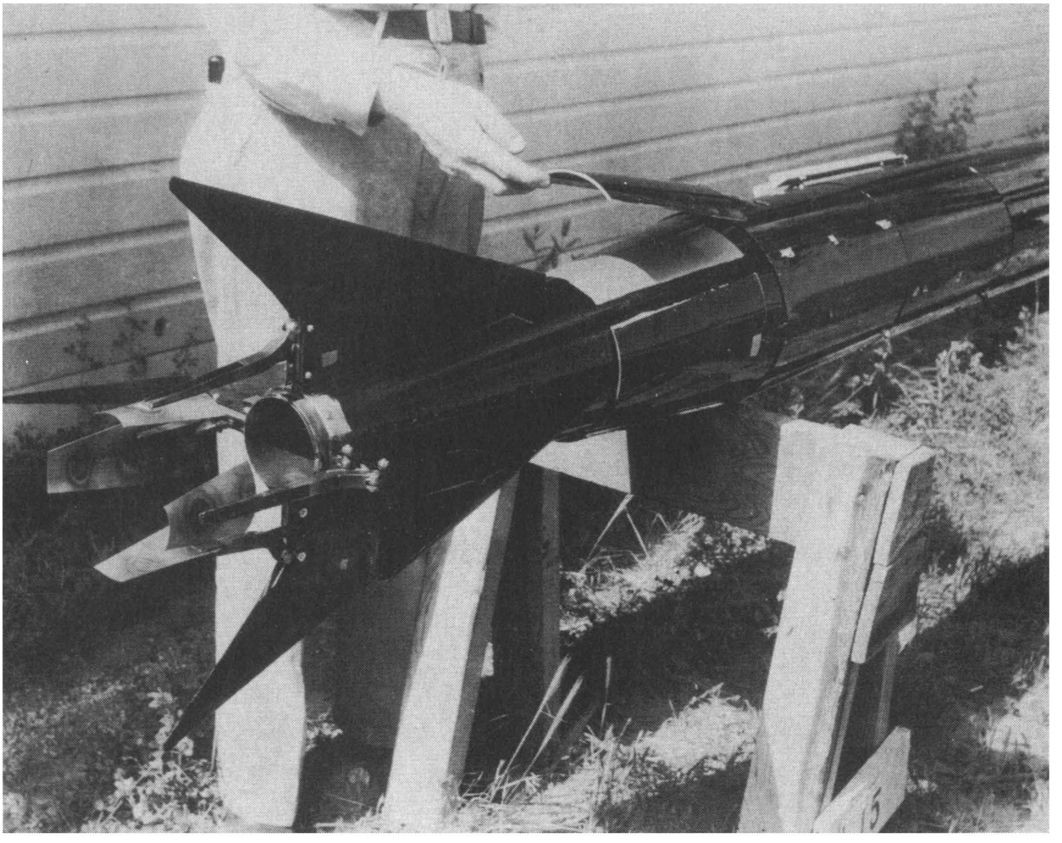

Figure 9 Tail piece, with flexed and movable air vanes, and vanes movable into the blast, of Dr. Robert H. Goddard's rocket, May 19, 1937. NASA Photo No. 74-H-1228.

The propellant load was reduced in L-13. The rocket rose rapidly but tracking was lost during the flight because of dust in the atmosphere. Propulsion ceased after 22.3 seconds during which time several corrections to vertical flight were observed. It was estimated that an altitude over 2440 m (8000 ft) had been reached.

Larger air vanes were tried on L-14 but were not found satisfactory. Tracking data were not obtained because the trajectory was directly over the tracking telescope. Propulsion lasted 21.5 seconds (Figure 11).

In L-15 the pressure storage tank was redesigned. The sheet nickel wall was reduced almost 50% in thickness. The tank was wrapped, both longitudinally and transversely, with fine music wire. To prevent distortion the tank was pressurized while winding. Weight of the tank was thus reduced by more than 50%. Other reductions in weigh by redesign brought the dry weight of this 5.4 m (17 ft 8 in.) rocket to just 41.1 kg (90 lb). In flight, the propulsion period lasted 29.5 seconds. Altitude reached was 991 m (3250 ft). The recovery parachute opened as the rocket tilted at zenith.

Figure 10 Roswell, New Mexico–Dr. Robert H. Goddard's rocket in flight, May 19, 1937, showing much improved stabilization. It reached an altitude of 3,250 feet. NASA Photo No. 74-H-1230.

The final section of the L-Series numbered 15 tests, which included 8 flights conducted between July 1937 and August 1938. Steady progress was made in redesign of new features and a reduction in weight. Static thrust increased to 216 kg (477 lb) and exhaust velocity to 1630 m/sec (5340 ft/sec).

Figure 11 Dr. Robert H. Goddard and colleagues at Roswell, New Mexico, Dr. Goddard is holding the cap and pilot parachute, parts of the successful operation, May 19, 1937. NASA Photo. No. 74-H-1231.

In Tests L-16 and L-17 Goddard made another innovation--steering was accomplished by gimbal-mounting the rocket engine. In this system, when the rocket deviated from the vertical, the gyro closed a circuit which operated pneumatic brass bellows, which tiled the rocket motor until recovery of vertical flight was obtained. Movement of the motor about either of two axes caused the estimated 91 kg (200 lb) thrust to be displaced 7.6 cm (3 in.) from the center of gravity. Propellant feed lines to the motor were flexible. In addition, these rockets carried clockwork-operated recording barographs to obtain pressure altitude data. A slowly rotating paper disc recorded a pencil stylus trace. The rockets were 5.6 m (18 ft 5 in.) long and weighed (dry) 42.4 kg (93 lb 5 oz). Propellant supply pressure was obtained from the previously discussed wire-covered tank of nitrogen gas.

On launch, L-16 rose to about 627 m (2005 ft) according to the recording telescope on the ground. Recovery was smooth, two parachutes being used. The barograph showed a jerky trace of 153 m (500 ft) only. It was redesigned for L-17 to be more sensitive, but still proved unsatisfactory. L-17 was assisted in launch by a dropweight, cradle catapult. An altitude of about 610 m (2000 ft) was reached (Figure 12).

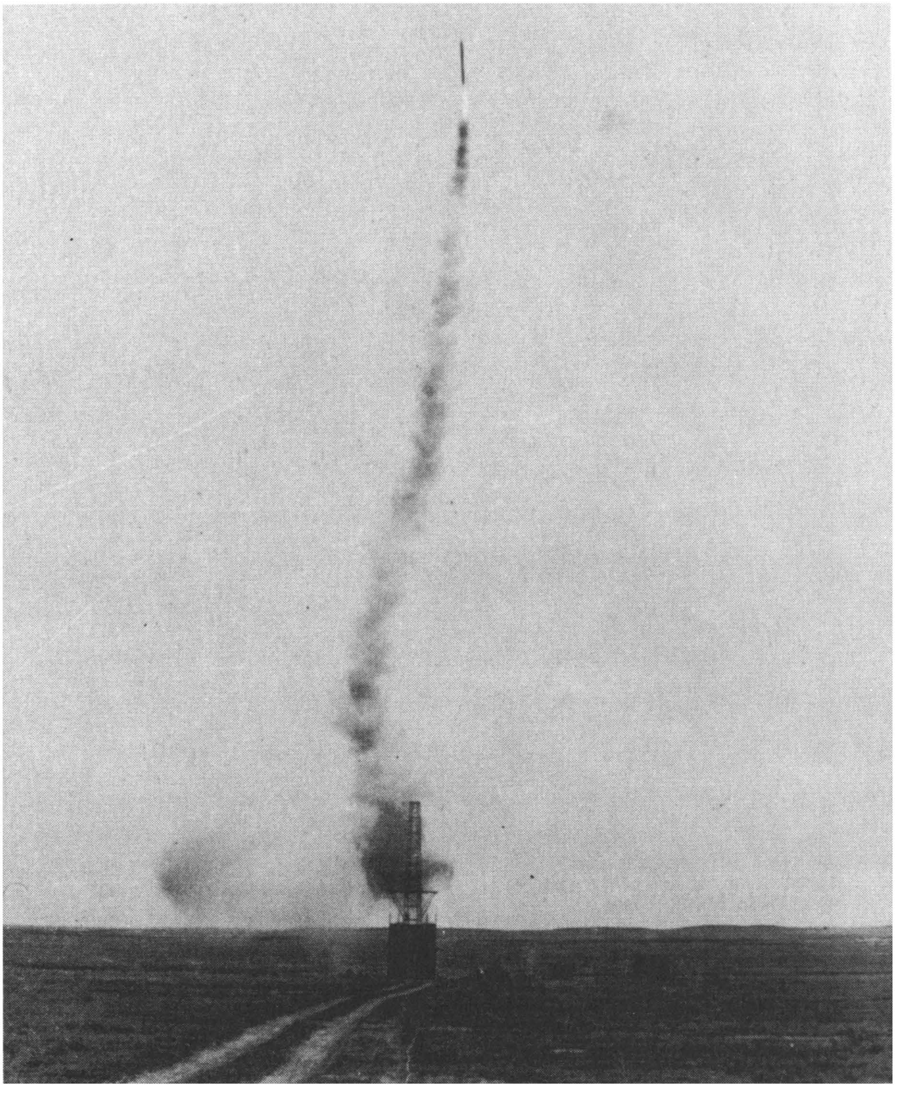

Figure 12 Roswell, New Mexico--Dr. Robert H. Goddard's rocket flight of August 26, 1937, with gimbal-steering and catapult-launching. NASA Photo No. 74-H-1232.

Goddard now returned to the liquid nitrogen, bellows pump and engine system for the next group of static tests, L-18 to L-20. The liquid nitrogen was vaporized by passing around the combustion chamber and nozzle within spiral-wound copper tubes. In the L-20 test firing the bellows pump and engine operated at 4 strokes per second. Gas pressure supply to the propellant tanks was above 13.6 atm (200 psi). Combustion chamber pressure was 8.2 atm (120 psi); thrust, 104 kg (228 lb); exhaust velocity calculated to be 1208 m/sec (3960 ft/sec). The rocket developed strong lift for 39.2 seconds. Weights of consumables were: oxygen, about 18.4 kg (40 lb); gasoline, 19.1 kg (42 lb); liquid nitrogen, about 4.5 kg (10 lb).

A flight was made in Test L-21 but the small excess of thrust over weight caused the rocket to rise slowly from the launch tower. Accordingly, when the jet deflector vanes diverted the exhaust jet, the vertical component of thrust was reduced and the rocket fell. Upward velocity was too low for the retractable air (drag) vanes to have correcting effect (Figure 13).

Figure 13 View of control shack 1,000 feet from launching tower, shown in background, Dr. Robert H. Goddard looking through telescope at control gauges. Firing, releasing, and stop keys are shown on shelf. Rocket is in tower. NASA Photo No. 74-H-1245.

The next series of static tests investigated the extent to which exhaust velocity would be increased by higher nitrogen supply pressures. L-22 was tested at 23.1 atm (340 psi) pressure. Combustion chamber pressure averaged 11.6 atm (170 psi); thrust 117 kg (258 lb) for 30.5 seconds. Jet velocity was 1250 m/sec (4100 ft/sec). An attempt was made to measure rates of flow from propellant tanks by use of cork floats on propellants and fluid sight-glasses mounted above tanks.

In L-23 a larger, 17.8 cm (7 in.) combustion chamber was used, three tangential fuel orifices instead of two, and propellant flow rates increased. A thrust of 212 kg (466 lb) was recorded for 22.3 seconds.

Returning to the smaller size motor, nitrogen pressure was increased to 31 atm (450 psi) with L-24. In L-25 the ratio of oxygen to fuel was increased. During a 20-second run, a chamber pressure of 29 atm (208 psi) was recorded; average thrust, 217 kg (477 lb); exhaust velocity, 1629 m/sec (5340 ft/sec).

Despite the proof of increased performance at these high pressures, Goddard decided that it was simpler to return to flight test with only slightly increased feed pressures. A wire-wound gas pressure tank was used and the propellant tanks likewise were constructed with thinner nickel stock, wound with fine piano wire.

A new barograph was carried as payload in L-27. Unfortunately, the motor ceased firing, apparently from depletion of oxygen and reached less than 300 m (1000 ft) altitude. L-27, which incorporated some valving changes, was recorded by observation to reach a height of 662 m (2170 ft).

L-28 carried a standard aviation barograph provided by the National Aeronautical Association (NAA), the U.S. member of the Federation Aeronauticale Internationale. An official observing committee was present. The rocket was about the same length and weight as L-16. An observed peak altitude of 1286 m (4215 ft) was achieved, but the recovery parachute did not open and the barograph was badly damaged. L-29 carried an official NAA barograph but the rocket veered sharply after leaving the tower, because of a wind gust, and traveled only a short distance. L-30 was more successful. A tracking telescope observed and recorded an altitude of 1500 m (4920 ft). The barograph registered a lower altitude, possibly because of acceleration load and vibration stress.

Goddard now turned to turbine pump development commencing with designs developed at Clark University, 1932-1934. For this work, conducted between September 1938 and February 1939, turbines and casings of both aluminum and brass were used initially. Five different designs were tested. An inlet pressure of 2 atm (30 psi) was used. Some two dozen cold-flow bench tests were made using compressed air supply at 6.8-12.2 atm (100-180 psi). Tests data were recorded by motion picture at 1 frame/second. Two designs were selected for "hot" tests. Pump performance for these two designs, at inlet pressure of 12.5 atm (160 psi) averaged a delivery pressure of 52.7 atm (775 psi); .74 kg/sec (1.63 lb/sec) at 40,000 rpm.

Four static tests, P-1 to P-4, were made with another rocket motor. The oxygen pump was 3.8 cm (1 in.); the fuel pump, 4.4 cm (1-3/4 in.) diameter. The turbines were driven by oxygen gas in two tests, separate gas supply in another, and combustion gas, bled from the chamber -- cooled by oxygen -- in the fourth test. In Test P-3 a thrust of 305 kg (671 lb) was obtained for 12 seconds.

The next 8 static tests, performed between March 1939 and April 1939, involved development of a warm gas generator to drive the turbine pumps. The gas generator was similar in design to a rocket chamber except that the oxygen was injected tangentially and the gasoline entered in a conical sheet. A large excess of oxygen was used in order to keep exhaust temperature low; about 60°. Ignition was by spark plug.

In Test P-8 a steady thrust of 315 kg (693 lb) was obtained. Propellant flow rates were: oxidizer, 1.4 kg/sec (3 lb/sec); fuel, 1.1 kg/sec (2.5 lb/sec). Chamber pressure was above 20 atm (300 psi). Changes in propellant quantities and mixture ratios were tried and, despite chamber burn-throughs and explosions, Tests P-11 and P-12 gave thrusts of 318 kg (700 lb) for about 15 seconds. P-12 was run with liquid nitrogen. The test set-up was complex with newly-designed reducing and starting valves controlled by time-delay dashpots. This test, too, ended in an explosion, but the recorded test data appeared to point the way to the cause.

For the next 23 months, between November 1939 and October 1941, Goddard integrated his refined designs of components in his largest rocket vehicle. These comprised tests P-13 through P-36. Since thrusts of 318 kg (700 lb) had been obtained with pump-fed systems, he designed for large tankage. These large rockets were about 6.7 m (22 ft) long, 45.7 cm (18 in) diameter, and carried about 65 kg (140 lb) liquid oxygen and 50 kg (112 lb) of gasoline. Dry weight was 86-109 kg (190-240 lb). The 14.6 cm (5-3/4 in.) diameter rocket motor, now operating at high chamber pressures, was tightly wrapped with copper tubing. Liquid nitrogen was contained within 2 tanks inside the liquid oxygen tank. The nitrogen, through a reducing valve, supplied pressure head to the propellant tanks and drove the steering gyro. The gas generator powered the propellant pumps. Propellant flow rates were about 1.4 kg/sec (3 lb/sec) each. Steering was provided by both retractable air vanes and jet deflectors. Barograph and recovery parachutes were carried in the nose cap. The turbopumps were spun initially by nitrogen gas from an automatically released "umbilical" in the launch tower. Valves opened automatically by three timed-dashpots.

P-13 and P-14 were static tests. P-15 was an attempted launch but the oxygen pump casing, made of magnesium alloy, failed. Later, the pump casing was strengthened, but in P-16 one of the starting controls failed and the engine shut down automatically and prematurely (Figure 14).

Returning to static tests for P-17, -18, -19, and -20, a series of explosions, pump and vibration failures occurred. In P-20, however, a firing of 43.5 seconds was achieved. As in all of these static tests, camera records were made of pertinent pressures and weights.

When P-21 was tested, the gas generator exploded, blowing off the head. P-22 had an electrical short-circuit. P-23 ignited and the white indicator light showed, indicating lift greater than rocket weight. The red indicator light showed, indicating

91 kg (200 lb) excess thrust and the rocket was automatically released. It traveled slowly out of the tower but rose only to about 100 m (300 ft).

Figure 14 January 1940--Cap, parachutes and barograph for Dr. Robert H. Goddard's rocket. NASA Photo No. 74-H-1240.

Returning to static tests, P-24 was shut down because of a flame near the gas generator. P-25 achieved the highest thrust obtained; 447 kg (985 lb). P-26 to P-30 followed and, in P-30, the oxygen pump was modified. The new pump, with a steel impeller, weighed only slightly more: 3 kg (6 lb). It contained 143 parts.

In Test P-31 the rocket left the tower but did not reach 100 m (300 ft) altitude. Goddard conducted two more static tests and three flight attempts, but a successful high-altitude flight of this sophisticated rocket was never achieved. Test P-36 on 10 October 1941 was his last rocket flight attempt at Roswell. Ninety-one kilograms (200 lb) thrust in excess of weight was quickly obtained. Ironically, on this last attempt, the "umbilical" release jammed. The rocket rose but a few centimeters and stopped. The engine was shut down.

The causes of the many difficulties in this last series of tests were understood by Goddard, but time had run out. War was raging in Europe, and the United States was about to become involved. For several years Goddard had responded to requests for proposals for applying rocket power to military ordnance and for aircraft propulsion. Both the Army and Navy sought his services. Harry Guggenheim had offered to make the Roswell facilities available to the military services, if desired. By November 1941 Goddard accepted a research contract with the U.S. Navy. He planned to return to New Mexico to resume his flight tests after the war but his health failed and death intervened on 10 August 1945.

During the Roswell years Goddard accomplished many pioneering steps along the way to liquid-propellant, rocket-powered flight:

- He secured relevant performance data in static tests enabling continual improvement in subsequent design.
- He engineered a total flight system including on-board controls for guidance, engine shut-down, parachute and payload recovery.
- He developed automatic launch sequence control; timed, sequential actuation of tank pressurization, ignition, umbilical release, automatic shut-down, thrust determination, vehicle release, etc.
- He developed gyro-stabilization and in-flight aerodynamic and rocket exhaust deflection controls, as well as gimbal-mounted motors.
- He devised gas-generator-powered, turbopump-fed rockets.
- He developed recording and optical telescope tracking systems.
- He established a remarkable safety record throughout his test work. Despite potential hazards of the combustible, high-energy propellants, there was never an operational, time-lost accident during the many static firing tests and 31 rocket launchings.

BIBLIOGRAPHY

Three main sources were drawn upon for this paper:

1. *The Papers of Robert H. Goddard*, Edited by Esther C. Goddard and G. Edward Pendray, Three Volumes, McGraw-Hill, New York, 1970.
2. *Rocket Development*, Edited by Esther C. Goddard and G. Edward Pendray, Prentice-Hall, Inc., New York, 1948.
3. Robert H. Goddard Collection, National Air and Space Museum, Smithsonian Institution, Washington, D.C. This collection comprises twenty-three illustrated, bound volumes of Dr. Goddard's notes, experiments and results from 1921-1943. In addition, there are 7 volumes of correspondence and reports submitted to the Smithsonian Institution dating from 1916 to 1945, and an extensive photographic collection.