THE 2003 GODDARD ROCKET REPLICA PROJECT: A RECONSTRUCTION OF THE WORLD'S FIRST FUNCTIONAL LIQUID ROCKET SYSTEM

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ABSTRACT

As a part of NASA's 2003 Centennial of Flight celebration, engineers and technicians at Marshall Space Flight Center (MSFC), Huntsville, Alabama, in cooperation with the Alabama-Mississippi AIAA Section, have reconstructed historically accurate, functional replicas of Dr. Robert H. Goddard's 1926 first liquid-fuel rocket. The purposes of this project were to clearly understand, recreate, and document the mechanisms and workings of the 1926 rocket for exhibit and educational use, creating a vital resource for researchers studying the evolution of liquid rocketry for years to come. The MSFC team's reverse engineering activity has created detailed engineering-quality drawings and specifications describing the original rocket and how it was built, tested, and operated. Static hot-fire tests, as well as flight demonstrations, have further defined and quantified the actual performance and engineering challenges of this major segment in early aerospace history.

INTRODUCTION

As a part of NASA's 2003 Centennial of Flight celebration, engineers and technicians at Marshall Space Flight Center (MSFC), Huntsville, Alabama, in cooperation with the Alabama-Mississippi AIAA Section, have reconstructed several historically accurate replicas of Dr. Robert H. Goddard's 1926 first liquid-fuel rocket.

The purposes of this project were to clearly understand, recreate, and document the mechanisms and workings of the 1926 rocket for exhibit and educational use. This paper provides an introductory record of the project and a general overview of the lessons learned by recreating Robert Goddard's early attempts at liquid rocketry.

Based on photographs of the time, these replicas are as historically accurate as possible, both inside and out, containing accurate reproductions of the launch structure, injector assembly, combustion chamber, nozzle, and other components. Whenever possible, the original designs were used throughout with minimal changes in materials and structures in order to satisfy modern safety and hazardous materials-handling requirements. Detailed technical comparisons between Goddard's 1926 rocket and the 2003 replicas will be described in future papers.

Not unlike an archeological effort, the MSFC team's reverse engineering activity has illuminated and documented the historical and technical significance of Dr. Goddard's accomplishments by creating detailed engineering-quality drawings and specifications describing the original rocket and how it was built, tested, and operated. Static hot-fire tests, as well as flight demonstrations, have further defined and quantified the actual performance and engineering challenges of this major segment in early aerospace history using modern test and data acquisition methodologies.

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The detailed plans and specifications for Goddard's first rocket developed by the project have created a vital new resource about the evolution of liquid rocketry (Fig. 1) with emphases on lessons learned and systems engineering, something which will help future students of aerospace engineering understand and appreciate the foundation on which their work rests.

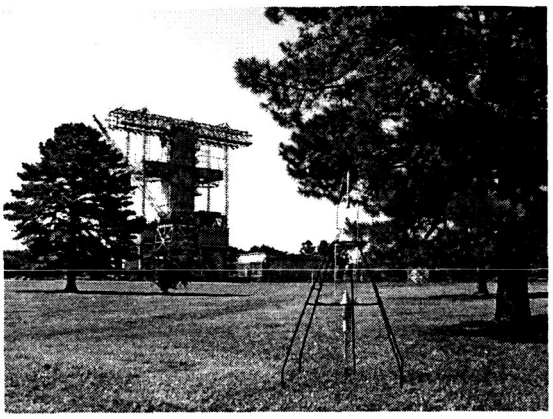

Fig. 1. Goddard rocket replica "Nell" and the massive S1-C test stand behind it at MSFC represent advances made in the first 40 years of liquid rocketry (1926–1966).

PROJECT PHILOSOPHY AND APPROACH

The 2003 Goddard Rocket Replica team decided to recreate Goddard's 1926 rocket as accurately as possible, based on the information available, using materials available today and within modern engineering limits. However, early confidence was quickly dampened when the team was faced immediately with a lack of complete plans or hardware to examine and duplicate. The team soon learned that, although Goddard took extensive notes and reported later on his work and his wife took numerous photographs of the 1926 event, almost no hardware remains.

Dr. Goddard experimented with this rocket design, which he nicknamed "Nell," for years before achieving his first successful flight in March 1926. Nevertheless, as his wife Esther said 40 years later in 1966, "None of us who saw this flight had any particular sense of destiny or very great importance."[1] Furthermore, within 4 years Goddard relocated his work from New England to New Mexico and was soon developing much larger rockets with turbopump engines, gyroscopic stabilization devices, and stabilizing vanes with full support from the Guggenheim Foundation. His notes show that following the first flight in 1926, he quickly moved on to other designs and cannibalized most of the usable parts from Nell to be used in later versions, leaving behind surprisingly sparse details about the 1926 rocket and virtually no drawings.

The Smithsonian National Air and Space Museum, Washington, DC, has on display the only known remaining Goddard rocket components from the March 1926 rocket which were reused in a later version that never flew.[2] The 2003 NASA team learned that other drawings[3] and replicas on exhibit around the country were based only on photographs and most had no internal detail.

With this lack of information to draw upon, it was decided to first build up a knowledge base by creating a highly accurate but nonflying static replica, using available information from 1926 (Fig. 2). In this initial effort, Ester Goddard's copious, highly detailed photographs of both internal and external components proved invaluable. An equally valuable source of information was Goddard's 1929 report to the Trustees of Clark University. This gave the team hands-on information about how the rocket was constructed, and allowed them to fine tune dimensions and materials and manufacturing methods while allowing them to move simultaneously towards building and testing operational components.

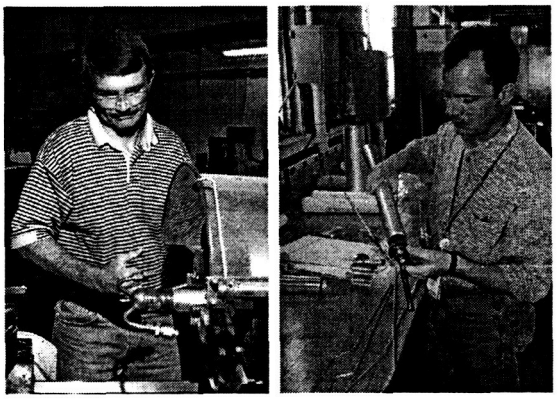

Fig. 2. Fabrication and assembly of the replicas.

In creating the replicas, the team tried to be as historically accurate as possible. In some cases, materials used by Dr. Goddard, such as asbestos, are no longer available today, so the conical liquid oxygen (lox) tank asbestos heat shield was recreated in fiberglass. Various paints and adhesives common in 1926 but no longer available today were replaced with modern counterparts. Other materials and components were

simply not specified, described, or photographed and the team had to make their best approximation. See Fig. 3 for an overview of the main components in the Goddard rocket.

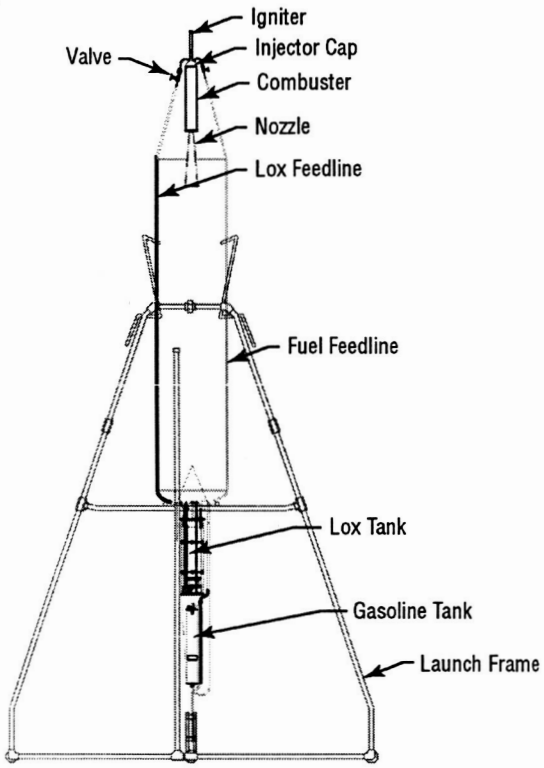

Fig. 3. Schematic of Goddard's 1926 rocket, showing launch frame, igniter, injector cap, combustion chamber, nozzle, valves, feedlines, and tanks.

In reproducing the flight version, it was decided to adhere to the original designs as much as possible, while assuring adequate robustness and safety margin for flight operation in today's environment. Thus, several changes to critical systems in the flight replica were deemed necessary to achieve safer flight and somewhat improved performance. A silica phenolic liner was used in the combustion chamber, while a ceramic liner was used in the nozzle. The nozzle throat was reinforced with a molybdenum-tungsten (Mb-W) washer, and the nozzle itself was shortened and optimized. A small spark plug was used as the igniter, but the injector design remained similar to Goddard's original version. A slight change was made in the lox tank drip rod mechanism, and no alcohol preburner was used.

Throughout his career, Robert Goddard used gasoline as a rocket fuel exclusively. However, gasoline was a new fuel to this team, and despite initial reservations about using it as rocket fuel, it was finally decided to retain the historically-correct fuel and oxidizer combination of gasoline and lox. Based on information and references provided by the Henry Ford Museum in Michigan, modern, unleaded regular 87 octane gasoline was used. Since our analytical combustion models are not calibrated to include properties of gasoline, kerosene was used as a close approximation in test planning and analysis.

The flight version was managed like any other NASA propulsion test project and was subject to all of the usual safety, design, test, and flight readiness reviews. The rocket and components were tested on existing hot-fire test stands and other test facilities at MSFC. Gaseous nitrogen (GN_2) was supplied via pressurized lines, and ignition was accomplished via remote electronics. Testing was conducted in a secure test area, and engineers observed the testing and launches from a blockhouse. Modern image recording devices and data collection systems documented the efforts.

Several high-fidelity static replicas and operational flight versions of the 1926 Goddard rocket were eventually constructed over the course of 2003. The static replicas have been exhibited at numerous conferences, shows, and educational activities since the first one was constructed in March 2003 (Fig. 4). Many operational test components were built and tested, both in component and system hot-fire tests. The project will culminate in the launching of a working flight version at MSFC in winter 2003–2004.

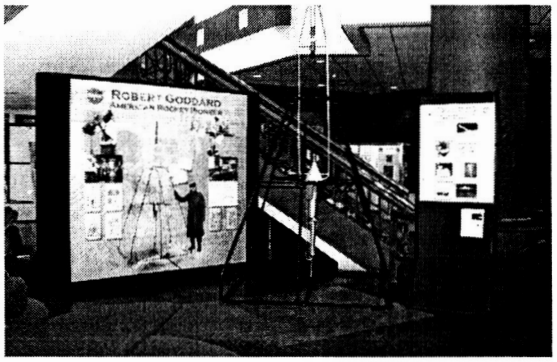

Fig. 4. Goddard replica exhibit on display at the Propulsion Measurement Sensor Development Workshop, May 15, 2003, Huntsville, AL.

REPLICA DESIGN

The flight of the Goddard rocket in 1926 was pivotal in the development of liquid rockets, and its historical significance cannot be overstated. Dr. Wernher von Braun said, "This event in the history of rocketry can only be compared with the first flight of the Wright Brothers at Kitty Hawk."[1] This first functional liquid rocket was comprised of the bare minimum of systems and components necessary to achieve operability. Thus, in developing this rocket, Dr. Goddard also developed, refined, and integrated—for the first time—all of the basic elements found in all subsequent, modern day liquid-fuel rocket systems.

In recreating Goddard's 1926 rocket, the 2003 NASA team, through hands-on experience, revisited and realized numerous technical details and nuances relevant to this rocket. The following discussion lists each major component and what was learned in reproducing it.

Propellants

In his notes, Goddard repeatedly states his combustion chamber pressure (P_c) was ~50 psig but gave little detail beyond that. With no gasoline-lox analytical models available, it was impossible for us to know the exact temperature or fluid state to expect inside the combustion chamber. Even the exact density of the oxidizer was unknown, whether it would be gaseous oxygen (gox), lox, or some combination of the two. As a best approximation, when modeling gox and kerosene at P_c ~50 psi and an oxidizer/fuel mixture ratio of 1:5, the temperature of the combustion environment would be ~2570 K.

Injector

Injector designs have become one of the most critical elements in liquid rocketry. Goddard's simple design mixed gasoline and lox well but did not take into account the momentum ratio between the propellant flow rates. Initial water flow testing of the injector replica clearly showed that the momentum of the resulting lox flow was higher than the fuel, causing the propellants to flow askew of the hardware's central axis (Fig. 5). Consequently, this "off-axis" flow caused the propellants to locally impinge on the forward end of the chamber wall. This likely caused some of the chamber wall burn-throughs that Goddard reportedly experienced. Yet, instead of changing the injector design for our replica to eliminate this flow problem, the team elected to enhance the design of the chamber liner to prevent potential burn-throughs.

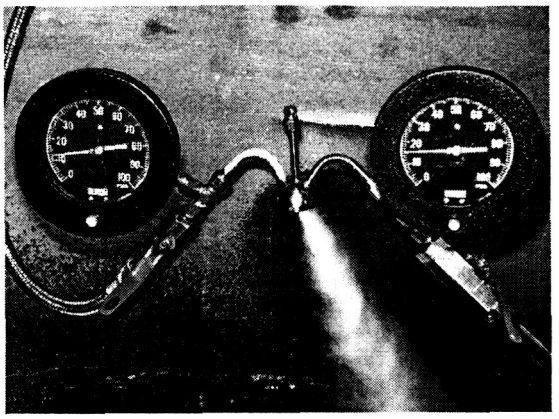

Fig. 5. Water flow test of Goddard's injector.

Indeed, Dr. Goddard experienced numerous difficulties with combustion chamber burn-through in this design. Over the years, injector design, combustion chamber engineering, and ignition optimization were recurring engineering issues for Goddard—123 of his 214 patents (57%) are related to combustion chambers and combustion devices.

Goddard also reported using alundum to coat the inside of his injector shell. Since this material was not readily available from current suppliers, the replica shell was instead coated with a thin layer of zirconia. Yet, subsequent hot-fire testing actually suggested that this coating was not even necessary, since the shell's interior did not appear to get hot enough to affect the stainless steel shell.

Some of our system-level tests displayed some ~1-Hz pulsations in the plume, showing it is possible in this very first rocket that Goddard experienced dynamic feedback between combustion instability in the combustion chamber and fluids in his feed system via the injector.

Combustion Chamber

Goddard reported using alundum to line the chamber's aluminum shell with a layer of asbestos between the two materials. Initial replicas in this task were lined with alumina (Al_2/O_3) instead, with no interface layer. Unfortunately, although the Al_2/O_3 was capable of handling high temperatures, it could not withstand the thermal shock created by the combustion environment, so this liner cracked and allowed hot gases to burn through the chamber wall—similar to Goddard's experiences.

The final replica used for hot-fire and flight testing used an Al_2/O_3 phenolic liner in the chamber. This ablative

material was more resistant to the thermal strains and high temperatures, and it experienced minimal ablation during testing. It was machined to fit within the aluminum shell with no interface layer. Despite the local impingement of the propellants at the forward end of the chamber, this liner prevented us from experiencing any further burn-throughs.

Nozzle

Goddard's 1926 conical nozzle was typical of designs of the time and had been documented in his patents—patent 1,102,653—as early as 1914. We know the 1926 nozzle was overexpanded and nozzle burn-through was a persistent problem. In fact, this first rocket did not lift off until a sizeable portion of the lower nozzle had eroded enough to produce adequate thrust for flight.

Goddard struggled for years with nozzle burn-through and experimented with many different materials and manufacturing processes to solve this problem. The 2003 flight replica has an optimized stainless steel nozzle shell, which was successfully lined with Al_2/O_3. To further enhance the heat protection in the throat area, an Mb-W washer was used at the forward end of the nozzle assembly. Occasionally, hot-fire testing with this design still experienced burn-throughs in the chamber/nozzle attachment area, but this was only after the washer had eroded too much. (Generally, the washer had to be replaced after two to three hot-fires tests, depending on the test durations.)

Igniter

Igniting a rocket like this safely was a challenge. Goddard's method of using a blowtorch inside a small brass tube lit with a torch that was on a broom handle or long stick left something to be desired, but it was effective, although potentially unsafe. Initially, we opted instead to use a small engine spark plug, which was readily available from any hobby store. To save more weight, we eventually switched to a special-order plug that measures <1 in long overall with a diameter of 0.15 in. The small spark plug was energized by ground power upon command. It proved to be a sensible and effective ignition alternative.

Valves

The needle valves used by Goddard were a critical element in his feedline and tank system. They had to be adjustable enough to allow controlling flow values, yet light enough to keep the entire system within stringent weight limits. Adjusting the valves a specific number of turns using a long stick was a key part of the 1926 preflight procedure. In the modern replicas, extensive static hot-fire testing had shown with high confidence the pressures required for adequate combustion. This allowed us to substitute Goddard's hand-adjusted needle valves with spring-loaded check valves, preset to open at 30 psi.

Tanks and Internal Flow Control Devices

While the gasoline tank was relatively straightforward in design and easy to replicate, the lox tank contained an inner tank and employed internal insulation made of thick brown paper, valves, and rather complex reverse-flow control devices that allowed the gox to pressurize the gasoline tank in order to pump the fuel up to the injector. Except for the needle valves near the injector, the lox tank contained all of the rocket's moving parts and was its most complex component.

In the 2003 replicas, the gasoline and lox feedline 30-psi check valves prevented backflow and premature mixing. After the gasoline and lox tanks were filled, the GN_2 system was pressurized to initiate flow. Goddard was unable to get his lox drip rod assembly to work, so it was wired open. We used a manual linkage that uncovered an ~0.040-in orifice to allow lox to drip onto the bottom of the outer lox tank after tanking was completed. The ambient air then transferred enough heat energy to the outer lox tank to convert the lox into gox, thereby pressurized the lox tank.

Fuel and Oxidizer Feed System

To conserve weight, Goddard used thin aluminum tubing for his feedlines. These fragile tubes also formed an integrating structure that held the entire rocket together. After the nozzle, these tubes were the most likely parts to be destroyed in testing or handling of the rocket.

Having now built the entire system, we realize that the tank and feedline system was just as critical to overall performance of the rocket as the injector and nozzle designs. Delivery of the correct pressures and flow rates were critical to successful, steady firing and generation of adequate thrust.

Launch Stand

The black pipe launch stand was not seen as a separate, unrelated element but rather as an extension of the entire rocket system. It supported the rocket adequately when at rest, yet allowed the rocket to lift off without impedence. It was thoroughly integrated to mesh with the rocket's structure and dynamics. We feel we were able to replicate it with very high accuracy.

Handling of Cryogenic Fluids

We know Goddard flew his rocket at a remote location miles from the laboratory. He must have learned how to not only acquire cryogenic fluids but also how to transport, store, load, and manage them safely at the launch site in order to perform a test flight before they evaporated.

On the test stand it was no problem to obtain and maintain adequate cryogens. Lox was stored in a dewar nearby and loaded into the lox tank via a funnel immediately before a firing. GN_2 was delivered to the system at a set pressure via umbilical.

There were some questions as to the effect of ambient temperature on the rocket's performance. We did most of our testing in Alabama in the summer while Goddard was working in Massachusetts in the winter and had no trouble generating sufficient fuel and oxidizer flow.

Thermal Protection

Goddard's "nozzle-first" design resulted in hot gas exhaust flow impinging onto the following lox and gasoline tanks. His solution of a conical heat shield on top of the lox tank to deflect the flow did not stop all heating but was adequate. Other insulation on the feedlines reduced heat gain there. These additions increased weight but were necessary to maintain proper temperatures, pressures, and flow rates in the tank and feedline system.

This unusual aspect of the 1926 design was addressed by Goddard himself:

> *"It will be seen from the photograph that the combustion chamber and nozzle were located forward of the remainder of the rocket, to which connection was made by two pipes. This plan was of advantage in keeping the flame away from the tanks, but was of no value in producing stabilization. This is evident from the fact that the direction of the propelling force lay along the axis of the rocket, and not in the direction in which it was intended the rocket should travel, the condition therefore being the same as that in which the chamber is at the rear of the rocket. The case is altogether different from pulling an object upward by a force which is constantly vertical, when stability depends merely on having the force applied above the center of gravity."*[4]

He quickly reversed the order of combustion chamber with nozzle and tanks in later designs. We applied similar insulation in all of the same places; the only difference was that we used fiberglass rather than asbestos.

Launch Sequence Procedures

In the process of ground testing, we learned to do things consistently and in a certain sequence. Goddard must have learned the same. For instance, in testing we learned the importance of prepressurizing the system with GN_2 in order to stabilize combustion and achieve adequate, steady thrust. Goddard used gox for the same purpose. This and other lessons learned were incorporated into the prelaunch procedures to enhance chances of a good firing and successful flight.

Component and System Testing

Testing and integrating the replicated elements were performed methodically to gather experience and apply important lessons learned along the way. Prior to integrating the completed replica assembly, the combustion components were hot-fire tested to verify thrust, performance, and operation (Fig. 6). Tanks and feedline systems were also separately tested under pressure to verify their integrity (Fig. 7). Finally, the entire system was integrated and tested with the replicated launch frame (Figs. 8 and 9). Yet, before the first launch attempt, a tethered test limited the movement of the rocket relative to the launch frame.

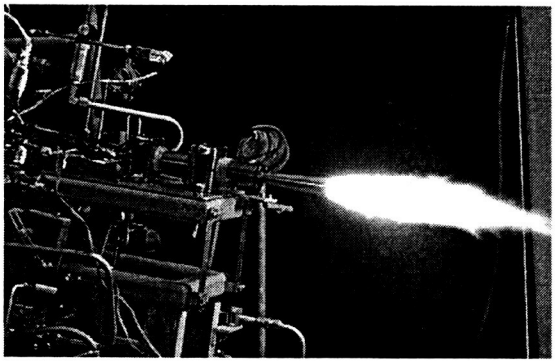

Fig. 6. A flight replica combustion component hot-fire test on the small Hydrogen Coldflow facility test stand.

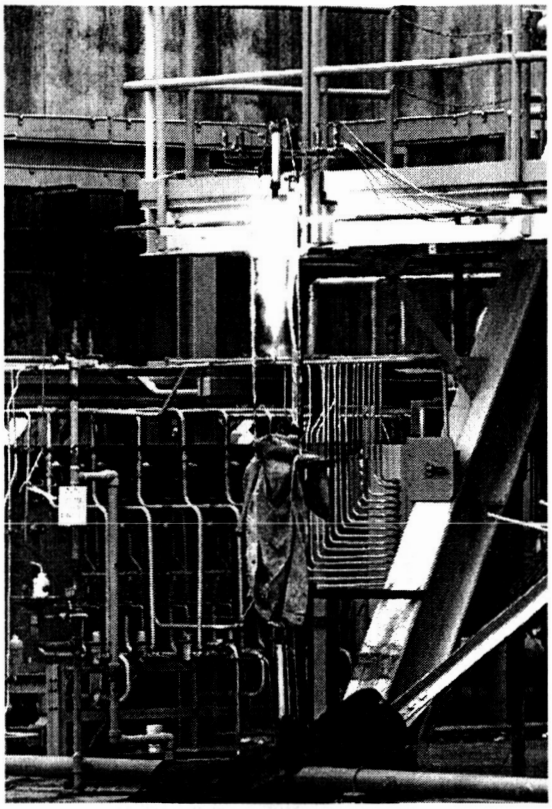

Fig. 7. Hot-fire system tests on test stand 116 verified the functionality of the combustor and tank-feedline system to support steady combustion.

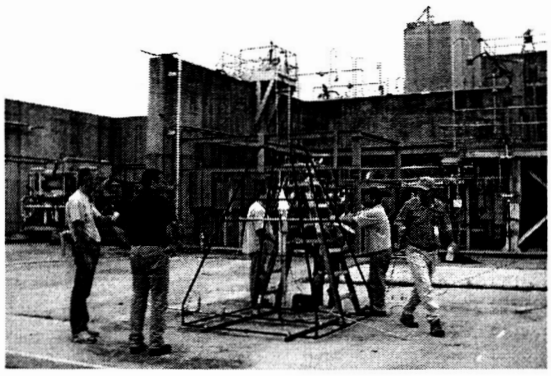

Fig. 8. Following a series of system tests bolted to test stand 116, the rocket was moved to its launch frame, which had been bolted to the concrete pad. A gaseous liquid nitrogen pressurization line still ties it to the test stand facility.

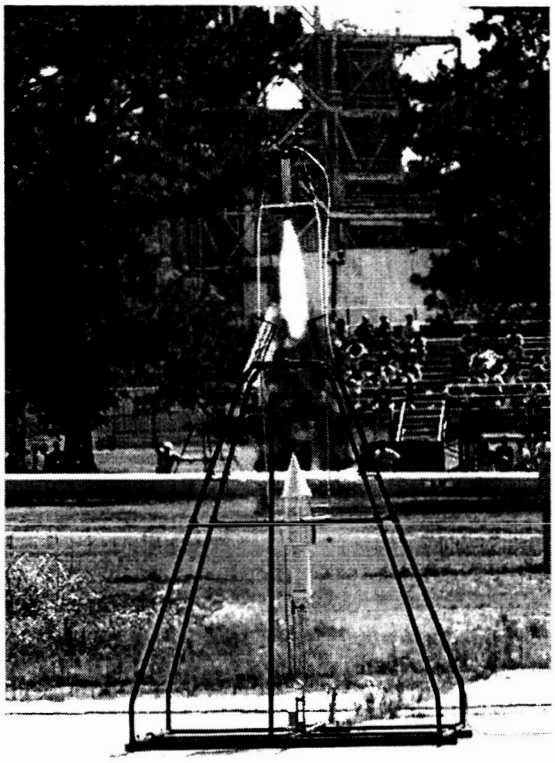

Fig. 9. The historic, first static firing of the Goddard rocket in its black pipe A-frame launch stand in near-flight configuration (July 23, 2003).

PRELIMINARY TEST RESULTS

Numerous combustion component tests were performed at the Hydrogen Coldflow facility test stand to verify required pressures and flow rates and to measure resulting thrust. In this configuration, only the thrust assembly (injector/chamber/nozzle) was tested. Fluids were delivered and controlled via the test facility. Since lox was unavailable at this facility, gox was supplied as the oxidizer for these tests. Figure 10 shows a typical thrust profile from one of these tests. With proper conditions, average thrust levels of 14 lb and chamber pressures close to 50 psi were measured.

Accelerometer data were collected during one static firing in the A-frame launch stand. In this test the rocket was restrained by an umbilical so that it was allowed to rise a few inches but not lift off. Three Endevco 2223D triaxial piezoelectric accelerometers collected data at a sample rate of 100 kHz with a 20-kHz low-pass filter on the combustor, lox tank, and gasoline tank. An example of one of the three data channels from the combustor in this test is shown in Fig. 11.

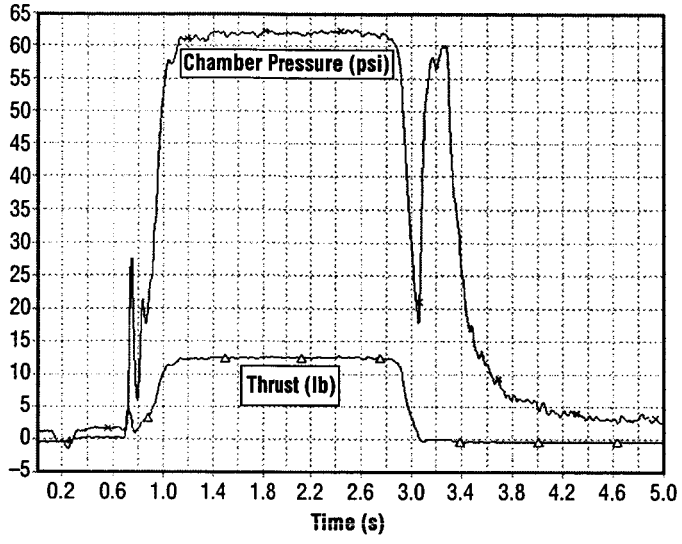

Fig. 10. Flight replica hot-fire thrust data (test No. P2354–017).

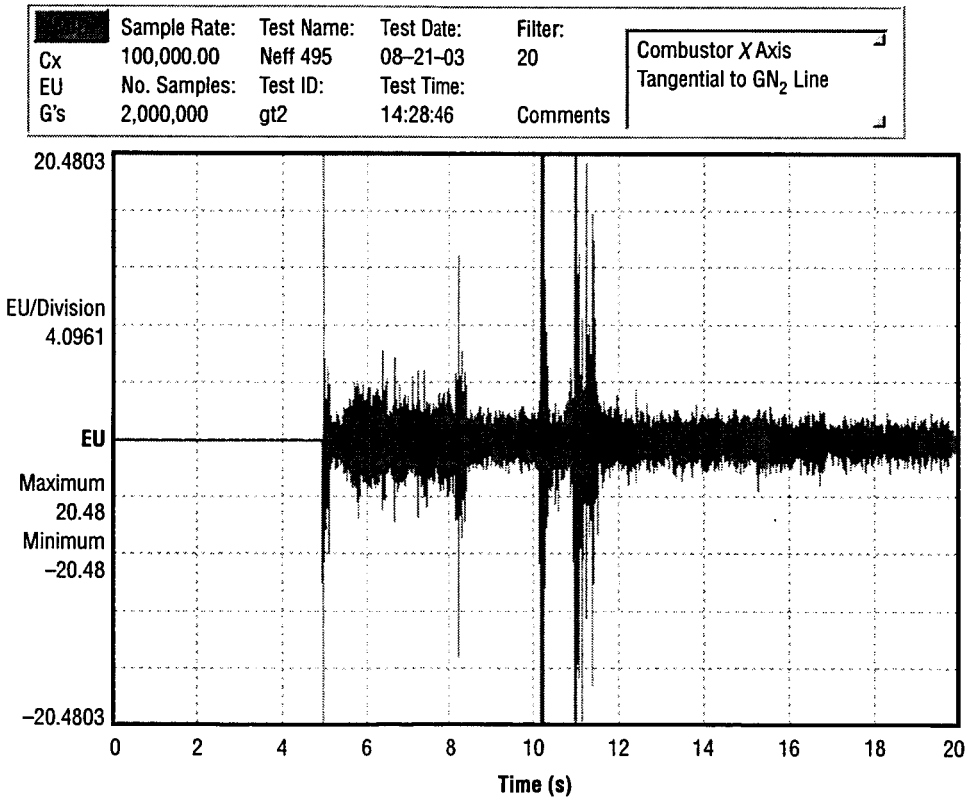

Fig. 11. Flight replica hot-fire accelerometer time series data.

These data show that the first 3 s of this test following the ignition impulse were nominal. However, as the rocket strained to lift itself, stresses induced by the off-axis umbilical resulted in structural bending and feedline failure. The rocket finally fell over and impacted the launch frame several times. These impacts on the launch structure are shown in Fig. 11 as sharp impulses in the accelerometer data 3-6 s after ignition. Although bent, the feedline tubes continued to support combustion by supplying propellant and lox for some time after that.

Figure 12 is a frequency spectrum of ~1 s of data taken from the dynamic data shown in Fig. 11. This spectrum shows the frequencies dominant in the combustor undergoing steady combustion, following the ignition impulse and before the first impact on the launch frame. Similar data exist for three channels each on the combustor, lox tank, and gasoline tank.

These data have not yet been analyzed, but on first inspection, the second peak may correspond to the first organ pipe mode of the combustor, which is 12 in long. A frequency of ~950 Hz would be expected for an open-ended organ pipe given a speed of sound of 1160 m/s and length 0.3048 m (12 in).

CONCLUSIONS

The reconstruction of Robert H. Goddard's first liquid-fuel rocket was not a trivial task, even for a team of experienced NASA propulsion engineers using state-of-the art materials and methods. It entailed a great deal of risk and should by no means be attempted by amateurs in an uncontrolled environment.

In the process of completing this project, we created a large amount of information, engineering drawings, hardware, exhibit materials, digital data, photographs, and videos. These resources will provide valuable insights to future students of Goddard's work and the history of liquid rocketry.

We also gained a great deal of respect for Dr. Goddard's skills, ingenuity, persistence, thoroughness, and methodical approach. We realized in retrospect the inherent personal risks he undertook using those components and combustion devices. We also realized he and his team were skilled technicians and excellent engineers in order to successfully accomplish their task.

Most of all, we learned that Dr. Goddard did not "tinker" with rockets. His 1926 design was based on indepth analytical techniques and verified by months, if not years, of thorough, methodical testing. Although some parts of Nell could have been better optimized, no component was superfluous, no part extraneous, no function irrelevant. The 1926 Goddard rocket is the epitome of liquid-fuel rocket system design at its simplest.

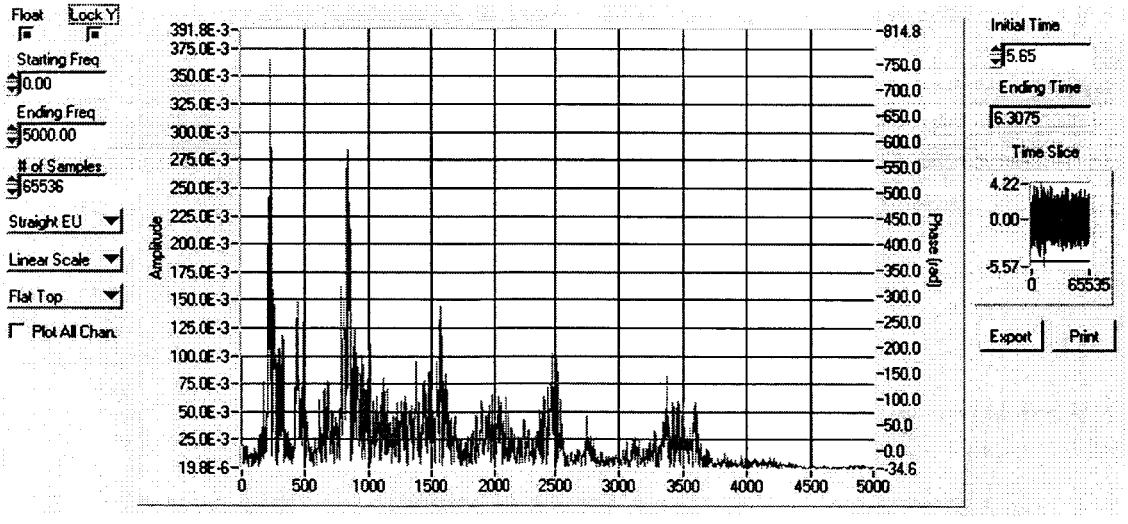

Fig. 12. Goddard combustor frequency spectrum.

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