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Reaction Motors (Thiokol) Family of Packaged Liquid Rocket Engines

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An archival paper is presented on the development and production by the Reaction Motors Division of Thiokol Chemical Corporation of the LR44-RM-4, LR58-RM-4, and LR62-RM-2 packaged liquid rocket engines. These factory-filled units were the only significant use by the United States of liquid propellant technology for airborne tactical missiles. The LR58 and LR62 were in worldwide use by the U.S. Navy and U.S. Air Force in the 1960s and 1970s, with some 50,000 having been produced. Total program costs in 1965 dollars were $120 million. These robust units were used without restrictions on flight-carrying cycles, catapult launchings, or carrier landings, with a recorded functional reliability of the LR58 at 90% confidence level of 0.9978. Commencing with early work in 1957 a review is made of the sequential programs and the technical and operational hurdles overcome in such novel designs. Brief insights are provided into the events that prevented further development of the family.

I. Introduction

As WORLD War II came to an end, a concentrated effort was made to absorb German rocket technology and encourage skilled personnel to find a new home in the West. Among the captured records was evidence that the Germans had been experimenting with small tactical rockets using storable propellants with nitric acid as the oxidizer. The Naval Ordnance Test Station at China Lake, California became interested in this effort and in the late 1940s designed a 5-in. system using the German technology. An uncooled chamber and nozzle were used with solid propellant pressurized liquid tanks with pistons. An unusual feature was the provision of liquid propellant mixing by means of a hot-gas bleed from the pressurizing grain. Although a number of problems occurred in this limited program, the test results were promising.

By the early 1950s, Reaction Motors, Inc. (RMI) had produced successful liquid rocket engines in the XLR-11 series for the Bell X-1 and the Douglas D-558 aircraft using liquid oxygen and alcohol as the propellants. A larger engine for the Viking missile was in the flight stages. The company also had considerable development experience and limited production of systems using white fuming nitric and mixed acids with inert gas pressurizing or turbo pump feed.

Having access to the China Lake results, Reaction Motors began to explore storable systems of this type and in 1952 received one of three feasibility contracts awarded by the Navy. The strengths and weaknesses of the China Lake unit were reviewed and the geometric limitations of the piston feed were noted. The hot-gas mixing injector was particularly attractive because it might permit a much wider range of liquid orifice arrangements than the usual shower head or impinging jet. A larger unit would enable much more robust parts to be constructed and might lead to a regenerative cooling system for the thrust chamber. Ordway [1] noted that the conclusion was reached that a bipropellant combination using a liquid oxidizer and a liquid fuel would be feasible for a storable system subject to the solution of three problems: 1) the selection of a propellant combination and tankage construction material suitable for long-term storage when hermetically sealed, 2) the choice of a compact energy source to pressurize and expel the liquids, and 3) the choice of an injector and initiation device that, although being robust and readily producible, would enable a high performance to be achieved.

These choices were conceived to be solved by a unit featuring red fuming nitric acid (RFNA) as the oxidizer and unsymmetrical dimethylhydrazine (UDMH) as the fuel stored in a high-strength aluminum tank shell. This propellant combination is hypergolic at all temperatures anticipated in airborne or ground service. A solid grain of double base or other composition would pressurize the system. A factory-loaded unit was anticipated, handled as a round of ammunition, and initiated by an electrically fired igniter for the pressurizing grain. The basic elements of such a system are shown in Fig. 1.

It is surprising that the initial criteria sidestepped the daunting possibility of pressurizing the liquids directly by hot gases from the grain. Pressurizing at 1000 psi with a gas at 2500°F is not a laboratory exercise. It was not known if the fuel-rich hot gas from the grain would react with the oxidizer to produce an unstable or explosive condition. It is unlikely that the omission of pressurizing considerations in the criteria was intentional. Perhaps it represented no more than the willingness of engineers to conduct experiments rather than enter an academic discussion for which they were ill-equipped.

Early in 1953, Reaction Motors, Inc. provided funds to design and build a workhorse unit embodying these features. The Navy funded some limited experiments in direct gas pressurizing and hot-gas injectors and later underwrote additional firings of the company unit. The initial workhorse was designed for 4000-lb thrust and a running time of 3 s using RFNA as the oxidizer and isopropyl alcohol as the fuel. A regeneratively cooled chamber was provided, operating at approximately 600 psia. The unit was 9 in. in diameter and was of 347 stainless steel with mechanical joints. Both liquid and gas seals were commercial O-rings with acid-resistant grease for added assurance on the oxidizer side. The pressurizing grain was of the double-base composition OGK with a flame temperature of 2940°F. Four annular grains with bonded outside inhibitors were used to give an essentially constant burning rate. The hot gas from the solid propellant impinged directly on both fuel and oxidizer without pistons and with a minimal diffuser to resist coring on the fuel side. The Hercules Company provided assistance in the choice of the grain composition and generously gave access to their wide experience in double-base propellants.

Because no more than $7000 was available from company funds, the prototype was a "can do" project in every sense of the word, with a sizable contribution by management personnel. The writer provided the design layout and the detail drawings for manufacture. Being on the indirect payroll he was the least expensive draftsman available. M. E. Parker, then Chief Project Engineer, and the writer

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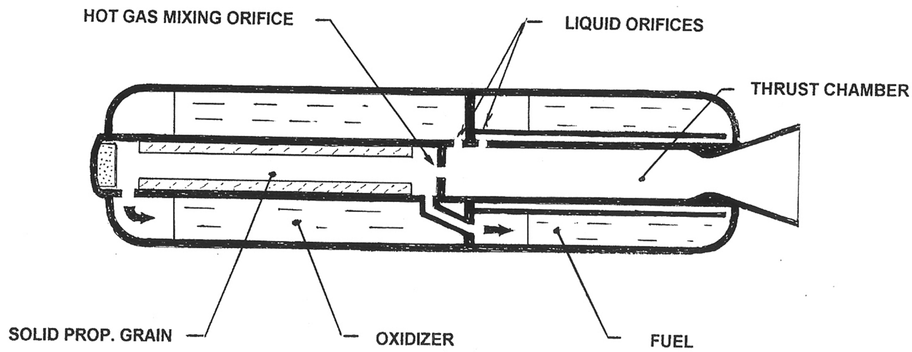


Fig. 1 Packaged liquid rocket engine: system elements.

put together the first mechanical assembly and inserted the solid grain components with a black powder igniter. The initial firing was conducted in the Reaction Motors A area at the U.S. Naval Air Rocket Test Station (USNARTS) facility at Lake Denmark, New Jersey.

Upon ignition in the first test there was a very rough run of about $\frac{1}{2}$-s duration accompanied by much smoke and acid fumes. On examination it was found that in the first few milliseconds of combustion a number of the oxidizer injector retainers had been pushed back into the tank, resulting in excessive oxidizer flow. Although the oxidizer/fuel (O/F) ratio would have been at least 12:1, combustion was sustained. The metal parts survived this adventure, and after minor modifications, subsequent tests were uneventful with thrust and running time were achieved. An examination of the data showed consistent solid grain and tank pressures without peaks or obvious abnormalities. During 1954, additional firings were made under Navy sponsorship with detail improvements in the solid grain configuration and a more professional means of ignition using a metallic oxidants igniter and booster. The thrust was increased to 5000 lb at a chamber pressure of 650 psia. This is the unit shown in Fig. 2. There is recollection that tests were also made with UDMH as a fuel, but records now available do not confirm this.

In the prototype unit the injection arrangement consisted of two sets of holes arranged radially around a precombustion chamber with a single hot-gas mixing orifice in the rear face. Aluminum burst disks under each liquid orifice set were supported before firing by a cylindrical slide. Upon ignition the slide moved aft about 1 in. under the differential pressure, and in that position the disks became unsupported and immediately popped open. Although this scheme did work, a much less precarious arrangement was quickly introduced by having the slide shear open the orifice closures. This arrangement, which was portrayed in the initial patent application, proved to be eminently successful and was retained in all future units. Figure 3 illustrates the slide operating function with the slide fully aft,

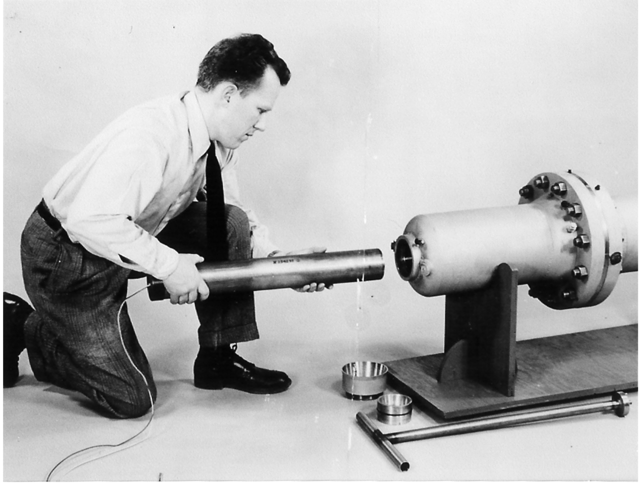
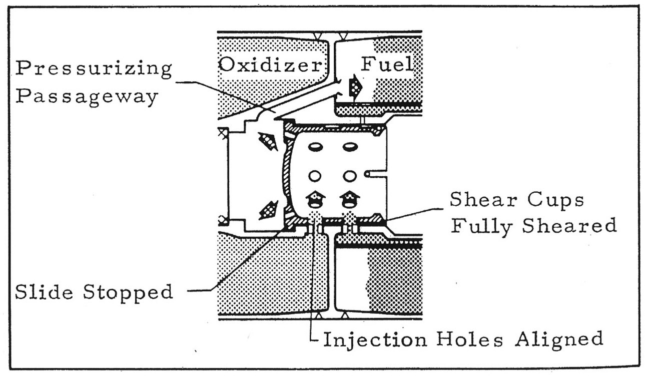


Fig. 2 Prototype unit (Sam Bell inserting grain).



Shear Slide Fully Actuated and
Liquid Propellant Flow Initiated

Fig. 3 Shear-slide operation.

exposing the fuel and oxidizer orifices. On the hot-gas side of the upgraded unit the initiation cycle consisted of bursting coined annular rings of 3000-series aluminum alloy. Other than the first few milliseconds of operation, the gas pressure gradient across the entrance was small and of little consequence to the stability of the system. The performance of the grain and the sizes of the hot-gas bleed and liquid orifices provided the fundamental control elements of the system. The grain running conditions were on a plateau in the burning rate/pressure curve and thus removed from asymptotic increases that would have been destructive.

In the Navy-funded exploratory tests, hot-gas pressurizing runs were made with OGK[†] and AGK compositions at tankage pressures up to 1800 psi, confirming that consistent results could be expected within reasonable temperature firing limits. There was some concern that the fuel-rich gases from the propellant grain might cause an excessive reaction with the acid oxidizer. High pressurizing "efficiencies" did confirm that a reaction with the acid was occurring, the more fuel-rich AGK composition having higher numbers than OGK. Pressurizing with UDMH fuel gave results not distinguishable from those with water. Tests with the hot-gas mixing injector showed that combustion was supported with a number of orifice arrangements and gave hope that good combustion performance would not be dependent on a highly contrived injector design.

II. Design Considerations for Safety and Reliability

In the initial design considerations for a flight unit, much thought was given to the long-term storage of propellants in aluminum tankage. By the mid 1950s, there was ample industrial experience with welding high-strength aluminum alloys in the 6061 family. With a 0.1% tensile proof strength of 40 ksi, the 6061T-6 material appeared to be well suited for tank shells with pressures of 1200 to 1500 psi. Limited experiments quickly convinced RMI that, rather

[†]AGK, OGK, and HDP are designations for particular double-base propellants. The letters are not acronyms for chemicals in the compositions.

than attempt to weld in the T-4 condition and then heat-treat the entire assembly, it was preferable to weld in the fully aged T-6 condition. The weld strength penalty was small when compared with the big advantage of improved dimensional stability. The capability of making the tankage from extrusions or forgings gave confidence that hoop stress joints could be avoided, the welds being placed in the more modest axial direction.

A greater challenge was presented in considering corrosion resistance and the effects of vapor pressure during high-temperature storage. Some data on long-term corrosion with nitric acid were available, although these were centered largely on white fuming nitric acid in low-strength aluminum alloys such as the 1000 and 3000 series. Storage temperatures were also less demanding than those of military specifications. Considering such data as were available, RMI became convinced that the 6061 aluminum family could be used with RFNA and that corrosion losses would not exceed 0.001 in. linear in five years under typical storage conditions. There was concern that even a modest loss might cause aluminum oxide debris to accumulate and restrict the orifices. Eventually, such fears were shown to be unfounded. The availability of red fuming nitric acid with a 0.75% hydrogen fluoride inhibitor (IRFNA) added greatly to confidence that a suitable system could be designed. It was demonstrated that with IRFNA in an application of this kind, vapor pressure, as such, is not of significance. Upon filling the tank, the inhibited acid will decompose to a pressure higher than that of the vapor and remain at that level. With a tank ullage of 2%, the decomposition pressure rose to 40 psia or so and then suppressed further increases. With ambient temperatures as high as 200°F, vapor pressure considerations were not limiting on the fuel side with UDMH or with the mixed amines used later. Storage safety was enhanced by avoiding welded joints separating the fuel from the oxidizer. In every design, the central header separating the liquid propellants was a substantial aluminum forging.

Other than the configuration and structural requirements, it seemed likely that the design specification would be one of extreme simplicity and broadly extrapolated from solid propellant practice. Although both the Navy and the contractor had mental images of the expected performance and safety considerations, data were not available to write a definitive document. However, this very lack was the catalyst at RMI for earnest thought on how to provide an abuse-resistant system that would have a failure rate almost two orders of magnitude better than that of typical liquid rocket systems of the day. There was also the consciousness that one catastrophic failure, and particularly one involving a loss of life, might bury the program. The design concept that evolved for the first unit (LR44) and for all subsequent units can best be described by quoting from a paper by the writer in 1964 [2]. The basic elements of the design philosophy were as follows: "1) extreme simplicity in functional and structural design, 2) application of large operating force margins for each of the functions of the engine starting cycle, 3) control of the dynamic level of the system by simple elements, and 4) absence of servicing, maintenance, and field checking."

A. Simplicity

In the matter of simplicity, it was recognized that to be successful, the liquid unit must compete with solid propellant motors that might contain as few as five or six major components. A liquid engine was visualized that would not contain more than 10 or 12 assemblies. The operation of a shear slide to control the starting function by one moving component was undoubtedly the prime element that permitted the RMI approach to succeed when more complicated approaches might have failed. The provision of hermetically sealed tanks without elastomers contributed to the high reliability and long life. The achievement of extreme simplicity will be recognized as a particularly difficult design task because the integration of functions usually denies the opportunity to test components independently.

B. Operating Force Margin

Large reserve forces were provided for each of the fundamental operating elements in the starting cycle. An igniter booster was used to sustain the flame for 110 ms and provide the pressure and the temperature for the grain to ignite. Fuel and oxidizer burst bands were set to burst at 150 to 170 psi, and the gas pressure available at the −65°F condition was close to 1000 psi. The force available to move the slide and shear the cups in the injection area was more than twice that required under the worse tolerance condition. The gas entry to the fuel and oxidizer tanks was required to be reliable under both storage and operating conditions. The storage pressure in the oxidizer tank at 160°F could be as high as 103 psia. The band, therefore, was designed in the manner of a supported check valve with a nominal breaking pressure of 160 psi in the flow direction and 900 psi under storage conditions. Although the fuel side storage conditions were less severe, the burst band was of the same style.

C. Dynamic Control Margin

The dynamic control level at which an engine of this type operates is a function of the output of the solid propellant pressurizing grain and the flow across the liquid orifices and the gas flow across the gas entry and bleed passages. If the pressure drop across the gas entry passages were to be a significant factor in the equilibrium, the dynamic pressure level might be precarious. By keeping the pressure drops in secondary passages at a low level, the bleed orifice(s) would be controlling. Wide variations in the physical dimensions of the upstream gas passages and burst elements did not result in a significant variation in the running level.

D. Absence of Servicing and Field Maintenance

A common criticism of liquid rockets had been the problem of the servicing required at the final launch station and a consequent loss of reliability. In the initial design of the packaged liquid units, it was well understood that no filling or servicing should be required throughout the life of the unit. However, this philosophy was extended to the concept that "no servicing is possible." Practical experience in service applications will recognize this feature as one of prime importance in maintaining reliability. Custom will show that if it is possible for operating personnel to carry out a service checking function, that operation will be carried out regardless of need. An inevitable degrading of reliability will result. The units, therefore, had no pressure taps or other access points of any kind, the only function that could be checked being the igniter electrical circuit. Engines subject to acceptance tests at the home plant were adapted readily to measure tank and gas generator pressures, but chamber pressure could not be measured on any production unit.

These design choices stood in good stead throughout the development of all units and later production. None of the basic concepts needed to be changed due to later events.

III. Initial Development of the LR44 Engine

In 1956, RMI responded to a request from the U.S. Navy Bureau of Aeronautics to develop a packaged liquid rocket engine for the Sparrow III missile. The contract was received in December of that year. At the time, the solid propellant motors in use in Sparrow I and Sparrow II were outdated and more advanced units were experiencing difficulty in development and in performance at the ambient temperature expected when carrying the missiles at high Mach numbers. An outline specification was issued for a liquid unit of 9000-lb thrust with a total impulse of 16, 550 lb · s. The outer shell would be the rear missile structure with attachments for the fixed tail fins. Storage limits for the unit were set at −65 to +165°F and firing limits of −40 to +180°F. Before the project commencement, the total impulse was increased to 17, 000 lb · s and a 6-h soak at 200°F was required before firing. The low firing limit was changed to −35°F. The high-temperature limits would permit carrying the missile close to the after burner or tailpipe of the aircraft. The unit was designated as LR-44-RM-2.

The detail design of the LR44 did not raise any unforeseen problems. The area under the missile tail fins was used for additional fuel space and a regeneratively cooled chamber with a chamber/nozzle area ratio of 1.4 was provided. The nominal chamber pressure was 1100 psi. A cooled conical nozzle of 5.0 expansion area ratio was used with a copper throat piece secured by a trapped snap ring. The chamber, nozzle, and throat piece were protected by zirconium oxide coating (Rokide Z), typically of 0.040-in. thickness. Aluminum alloy 6066T-6 was chosen for the tankage shells and major components, permitting a stress level about 25% higher than 6061T-6 without compromising corrosion resistance. Although there was little experience in welding the 6066 alloy, it was quickly proved that procedures already in place for 6061 would be satisfactory for 6066.

IRFNA was retained as the oxidizer and a higher-density mixed amine fuel was substituted for the UDMH of the proposal. The fuel consisted of 40.5% UDMH, 50.5% diethylenetriamine, and 9% acetonitrile. This provided a specific gravity of 0.865. Although classified as a class-B poison, the fuel was, in fact, a skin irritant, requiring care but not exceptional handling procedures. An O/F ratio of 3.0 was chosen for maximum density impulse. In view of the high ambient temperature requirement, the composition AGK was initially chosen for the pressurizing grain. However, high-temperature tests showed some grain decomposition, which could lead to a runaway burning rate. OGK composition, by that time redesignated as HDP, was substituted. A keyhole perforation with a bonded outside inhibitor gave an essentially constant flow rate. Although satisfactory in pressurizing, the HDP grain exhibited radial cracking when cycled over the temperature range. RMI chose to modify the perforation by slotting the keyhole and the inhibitor to reduce radial stresses under temperature gradients. This simple modification, which permitted unlimited thermal cycling and safe operation of the grain up to 200°F, was patented in the United States and in many foreign countries (Fig. 4). Ammonium perchlorate grains with a star perforation were also tested but, in view of the success with HDP, were not pursued.

The total impulse of a liquid rocket system is critically dependent on outage control to ensure that each liquid runs out at the same time. With the LR44 running time of only 2 s, the detail design of the liquid orifices was critical. Experiments to determine the discharge coefficients of both sharp-edged and radius-edged orifices were disappointing and gave promise of trouble in quantity production. The discharge coefficient problem was solved by making engine sets of both fuel and oxidizer orifices that could be preselected under full-scale pressure testing with water. Although the absolute flow might vary slightly, the relative level was accurately controlled. With an O/F ratio of 3.0, it was important that the injector tolerances favor the oxidizer side to avoid skewing the total impulse loss should the fuel run out first. Data are not available to show how successful the design of the LR44 was in this respect, but an assessment of the later LR58 can be made by examining the performance and outage diagrams in Figs. 5 and 6.

Development of the LR44 commenced briskly with the construction of mechanically jointed workhorse units in both aluminum and steel with the chamber and other functional parts closely simulating the flight unit. A chamber performance rig also was constructed to measure specific impulse and assess the ability of various injector and combustion chamber configurations. Early testing indicated that the volume of the combustion chamber needed to be increased and a design change to a chamber/nozzle area ratio of 1.8 was made. It was shown, also, that by restricting the exit from the

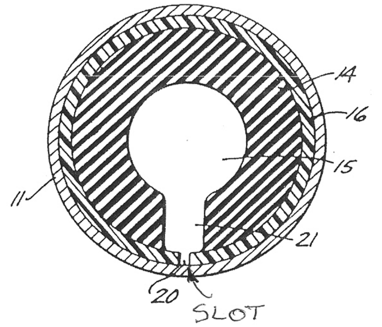


Fig. 4 Solid grain perforation.

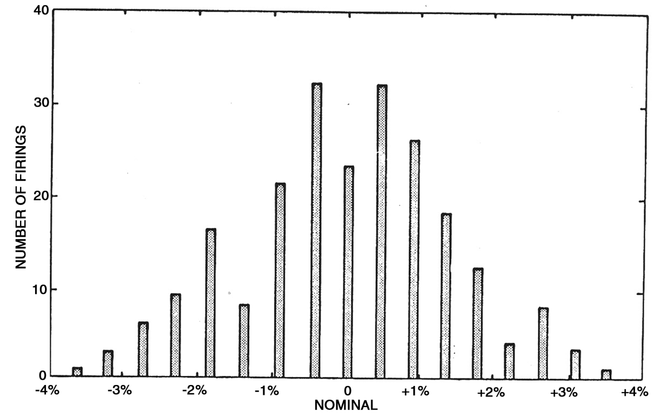


Fig. 5 Variation in total impulse for 160°F firings of the LR-58-RM-4.

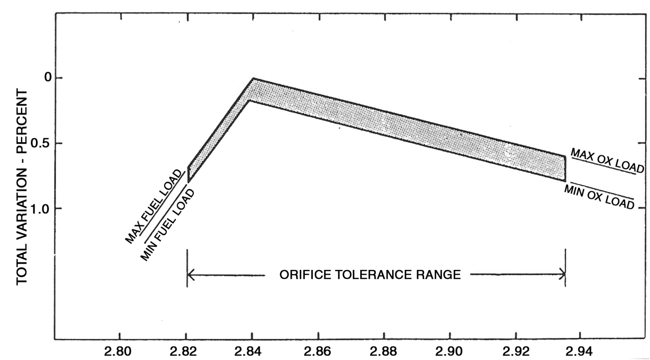


Fig. 6 Theoretical variation in total impulse due to orifices of the LR-58-RM-4.

shear-slide precombustion area, a performance very close to theoretical could be obtained. However, erosion of the metal parts occurred sporadically and although this was not damaging physically, it did cause measurable performance variations. The precombustion restriction, therefore, was backed off of to reflect a specific impulse of approximately 225 $lb \cdot s/lb$, at which level consistent results were obtained. The regenerative chamber and nozzle worked well and no changes were needed to optimize cooling. That the cooling margins were large was demonstrated later in development when successful runs were made at a propellant temperature of 250°F. To reduce the possibility of hot pressurizing gases impinging directly on the outer aluminum shell, annular diffusers of 0.032-in. stainless steel were located over the gas entry holes in both tanks. This reduced coring by the hot gases and turned the flow to a more axial direction.

Development progressed smoothly except for failures in the oxidizer tank. The original central boss had to be increased in size to avoid "umbrella" rotation and releasing the end cap. Of a more serious nature were structural failures of the oxidizer tank head due to a weakness in the igniter area. Replacing the weldment with a single forged head solved these problems without adding significantly to cost. A careful dissection and examination of preflight units showed that after shutdown the structural integrity of the shell to sustain missile flight loads was not compromised. In the development phase, there were 137 runs of workhorse units, 69 runs of the combustion rig, 167 firings of the pressurizing grain and igniter, and 46 firings of the flight type unit [3].

Preliminary flight rating tests (PFRT) were based on the U.S. Navy's Bureau of Ordnance specification ORD-X-W3a, which was typically used for solid propellent motors, with 31 units fired and two subject to hydrostatic testing. The total impulse of the LR44 was close to 17,000 $lb \cdot s$ over a temperature range from 0 to 200°F and fell off approximately 8% at the −35°F condition. The starting interval from ignition to full thrust varied from 180 ms at −35°F to approximately 40 ms at the high-temperature limit, both of these figures being acceptable for the anticipated launch conditions. Of the

31 PFRT units fired, eight were at 180°F, eight were at −35°F, and the others were at normal ambient temperature. Included in the group were four units subjected to catapult takeoff and carrier landing shock followed by a simulated flight cycle up to 28 *g* on a sled at the B-4 track at China Lake, California. Positive gravity starting conditions on the sled were uneventful, but negative gravity starting resulted in detachment of the fuel cooling baffle followed by local burnouts of the fuel tank approximately 2 s after shutdown. This problem was cured by a more secure attachment of the baffle and subsequent runs were without incident. With the successful conclusion of PFRT, the LR44-RM-2 was ready for initial flight tests.

Because the flight design was essentially unchanged, the qualification tests were run concurrently with the PFRT. Forty-four units were fired in qualification: 13 after the 6-h 200°F exposure, 6 at ambient, 6 at 160°F, and 19 at the −35°F lower limit. Vibration, jet pattern, shipment freight, drop tests, and storage tests were included following the ORD-X-W3a pattern. These tests were completed satisfactorily.

Concurrent with the LR44 development came a number of specialized tests to increase confidence in flight safety. Units were normally tested in the nozzle down position, equivalent to 1 *g* forward in flight. Thus, the hot pressurized gases entered into a free ullage space at the head of each tank. To assure that satisfactory starting would be obtained under flight carrying conditions, units were fired in a horizontal attitude and nozzle up and fired up to 3 *g* sideways in testing on a centrifuge. Starting and pressurization were within expected parameters and both propellants were completely expended. Six-foot drop tests, which were required not to go propulsive, caused minor damage and enabled units to be fired within the specification acceptance limits. Preflight configuration engines were used for these tests.

The PFRT units were made on preproduction tooling with conditions close to quantity manufacture. Although machining operations could be specified with some confidence, automatic welding operations required development, with electrode feed rate, gas flow, and rotational controls fully specified. Structural integrity of the shells was confirmed by hydrostatic testing with water at 1.5 times the pressure at the high ambient temperature. A seemingly unusual choice that was to pay excellent quality dividends in subsequent production was to use only trained welding operators rather than welders certified under military standards. The intent was to ensure that each weld would be controlled by a defined machine process and not permit unrecorded adjustments by individual craftsman that could compromise quality. If a specified procedure could produce substandard welds under any condition, that fact was to be discovered during manufacturing development, when the tolerances of the process could be explored. This approach served well and no structural failures occurred during qualification testing or later production.

Flight tests with PFRT level units were carried out on Sparrow II missiles at Point Magu, California. The six tests were without incident with respect to launching, but in each case the missile behaved erratically and in some cases diverted wildly from the expected flight path. Telemetered data suggested that the problem was due to high acceleration or shock and vibration beyond the capability of the missile electronics. What was not known to the engine contractor at the time was that the Sparrow II missile had a history of ringing of electronic tube components and that the system had been carefully tailored to the environment of the existing solid propellant motor. The LR44 problems seemed to be related to the starting phase, because the flight excursions occurred early in the run. Although there was a discernible difference between the running vibration of the two systems, the amplitude was similar and in each case there was much "noise." Because of the high thrust required by the LR44 specification, the missile acceleration was much greater than with the solid propellant motor.

RMI measured the starting conditions on the ground by test firings of a complete Sparrow missile suspended by bungee cords to provide about 24 in. of free flight (Fig. 7). High-frequency pickups at various missile locations confirmed that upon starting there was a shock of 400 to 600 *g* with a base of less than 1 ms. This was damped out in seven or eight excursions, some of which were significant in amplitude. Although there was some excitation upon the igniter firing, the large shock appeared 18 to 20 ms into the run and suggested a mechanical or hydraulic event. It appeared that the shock occurred too late to be due to the slide movement. Testing confirmed this and indicated that the cause was hydraulic shock due to the oxidizer being slammed into the central header at the initial pressurizing.

Fig. 7 Tethered test of the Sparrow missile with the LR44 unit (Lake Denmark, New Jersey).

IV. Development and Qualification of the LR44-RM-4 Unit

In the fall of 1959, the Navy redirected RMI to redesign the LR44 as needed to provide an acceptable starting condition and to lower the nominal thrust to 5500 lb. This unit would be designated LR44-RM-4. By that time, some 200 of the original engines had been constructed. The thrust change was accommodated simply by dropping the chamber pressure to 700 psi and resizing the liquid orifices and the nozzle throat piece. A minor redesign of the grain provided the reduced flow for the longer burning time. The metal parts remained unchanged except that a large conical baffle was located 8 in. aft of the central header to reduce oxidizer slosh in starting. The baffle was sized by ad hoc shock testing in a workhorse unit. The igniter booster package was also reduced substantially. The engine redesign, development, and PFRT testing was completed in six months.

The nominal total impulse of the −4 unit was 16,300 lb · s., the longer running time being accomplished without adverse effects to the chamber or the shells. Tethered tests showed that the starting cycle was much improved with greatly reduced shock. The Navy was satisfied with the results and the LR44-RM-4 was committed to PFRT testing. The Sparrow II was again used for flight testing, which was accomplished without incident. Although there were none of the wild excursions as on the earlier flights, there were some flight abnormalities that the missile contractor was quick to lay at the engine manufacturer's feet. However, because the inconsistent behavior appeared late in the flight, the Navy was convinced that the problems were unrelated to the engine. Although the Sparrow III missile, with its robust electronics package, was in short supply, it seems illogical that it was not used for these tests. To say the least, the Sparrow II, with its own liabilities, was not a representative vehicle for the LR44. A launch in one of these flights is shown in Fig. 8. The smokeless exhaust is notable and typical of all of the packaged liquid engines.

Upon completion of qualification testing, the LR44-RM-4 was accepted and committed to quantity production. At this point, the

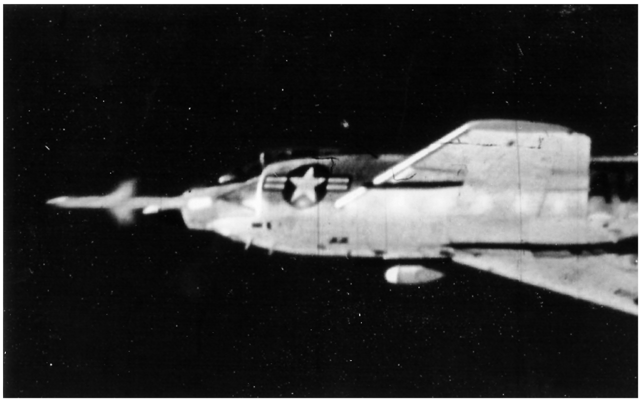


Fig. 8 Launch of the Sparrow missile with the LR44 unit.

engine was approved by the Navy as the prime contractor but was by no means acceptable to the missile contractor. In fairness to Raytheon, it can now be seen that the liquid unit did not fit into that company's plans for a missile with worldwide use. Despite the factory-loaded features of the LR44 and the considerable safety margins applied by RMI, it could be anticipated that any acid-based system would meet with resistance from NATO nations and from other users worldwide. Although not stated explicitly, it is probable that Raytheon also had doubts regarding the long-term safety of the liquid system. That such fears would later prove to be unfounded does not imply that they were unreasonable at the time. That the missile contractor did not press the Navy for changes when the LR44 specification was first written may have been due to a conviction that the liquid system would not go beyond the development stage.

In 1958, the Navy had turned its attention to the possibility of a more modern rocket system for the Martin Bullpup A missile (ASM-N-7a). A packaged liquid rocket engine (later designated LR58) would provide a smoke-free exhaust for the visually guided weapon and promised a most robust unit with freedom from restraints on flight carrying cycles. Because of the priority of this program, the Navy, at its convenience, terminated production of the LR44 after some 800 units had been completed. This freed Reaction Motors' manufacturing operations for a larger and more urgent task and conveniently avoided the need to apply pressure on Raytheon to accept the LR44 unit. However, the LR44 provided most useful lessons in design and manufacturing and these smoothed the way into the early production of the LR58.

V. Safety Considerations and Battle-Damage Testing

Although the LR44s were now homeless, the units did represent a most useful pool for a number of specialized tests with respect to shipboard handling and battle damage. Gun fire tests, drop tests, and handling safety experiments were conducted and confirmed that the claims of abuse resistance were well-founded. The Navy set up a formal long-term storage program, withdrawing four to six units every year to determine that performance was within original limits. After five years of storage, including 15 months at 120°F, LR44 engines remained within the original acceptance limits and showed no indication of deterioration. These tests were continued in later years, but the writer has been unable to confirm the results.

To provide confidence that there would be little risk of auto decomposition of the fuel at higher temperatures, some of the prototype LR44 units were subjected to tests above the specification temperature limits. Firings were made without incident with both liquid propellants at 220°F and in one case at 250°F. Other than a propellant filling adjustment to ensure that there would be adequate ullage at the high temperature, the units were standard in all respects. Because the solid propellant grain could not be safely run above 210°F, a nitrogen bleed into the grain cavity was provided for cooling during these special tests.

Late in the development of the LR44 came an intense effort by the Navy to convince both operational and safety personnel in the services that packaged liquids would compare favorably with existing solid propellant units. Some old hands had been so negative as to assume that a nitric acid leak would bore a hole through the deck! Service personnel were encouraged to visit the test stands at RMI, which had been used with acid systems for many years and which showed no obvious deterioration. Propellant fire experiments were conducted with various degrees of fire extinguishing. Because both propellants are miscible with water, instructions were given to use generous amounts of water as the primary fire-fighting means. RMI conducted open cup tests with up to two gallons of each propellant poured directly into the other. A most vigorous fire would ensue, which could be controlled by a direct stream of water. Contrary to anticipation based on high school chemistry, no obvious difference could be seen with respect to which propellant was poured into the other.

The Navy conducted battle-damage testing by firing 0.50-in. and 20-mm armor piercing rounds into loaded units through the individual tanks and through the oxidizer tank and solid grain. The units did not go propulsive, although fires often resulted. Drop tests were conducted on the LR44 and extended beyond the specification limit. A unit that had been dropped 6 ft could still be fired safely and meet the production acceptance test performance. Bonfire tests using six LR44s at a time did not result in propulsion. These encouraging results did much to allay fears in the services and laid the ground work for acceptance of packaged liquids when the units were qualified.

The services did require that transport aircraft, bunkers, and storage spaces on ground and shipboard be equipped with ionizing type monitors to sound an alarm should acid or amine fumes be present. In theory, such devices were supposed to discriminate propellant odors from the more common ones such as kerosene. The reliability of these devices was most inadequate and remained a source of annoyance throughout the entire service deployment. Onboard ship, there was often the suspicion that the monitors were recording mess room smells rather than those of a more compelling nature. In no case was a leak found.

For explosive classification, the Navy chose to rate the LR44 and all later units as group II, equivalent to class B under Interstate Commerce Commission rules. The category is considered a "flammable hazard" and as such was typical of solid rocket motors and smokeless powders in bulk. Experience later justified this choice. Transportation restrictions and quantity distance requirements for all three engines were manageable and did not require unusually remote storage or loading facilities. In much later production of the LR62 engine, the loading facility at Lake Denmark, New Jersey was obliged to store more than 500 of those large units awaiting the arrival of Navy supplied shipping containers. State authorities did not challenge the hazard rating chosen by the service and no untoward incident arose in storage or transportation. Because of the robust construction, units in their boxes were handled confidently with conventional fork lift equipment and shipped in quantity by commercial road carriers and by air in military aircraft. Ammunition ships and other supply vessels carried large quantities of LR58 and LR62 units and remained at sea without restrictions.

VI. Performance Improvements and Scaling

Concurrent with the development of the LR44, RMI continued to examine larger systems and to bid on proposals as appeared to be appropriate. However, during the engine development period, important corporate and technical events occurred that were to have a significant impact on the future. From May 1958, Reaction Motors Incorporated was merged into Thiokol Chemical Corporation and became the Reaction Motors Division (RMD). Because it was then a smaller element of a large corporation involved in chemical technology and solid propellant engines, it is not surprising that the concepts of the larger constituency came to dominate corporate thinking. At that time, Thiokol was making significant strides in the improvement of solid propellant units in design and manufacturing. Also, the corporation had become a protagonist for large solid rocket boosters and work was underway on segmented units of truly

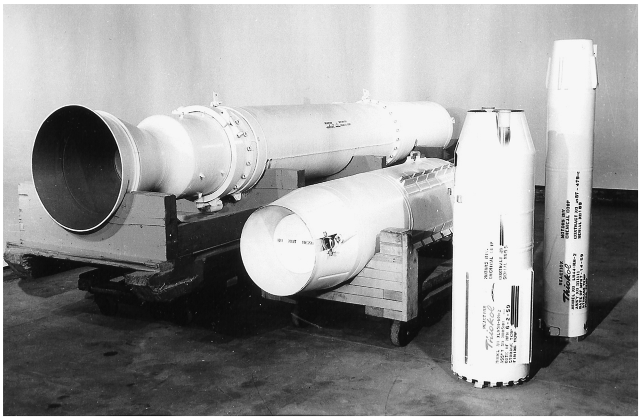


Fig. 9 Reaction motors family of packaged liquid rocket engines: 50,000-lb-thrust workhorse, LR62, LR58, and LR44.

monumental dimensions. Beyond the anticipated competition for corporate attention and finances, the earlier years of the merger went smoothly, but as noted by Ordway [1], the situation eventually deteriorated. At its core, RMD was on a radically different course from its parent corporation. This became particularly evident later when RMD came under corporate directors who seemed to find it hard to conceive of any application for a liquid rocket engine other than that of a controllable unit in space.

Late in 1957, RMI had commenced a company-funded project to make a packaged liquid workhorse of 50,000-lb thrust with a running time of 6 or 7 s. This was a scale-up of 6:1 in thrust and 17:1 in total impulse over the LR44 then in development. This is the large unit shown in Fig. 9. A conventional shear slide was used with aluminum shear cups and orifice retainers typical of a flight unit of that size. An uncooled ceramic-lined chamber was used, being redundant from an earlier program for the Bomarc missile. The chamber pressure was 450 psi with tank pressures between 650 and 700 psi. Solid propellant grains of HDP composition weighing 70 lb were provided by the Kenvil, New Jersey plant of Hercules. Because there were insufficient funds to pay for testing, Hercules agreed to provide six grains on a "best efforts" basis to perform as specified.

In November 1958, the complete unit was fired and performed as expected in thrust and duration. Total impulse was approximately $280,000\ \text{lb}\cdot\text{s}$. However, this venture into much larger units was viewed with concern by Thiokol corporate management as a possible competitor to the large solid propellant booster. No further testing of the large liquid unit was permitted (see Ordway [1]). However, the experience was of value when the LR62 system was proposed in convincing the Navy that a substantial scale-up from the LR58 would be feasible.

It had been recognized that the IRFNA mixed amine propellant combination might not be competitive with the more promising solid propellant combinations with respect to density impulse. This was particularly important in flight applications in which the aircraft geometry and ground clearances might dictate volumetric restrictions on the missile rather than weight. In a search for high-density propellant combinations, the RMD Research Department had investigated many possible fuels, including acetylene compounds that had not been previously synthesized. The usual oxidizer chosen was one of the interhalogen compounds such as chlorine trifluoride or bromine pentafluoride. With such combinations it was anticipated that an improvement in density impulse over the acid-amine system would be as large as 50% (Maier [4]). Overlooked at the time was the possibility of a much more benign combination using red fuming nitric acid at maximum density with a hydrazine-based fuel. This would have provided a density improvement of at least 25%. Such a system, with the inherent advantage of liquids in being able to better use the installation envelope, would have been competitive with metallic loaded solids. Later events would show that the neglect of these less venturesome propellant combinations was a most serious mistake.

Another area of interest was the use of thixotropic propellants to provide a gel at storage conditions and then change to a liquid under pressure. A gelled fuel, in particular, would provide a safety advantage under battle-damage conditions by reducing spillage. Thixotropes, also, might lead to the possibility of a fuel with metallic additives such as aluminum, which would increase both specific impulse and density. A number of the redundant LR44 units were operated with a mixed amine thixotropic fuel and performed normally, including some at an ambient temperature of −40°F The consideration of loaded thixotropic fuels did not proceed beyond the research stage and, in hindsight, suggests another area in which possible performance improvements were not pursued with vigor.

From 1959 on, a number of experiments were made using chlorine trifluoride as the oxidizer with a hydrazine-based fuel. Rig tests had shown that excellent specific performance could be obtained although accompanied at times by unpredictable erosion in the injector area. A few dramatic bursting failures of workhorse units gave a vivid reminder that, should a leak should occur, this propellant combination would be most unforgiving. Six LR44-RM-2 units were reloaded with chlorine trifluoride and a mixed hydrazine fuel and run at room temperature. Physically, these units were unchanged from standard production, the compromise in O/F ratio and outage being of minor consequence to the overall purpose of experience. Although the units did stay together on testing, severe erosion occurred in the injector area and there was evidence of an energetic reaction at the hot-gas entry into the oxidizer tank. Neither of these conditions would have been acceptable in a flight unit. The oxidizer tank activity was particularly discouraging because it suggested that the basic simplicity of direct hot-gas pressurizing might not be attainable with the interhalogen family of oxidizers.

VII. Development of the LR58-RM-2 and LR58-RM-4 Engines

In 1958, the Martin Bullpup A missile was in early service and propelled by a double-base solid propellant motor of a somewhat older design with a nominal total impulse of $18,000\ \text{lb}\cdot\text{s}$. The motor was enclosed by an aluminum structural shell to support the missile wings. The visually guided missile had a high reliability but the motor was plagued by limitations in the number of flight cycles and temperature limitations in use and storage. Within the existing system weight and dimensions, it seemed probable that a packaged liquid unit would give substantially increased total impulse and thus improve the missile standoff distance. The smokeless exhaust of a liquid unit also would improve visibility during the firing stage and assist in the visual guidance. In September 1958, Reaction Motors received a contract from the Navy to develop the Bullpup unit to be designated LR58-RM-2. The unit was to have a nominal thrust of 12,000 lb and a total impulse of $24,500\ \text{lb}\cdot\text{s}$. The unit tankage shell would be used to support the fixed wings of the missile and provide attachments for rail launching. The loaded weight of the unit was 203 lb. As with the LR44, IRFNA was chosen as the oxidizer with the mixed amine fuel MAF-1. A double-base pressurizing grain of HDP composition was selected.

The design was quickly underway and followed the LR44 in main features (Figs. 10 and 11). Although the electronic controls of the Bullpup missile were of a very robust character, care was taken to tailor the starting cycle of the engine. Provisions were made for a baffle in the oxidizer tank and the igniter booster was chosen judiciously from LR44 experience. The nominal chamber pressure was 950 psi with a corresponding propellant tank pressure of 1270 psi. Because it was necessary to provide space for flares to be ignited from the exhaust flame, the volume around the nozzle could not be used for propellants. An uncooled nozzle of a chrome copper alloy was protected by a coat of zirconium oxide (Rokide Z). The nozzle was bell-shaped with an axial exit and an area ratio of 5.50. As with the LR44, the tank shell and inner members were of the 6066 T-6 aluminum alloy. For shipboard safety, the LR58 was fitted with a "last-minute" side igniter inserted by a half-turn bayonet tool. Usual practice would be to insert the igniter when the aircraft began running up on the deck. The igniter could be removed by the same tool to

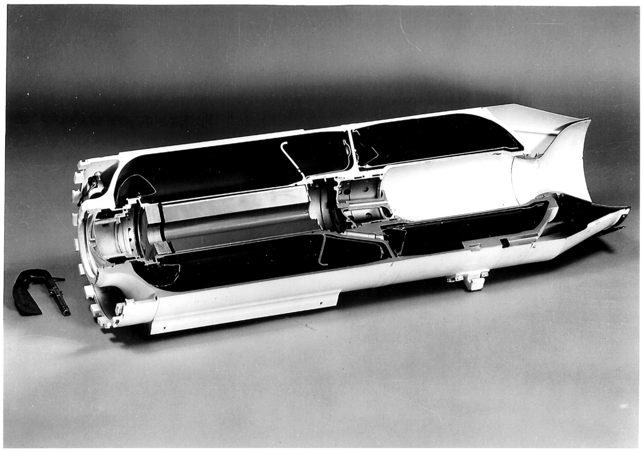


Fig. 10 Sectioned view of the LR58-RM-4.

provide a safe unit. This feature allowed aircraft on decks and elevators to be within 1 min of a "go" condition and yet completely inert.

Development of the LR58 proceeded without major hurdles and by the fall of 1959 PFRT testing was in progress. Because ceramic coating continued to be a manufacturing pinch point, much of the development testing was involved in determining the minimum thickness of the zirconium oxide protection for the chamber and the nozzle. The only significant problem with development occurred in the poor performance of the combustion chamber. A ceramic-coated central pintle was used as a restricter in the precombustion area to bring performance to the specification conditions. Although the total impulse was within limits over most of the temperature range, there was a significant falloff at the low-temperature limits. This was shown to be due to fuel starvation resulting from a high-pressure drop in the chamber cooling baffle. At −65°F, the viscosity of the MAF-1 fuel is close to 100 cP. Increasing the baffle gap solved this difficulty without compromising cooling under any condition. Testing over the temperature range provided sufficient data to write a meaningful acceptance test specification. Concurrent with the development, the Navy provided funds for production tooling and added to the complement of machine tools at the Bristol, Pennsylvania facility. PFRT units were built on production tooling, providing a valid assessment of the manufacturing approach for an expected delivery of 1100 units a month.

Flight tests began without incident but were followed by the most serious accident in the entire packaged liquid development. Upon launch from an A4D aircraft in the Point Magu area, a unit broke up during starting, resulting in a high-pressure burst of the shell while still on the launch rails. The aircraft was severely damaged, losing a large portion of the skin under the wing and most of the flaps on one side. However, the pilot was uninjured and, with remarkable skill, made a safe return to base. The debris from the engine was recovered and showed that a structural failure had occurred at the snap-ring groove in the central boss of the oxidizer header, the fracture then quickly migrating to the tank wall. Because static testing had gone well and there had been no reason to question structural integrity, such a serious accident came as a shock to RMD and to the Navy. A formal inquiry was set up and for a few weeks the LR58 program was hanging in the balance.

RMD had continued to investigate the welding of a number of high-strength aluminum alloys and at the time of the LR58 failure had demonstrated success with the 2014 T-6 alloy, using weld rods of 4043 material. This provided an increase in structural capability of 30% over the 6066 without an increase in weight. The company therefore proposed to redevelop the LR58, substituting 2014 T-6 for the original alloy without changing the metal sections. It was decided also to investigate the starting cycle of the engine and modify it if needed to reduce the strain application rate. It had been recognized that discontinuities in the structure might require special design care to permit stress redistribution. However, the failure was a reminder that the unit starting cycle could produce tensile stress application rates as high as 300,000 psi/s in some parts of the aluminum structure without allowing for stress raisers. Such conditions could not be simulated by hydrostatic testing.

The Navy accepted the contractor's proposals and redesign proceeded with the new unit now designated LR58-RM-4. The new structure provided generous stress margins over that of the earlier unit, and the welding of 2014T-6 proved to be amenable to quantity production with the process control disciplines already in place. PFRT testing of the −4 unit was followed by flight tests that were entirely successful. In the true tradition of the service, Navy pilots at Point Magu launched the missiles without complaint and the memory of the earlier failure passed quickly. Full flight qualification tests were completed without incident and early in the fall of 1961 the

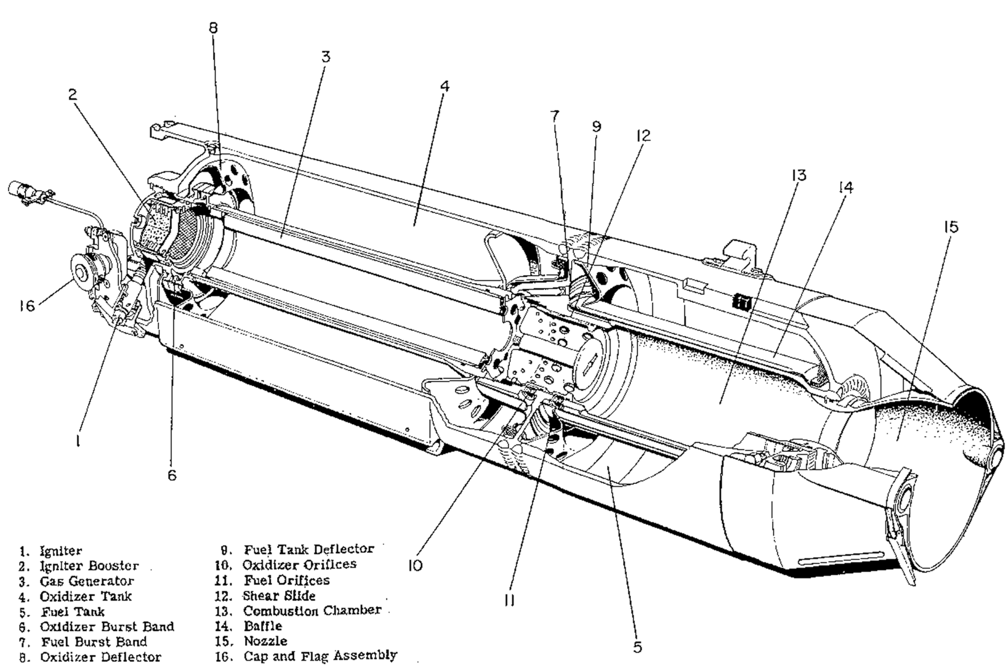


Fig. 11 LR58-RM-4 engine.

Navy made its commitment to the first buy of 4052 units, which was followed quickly by another for 12,421.

As in any one-shot device, considerable attention was paid to appropriate production acceptance test requirements to assure safety and reliability. It was decided to establish an arbitrary production lot of 300 units from which seven would be tested. One unit was subjected to hydrostatic testing at 1.55 times the high ambient tank pressure. Two others were fired at the high-temperature limits, two at the low-temperature limits, and two at room temperature. The conditioning of engines was accomplished in the test stand by box enclosures with commercial heating and cooling sources. Because of the robust nature of the LR58, it was usual to leave units unattended overnight when in the cooldown cycle. In view of the difficulties with the starting cycle of the LR44, tethered missile tests were initially included in the LR58 acceptance requirements, measuring the starting shock at four missile locations. Starting shocks of 120 g were typical and were well within the capability of the robust electronics of the missile. Eventually, such tests were discontinued. Out of each production lot, the local Navy QA representative made a choice of the units to be tested without regard to process history or date sequence. Acceptance testing of the solid grains was conducted at the Hercules Kenvil, New Jersey facility and RMD monitored quality by a computerized statistical program using upper and lower control limits. Only on one occasion was a batch rejected due to performance outside of the limits.

During the LR58 production, the Navy continued specialized testing for battle damage and handling. After 6-ft drop tests in any axis, the units were safe to fire and remained within acceptance test limits. Forty-foot drop tests were also conducted, although not as a specification requirement. In such tests, the units did not go propulsive but tank ruptures resulted in significant fires, which could be controlled by the application of water. Centrifuge tests were also conducted to confirm starting and running conditions under an acceleration of 3 g sideways. Sled acceleration tests were run at China Lake with conditions closely simulating flight. A number of the HDP grains were subjected to 250°F for 8 h to prove that they would not cook off under such damage conditions. In common with most double-base propellants, the composition requires both pressure and temperature to be propulsive. In later tests unrelated to the Bullpup missile, underwater firings of the LR58 were conducted without incident.

Production of the LR58-RM-4 continued through four buys to a total of 33,034 units, the engines then being deployed worldwide, including many in Europe and in the Vietnam war zone. The high reliability of the −4 unit was convincingly demonstrated in service use. Late in the program when 1420 flight and ground firings had been recorded, only two failures had occurred. One was a high vibration level in an acceptance test and probably caused by an instrumentation error. The other was an igniter misfire in flight, later rerun successfully. These results demonstrated a functional reliability of 0.9978 at a 90% confidence level, a figure equal to the best attained by solid propellant motors. Structural safety reliability would have been at least an order of magnitude higher, because there were no failures on record.

Of particular value to the services was the freedom to fly the system without special restraints. Flight limitations of the LR-58-RM-4 were specified as shown in Table 1.

The only difficulty experienced with the LR58 in service related to the fuel filling plug. Although from the beginning, the oxidizer had been sealed by a tungsten inert arc welded cap, a taper plug with sealant was used initially for the amine fuel. After some 5000 units had been completed, military personnel noticed brown stains in the paint around the plug. No leakage occurred, nor was there any odor. By that time, the units were deployed in Europe in significant numbers. The immediate problem was solved by RMD service personnel reworking each unit in the field and in storage with a more suitable sealant and a stronger tapered plug. For the remainder of production, a minor redesign of the fuel filling point introduced an aluminum cap that could be closed by tungsten arc welding applied remotely. A small planetary welder had been developed by the Hobart Company for inaccessible welds in nuclear heat exchangers and was ideally suited to this task. The bulk of the LR58 units and the entire production of the later LR62s were shipped with both fuel and oxidizer sealed by welding. Other than the fuel plug problem, no complaint was received with regard to service use or handling of either unit.

Table 1 Flight limitations of the LR-58-RM-4

Launch acceleration limits	+2 to −2 g (all axes)
Attitude at launch	No limits
Rate of climb and descent	No limits
Altitude limits	0 to 50,000 ft
Number of flights	No limits
Number of catapult launches	No limits
Number of carrier landings	No limits

VIII. Development of the LR62-RM-2

In seeking a heavy attack weapon, the Navy decided to develop the Bullpup B missile, which carried a 1000-lb warhead. The missile was approximately three times the weight of the Bullpup A but was controlled in a similar manner with many common components. A rocket engine of some 32,000-lb thrust was sought with a nominal total impulse of $73,000\ \mathrm{lb}\cdot\mathrm{s}$, the temperature and other environmental conditions being essentially the same as the Bullpup A. In view of the excellent experience with the LR58, the Navy bid request called for a packaged liquid system. Although in theory the bid request was an open one, practical considerations made it unlikely that another company could provide a competitive system. RMD proposed a scale-up of the LR58 with a performance to meet the thrust and total impulse requirement with a weight of 563 lb. The outside diameter of the engine was 17.32 in., with the length of 61.2 in. As on the earlier unit, the shell provided the support for the fixed wings of the missile. Provision was made for signal flares ignited by the rocket engine flame. The missile was not rail launched but was dropped on a lanyard to ignite some 15 or 20 ft below the aircraft. The LR62 was essentially a 1.44^3 scale-up of the LR58. The same propellant combination was used with a pressurizing grain of HDP composition. The storage temperature range was −80 to +165F with firing limits of −65 to +165F.

The bid from RMD was accepted and development commenced in February 1960. In view of earlier experience, it was possible to go directly to full-scale workhorse testing without an independent check of the injector and chamber. Only minor adjustments to the liquid and gas orifices were needed to bring the thrust and total impulse within specification. Refinements were made to the zirconium oxide coating of the chamber, which was applied by an electric arc plasma process to reduce application time. As in the LR58, much of the development running time was devoted to testing various thicknesses of the ceramic coating in critical areas. Although the extrusions for the oxidizer tank were at the capability limits of the largest presses available, Alcoa was able to provide raw parts of excellent quality, enabling hoop joints to be avoided in the tank shell. Welding was by both tungsten inert arc and metallic inert arc methods, the largest welds requiring a root pass and up to four subsequent passes. Excellent structural integrity was obtained with a proof stress margin at least 25% above the high-temperature running condition. The oxidizer tank included a large conical baffle to minimize propellant slosh forces, and the igniter booster was carefully proportioned from LR58 experience. Figure 12 provides a cutaway view of the LR62, and Fig. 13 is a photo of one of the YLR62 qualification engines. An acceptance test firing is shown in Fig. 14.

The propellant slosh features of the design were successful and, despite the size of the unit, the starting shock did not exceed that of the LR58. As a precaution, tethered missile tests were included in the first acceptance tests but were dropped when it was shown that the starting shock levels and running vibration were consistently within the missile capability. PFRT tests proceeded without difficulty and a release for production tooling was made in August 1962.

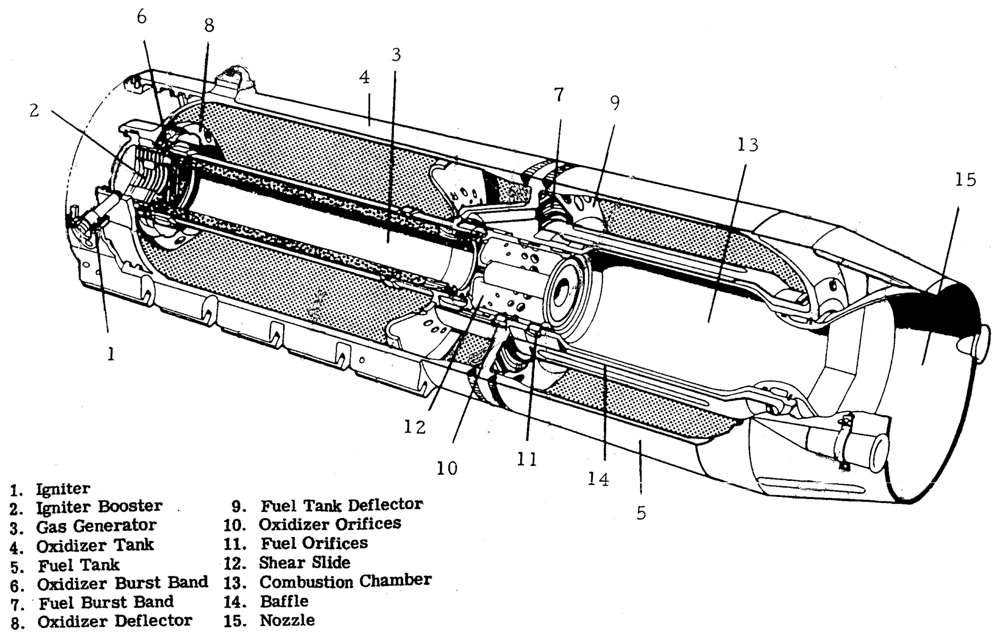


Fig. 12 LR62-RM-2 engine.

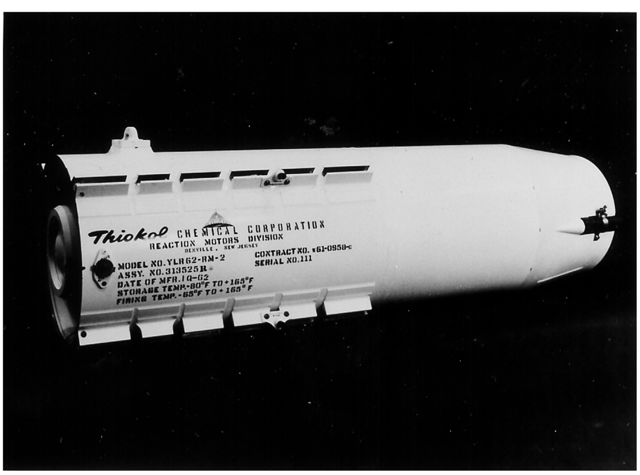


Fig. 13 YLR62-RM-2 for qualification tests.

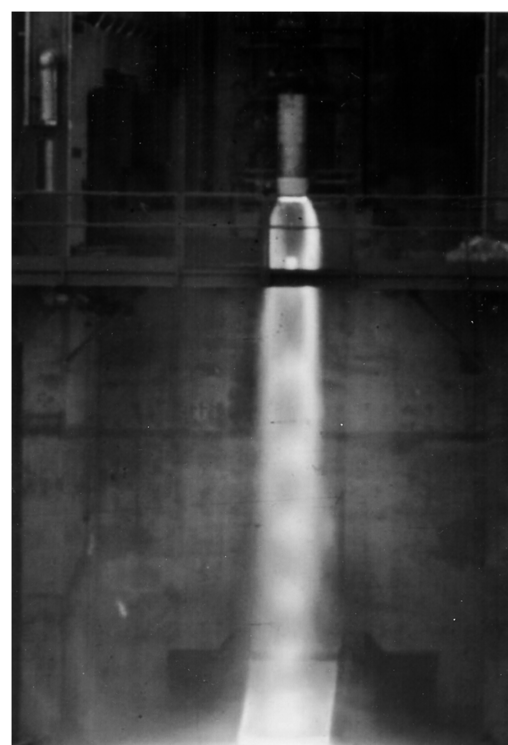


Fig. 14 LR62 acceptance test firing.

Initial flight tests made at Point Magu with inert missiles were satisfactory in all respects. The reliable behavior of the engine in starting gave every confidence that the lanyard drop would not endanger the launching aircraft. However, when testing continued with live warheads, an air burst occurred that resulted in complete destruction of the missile while the engine was still running. The Navy provided dramatic photo footage of a 1000-lb warhead exploding less than 1200 ft ahead of the aircraft. Fortunately, no personnel were injured and the aircraft was able to return safely. An intense investigation then ensued and, true to the script, the missile contractor blamed the engine supplier. Much of the debris had landed on a small island in the Santa Barbara Channel, and through the prodigious efforts of U.S. Marines and RMD personnel, most of the pieces of the LR62 were recovered. The oxidizer section of the engine had suffered a pressure burst while still in operation, resulting in a general breakup, as shown in Fig. 15. However, RMD was able to demonstrate that the oxidizer head had been driven in by a large external force, suggesting that the failure had been initiated by a premature burst of the warhead. Investigation by the Martin Company confirmed this, tracing the fault to a malfunctioning integrating accelerometer that was used to arm the warhead in flight. The LR62 was exonerated and further flights with modified live warheads were conducted without difficulty. Full qualification tests were completed, and early in 1963, the Navy released the LR62-RM-2 into quantity production; 17,000 units were produced and entered into a well-ordered and uneventful service experience.

During the preflight phase of the development, the Navy conducted side load starting tests with the LR62 to confirm that flight accelerations would not cause an abnormal starting condition. With a lanyard drop, a delay or reduced thrust might contribute to a missile upset and the possibility of hitting the aircraft. Because the thrust of the LR62 was too great for side testing on a centrifuge, tests were conducted on a sled at the B-4 track at China Lake, California. Two LR62s were mounted transversely and facing outward across the frame of a sled propelled by a battery of solid propellant motors. At a

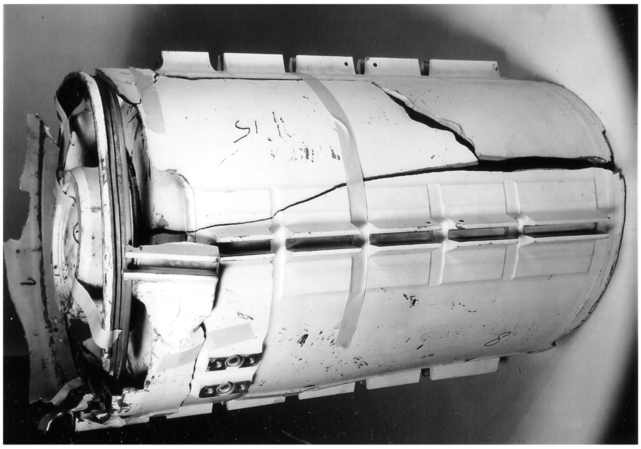


Fig. 15 Breakup of LR62 oxidizer tank due to premature burst of the warhead.

Fig. 16 LR62 side acceleration firing sled test at China Lake, California.

sustained side acceleration of 2 g, the liquid engines were fired simultaneously. Three runs were made with this arrangement, resulting in normal starting for the LR62s and complete expulsion of the liquid propellants. A photograph of one of these tests is given in Fig. 16. Because the engines were mounted across the frame of the sled, some concern had been expressed that if one unit should start before the other, the thrust offset might destroy the vehicle. This condition did not occur and the sled remained undamaged.

During qualification testing, 6-ft drop tests were made with uncrated units in the usual head down, tail down, and side attitudes. Static firing of these units showed them to be safe and within normal acceptance limits. Forty-foot drop tests were later conducted in the A area of the USNARTS facility at Lake Denmark, New Jersey. These tests were in the uncrated condition and used guiding wires to ensure that the desired attitude was maintained. The drama of a 560-lb round falling 40 ft can be imagined. The units did not explode or go propulsive, and although vigorous fires occurred, they were controllable with water and conventional fire fighting equipment. This ability to withstand abuse was acknowledged to be exceptional because it had been usual to waive the 40-ft drop test for large units. It is known that additional battle-damage tests were carried out on the LR62s, but the writer has been unable to locate the appropriate records.

IX. Manufacturing Operations

At the outset of the packaged liquid concept, it had been recognized that the production price of these engines would have to be fully competitive with their solid propellant counterparts. However, the novelty of the system allowed RMD to be unfettered by precedent and able to integrate the technical and industrial engineering aspects of the design for maximum economy. In view of the encouraging progress with the LR44 development, a contract was received from the Navy in the fall of 1958 to fund the tooling for production and provide machine tools, when available, from its machine tool reserve. Thiokol had recently purchased a site in Bristol, Pennsylvania, where it was establishing corporate headquarters. The facility contained many useful buildings that earlier had been used to produce munitions. This site was made available to RMD to provide 116,000 ft^2 of manufacturing space. Included were a number of smaller buildings with sufficient safety distances for propellant loading operations. Because the facility was unoccupied, the opportunity was taken to make a dedicated manufacturing plant with a work force committed to that purpose alone and without restraints from earlier practice.

In the make–buy decisions for the LR44, it was obvious that items such as the solid propellant grain and the igniter would need to be in the hands of experienced commercial suppliers. The sheet metal parts, being relatively simple in nature, could be readily subcontracted. It had always been assumed that the major welded parts and the final structure would be assembled in-house, as would the propellant loading operations. In theory, the machining operations for the structural shell, chamber, and inner core could have been in either camp. However, the cost targets for these parts required a man-hour improvement of approximately three to one over the usual industry practices. RMD was confident that by retaining these elements in-house, such an improvement could be achieved. Later experience would prove it to be true.

A working philosophy was established to provide the tone for the work. The following criteria were used:

1) Shop activities were confined to production operations only.

2) Operations were run continuously; batches were so designated for the convenience of quality assurance only.

3) Component operations were set up for in-line flow.

4) All operations, including quality functions and raw material, were under full process control.

5) To assist in process discipline, only machine operators and welding operators were used.

6) Quality operations were integrated into the manufacturing line with "go/no-go" standards.

7) An active program of process improvement was engaged in with participation from the floor and from engineering.

Many of the larger machine tools were provided from the U.S. Navy Industrial Reserve at Mechanicsburg, Pennsylvania and by the transfer of idle equipment from other facilities. Heavy turret lathes were particularly useful, requiring only adaptation with automatic tracing equipment. Some purpose-designed machinery was used, especially for multiple drilling and facing operations on the central header. Welding equipment was obtained from commercial concerns, with fixtures and the basic processes determined by RMD. Rotating equipment for ceramic coating was of in-house design, with guns from commercial suppliers. The process control for ceramic-coating operations had to be derived from scratch.

As LR44 production began, the machine-welding operations were established quickly and required minor process development to provide satisfactory joints. Radiographic testing was used for every structural joint, with dye penetrant methods for those of less importance. Machining of aluminum shells demonstrated that most operations could be run at the maximum rotational speed of the machine, resulting in turning surface speeds as high as 1000 ft/min. Other than a generous amount of coolant and the obvious need to protect the operator from spray, no special considerations were required. Conventional machine tools stood up well to the high running speeds and, with the exception of some clutch problems, were trouble-free. However, a major pinch point was evident in the ceramic-coating process for combustion parts. Coating quality was not difficult to maintain, but the application rate was far below expectations. Continual process improvement provided some relief, but ceramic coating remained the pacing item during the LR44 production and into the first buy of the LR58. Schedules were maintained on a temporary basis by running three shifts plus a swing shift.

The extensive experience of RMI in handling acid oxidizers and UDMH gave much confidence in setting up production loading operations. The supply of both fuel and oxidizer followed conventional commercial practices using either road or rail transport, with bulk storage at the site. Because the amine fuel is a skin irritant, it was occasionally found that an individual was highly sensitive and needed to be removed from the work. Acid filling was carried out using vinyl hoods with standby breathing equipment. To ensure the accuracy required for outage control, each propellant was weighed in the unit using a visual dial with a tare feature. Units selected for acceptance testing were run at the S-area test site at Lake Denmark, New Jersey. Usually, it was only necessary to hold delivery for a few days for the acceptance testing results to be approved. During the LR44 production, no batches of units were rejected due to out-of-specification performance. Some measure of the confidence in the system may be judged from the fact that each loaded unit was heated to 120–130°F to advance the drying of the paint. This practice continued with the LR58 and the LR62.

Manufacturing operations with the LR58 followed the experience gained on the LR44 and required only a minor addition to the machine tool complement. The use of 2014 T-6 aluminum alloy presented no new problems because its machining characteristics are superior to those of 6066 T-6. Welding operations using 4043 rod demonstrated that reliable welds could be produced with only occasional rework. As earlier, ceramic-coating operations were limiting, but persistent improvement eventually reduced these operations to 24% of the levels in the LR58 first buy. The production contracts of the LR58-RM-4 totaled 33,034 unit, with a fixed price of \$50.62 million (essentially in 1963 dollars). RMD was able to earn the allowed profit and the delivery schedule, which rose to 1100 a month, was met in every case.

When the LR62-RM-2 tooling was committed in the summer of 1962 it was recognized that additional manufacturing facilities would be required. Consideration was first given to producing the metal parts at the Bristol, Pennsylvania plant and completing the assemblies in northern New Jersey. However, because the LR58 was still in production, space considerations ruled out this choice, and facilities for both machining and assembly were established at Rockaway, New Jersey. Machining and assembly operations occupied $92,000\ \mathrm{ft}^2$ and were accompanied by a new facility of $11,500\ \mathrm{ft}^2$ for propellant loading and final assembly at the RMD test site at Lake Denmark, New Jersey. Initial production of the LR62 was at a rate of 300 units per month, rising to 670 units per month in later buys; 17,000 LR62-RM-2 units were delivered, with a cumulative procurement price of \$53.1 million in 1965 dollars. As before, all of these contracts were fixed-price.

Although from an engineering viewpoint the LR62 was close to the LR58, the increase in size of almost three times made for some contrasts in manufacturing. Some of the machining operations were limited by the maximum rotational speeds of lathes and boring equipment, yet cutting operations remained highly competitive. Both tank shells required lifting gear for handling at machine locations. The large multipass welding operations were mastered, although metallic inert gas welding was occasionally troubled by porosity in the summer humidity. Air conditioning of individual welding booths provided relief. LR62 production schedules were met, although there were many months in the second buy in which the Navy was unable to provide the metal transport cans in sufficient quantities. At times, this resulted in as many as 500 of these large units being stored at the Lake Denmark facility, in addition to current production.

In both the LR58 and the LR62 production, an energetic attempt was made to reduce manufacturing costs by value analysis and process improvement. Because the design was fixed and the units fully qualified, such improvements were largely confined to industrial engineering on the floor and process changes in raw material forms. Figures 17 and 18 give the results of that effort for the LR58, showing a unit price of \$7.00 per pound in 1966 dollars. Similar numbers applied to the LR62. A summary of the process improvement effort is given in [5]. Figures 19–26 show manufacturing operations, principally of the LR58 and LR62 units.

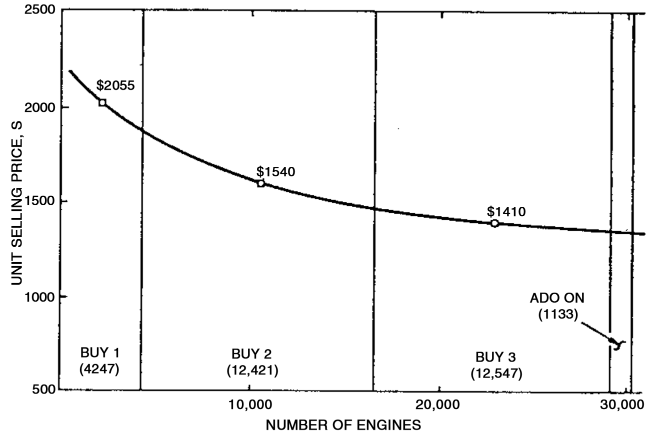


Fig. 17 LR58 unit selling price for successive buys.

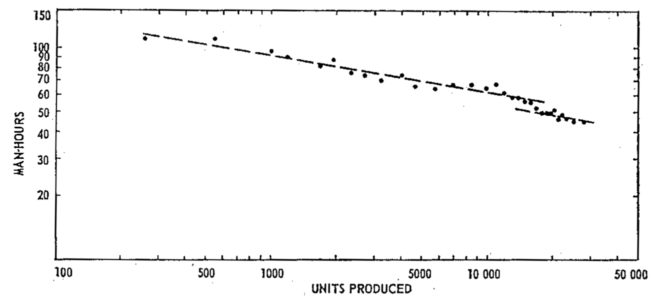


Fig. 18 LR58 learning curve for production Bristol, Pennsylvania plant.

Fig. 19 Manufacturing floor in Bristol, Pennsylvania (G. Pacella and R. L. Hoetger).

X. Additional Applications

The very practical nature and high reliability of the Bullpup A weapon lead to interest by NATO and the decision to manufacture the missile in Europe. Kongsberg Vaapenfabrikk of Norway was chosen as the prime contractor, with the United Kingdom taking the


Fig. 20 LR58 ceramic-coating operations.

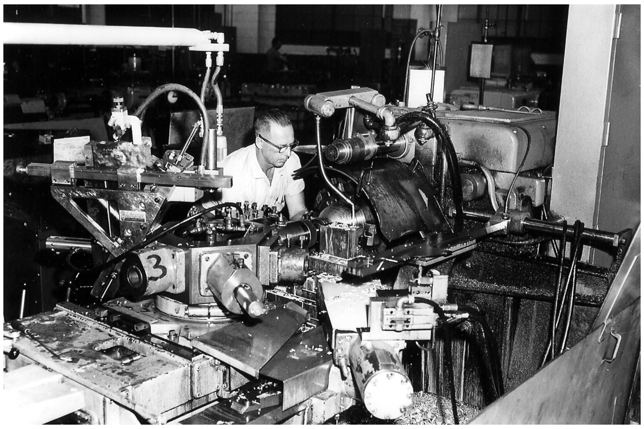


Fig. 21 Typical turret lathe operation of the LR58 oxidizer tank.


Fig. 22 Sealing loaded oxidizer tank for the LR58.

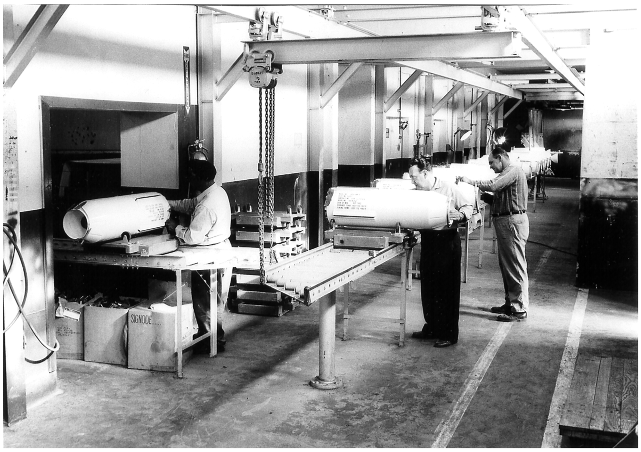


Fig. 23 LR58 packing line.


Fig. 24 LR44 units being loaded into a commercial carrier.

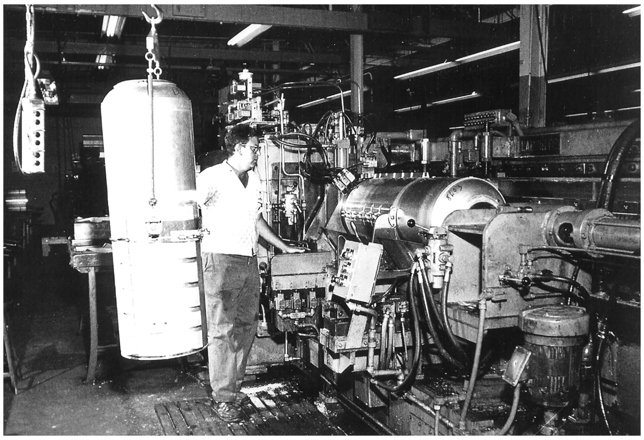


Fig. 25 Broaching wing slots of the LR62.

lion's share of deliveries. There was interest in the technically superior LR58 engine, but it was realized that setting up production in Europe would present a major manufacturing effort in a novel technology, and the challenge of handling a liquid unit in NATO service should not be ignored. To import the LR58 from the United States would have broken the NATO quantity and cost-sharing ratios and endangered political support for the project. Eventually, it was decided to produce the original solid propellant motor in the United Kingdom. This course of action was determined before the final qualification of the LR58-RM-4 and, although disappointing to RMD, was probably well-chosen.

The Bullpup B missile, for which the LR62 was the only propulsion, attracted particular interest from the Royal Navy, which had responsibilities beyond the NATO umbrella. It was a weapon able to take out a frigate or a small cruiser with a single hit. However, the Royal Navy service staffs were under no delusions regarding the hurdles they might face should they attempt to introduce a liquid rocket system on British ships and, much more, one based on nitric

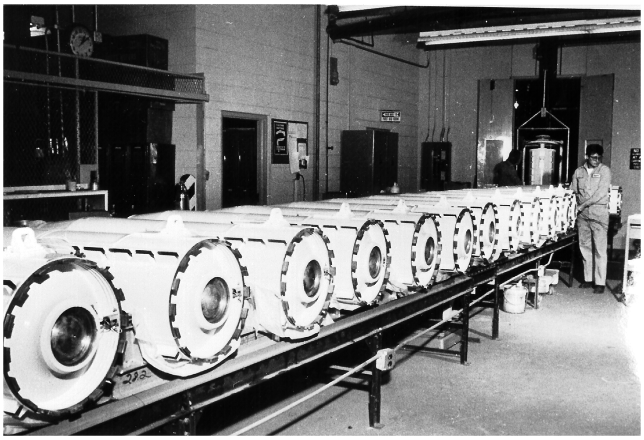


Fig. 26 LR62 shipping line at Lake Denmark, New Jersey.

acid. Since World War I, when the Royal Navy had lost some major vessels due to magazine fires, the safety aspects of handling weapons had been in the hands of extremely conservative shore-based technicians. Because the United Kingdom's requirement would have been less than a thousand missiles, it was obvious that the LR62 would have to be imported. Because of these considerations and the ever-present budget restraints, this wider use of the missile was not pursued.

The writer would have been pleased to report a further advance in the RMD packaged liquid concept. It was not to be. A bid for the development of a packaged liquid unit for the Army's Lance missile was not accepted, although RMD did receive some concept investigation contracts. The prime contractor for the Lance was seeking thrust chambers from outside suppliers, because it was intended to build the tankage in-house. This had seemed to be an ideal application for a packaged liquid handled as a round of ammunition, but the Army was set on its original course. RMD then pinned its hopes on a boost-sustain system for the airborne Condor missile. A contract from the Navy was received to develop this unit, which used chlorine trifluoride as the oxidizer with a mixed hydrazine fuel, both propellants being contained in a high-strength steel shell. However, as noted by Ordway [1], the use of the interhalogen oxidizer involved many complexities and proved to be a most difficult task. Injector-area erosion problems were troubling and despite some clever concepts, a satisfactory metallic barrier between the oxidizer and the pressurizing gas proved to be beyond reach. With project benchmarks falling increasingly behind schedule, the contract was terminated for default. Rocketdyne then took over the program and similarly ended in failure. Meanwhile, RMD continued with the last buy of the LR62 that, when completed, left it without an adequate sales base to sustain operations. RMD was closed in 1972.

XI. Conclusions

The large-scale production and use of the LR58 and LR62 packaged liquid rocket engines for the Bullpup missiles proved that with red fuming nitric acid as the oxidizer, a reliable and cost effective system could be produced. The smokeless exhaust of these units was an advantage for these visually guided missiles. The robust construction and lack of flight cycle restrictions led to complaint-free service, the units being eventually withdrawn due to obsolescence of the missile rather than for safety concerns. It can be argued that three elements in the design were key to this success: the simple shear-slide initiation device, the choice of a pressurizing grain that could be temperature cycled indefinitely, and the provision of factory-filled propellants without access for servicing. Considerable improvements in density impulse with this system could have been obtained by the use of the nitric acid oxidizer at maximum density with a hydrazine fuel or a loaded hydrazine thixotrope. However, by putting its faith in the interhalogen oxidizers, the Reaction Motors Division set before itself a number of critical tasks that proved to be fatal. The extreme ability of chlorine trifluoride to react vigorously with any fuel-rich gas and the dimensional scaling problems of metallic bag or piston tank barriers presented technical hurdles that could not be overcome within the schedule and cost restraints of the programs at hand.

Acknowledgment

Recognition is made of the fine contribution by the many team members in the programs under review.

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