TRW Pintle Engine Heritage and Performance Characteristics

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Abstract

The pintle injector rocket engine is fundamentally different from other rocket engines, which nearly universally employ a series of separate propellant injection orifices distributed across the diameter of the headend of the combustion chamber. The pintle's central, singular injection geometry results in a combustion chamber flowfield that varies greatly from that of conventional rocket engines. These differences result in certain operational characteristics of great benefit to rocket engine design, performance, stability, and test flexibility.

The mid-1950's origin of the pintle injector concept and the subsequent early development work and applications in rocket engines are reviewed. The pintle engine's key design and operational features are compared to conventional rocket engines. Pintle injector design refinements and associated recent applications are discussed. The presentation includes photographs and summaries of many different rocket engines that TRW has developed and successfully flown, each of which used the pintle injector.

Introduction

The pintle injector is distinguished by its unique geometry and injection characteristics compared to the impinging or coaxial distributed-element injectors typically used on liquid bipropellant rocket engines. The pintle injector design can deliver high combustion efficiency (typically 96–99%) and enables implementing some unique operating features, such as deep throttling and injector face shutoff. Its design simplicity makes it ideally suited for use on low cost engines. Significantly lower development and qualification costs are realized with pintle engines because their injectors can be easily adjusted and optimized by changing only two simple parts.

The TRW pintle engine has a demonstrated heritage of being low cost, highly reliable and safe to operate. The origins of the pintle injector were early laboratory experimental apparatus, used by JPL in the mid-1950's, to study propellant mixing and combustion reaction times of hypergolic liquid propellants. The pintle injector was reduced to practice and developed by TRW starting in 1960; however, it was not until 1972 that the pintle injector design patent was publicly released. Over the last 40 years, TRW has developed over 60 different pintle engine designs at least to the point of hot fire characterization testing. Bipropellant pintle engines have encompassed a wide range of thrust: 5 lbf on a Brilliant Pebbles thruster, 100 lbf on liquid apogee engines for spacecraft, 1,000–10,000 lbf on the Apollo lunar module descent engine, 250,000 lbf on a "Big Dumb Booster" engine, and 650,000 lbf on a development LOX/LH2 engine currently being readied for testing at NASA Stennis Space Center. Over 130 bipropellant engines using a pintle injector have flown successfully. Flight programs relying on TRW bipropellant engines have included Apollo LEMDE, Delta launch vehicle, MMBPS, ISPS, ANIK E-1/E-2 and Intelsat-K, ERIS KKV stage, FMTI, and NASA Chandra. There has never been a flight failure of a TRW bipropellant engine.

Significantly, there has never been an instance of combustion instability in a pintle engine during any ground or flight operations, despite scaling over a range of 50,000:1 in thrust and 250:1 in chamber pressure and operation with 25 different propellant

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combinations. The pintle injector has demonstrated direct injection of near-normal boiling point LOX/LH2 propellants with high performance and proven dynamic combustion stability. “Bomb” stability testing has been performed on six different pintle engines with four different propellant combinations, including the physically large 250,000 lbf engine.

With its unique capabilities, the pintle injector has been used in very demanding applications, such as an 8,200 lbf engine that could throttle over a 19:1 thrust range and perform 8 millisecond pulses. Also, with its ready adaptability to shut off propellants at the injector face, the pintle injector is ideally suited to operation with gelled propellants and has enabled the first successful flight of a gel propellant tactical missile. Most recently, the pintle engine design has been investigated as a means of easily reducing the cost of large engines for launch vehicles by as much as 75% beyond that achieved on recent programs, such as EELV.

The history of development and flight applications of the pintle engine over the last forty years will be summarized. The features and performance characteristics of the TRW pintle injector and associated engine designs will be described. Features of the pintle injector will be compared to those of other injectors commonly used in rocket engines.

Pintle Injector Design Concept

The basic concept of the bipropellant pintle injector is shown in Figure 1.

One propellant (here shown as fuel) is fed through outer injector flow passages into a circumferential annulus—formed between the injector body "snout" and the central injector element—which meters the flow into the combustion chamber. This propellant exits the injector as an axially flowing annular sheet that arrives at the impingement point with a circumferentially uniform velocity profile.

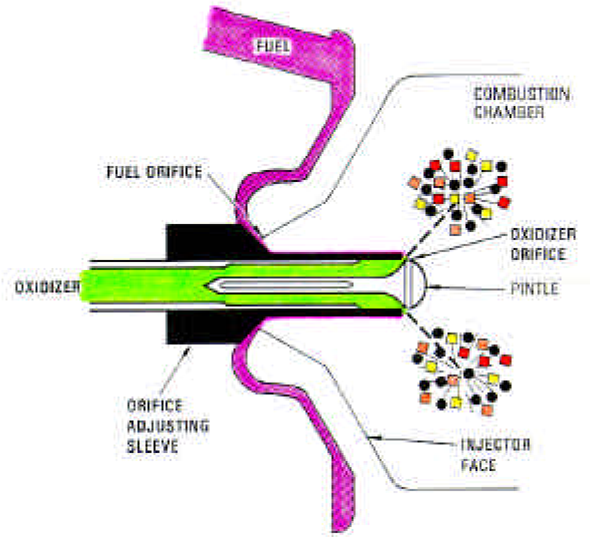


Figure 1. Pintle Injector Concept (Continuous Gap, Fixed Thrust or Thottling Designs)

The other propellant (here shown as oxidizer) enters the injector body via a separate centrally-located passage and flows axially through a central pintle sleeve toward the injector, where it is turned to uniform radial flow by the pintle tip's internal contoured surface. This propellant is metered into the combustion chamber by passing through: (a) a continuous gap formed between the cylindrical sleeve and pintle tip, or (b) slots or holes of certain geometry machined into the end of the sleeve which may be integral with the tip, or (c) a combination of the above two designs. Thus, the pintle injector can meter the central propellant as a continuous radial sheet, a series of radially flowing “spokes”, or combination of both. Figure 2 shows the injection geometry of the slotted, or “toothed” pintle injector with attached tip.

Experience has shown that the pintle injector can be designed to give high performance with either fuel or oxidizer being the centrally-metered propellant. Generally, fuel is chosen as the central propellant in radiation-cooled engines because the radial injection momentum can be designed to persist to the wall, thus enabling a convenient

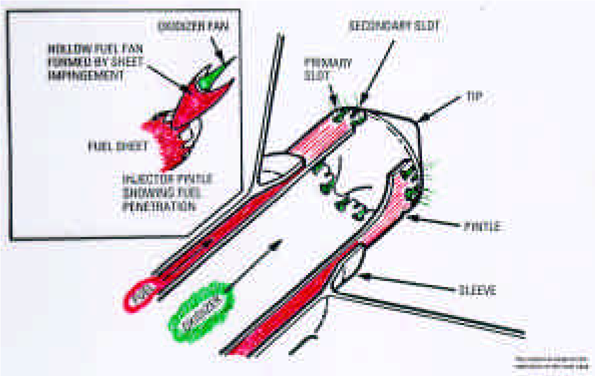


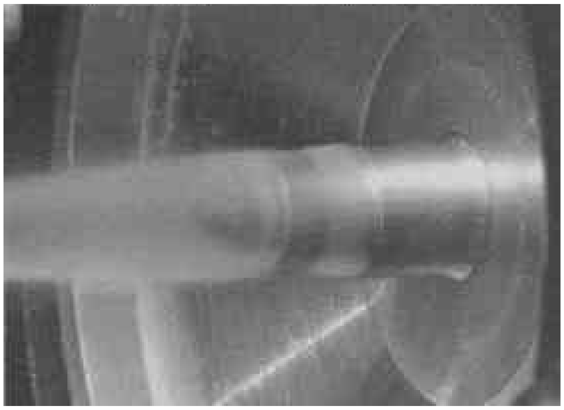
Figure 2. Pintle Injector Concept (Slotted Injection, Fixed Thrust Design)

means of "tuning" the injector to provide fuel film cooling of the combustion chamber. Ultimately, the decision to meter either fuel or oxidizer as the central propellant depends on many design trade-offs. TRW has successfully flown both ox-centered and fuel-centered pintle engines.

The 90°, axial-radial impingement of the two propellant streams combined with the specific geometry of the resulting atomization and mixing "fan" is fundamental to the pintle injector providing both high combustion efficiency and inherent combustion stability.

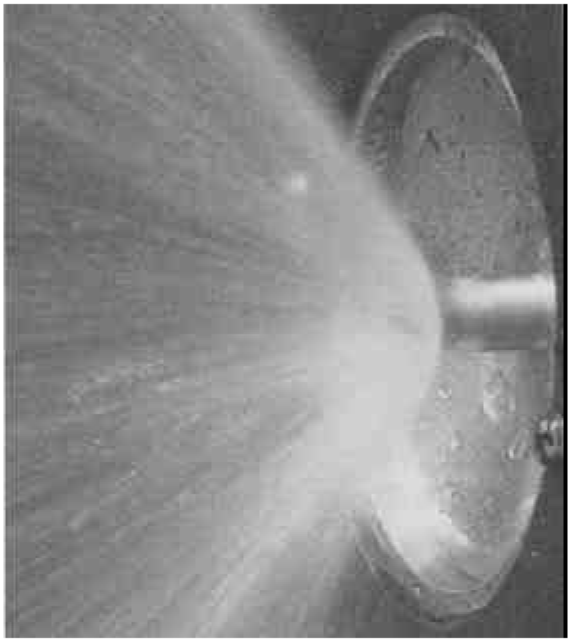
Figure 3 is a series of photographs of water flow tests on a single pintle injector, looking back toward the injector element and headend dome. Figure 3(a) shows characteristic flow for the outer, annular injection; Figure 3(b) shows a wider-angle view of the inner passage flow being injected as a radial sheet; and Figure 3(c) shows the spray fan resulting from the combined injected, but non-reacting, flows.

The single central injector sleeve, shown in Figure 1, is easily designed to be movable. This provides a convenient and reliable means of throttling the injector to maintain nearly constant injection velocities across a wide range of injected propellant flowrates. TRW has used this feature to great advantage, as discussed below, to produce deep (>10:1) throttling engines that maintain high



(a) Outer Flow Only

(b) Inner Flow Only



(c) Combined Flows

Figure 3. Photographs of Injector Water Flows

combustion efficiency and insensitivity to chug instability across their operating range.

Where injectors employ a movable sleeve, a separate on-axis support rod (or tube) and cruciform guide vanes are used to support the pintle tip independent of the sleeve. It is seen that movement of the single sleeve can simultaneously meter both the fuel and the oxidizer at their immediate points of injection. Furthermore, with proper design the sleeve can be made to fully shutoff both propellants at the injector face (hence, "face shutoff"), thereby eliminating all dribble volume from the injector. In fact, TRW has implemented "face shutoff only" injectors where this movable sleeve was the only "valving" locking off propellant supply pressures up to approximately 3000 psia.

The distance from the outer propellant's annular entrance point into the combustion chamber to the point of contact with the injected central propellant stream is referred to as the injector's "skip distance". This parameter, together with others such as the pintle's insertion depth into the chamber, it's diameter relative to the chamber diameter and injection stream thicknesses, velocities and relative momentums, must be considered in proper design of pintle injectors.

Careful design of the pintle injector ensures (a) good atomization and mixing of the two propellant streams for high combustion efficiency, (b) proper fuel film cooling at the chamber wall, and (c) evaporative cooling of the exposed headend dome for good thermal margin.

The momentum of the injector's resultant spray "fan" of mixing and combusting propellants pumps two major zones of recirculation within the combustion chamber, as indicated in Figure 4.

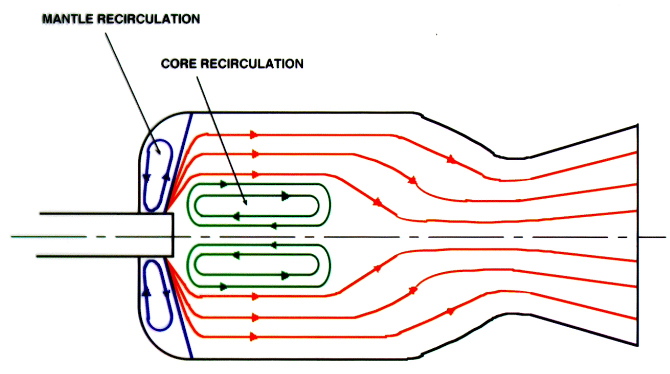


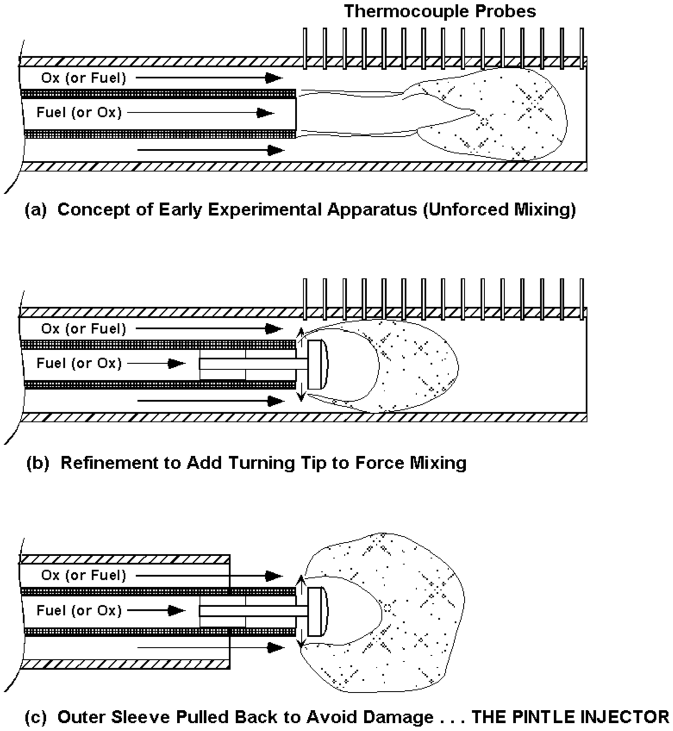
Figure 4. Combustion Chamber Flowfield Resulting from Pintle Injection of Propellants

There is: (1) an upper torroidal zone that is predominantly outer propellant-rich and acts to cool the headend via evaporation of entrained and impinging droplets of liquid propellant, and (2) a lower torroidal zone that is predominately central propellant-rich and recirculates back on-axis toward the pintle, thereby acting as a deflector and mixer for any unburned droplets that would otherwise tend to travel directly from the injector to the nozzle throat.

Pintle Injector Development History

The pintle injector for rocket applications has its origins in simple but elegant laboratory apparatus and experiments first employed at the Caltech Jet Propulsion Laboratory, starting about 1957, to characterize reaction rates of candidate rocket propellants (Ref. 1). This work was performed initially by Jerry Elverum under the supervision of Art Grant, with later theoretical analysis and engineering support from Dr. Pete Staudhammer and Jack Rupe.

As indicated in Figure 5(a), two concentric metal tubes were used to flow combinations of hypergolic propellants at known stream velocities. In this manner, the start of propellant mixing could be controlled and the delay time to initiation of chemical reaction could be derived from measurements of



(a) Concept of Early Experimental Apparatus (Unforced Mixing)

(b) Refinement to Add Turning Tip to Force Mixing

(c) Outer Sleeve Pulled Back to Avoid Damage . . . THE PINTLE INJECTOR

Figure 5. Evolution of JPL Laboratory Apparatus for Studying Reaction Rates and Combustion Phenomena of Hypergolic Propellants

downstream thermocouples, with known distances and flow velocities.

Early experimental data revealed that a large degree of uncertainty in timing the chemical reaction rates was due to the poor mixing between the annular flow streams, especially with nearly matched flow velocities (~ zero shear mixing). This was exacerbated by wake effects from the inner tube's wall end and by the well-known "blow apart" characteristic of hypergolic propellants. The innovative solution to this problem, attributed to Elverum (Ref. 1), was to place a tip at the end of the innermost tube (attached to an internal cruciform support) that would force this propellant stream to turn radial, thereby insuring a definite point of intense mixing of the two propellants. This design refinement is shown in Figure 5(b).

While this apparatus proved quite useful in characterizing reaction rates of lower energy hypergolics (e.g., RFNA/UDMH) to sub-millisecond resolution, it proved impractical with higher energy hypergolics (e.g., N2O4/MMH) due to their extremely short reaction times. Reactions were observed to be nearly instantaneous at the point of impingement. This laboratory equipment, however, showed a possible path to developing a new type of injector with demonstrated high mixing efficiency. Indeed, later experiments at JPL featured the tipped inner tube protruding beyond the exit plane of the outermost tube in order to study combustion phenomena without destroying the outer tube . . . thus, the basic pintle injector was born, Figure 5(c).

Staudhammer is credited with developing the "toothed" injector concept. As related to one of the authors (Ref. 1), he was looking for a way to further improve upon the already good mixing and decided that having "slots" of one propellant penetrating into the other, outermost propellant would accomplish this. In an expedient manner, he had a technician make multiple hacksaw cuts across the end of an available inner tube and, indeed, subsequent tests of this new end configuration showed a substantial improvement in mixing efficiency.

By about 1960, Grant, Elverum and Staudhammer had moved to the newly-formed Space Technology Laboratories, Inc. (now TRW, Inc.) to pursue applied development of monopropellant and bipropellant rocket engines. It was at STL that the pintle injector was finally developed into a design usable in rocket engines. TRW's first IR&D reporting on the pintle injector is for CY 1961 (Ref. 2), from which Figure 6 has been extracted. This shows the variety of different pintle injector geometries that were then being evaluated. Subsequently, the pintle injector design was matured and fully developed by a number of TRW personnel (inc. Elverum, Staudhammer, Voorhees, Burge, Van Grouw, Bauer and Hardgrove), adding such features as throttling, rapid pulsing capability and face shutoff.

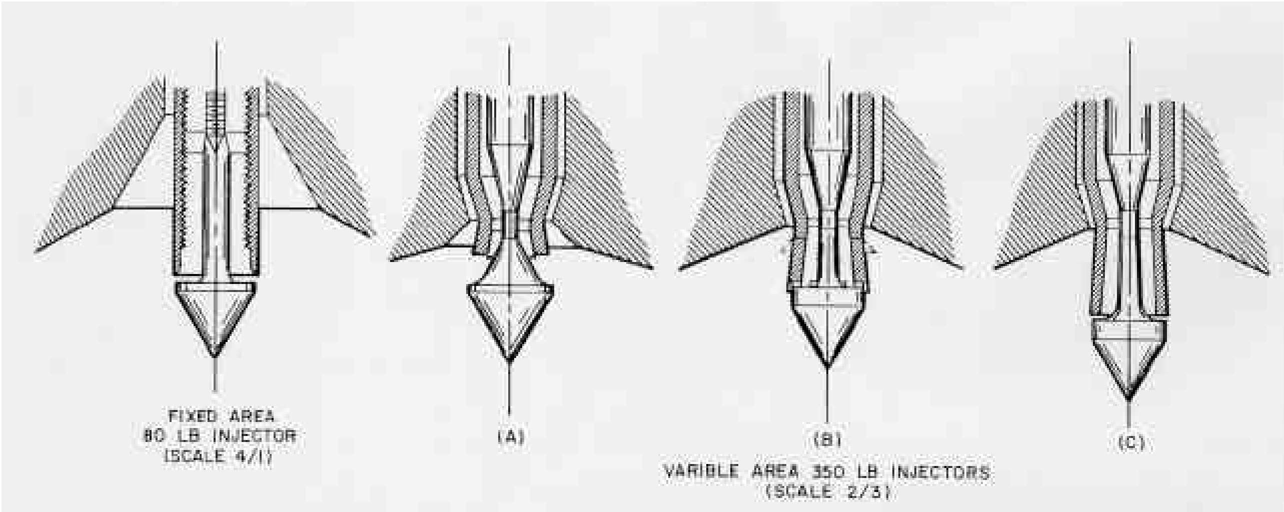


Figure 6. Early Designs of Pintle Injector Configurations Evaluated at Space Technology Laboratories, Inc. (now TRW, Inc.), ***extracted from Ref. 2.***

The pintle injector design was quickly adapted to throttling applications due to its unique ability to retain performance and combustion stability across a wide range of operating conditions. Indeed, the first flight use of a pintle injector rocket engine was the 10:1 throttling Lunar Module Descent Engine used on the Apollo program (see "Early Applications" below). A US patent (#3,699,772) for invention of the pintle injector was granted to Gerry Elverum, assigned to TRW and made public in October 1972.

Pintle Engine Design Fundamentals: A Comparison with Typical Rocket Designs

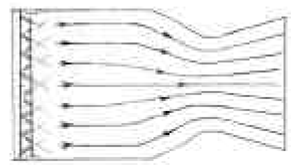
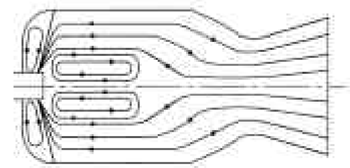
Typical injectors for rocket engines consist of multiple, separate injection orifices distributed more or less uniformly across the diameter of the engine's headend. In comparison, the pintle injector injects propellants only at a relatively small area located at the center of the headend. And whereas conventional injectors create propellant mixing in a planar zone immediately adjacent to the headend, the pintle injector creates a torroidal mixing zone that is significantly removed from the chamber headend. As was shown in Figure 4, the pintle injector therefore creates a combustion chamber flowfield that is significantly different from that of conventional rocket engine injectors. This leads to operating characteristics favoring combustion stability and performance, which are summarized in Table 1.

One extraordinary benefit of such fundamental characteristics is that the pintle injector has been proven to be scalable over a wide range of thrust level and different propellant combinations without any need for stability augmentation, such as acoustic cavities or baffles. There has never been an instance of acoustic instability observed in a TRW pintle injector rocket engine.

Another major benefit is that the pintle injector has demonstrated the ability to consistently deliver high performance (typically 96–99% of theoretical combustion performance, c*) with proper design and hardware buildup.

In comparison with conventional rocket engines operating at the same chamber pressure and thrust level, pintle rocket engines are generally longer in physical length and higher in chamber contraction ratio (both being required to support the chamber's major recirculation zones).

Table 1. Comparison of Key Engine Operating Parameters for Typical Liquid Rocket Engines versus TRW's Pintle Rocket Engine

Parameter	 ***Chamber Flow Pattern in Typical Liquid Rocket***	 ***Chamber Flow Pattern in TRW Pintle Rocket***
Propellant injection	Distributed across injector face	Only at central location
Fuel and oxidizer injection geometry	Multiple intersecting or shearing propellant streams; intersecting streams are of like or unlike propellants	Single annular outer sheet of one propellant impinges on (a) multiple radial "spokes" of other propellant, or (b) thin radial fan of other propellant
Fuel and oxidizer collision geometry	In plane immediately adjacent to injector face	In torus significantly offset from injector face
Droplet trajectories	Approximately axial down chamber	Initially at large angle to chamber axis
Chamber recirculation	None	Two major recirculation zones in chamber
Droplet vaporization and combustion	Proceed in planar fashion down chamber length	Proceed along axially symmetric, but highly non-planar, contours in chamber
Secondary droplet breakup	Comparatively small due to axial flow and homogeneous distribution	Comparatively large due to wall impingement and recirculation zones
In passing through chamber, droplets see:	Little "relative wind" away from injector face (pressure perturbations thus cause large change in energy release rate)	Large "relative wind" throughout chamber (pressure perturbations thus cause only small change in energy release rate)
Energy release zone geometry	Uniform and planar across chamber diameter (facilitates acoustically-coupled combustion instability)	Radially-varying and canted down and across chamber—together with stable zones having different gas properties (O/F, MW, gamma and T) — serve to prevent acoustic instabilities
Chamber for optimum combustion performance	Is relatively short and has relatively small contraction ratio	Is relatively long and has relatively high contraction ratio
Wall film cooling	Established by separate injection ports	Established by pintle injector "tuning", eliminating need for separate ports
Injection metering orifices	Relatively small and contamination sensitive	Relatively large and insensitive to contamination

Pintle Engine Development and Production History

Figure 7 (next page) summarizes the development and production history of high thrust (=2000 lbf) pintle engines programs that have occurred at TRW over the last 40 years.

Table 2 summarizes TRW's flight experience with pintle engines, including those with thrust levels down to the 100 lbf class (i.e., Liquid Apogee Engine, LAE, class).

Table 2. Summary of TRW Pintle Injector Rocket Engines Used on Flight Programs

Engine	Thrust (lbf)	Propellants	Pc (psia)	Duty Cycle	Development Funding Source	Number Produced	Cooling Method	Isp (Sec)	Comments
LMDE	1000 to 9850	N2O4/A-50	100	• 3 starts • 10:1 throttling • 1000 sec max single burn duration	NASA	84	Ablative	303	Perfect reliability record as LEM descent engine, saved Apollo 13 mission
TR201	9900	N2O4/A-50	100	• 5 starts, 500 sec total • 10 to 350 sec single burn duration	TRW	77	Ablative	303	Perfect reliability record as second stage Delta engine 77/77
ISPS	100 lbf class	HDA/USO	94	• 300 pulses • 1 to 570 sec. single burn duration	LMSC	28	Radiation, Columbium	272	Flown successfully on orbital Agena program 28/28
MMBPS	88	N2O4/MMH	90	• 25,000 sec. total burn time • 130 starts • 9000 sec. max single burn time		21	Radiation, Columbium	305	Derived from TRW URSA 100R engine
DM/LAE	105	N2O4/ N2H4	100	• 25,000 sec. total burn time • 20 starts • 6000 sec single burn time	Commercial G.E./TRW	10	Radiation, C-103	315	Six successful spacecraft flight engines (Anik, Intelsat)
AC/LAE	120	N2O4/ N2H4	100	• 24,000 sec. total burn time • 100 starts	Commercial G.E./TRW	6	Radiation, C-103	322	4 Engines flown successfully on NASA Chandra S/C-1999
ERIS Divert Thruster	910	N2O4/MMH	1600	• pulsing	Army	12	Ablative	284 (ε =16)	Flown successfully on two ERIS flights-4/flt
FMTI	1050	Gels: IRFNA/ C-loaded MMH	1750	• pulsing	Army/ AMCOM	6	Ablative	240 (s.l.)	Program on-going; 2 flight successes in 2 launches

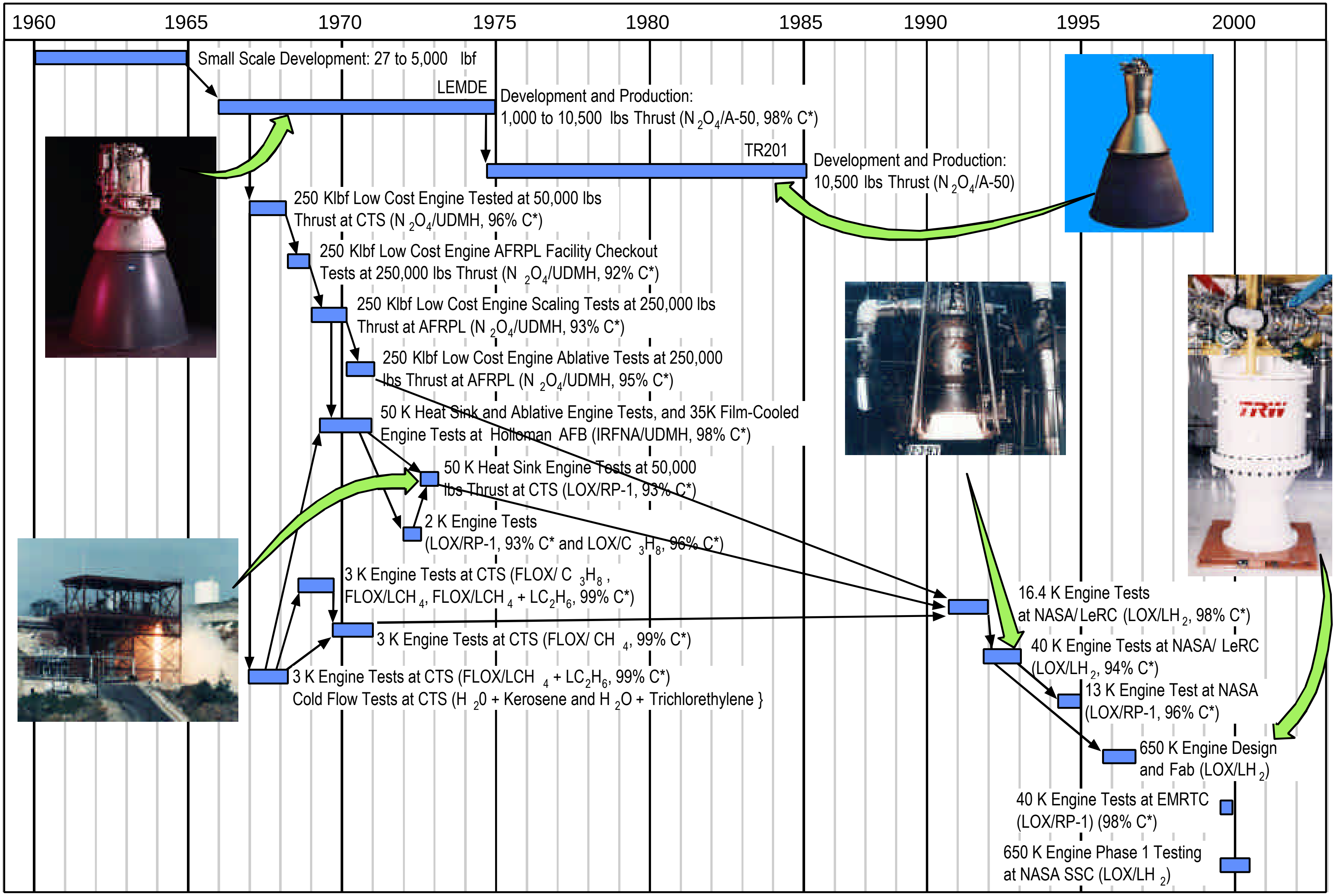


Figure 7. Chronology of Development and Production of Large Thrust (= 2000 lbf) Pintle Rocket Engine Technology at TRW

Early Applications

The first experimental pintle rockets tested at TRW Space Technology Laboratories were the MIRA 500 (a 25 to 500 lbf variable thrust engine), originating in December 1961, and the MIRA 5000 (a 250 to 5000 lbf variable thrust engine), originating in May 1962, shown in Figures 8 and 9 respectively. These IR&D units led to development of the backup Surveyor Vernier Engine, a.k.a. the MIRA 150A (a 30 to 150 lbf variable thrust engine built for JPL starting in 1963) and the famous Apollo Lunar Excursion Module Descent Engine (built for NASA/Grumman starting in 1963). These units are shown in Figures 10 and 11, respectively.

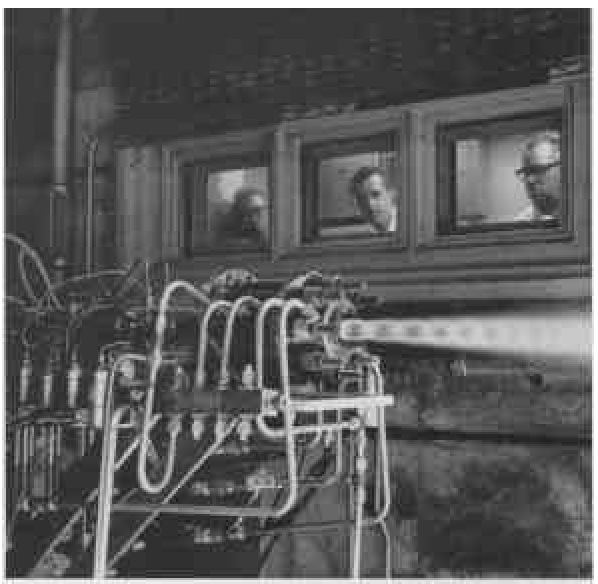


Figure 8. Test Firing of Earliest TRW Pintle Injector Engine, a Water-Cooled MIRA 500

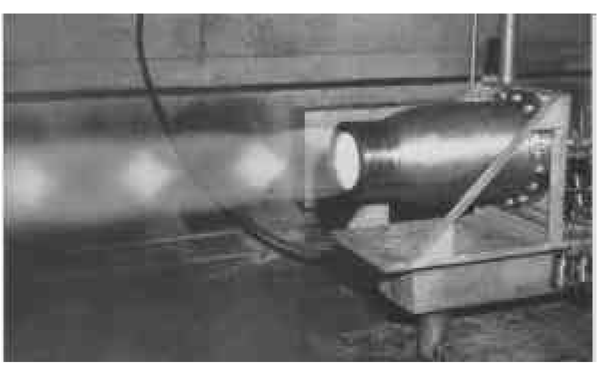


Figure 9. Test Firing of Ablative-Cooled MIRA 5000

Figure 10. MIRA 150A Engine

Figure 11. Apollo Lunar Excursion Module Descent Engine

The capability of a given pintle injector to perform deep throttling without large loss in combustion efficiency was demonstrated and documented at TRW as early as 1962. Figure 12, extracted from STL's 1962 IR&D Report (Ref. 3), presents hot firing test data from the MIRA 5000 engine throttled up to 35:1. Performance in excess of 93% theoretical c* was maintained over a 10:1 range with N2O4/A-50†, and performance efficiency in excess of 95% was maintained at the extremes of 35:1 throttling with IRFNA/UDMH. Maximum performance values obtained were in the range of 98–99% of theoretical c*.

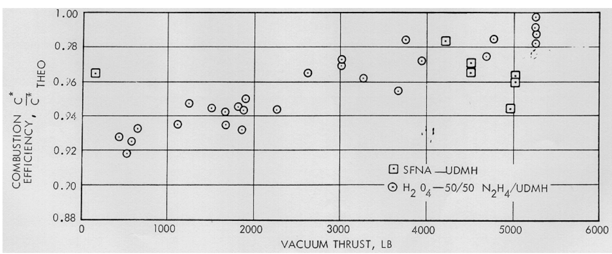


Figure 12. Early Demonstration of Deep Throttle Capability of Pintle Injector

The first flight application of a TRW pintle injector rocket engine was the throttling Lunar Excursion Module Descent Engine (LEMDE, sometimes shortened to LMDE). Engine development started in 1963, qualification was completed in 1967 (Ref. 4), and production ran through 1972 (Ref. 5). During the NASA contract for this engine, 3,857 tests were conducted, accumulating 233,000 seconds firing time. A total of 84 engines were produced. This engine performed flawlessly during 10 flights, landing 12 astronauts on the Moon and enabling the space rescue of the Apollo 13 crew. Design characteristics included: (a) continuously variable, on-demand vacuum thrust between 1,050 and 10,500 lbf, (b) N2O4/A-50† propellants at a mixture ratio of 1.60 ± 2% over 100–25% throttle, (c) design operating life >1040 seconds, (d) weight of 393 lbm, and (e) envelope of 85 inches high by 60 inches diameter at the nozzle exit.

In parallel with the LEMDE program, TRW continued development of lower thrust pintle engines, including by 1966 a product family known as the URSA-series (Universal Rocket for Space Applications) shown in Figure 13. These were storable (N2O4/MMH or N2O4/A-50) bipropellant engines offered at fixed thrusts of 25, 100 or 200 lbf, with options for either ablative- or radiation-cooled combustion chambers. These engines were capable of pulsing at 35 Hz, with pulse widths as small as .020 seconds, but also had design steady state firing life in excess of 10,000 seconds (with radiation-cooled chambers). Planned applications for these engines included Gemini, Apollo, Dyna-Soar, Manned Orbiting Laboratory, and the Multi-Mission Bipropellant Propulsion System (MMBPS).

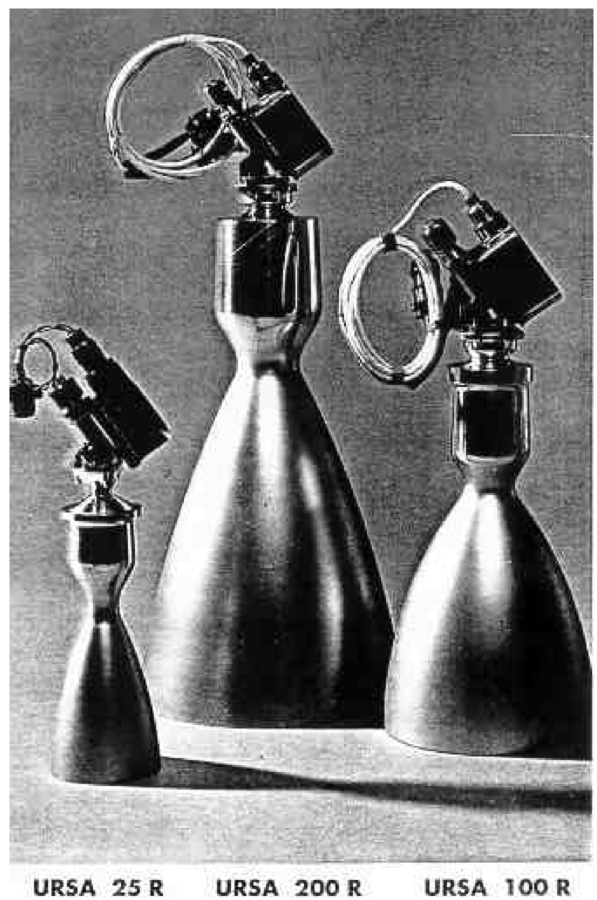


Figure 13. TRW's URSA Family of Pintle Engines (from 1966 brochure)

† A-50, "Aerozine 50", is a 50%N2H4 + 50%UDMH blend

Two other early, low thrust pintle engines of historical note were the Lunar Hopper Engine (a 12–180 lbf variable thrust, MON-10/MMH engine developed in 1965 for NASA/MSFC in support of the Manned Flying Vehicle program) and the Apollo Common Reaction Control System Engine, a.k.a. C-1 (a 100 lbf fixed thrust, N2O4/MMH engine developed in 1965 for multipurpose attitude control on such programs as Apollo, Gemini and Saturn IVB). The C-1 was a long life (>2000 seconds), pulsing (up to 35 Hz), ablative engine that employed a coated Ta-W throat insert.

Starting in 1974 and continuing through 1988, a simplified, low cost derivative of the LEMDE was used as the second stage of the Delta 2914 and 3914 launch vehicles. This 9900 lbf fixed thrust ablative engine, designated the TR201 and shown in Figure 14, had a 100% successful flight rate (including 69 non-classified launches).

Figure 14. TRW's TR201, Derived from LEMDE, was Used as the Delta Upper Stage with a 100% Flight Success Rate

Also, beginning about 1962, TRW conducted numerous studies to apply pintle injector technology to large booster engines with the goal of achieving minimum vehicle cost via absolute simplicity; these designs were generically nicknamed "Big Dumb Boosters".

Perhaps the most ambitious of these TRW-led projects was the 1963 "Sea Dragon" study for NASA MSFC that designed a sea-launched, pressure-fed TSTO vehicle to place a 1.1 million pound payload into a circular 300 nm orbit (Ref. 6). The vehicle was nominally 75 ft in diameter and 500 ft high. Its first stage was to employ a single 80 million lbf engine using LOX/RP-1 and the second stage used a single 14 million lbf LOX/LH2 engine. At a design chamber pressure of 300 psia, the first stage engine had a throat diameter of 42 ft, a nozzle exit diameter of 94 ft and an overall height of 102 ft. To say the least, these early efforts at achieving a heavy lift launch vehicle were based on quite expansive thinking.

By 1965, TRW was under contract to the Air Force (under the Minimum Cost Design Space Launch Vehicle Program) to show scalability of the pintle injector for booster engines having thrust levels in excess of one million pounds thrust. This led to the fabrication and hot fire testing of a pressure-fed 250,000 lbf N2O4/UDMH pintle engine (Ref. 7), a scaling jump of 25:1 from the largest pintle engine then in existence (LEMDE). A water flow test of this engine's injector is shown in Figure 15; note the far field persistence of the "spokes" of the central, radially-injected, propellant. In total, 44 separate 250K hot fire tests were conducted (including steady-state tests of 66, 83 and 98 seconds duration), demonstrating dynamic combustion stability via "bomb" testing and evaluating performance and ablative chamber durability. All firings were performed at AFRPL, Edwards AFB, CA from Oct 1968 to Jan 1970. A test firing is shown in Figure 16.

Figure 15. Water Flow Test of Pintle Injector for Air Force 250,000 lbf Engine

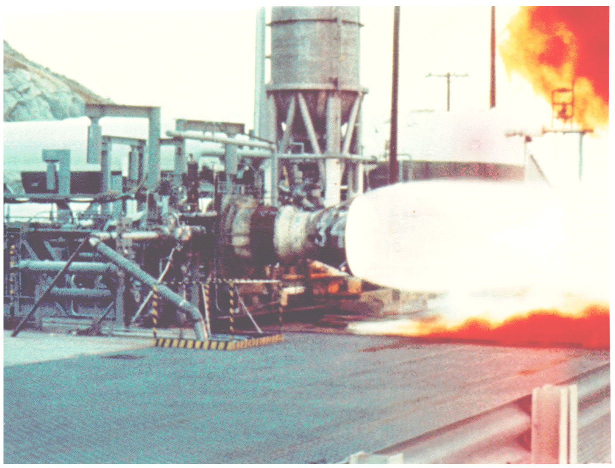


Figure 16. Hot Fire Test of Pressure-Fed 250,000 lbf Ablative Engine

In the period 1969 to 1971, TRW also fabricated and conducted demonstration test firings on 35,000 and 50,000 lbf pressure-fed pintle engines with the goal of using these storable propellant rockets to power high speed sleds at Holloman Air Force Base.

Design Refinements

Beginning in the early 1980's, a series of design refinements were applied to the pintle injector to adapt it to a wide variety of developing, challenging applications.

First, improving sensor, guidance and missile technologies indicated that ballistic missile defense with "hit-to-kill" missile interceptors was possible. However, such missiles required attitude control and lateral ("divert") rockets that could provide exceptionally fast and repeatable pulses on command. Certain applications also required linear throttling capability in addition to pulsing. By conveniently enabling shutoff of propellants at their injection point into the combustion chamber (using a movable sleeve), the pintle injector provided greatly improved pulse response by eliminating injector "dribble volume" effects. A pintle injector with the face shutoff feature is shown in Figure 17.

Figure 17. Face Shutoff Pintle Injector in Closed Position

A very compact, 8,200 lbf N_2O_4/MMH engine employing this feature is shown in Figure 18. This engine was developed starting in 1981 as a pitch and yaw thruster for the Army SENTRY missile program. Tight packaging into the generally cylindrical shape of such missiles required that a "turned flow" nozzle be employed (here the flow was turned about 110° off chamber axis). This particular rocket application also required a slot nozzle to produce jet interaction effects that increased effective vehicle side thrust for operation within the atmosphere. This pintle injector engine, utilizing cavitating venturi control valves in a manner similar to LEMDE, could throttle over a 19:1 thrust range with ±8% linearity and could deliver repeatable "on" pulses as small as 8 milliseconds (to 90% s.s.

Pc) at any thrust level. It operated at 2200 psia chamber pressure to achieve small size and light weight (<13 lbm). Deliverable combustion efficiency was 98% of theoretical at full thrust, rolling off to 94% at $^1/_{10}$ throttle and to 71% at $^1/_{19}$ throttle (Ref. 8).

Figure 18. SENTRY Jet Interaction Pitch and Yaw Thruster (19:1 linear throttling and 8 msec pulsing)

A similar compact, face shutoff pintle engine—designed and ground demonstrated on one of the Air Force's earliest Strategic Defense Initiative Kinetic Energy Weapon programs (KEW 10.2)—is shown in Figure 19. This 90° turned-flow, N2O4/MMH engine operated at 1700 psia chamber pressure, delivering 300 lbf vacuum thrust with pulsing response to 12 milliseconds (Ref. 9).

A further refinement of the face shutoff injector was used on the Army Strategic Defense Command's Exoatmospheric Reentry-vehicle Interceptor Subsystem (ERIS), for which TRW provided the kill vehicle propulsion subsystem under contract

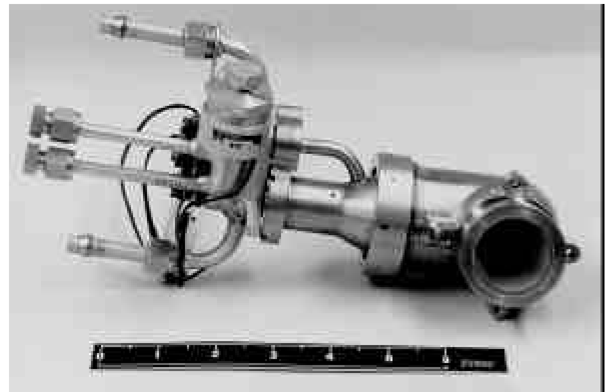


Figure 19. KEW 10.2 Divert Thruster for Early SDI Kinetic Kill Vehicle

to Lockheed Missiles and Space Company. The 900 lbf, 90° turned-flow, lateral divert engines used on this KV were pintle engines wherein the injector shutoff element provided the only control of propellant flow. The large bipropellant valve normally required in such engines was replaced by a small pilot valve that used high pressure fuel (MMH) to actuate the moveable injector sleeve. This feature—the face shutoff only (FSO) injector—greatly improves overall thruster response and significantly reduces engine size and mass. This injector sealed off liquid N2O4 and liquid MMH feed pressures of approximately 2300 psia during periods of thruster inactivity over a mission time exceeding 6 minutes. This technology innovation, together with many others incorporated into the KV, enabled the first exoatmospheric kinetic kill of a simulated (but actual size) reentry warhead off Kwajaline atoll on 28 January 1991 on the first flight of ERIS (Ref. 10).

More recently, FSO pintle injectors have been used very successfully to meter and control gelled propellants, which have a normal consistency like that of smooth peanut butter. Gelled propellants typically use either aluminum powder or carbon powder to increase the energy density of the liquid fuel base (typically MMH) and they use additives to rheologically match the oxidizer (typically IRFNA base) to the fuel across a wide range of both temperature and flow/shear conditions.

Gel propellants provide nearly the energy density of solid propellants and the controllability of liquid propellants, but with much safer storage, handling and operating characteristics. Unlike either solids or liquids, gel propellants have been shown to be insensitive munitions (IM) compliant. For gelled propellants to be used on rockets needing energy management, face shutoff is mandatory to prevent dry-out of the base liquid propellants during off times between pulses, which would otherwise result in the solids within the gels plugging the injector passages.

FSO pintle injectors have been used on a variety of programs, as summarized in Table 3. Of particular note, the McDonnell Douglas Advanced Crew Escape Seat – Experimental (ACES-X) program and it's successor, the Gel Escape System Propulsion (GESP) program, refined the FSO pintle injector (with a hydraulic servo valve acting as injector pilot valve) to the point that 2 millisecond pulses could be repeatedly delivered at >100 Hz on a 1700 lbf rocket engine using gelled oxidizer and aluminum-loaded gel fuel propellants (Ref. 11). A cross-section sketch of the FSO injector from the GESP program is shown in Figure 20. The GESP engine operated at a combustion chamber pressure of 2500 psia, the highest of any pintle engine that has ever been tested. The FSO injector on this engine sealed against supply pressures of approximately 3000 psia.

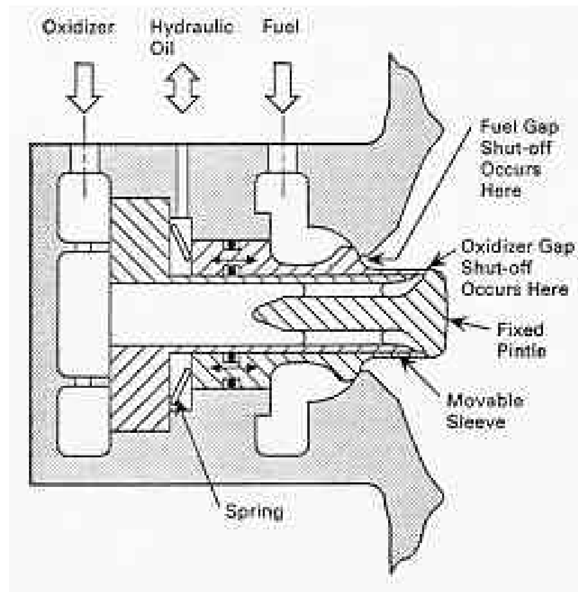


Figure 20. Face Shutoff-Only (FSO) Pintle Injector Concept Used on GESP

Table 3. Summary of Major Applications of TRW Face Shutoff Pintle Engines

	Advanced Throttling Slurry Engine (ATSE)	**SENTRY Pitch & Yaw Engine**	**KEW 10.2 Divert Thruster**	**ACES-X/ GESP**	**ERIS Lateral Thruster**	**FMTI**
Propellants	CLF3/ NOTSGEL-A	N2O4/MMH and gel IRFNA/ gel MMH (Al-loaded)	N2O4/MMH	gel IRFNA/ gel MMH (Al-loaded)	N2O4/ MMH	gel IRFNA/ gel MMH (C-loaded)
Full Thrust (lbf)	5000 (s.l.)	8200 (s.l.)	300 (vac)	1500/1700 (s.l.)	910 (vac)	1050 (s.l.)
Full Pc (psia)	1000	2200	1700	2500	1600	1750
Throttle Range	7:1	19:1	fixed thrust	fixed thrust	fixed thrust	fixed thrust
Upstream Valve	servo-piloted, hydraulically operated, linearly positioned, cavitating venturi, linked biprop	servo-piloted, hydraulically/MMH operated, linearly positioned, cavitating venturi, linked biprop	solenoid-piloted, MMH operated, on-off, linked biprop	None	None	None
Pintle Injector Type	continuously variable area, mechanically linked to valve stroke, only fuel side fully shutoff	continuously variable area, spring vs. pressure balanced	on/off, pressure opened, spring closed	FSO, on/off, pressure opened, spring closed, servo pilot valve, hyd oil actuated	FSO, on/off, pressure opened, spring closed, miniature 3-way solenoid pilot valve, MMH act'd	FSO, on/off, pressure opened, spring closed, miniature 3-way solenoid pilot valve, hyd oil act'd
Demonstrated Pulse Widths	steady state only	.008 – .600 sec	.010 – 1.13 sec	.002 – .800 sec	.020 – 1.76 sec	.115 – 1.66 sec
Comments	used toothed element for ox injection (center propellant)	>150 firing tests	67 pulses and 9.4 sec firing time on one engine	also tested in mockup escape seat (4 engine firing)	flown, 100% success (8/8)	flown, 100% success (2/2)

Another design challenge from the mid-1980's and early 1990's was that of obtaining miniaturization of rocket engines. As part of the Air Force Brilliant Pebbles program, TRW developed a very small 5 lbf N2O4/hydrazine thruster using a pintle injector. This radiation-cooled engine weighed 0.3 lbm (135 grams) and was successfully tested in August 1993, delivering >300 seconds Isp with a 150:1 nozzle expansion ratio. The pintle diameter was .066 inches and scanning electron microscopy was needed to verify as-built dimensions on the .0030±.0003 inch radial metering orifices. Figure 21 is a SEM photograph of this pintle injector, the smallest ever built.

Figure 21. Pintle Injector on Brilliant Pebbles 5 lbf Engine

Another major design adaptation in this time period was use of the pintle injector with cryogenic liquid hydrogen fuel. Previously, various pintle engines had been tested with liquid oxygen or liquid fluorine-oxygen (FLOX) as the oxidizer in combination with a near-ambient temperature liquid fuel such as methane, ethane, propane, RP-1 or hydrazine. Beginning in 1991, TRW joined with McDonnell Douglas and NASA Lewis (now Glenn) Research Center to demonstrate that TRW's pintle engine could use direct injection of near-normal boiling point LH2 (~50 R or 28 K) to simplify the design of high performance booster engines. Attempts to use direct injection of cryogenic hydrogen in other types of injectors had consistently resulted in the onset of combustion instabilities ("screech"), so verification of the inherent combustion stability of the pintle injector was a key part of this effort.

In late 1991 and early 1992, a 16,000 lbf LOX/LH2 test engine was successfully operated at sea-level at LeRC with direct injection of liquid hydrogen and liquid oxygen propellants (Ref. 12). A total of 67 firings were conducted. The engine demonstrated excellent performance, with 97% average combustion efficiency and total absence of combustion instabilities, including dynamic recovery on five runs having radial and tangential "bomb" excitations. Although the engine used a fixed-element injector, it was operated at 60%, 80% and 100% thrust levels by throttling facility propellant valves. Figure 22 shows a full thrust firing on this test engine.

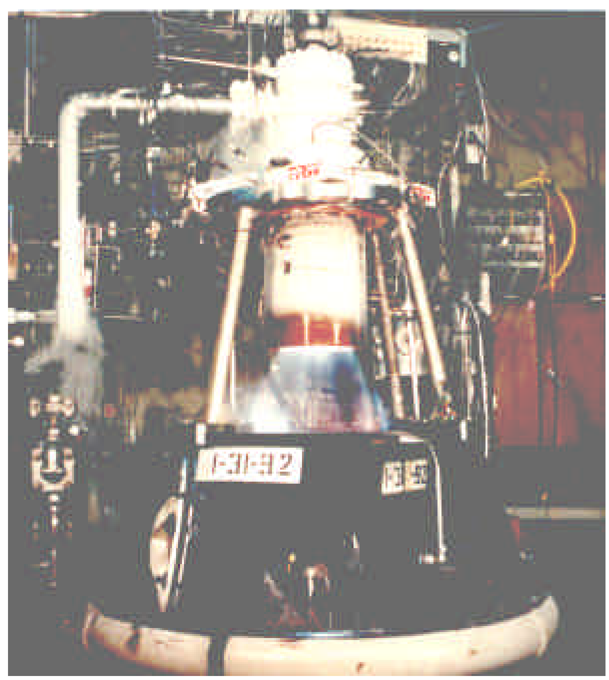


Figure 22. Pintle Injector Operation with Direct Injection of LOX and 45–50 R LH2

Subsequently, this same test engine headend was adapted for and was successfully tested with LOX/LH2 at 40,000 lbf and with LOX/RP-1 at 13,000 and 40,000 lbf. Significantly, this was accomplished by changeout of just three[†] injector parts, shown in Figure 23.

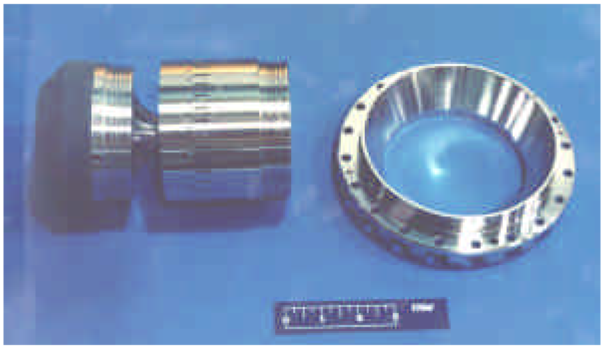


Figure 23. Pintle Tip, Oxidizer Orifice Ring and Fuel Gap Ring from 16K LOX/LH2 Engine

This demonstrates a key feature of the pintle injector: the low cost and ease by which it can be adapted to a change in operating conditions or propellants. Furthermore, optimization of a given injector's performance is empirically obtained by simply varying the geometries of the outer propellant's annular gap and the central propellant's slot geometries (and/or continuous gap, if used), two of the three parts shown in Figure 23.

Recent Applications

Within the last ten years the pintle injector has continued to be used across a diverse range of applications, with much of the hardware heritage traceable to work described above.

In the field of space propulsion, the URSA-series of radiation cooled engines—which led to the MMBPS and ISPS engines of the 1970's—provided the heritage for the N2O4/hydrazine ("dual mode") TR306 liquid apogee engines (LAEs) used on the Anik E-1/E-2 and Intelsat K spacecraft in 1991–1992 and most recently the dual mode TR308 LAEs used to place the NASA Chandra spacecraft on final orbit in August 1999. The TR308, shown in Figure 24, delivers 322 seconds of vacuum Isp using a radiation-cooled columbium chamber. A next-generation LAE design, the TR312, which uses a rhenium combustion chamber has been demonstrated to deliver 325 seconds Isp with N2O4/MMH and 330 seconds Isp with N2O4/hydrazine.

Figure 24. TR308 N2O4/Hydrazine Liquid Apogee Engine Used to Place NASA Chandra Spacecraft on Final Orbit in Aug 1999

The early FSO injector and gel propellant development work of late 1980's/early 1990's led to the world's first missile flights using gelled oxidizer and gelled fuel propellants. These were successfully performed on the Army/AMCOM Future Missile Technology Integration (FMTI) program, with the first flight in March 1999 (Ref. 13) and the second flight in May 2000. The 1050 lbf, 1750 psia chamber pressure engine, shown in Figure 25, is extremely lightweight (1.6 lbm, including 0.1 lbm solenoid valve). It is an ablative engine using a miniature solenoid valve to hydraulically control a FSO injector which meters gelled IRFA and carbon-loaded gelled MMH propellants for pulse-width modulated energy management during time-of-flight.

[†] On the 40K LOX/RP-1 engine, it was found that changing the 4 inch diameter pintle sleeve to 5 inch diameter permitted an oxidizer injection slot geometry delivering higher performance

Figure 25. FMTI Flight Engine (uses FSO pintle injector to control gel propellants)

In the area of booster engines, TRW has continued development of large LOX/LH2 pintle engines to the point that a 650,000 lbf test engine is currently undergoing pre-hot fire checkout testing at the NASA Stennis Space Center E-1 test stand. This engine, shown in Figure 26, represents a 16:1 scale-up from the largest previous LOX/LH2 pintle engine and about a 3:1 scale-up from the largest previous pintle engine ever tested, the 250,000 lbf N2O4/UDMH Air Force demo engine. As with the previous 16K and 40K LOX/LH2 pintle engines, the 650K engine will use direct injection of near-normal boiling point LH2. An extensive test series, including performance mapping, ablative durability demonstration and combustion stability (i.e., "bomb" tests) demonstration, has been planned for this engine. Testing will initially involve short (<10 second) pressure-fed firings, with later pump-fed firings demonstrating full mission duty cycle operation (>200 seconds). Additional details on this engine's development, features and test plans are given in Reference 14. For comparison, this injector's pintle diameter is 22 inches, by far the largest built to date.

Figure 26. The 650,000 lbf LOX/LH2 Low Cost Pintle Engine (LCPE) . . . the Largest Pintle Engine Built to Date

Summary of Design Features

The pintle injector design has been proven to be amazingly flexible and adaptable across a wide range of conditions. The features and operating characteristics of pintle engines are summarized here.

High Performance. With proper design and manufacturing—in some cases assisted by empirical "tuning' of injection geometries—pintle injectors can typically deliver 96–99% of theoretical combustion performance (as measured by characteristic velocity, or c*). Figure 27 summarizes combustion efficiency for some of the major pintle engine programs at TRW. Included in this figure are some quick, low cost demonstration engines where budgets or schedules prevented optimization of injector parameters.

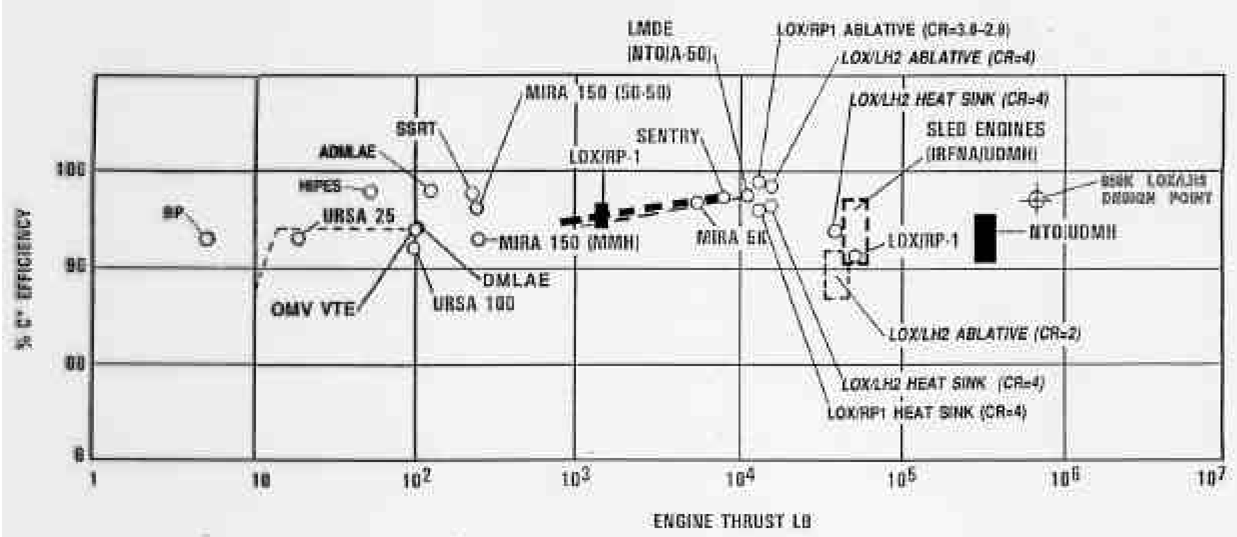


Figure 27. Summary of Combustion Efficiencies Measured on Major Pintle Engine Programs

Scalability. As also indicated in Figure 27, the basic pintle injector design has been demonstrated to be scalable over a range of 50,000:1 in thrust. With the expected, imminent firing of the 650K LOX/LH2 engine on the SSC E-1 test stand, this range will be extended to 130,000:1.

Inherent Combustion Stability. Three major, non-exclusive theories have been developed to explain the inherent combustion stability of the pintle injector:

1) lack of energy release availability at any antinode for all possible chamber acoustic modes (classical theory of combustion instability; Rayleigh, et. al.),
2) unvaporized, liquid droplets within the chamber's recirculating flowfields always experience a relative wind of combustion gases (C. Johnson, SEA),
3) the zones of highly varying sound speed within the combustion chamber (due to varying O/F, T, MW and c_p/c_v) disperse and dampen acoustic waves before onset of resonance (F. Stoddard, TRW).

Table 4 summarizes "bomb" tests performed on various pintle engines, each of which demonstrated complete dynamic combustion stability and critically damped recovery from the induced pressure transient.

Table 4. Summary of Dynamic Stability Tests Performed on Various Pintle Injector Engines

Propellants	Thrust Level (Klbf)	Stability Test Type *[grains RDX]*
LOX/LH2	**16**	5 pulse gun tests (2 radial, 2 tangential, 1 combined) *[20–60]*
LOX/LH2	**40**	5 pulse gun tests (all radial & tangential combined) *[40 + 40]*
LOX/RP-1	**13**	5 pulse gun tests (2 radial, 1 tangential, 1 combined, 1 non-directional) *[20–80]*
LOX/RP-1	**50**	4 "bomb" tests; <15 msec damping
N2O4/A-50	**1, 2.5, 3, 4, 5, 10 and 10.5** (LEMDE)	31 non-directional RDX bomb tests with pressure spikes >150% Pc s.s. (including ND bombs located on face of pintle tip and at nozzle throat) *[5–40]*
N2O4/UDMH	**250**	13 pulse gun tests (7 radial and 6 tangential) and 8 non-directional bomb tests *[40–120]*
N2O4/UDMH	**50 (throttled 250K engine)**	2 non-directional bomb tests, <15 msec damping *[20–30]*

Range of Propellants Tested. Pintle injectors have successfully operated with 25 different combinations of propellants, which are summarized in Table 5.

Table 5. Propellant Combinations Tested Using Pintle Injectors

LOX/H2(l)	LOX/RP-1
LOX/C3H8	LOX/N2H4
LOX/ETHANOL	GOX/ETHANOL
FLOX/CH4(l)	FLOX/CH4(g)
FLOX/C3H8(l)	FLOX/CH4+C2H6(l)
N2O4-MON3/MMH	N2O4-MON3/N2H4
N2O4/UDMH	N2O4/A-50
ClF3/N2H4	ClF3/NOTSGELA
F2(l)/N2H4	MON10/MMH
IRFNA/UDMH	IRFNA/JP4
IRFNA/NOTSGEL-A	HDA/USO
Gelled IRFNA/ Gelled MMH+60%Al	Gelled IRFNA/ Gelled MMH+60%C
Coal Dust/Air	

Throttling Ability. As discussed previously, single pintle injectors have operated over throttle ranges as high as 35:1 while still retaining high combustion efficiency. TRW's most famous throttling engine is the man-rated Apollo LEMDE, which provided 10:1 throttling capability to perform lunar landings. A summary of throttling pintle engines is given in Table 6.

Simplicity. A complete pintle injector can be made with as few as five parts, excluding the engine headend dome and fasteners. Only two simple parts need to be changed to empirically and rapidly optimize the injector's performance. The simple design of pintle injector parts and their operation at benign temperatures (except for the pintle tip) assures ease of manufacturing using non-exotic metal alloys and common machining and welding methods. The inherent combustion stability provided by the pintle injector eliminates the need for any headend baffles or acoustic cavities and this simplifies thrust chamber construction, enhances reliability and reduces manufacturing cost.

Table 6. Summary of Major TRW Throttling Engines

	MIRA 500 Variable Thrust Engine	MIRA 5000 Variable Thrust Engine	Surveyor Vernier Engine (MIRA 150)	Lunar Hopper Engine	LM Descent Engine	8K Engine	Advanced Throttling Slurry Engine (ATSE)	Sentry Engine	OMV VTE
Throttling Capability	20:1 500 to 25 lbf	35:1 5,200 to 150 lbf	5:1 150 to 30 lbf	15:1 180 to 12 lbf	10:1 10,000 to 1,000 lbf	15:1 8,250 to 553 lbf	7:1 5,000 to 700 lbf	19:1 8,200 to 430 lbf	10:1 130 to 13 lbf
Propellants	N2O4/A-50 N2O4/N2H4	N2O4/A-50 N2O4/MMH	MON-10/ MMH	MON-10/ MMH	N2O4/A-50	N2O4/A-50	CLF3/ NOTSGEL-A	N2O4/ MMH	N2O4/ MMH
Sponsor	TRW IR&D	TRW IR&D	NASA/ JPL	NASA/ MSFC	NASA/ Grumman	USAF/ LTV	Navy/ NWC	US Army/ Bell	NASA/ MSFC
Program Duration	1961-63	1962-63	1963-65	1965	1963-72	1967-68	1967-68	1981-84	1986-89
No. of Engines	1	1	16	1	84	2	1	4	2

Design Adaptability. As discussed previously, the pintle injector design enables incorporating features such as deep throttling, rapid pulsing, face shutoff with upstream valving, face shutoff only (FSO), direct injection of near-normal boiling point LH2, and the demonstrated ability to use gelled propellants in pulsing applications.

Low Cost. With its inherent stability and ease of optimization, the pintle injector minimizes risk and cost for development and qualification of new engine designs. Its ease of manufacture provides for significant reductions in recurring costs, especially in booster-class engines.

Conclusion

In the field of rocket engines, the pintle injector is unique in its configuration, operating characteristics and performance features. It is a patented technology that has provided the base for a diverse product line of bipropellant rocket engines of one company, TRW (formerly Space Technology Laboratories), for more than 40 years.

There has never been a flight failure of a pintle injector engine. Moreover, there has never been an instance of combustion instability in a pintle engine during any ground or flight operations, despite scaling over a range of 50,000:1 in thrust and 250:1 in chamber pressure and operation with 25 different propellant combinations, including LOX/LH2 and F2/hydrazine.

The pintle engine has been developed, ground demonstrated and successful flown across a wide and challenging range of applications, including programs of national importance such as Apollo and the recent NASA Chandra "Great Observatory" spacecraft. The pintle injector has enabled the world's first successful flight of a missile using gelled propellants. Even at the time of publication of this paper, pintle injector technology is being extended into a new realm on the 650,000 lbf LOX/LH2 LCPE. This technology offers the potential to dramatically reduce the cost of access to space ". . . for all mankind."

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14. "TRW LCPE 650 Klbf LOX/LH2 Test Results," K. Gavitt and T. Mueller, AIAA 2000-3853, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 16-19 July 2000

Addendum

1. An excellent reference for the early development work at Caltech, cited in the first three full paragraphs on Page 5 is:

   "The Effect of Rapid Liquid-Phase Reactions on Injector Design and Combustion in Rocket Motors," Gerard W. Elverum, Jr. and Pete Staudhammer, Jet Propulsion Laboratory, Progress Report No. 30-4, 25 August 1959

2. Commenting on the early Caltech JPL work on characterizing reactions of hypergolic reactions, Jerry Elverum provided the following comment to the paper's authors:

   "Early experimental data revealed that the speed of liquid-phase reactions at the contact interface of hypergolic propellants generated an expanding confined annular gas boundary which limited the effectiveness of premixing downstream of the retracted inner tube. Subsequent experiments with stabilized impinging streams definitely demonstrated for the first time that for highly hypergolic propellants, this essentially instantaneous gas evolution at the contact interface caused major separation of oxidizer and fuel in the resulting spray pattern. The desire to use "pre-mixing" of hypergolic propellants in a simple concentric tube configuration as a way of forcing intermixing was also shown to be severely limited by the extreme rapidity of this interface reaction."