MOONBURNER: AN ULTRA-HIGH WEB FRACTION GRAIN DESIGN

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ABSTRACT

(U) This paper describes the development of a new ultra-high web fraction solid propellant grain design. The concept allows the design of progressive, regressive, or neutral burning grains with web fractions as high as 1.6 combined with high volumetric loading. The ultra-high web fraction feature allows the typical tactical or sounding rocket motor to burn for at least twice as long, with current propellants, as with previous grain designs. In addition, the pressure-vs-time profile can be tailored to be more rectangular, as is illustrated with a comparative overplot. Volumetric loading as high as 96% is achievable in some designs. A computerized mathematical model of the new grain design was created and exercised to obtain predictions of performance. This model is presented, as well as plots of predicted chamber pressure-vs-time for a typical tactical sustainer motor.

(U) Experimental development of the concept, from initial motor tests up through static tests with up to 13.5 Lb_m of propellant is detailed. The burning time of a 6.25 inch diameter motor was 54 seconds. Larger 13-inch diameter hardware under construction is also described. A small, commercially available, flightweight engine utilizing this grain design is described and its thrust/time plot is shown. Flight tests of the new grain design are described. They range from small sounding rocket flights to 3 miles with 1 Lb_m of propellant to larger tactical-sized rockets using a modified version of the new grain design that reach 65,000 feet altitude with up to 186 Lb_m of propellant. To date, 27 five-inch diameter flightweight motors, each with 46.5 Lb_m of propellant, have been fabricated. Twenty-four of these motors have been flown with a success rate of 92%. Potential applications of the design in solid propellant tactical and sounding rocket and ramjet motors are described.

INTRODUCTION

(U) In solid rocket propellant grain designs web fraction may be defined as the distance the propellant burns from ignition to burnout divided by the radius of the propellant grain. In the industry, a web fraction of 0.8 is considered very high. The author conceived an ultra-high web fraction solid propellant grain design that permits the fabrication of grains with web fractions as high as 1.6. Dubbed "Moonburner" because of the configuration that an end view of the regressing propellant surface adopts, the concept allows the design of progressive, regressive or neutral burning propellant grains with a volumetric loading as high as 96%. The concept, in its simplest form, consists of a circular port that is offset to one side of the longitudinal axis of the propellant grain as shown in Figure 1.

CURRENT STATE OF THE ART

EARLY RELATED RESEARCH

(U) Unknown to the author, and to the propulsion community at large, a modified version of the Moonburning concept was introduced in 1973 by R. Bennett. This version, illustrated in Figures 2 & 3, combines a web fraction of 1.05 with a 93% volumetric loading and has been produced in twenty-seven five inch diameter flight weight motors, each containing 46.5 Lb_m of unaluminized composite propellant. Twenty-four of these motors have been utilized in sixteen flight tests, demonstrating a reliability of 92%. The two motors that failed have been linked to low temperature cracking of the propellant at the acute angle near the motor centerline. The twenty-two successful motors have flown in a dozen single engine flights, two three engine cluster flights and a four engine cluster flight utilizing a total of 186 Lb_m of propellant to propel vehicles as large as two feet in diameter and twenty-eight feet long and weighing 2,120 Lb_m. These flight vehicles have carried accelerometers, transmitters, cameras, timers and pyrotechnic actuators. Pyrotechnic flares and smoke generators have been used to aid in optical tracking. The entire vehicle has been recovered by parachute from altitudes of up to 43,000 feet. This year a single motor will be used to launch an eight-inch diameter 15.5 foot long high payload vehicle and recover it by parachute. The remaining two motors will be tested, also this year, in a launch to an anticipated altitude of 65,000 feet with a highly instrumented vehicle in the first two-stage configuration attempted with these motors. A delay will

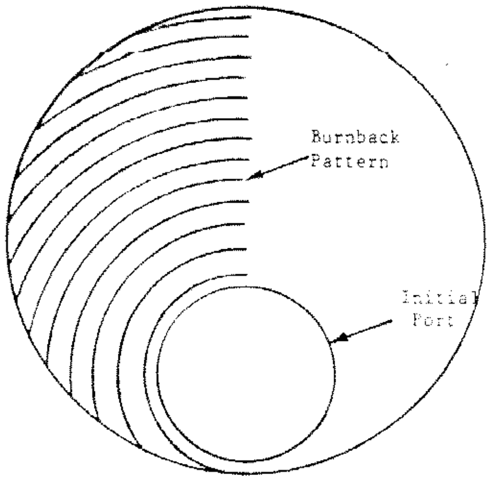


FIGURE 1
Moonburner Grain Design,
End View, by the author.

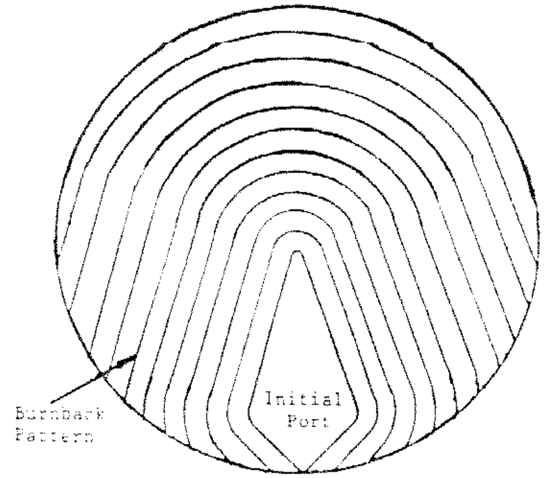


FIGURE 2
Modified Moonburner
Grain Design, End View,
by R. Bennett.

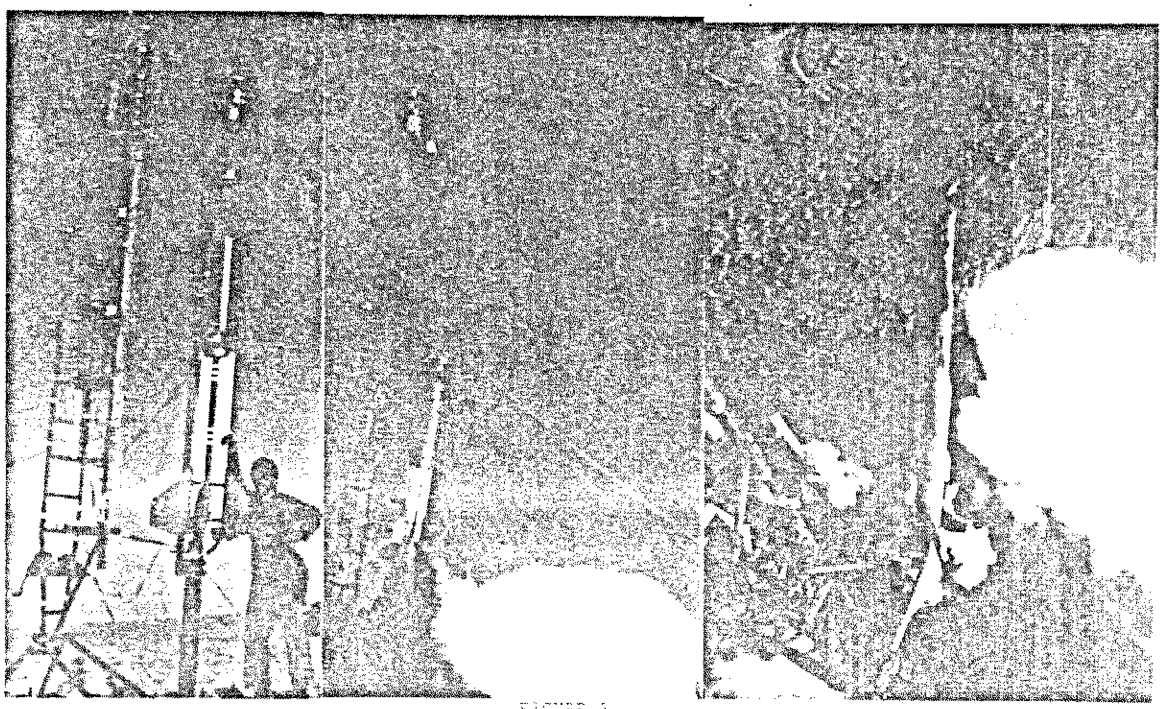


FIGURE 3
Launch of recoverable, instrumented, tactical-sized, supersonic, multiengine test vehicle utilizing modified moonburner grain design by R. Bennett.

be used between stages to increase the altitude obtainable.

INITIAL MOONBURNER RESEARCH

(U) In early 1981 the author began static tests of ultra-high web fraction (1.25) moonburner solid propellant motors utilizing AP/HTPB/AL propellants in filament wound epoxy-fiberglass cases with graphite nozzles. Results of this research were shared with the other researchers mentioned in this paper. Seeing the potential of the new grain design, they initiated their own research programs to investigate this concept. Internal and aft end burning, 86% volumetric loading, grain designs similar to that shown in Figure 1 were tested. Additional static tests were conducted with similar hardware and utilizing other HTPB binder propellant types. These tests were conducted with three families of high density propellants: Lead Nitrate/AP, ZN/AP and ZN/KP as well as an AP/Ti formulation and a MG/AP propellant suitable for use in ducted rocket gas generator applications. In general these tests demonstrated the steady thrust and long burning times (up to 14 sec.) possible with these ultra-high web fraction configurations.

SMALL MOTOR TESTS

(U) From late 1981 to the present, G. Rosenfield fabricated and tested, both statically and in flight, thousands of small moonburning rocket motors with graphite nozzles. The largest are 2.125 inches in diameter with 1 Lb_m of 84% solids reduced smoke AP/HTPB propellant and delivers 21 Lb_f thrust for 9 seconds. The thrust/time curve is shown in Figure 4. These motors combine a web fraction of 1.34-1.444 with volumetric loadings of 92-93% and have been flight tested to 3 miles. Some motors have achieved volumetric loadings as high as 96% by combining the moonburning configuration with a substantial end burning head end web as first tested by the author. This delivers a dual thrust profile that is tailorable.[2]

LARGER MOTOR TESTS

(U) From 1982-1984 J. Krell conducted 12 static tests of larger high web fraction epoxy/fiberglass moonburning solid propellant rocket motors with graphite nozzles. These motors utilized AP/HTPB/AL propellant grains that were inhibited from burning on the ends. Six static tests with two inch diameter motors containing up to 3 Lb_m of propellant have been conducted producing 500 psia chamber pressure and 10 second burning time. These motors utilized 0.1 inch EPDM chamber insulation and combined a web fraction of .97 with 83% volumetric loading. A seventh motor was flight tested.

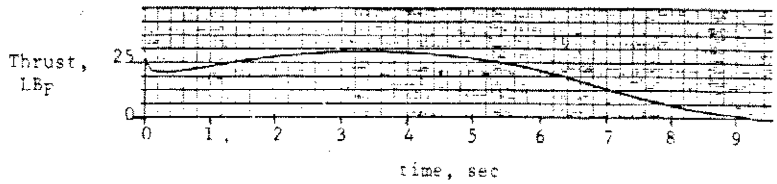
(U) Five three-inch diameter motors containing 2-4 Lb_m of propellant have been fabricated and four have been static tested. These motors combined web fractions of .67-.89 with volumetric loadings of 72-80% and burn for 15 seconds. The fifth motor, a .33 web fraction regressive moonburner, contains 2.75 Lb_m of propellant. It has a 56% volumetric loading and is expected to burn for 7 seconds when it is flight tested this year to 3 miles in an 8 Lb_m rocket.

(U) Two 6.25 inch diameter motors combining web fractions of .89 with 80% volumetric loading were static tested. The first, containing 11 Lb_m of slow burning propellant, burned for 54 seconds. The second, containing 13.5 Lb_m of faster burning propellant, burned for 35 seconds. Both motors were insulated with 0.375 inch EPDM. A thirteen inch diameter motor with 60 Lb_m of propellant is being fabricated for static test this year. It combines a web fraction of 1.18 with an 55% volumetric loading and is also insulated with 0.375 inch EPDM. It is expected to deliver 160 Lb_f thrust for 80 seconds.[3]

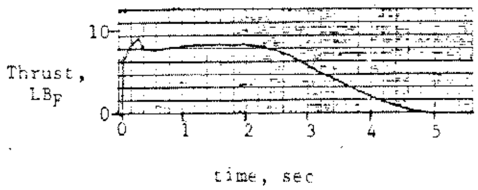
ADDITIONAL MOTOR TESTS

(U) From 1983 to the present T. Johnson has fabricated and tested over 100 moonburning epoxy/fiberglass rocket motors with graphite nozzles. These motors contain 82% solids AP/HTPB/MG/AL propellant and are insulated by .04 inch asbestos/rubber. Over 80 of these motors have been 2.125 inch in diameter and contain 0.7 to 1.4 Lb_m of propellant. They combine web fractions of 1.23-1.27 with 86-89% volumetric loading and burn on the aft end, as well as internally, for 6 seconds.

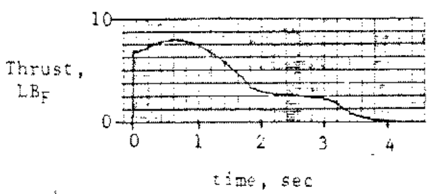
(U) Four 2.65 inch diameter motors containing 2 Lb_m of propellant were tested in 1984. These motors combined a web fraction of 1.25 with a 91% volumetric loading and used aft end inhibition that prevented the aft propellant surface from burning until 4 seconds into the 10 second burning time. Three motors were tested statically, producing 550 psia chamber pressure. The fourth motor was flight tested to 3 miles and recovered a mile from the launcher.[4]

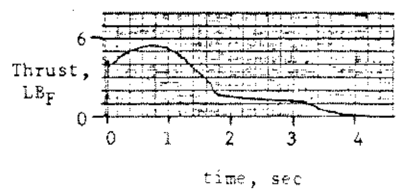


High web fraction, high volumetric loading moonburner thrust vs time curve obtained during static test. Total impulse: 193 LBF-sec. Motor size: 2.125 in. dia. x 9 in. long.



Smaller high web fraction, high volumetric loading moonburner static test results showing the effect of a gap between the port and the near chamber wall.





Static Test results of small, high web fraction, ultrahigh volumetric loading (96%) boost-sustain moonburners with substantial head end webs.

FIGURE 4: Static Test Results by G. Rosenfield

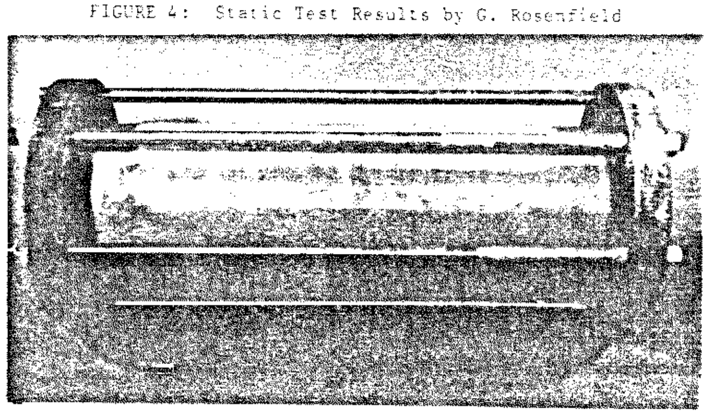
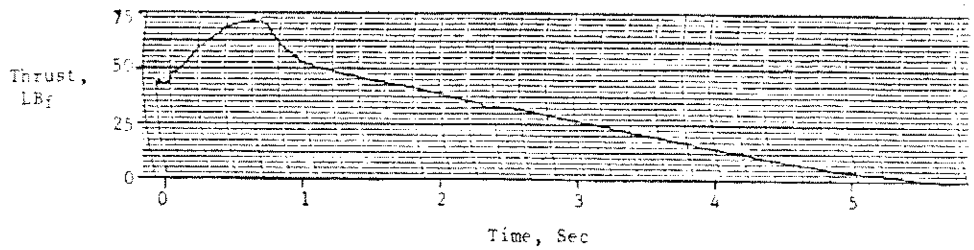
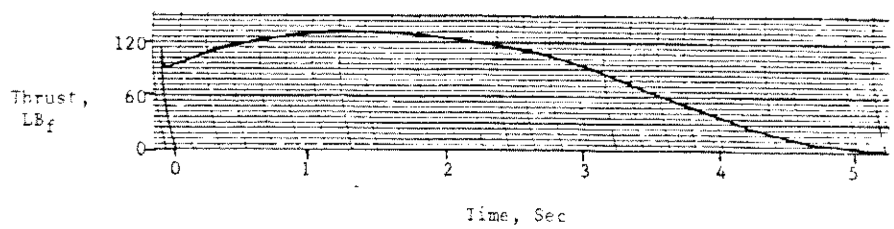


FIGURE 5: 6.25 inch diameter moonburner heavyweight static test hardware by J. Krell

(U) The largest motor in this series, 3.75 inches in diameter with a submerged graphite nozzle, was static tested this year. It contained 4.6 Lb_m of propellant and delivered 45 Lb_m thrust for 20 seconds. It combined a web fraction of 1.36 with a 92% volumetric loading and included aft end inhibition for the first 5 seconds of burning. A larger motor with 8.8 Lb_m of propellant is being fabricated for static test later this year.



High web fraction, high volumetric loading moonburner thrust vs time curve obtained during static test. Total impulse: 224 LB_f-sec. Motor size: 2.125 in. dia. x 12 in. long.



Larger high web fraction, high volumetric loading moonburner static test results. Total impulse: 448 LB_f-sec. Motor size: 2.15 in. dia. x 24 in. long.

FIGURE 5: Static Test Results by T. Johnson

(U) Computerized mathematical models of moonburner grain performance have been created. The earliest, in 1981, was created by the author to run on a TI-59 hand held magnetic card programmable calculator and provided predictions of the variation in burning surface area vs web burnback for moonburning grains with both ends inhibited. In 1983 J. Krell created a similar program for the Apple II in basic. The latest version, in Fortran 5, has been implemented at Westinghouse by Y. Yang in co-operation with the author and runs on the CDC 7600 computer. It can be exercised in 3 options: internal burning with both ends inhibited, internal and one end burning and internal and both ends burning. By supplying nozzle impedance, grain dimensions and propellant ballistics (burning rate coefficient and exponent) digital and graphical displays of burning surface area and pressure vs web burnback and pressure vs time are obtained as well as average pressure and pressure action time. The product of these last two values is the pressure-time integral.

(U) Figure 6 shows a computer generated pressure-time curve for a 5 inch diameter moonburning rocket motor with a web fraction of 1.6 and a volumetric loading of 96%. The propellant grain burns internally and on the aft end. The maximum pressure is 1315 psia, average pressure is 1003 psia and the pressure action time is 19.58 sec. By changing grain L/D and/or inhibiting the ends of the propellant grain the pressure-time trace can be made more or less progressive if desired.

(U) Two examples are presented to illustrate the changes in performance that can be produced by application of the moonburner grain design to existing rocket motors. The motors selected for modification were chosen from among a group of sounding rocket motors to be able to present unclassified information. These motors, however, are similar in size and total impulse to many tactical motors and the same techniques to improve performance may be employed. Data on these motors is presented in table I.

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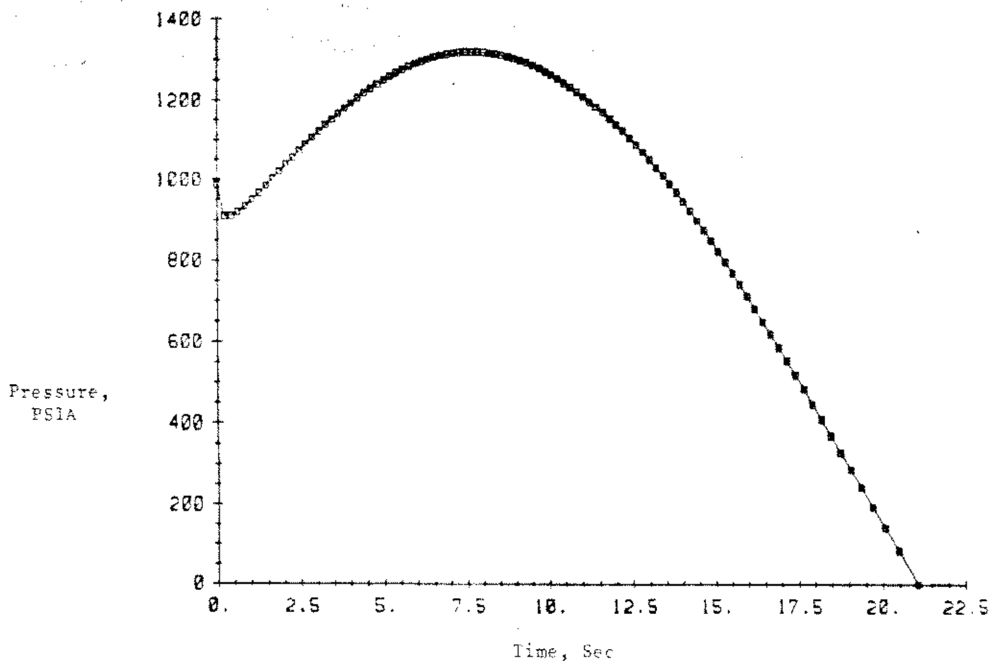

FIGURE 6

Calculated pressure vs time for ultra high web fraction (1.6), ultra high volumetric loading (96%) moonburning propellant grain.

Table I[5]

Motor	HOPI II	HYDAC
Diameter, in	4.5	9.0
Length, in	79.7	140.1
Total Weight, LB_m	76.1	545.2
Propellant Weight, LB_m	57.8	405.1
Web Fraction	.63	.61
Volumetric Loading, %	86	85
Average Thrust, LB_f	3,080	12,010
Average Pressure, PSIA	780	980
Maximum Pressure, PSIA	1,120	1,390
Pressure Action Time, Sec.	3.9	8.25
Total Impulse, LB_f-Sec.	12,000	99,100

(U) Both motors are relatively high web fraction (for center-perforate designs) and have reasonably high volumetric loading. Initial port cross sectional area for HOPI II is less than 54% of the nozzle throat area. Thus, it operates as a "nozzleless" rocket motor with erosive burning for the first 20% (0.5 sec) of web burning. Modifications for both motors involve asymmetric application of insulation (much thicker on the port side) and installation of higher expansion ratio nozzles with 62 and 54% smaller throat areas. Both motors maintain the previous dimensions, weights and volumetric loading, as well as maximum pressure. Reduction in the HOPI II nozzle throat area allows it, like the HYDAC, to operate as a nozzled rocket motor from ignition.

(U) Utilizing the moonburner computer program, predictions of HOPI II and HYDAC pressure vs time performance were obtained for grains with both ends inhibited. Figure 7 shows a comparison between current published and moonburner HOPI II pressure vs time. Increasing the web fraction to 1.21 and utilizing the same propellant increases the average pressure by over 14% to 893 psia, delivers an average thrust of 1730 LB_f for a pressure action time of 7 sec. and increases total impulse by about a percent. The new nozzles have exit areas about 60% as large as the current designs, providing higher thrust coefficients and lower base drag (with boattails) during coasting than the current designs.

(U) Figure 8 shows a comparison between current and moonburner HYDAC pressure vs time as predicted by the computer program. Utilizing the same HYDAC propellant and increasing the web fraction to 1.21 increases the average pressure by nearly 17% to 1144 psia, delivers an average thrust of 6480 LB_f for a pressure action time of 15.4 sec. and increases total impulse by about a percent.

(U) Boost-Sustain thrust profiles may be obtained, as mentioned previously, by using a propellant grain with a moonburning port aft of a substantial head end web, with the endburning portion providing the sustain portion of the impulse. This type of thrust profile may also be obtained by utilizing a highly convoluted port cross section such as a multipointed star as first tested by the author, which burns rapidly into a more circular port cross section that is offset from the motor centerline as shown in Figure 9. Both of these configurations can deliver extremely high volumetric loadings while providing the stepped boost-sustain thrust profile often preferred for tactical missions.

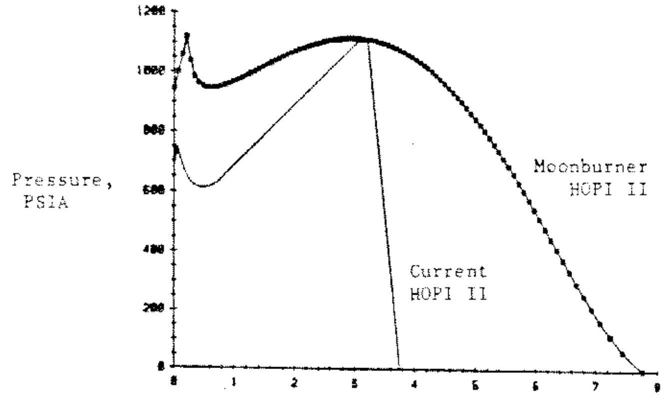

Figure 7

Comparison between current HOPI II and Moonburner HOPI II Pressure vs Time

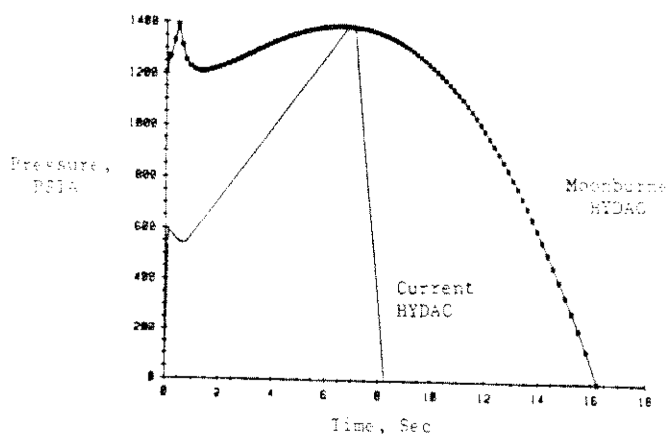

Figure 8

Comparison between current HYDAC and Moonburner HYDAC Pressure vs Time

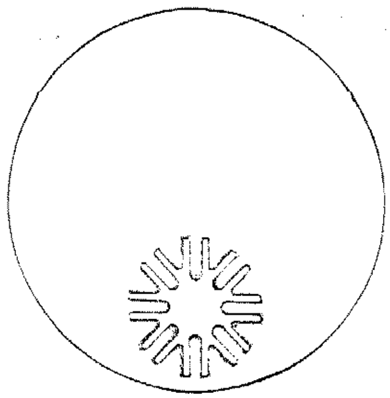

FIGURE 9
Moonburner boost-sustain grain design, end view

(U) The moonburner grain design may be usefully employed in ducted rockets and solid propellant ramjets where a relatively constant burning surface area vs web burnback is desired. Swirl combustion may be used in solid propellant ramjets, to improve combustion efficiency, with the smooth bore moonburner since there are no radial swirl dampeners (star points) present. The greater web thickness provided by the moonburner design can be used to provide longer range for small diameter solid propellant ramjet tactical weapons.

References

1. Bennett, Richard: private communications, 1982-1985.
2. Rosenfield, Gary C.: private communications, 1981-1985.
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4. Johnson, Thomas: private communications, 1983-1985.
5. CPIA/M1, Rocket Motor Manual.