Gas-Deployed Skirt for Rocket Motor Nozzles

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The gas-deployed skirt (GDS) is a metal nozzle extension that is folded radially inward and packaged entirely within the cavity of a rocket motor nozzle. The skirt is deployed by low-pressure motor ignition gases and then stabilized in the open position by the internal pressure of fully developed nozzle exhaust gas flow. The conception, design, and analysis are discussed in the context of seven successful GDS tests on 100-lb liquid rocket rocket motors and 5000-lb solid rocket motors. Typical applications and the resulting performance improvements are also discussed.

Introduction

THE necessary nonoperating enclosure of upper stage and spacecraft rocket motors limits the size, and therefore the performance, of the rocket motor nozzle. However, a large nozzle extension or exit cone can be designed for installation in a retracted configuration (in the nonoperating enclosure) and extended to the operating position during or after motor staging and ignition. In this manner, the extendible exit cone (EEC) concept can provide maximum motor performance with an optimum nozzle expansion ratio for the operating altitudes of the motor.

Refractory metal extendible nozzles have been under development since 1970 to capitalize on two intrinsic advantages of this type of EEC. These advantages are 1) unlimited run duration provided by high erosion resistance and radiation cooling, and 2) high reliability provided by design simplicity and the elimination of hot gas seal closure during deployment.

The first successful EEC was a rolling metal convoluted nozzle.[1,2] The convoluted nozzle is an otherwise conventional sheet metal nozzle extension that is formed with a portion of the nozzle convoluted (i.e., turned inside out) to reduce the installed length of the nozzle extension to approximately one-third of the deployed operating length. The nozzle is extended by simple roll-through. The convoluted nozzle may be self-actuated by motor ignition pressure retained, during deployment, by a jettisonable exit closure[1] or it can be deployed by an external system of three or more actuators. The actuator deployed rolling metal EEC has been successfully tested on Minuteman and Trident third-stage development motors.[2,3]

The gas-deployed skirt (GDS) is a folded metal exit cone that was conceived to produce a metal EEC that is extendible in both length and diameter. Used in combination with the rolling metal convoluted nozzle, the GDS provides the design flexibility to package the maximum EEC expansion ratio in a given envelope. Installed directly on the exit of the rocket motor nozzle, the GDS is a lightweight, low-cost EEC of high intrinsic reliability. This version of the GDS is the subject of this paper.

Design and Analysis

The gas deployed skirt (GDS) is a metal cone that is folded radially inward in a tapered pattern such that, when installed on the exit of a rocket motor nozzle, it is packaged entirely within the cavity of the nozzle, as shown in Fig. 1. The skirt is deployed to a partially open position by low-pressure motor ignition gases, as shown in Fig. 2, and then expanded to the full open position by the internal pressure of fully developed nozzle exhaust gas flow. This two-phase deployment applies to the starting characteristics of typical rocket motors. On fast-starting motors, the two phases merge into one continuous movement. On very fast-starting motors, the GDS is fully opened by ignition gases and kinetic energy dissipation must be considered in the design.

An analytical study of the GDS was therefore carried out to support the design and test effort. By equating the bending moment on the folds to the hoop tension produced by internal pressure, an expression for the static pressure required to fully open the GDS was developed, indicating that the required pressure is a function of the number of folds, the material yield strength, and the square of the skirt thickness. However, in a fast-starting rocket motor, the folded and stowed GDS is accelerated to high angular velocity by motor ignition gases. The kinetic energy invested in the GDS is then converted to strain energy as the skirt rotates and stretches to the fully open position. By equating the kinetic energy to the strain energy at the elastic limit, it was shown that the minimum deployment time can be defined in terms of the GDS length, deployment angle, and material properties. The limiting time is independent of thickness because both the kinetic energy and the elastic strain energy capability vary directly with thickness.

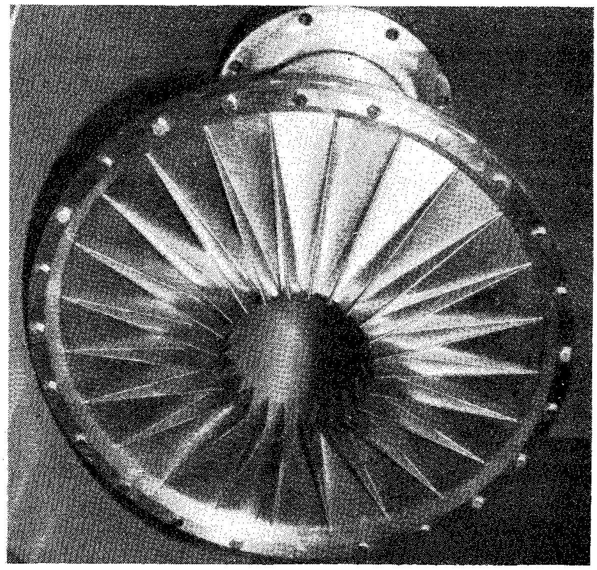

Fig. 1 Folded metal GDS.

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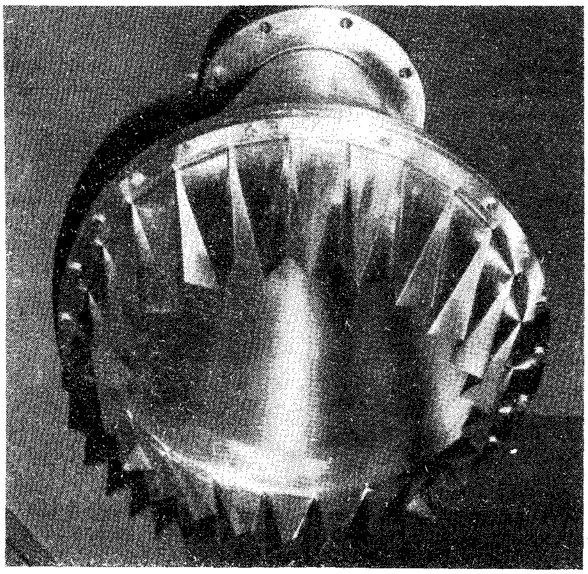

Fig. 2 Partially open GDS.

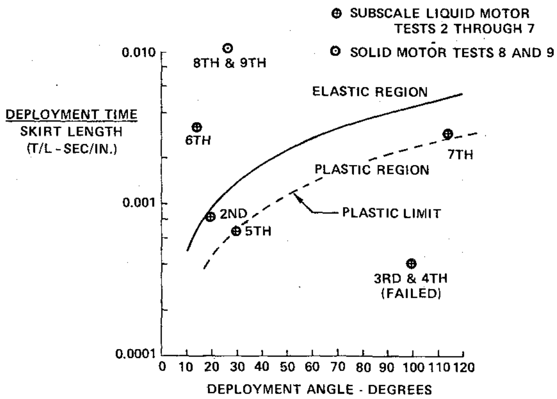

Fig. 3 GDS deployment time limits.

This relation is plotted in dimensionless form in Fig. 3. The curve defines the elastic limit opening time for the GDS materials selected for the test units. The area above the curve is the region of completely elastic opening of the GDS. The area below the curve is the region requiring plastic deformation of the GDS to absorb the kinetic energy. To verify this theory, testing was planned on both sides of the threshold shown in Fig. 3.

A subscale GDS was designed to demonstrate feasibility and verify the kinetic theory on small liquid rocket motors. A 16-fold stainless steel GDS of 1.25 in. length was selected for attachment at a diameter of 3.2 in. and expansion to a diameter of 3.6 in. with a deployed half-angle of 9.5 deg. The skirt thickness and alloy was 0.0018 in. 304SS. The subscale GDS was designed to attach to the liquid rocket motors at a nominal expansion ratio of 20/1 and deploy on ignition to a nominal exit expansion ratio of 26/1.

The refractory metal GDS was designed to evaluate deployment and performance on a Ballistic Test Evaluation System (BATES) solid rocket motor at the Air Force Rocket Propulsion Laboratory (RPL). A 6 in. long skirt of C103 columbium was selected on the basis of kinetic opening analysis to provide a GDS that is capable of opening in 29 ms elastically (with a potential of approximately 16 ms in plastic strain). To provide for a slow start on the BATES motor, the GDS was also designed for complete deployment on the static pressure developed in the GDS during steady-state operation of the motor.

A skirt thickness of 0.0055 in. was selected to provide a safety factor of 3 on thrust buckling. The calculated static pressure in the deployed GDS ranges from 0.69 to 0.45 psi based on isentropic expansion from a chamber pressure of 930 psi in the BATES motor. The calculated temperature transient during the 5-s run is R.T. to 2700°F. At this thickness and these pressures and temperatures the static pressure deployment analysis indicated that 24 folds were required for full opening.

On this basis, the 24-fold GDS shown in Figs. 1 and 2 was designed for test on the BATES motor with motor drawings and data supplied by RPL. The resulting design data are summarized as follows:

GDS	
Number of folds	24
Skirt length	6 in.
Attach ϵ and diam.	90 at 16.1 in.
Exit ϵ and diam.	130 at 19.4 in.
Deployed half-angle	15 deg nom.
Skirt material and thickness	5.5 mils C103
Motor	
BATES, throat diam.	1.7 in.
Avg. chamber pressure	930 psi
Duration	4.5 s
Spec. heat ratio (γ)	1.2

Subscale GDS Tests

The first five tests were 2-s runs conducted on a 100-lb liquid bipropellant (N_2O_4-MMH) motor in an altitude test cell at Bell. This was an attitude control pulse motor with a very rapid P_c rise rate. The first test was a checkout run with a fully deployed GDS. The second test was a GDS folded inward 19.5 deg which was successfully deployed near the elastic limit (see Fig. 3). The deployment times were determined by 1000 frame/s photography. The third GDS was folded inward 99.5 deg to probe deep into the plastic region of Fig. 3. This GDS split and tore off the mount. The fourth GDS was also folded inward 99.5 deg to confirm the results of the third (to be sure that the results were not due to hardware discrepancies). The fourth GDS failed in the same manner as the third. The fifth GDS was folded 29.5 deg to move back towards the elastic limit line (but remaining clearly in the plastic region). The fifth GDS deployed successfully but showed evidence that it came close to splitting.

It was clear at this point that the bipropellant motor ignition was too fast to obtain data for a fully folded GDS. The test program was therefore switched to a controllable 125-lb monopropellant (N_2H_4) motor to make two tests of fully folded GDS's, one in the elastic region and one just across the threshold into the plastic region. The results of these tests (determined by 2000 frame/s photography) are also shown on Fig. 3.

The sixth test was a two-phase deployment in 60 ms. The skirt rotated 85 deg in the first 30 ms in response to ignition pressure and remained in this position until full chamber pressure rise started at 56 ms. In the last 4 ms the GDS deployed the remaining 14 deg to the full open position. Only the last motion is significant in terms of the elastic limit of the skirt and so this run is plotted with a 14 deg deployment angle in Fig. 3.

The GDS was folded inward 114 deg for the seventh test to demonstrate the fast opening capability of the fully folded GDS. The seventh GDS deployed in one continuous movement in 3.6 ms and operated successfully for the remainder of the 10-s run.

The results of the subscale test series plotted on Fig. 3 confirmed the utility and the conservatism of the elastic limit strain as design criteria for the GDS.

BATES Motor GDS Tests

The Air Force Rocket Propulsion Laboratory (RPL) conducted a series of four BATES motor test firings to

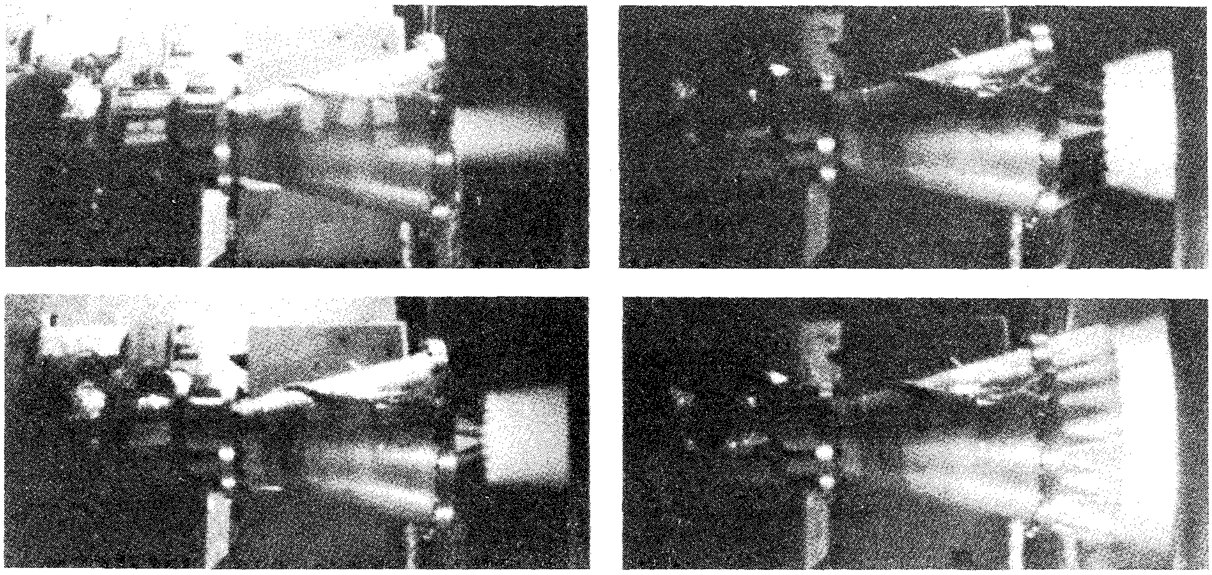

Fig. 4 GDS fire test at RPL.

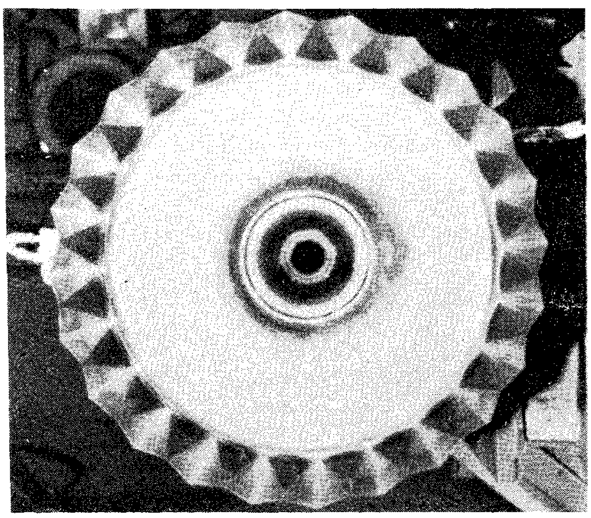

Fig. 5 Post-fire view of GDS.

evaluate the GDS. The tests were conducted at a minimum pressure altitude of 100,000 ft in test cell 1-42A at RPL. The final test of this series on Feb. 25, 1977 was an all-up demonstration of the GDS on this 5000-lb solid propellant motor.

The first two BATES motors were equipped with fixed 15 deg half-angle nozzles with an exit ratio of 130/1. The fire test of these motors served to check out the motor/facility test setup and establish a performance baseline for the propellant grain and nozzle expansion ratio. Performance was measured by redundant chamber pressure and thrust transducers.

The second two BATES motors were equipped with GDS's attached at an area ratio of 90/1 and deployed to a nominal exit area ratio of 130/1. Deployment was evaluated by a close coupled chamber pressure transducer and 400 frame/s photography. The eighth GDS (1st BATES) was folded inward 28 deg from the full open position, as shown in Fig. 2. This GDS was rotated 2 deg open by igniter pressure and remained at this level until the propellant grain ignited and full chamber pressure rise started at 192 ms. In the following 64 ms the GDS deployed the remaining 26 deg at essentially constant velocity to the full open position. The ninth GDS (2nd BATES) was folded inward 105 deg from the full open position as shown in Fig. 1. This test was a two-phase deployment in 220 ms. The skirt rotated 72 deg in the first 40 ms in reponse to igniter pressure, opened further to 77 deg with igniter pressure rise until the propellant grain ignited and full chamber pressure rise started at 157 ms. In the last 63 ms, the GDS deployed the remaining 28 deg at essentially constant velocity to the full open position. This opening sequence can be seen in the motion picture frames of Fig. 4.

The final opening motion (on propellant grain ignition) was essentially identical on both BATES motor GDS tests. This is the significant motion in terms of the elastic limit of the skirt and it confirmed and supplemented the deployment data base as shown in Fig. 3.

Both GDS's performed normally throughout the 4.5 s nominal action time of the BATES motors. The 400 frame/s film showed no trace of flutter and a normal temperature rise for the radiation cooled hardware. The GDS response to the test cell diffuser tube blowback on shutdown was light fluttering. Post run inspection showed that both GDS's were in excellent condition and capable of further firing as shown in Fig. 5.

The total impulse and specific impulse measurements on the two GDS tests were essentially identical (i.e., within 0.3%) to the measurements on the two fixed-nozzle tests. However, the indicated chamber pressure (and action times) were different and greater than theoretical values. The discrepancies were traced to a bias error in the data tapes but correction factors could not be derived. With this reservation, the test data indicated that the performance of the GDS is identical to the equivalent fixed-nozzle extension.

GDS Applications Studies

Design studies have been completed applying the gas-deployed skirt concept to a variety of rocket nozzles. Two of these potential applications are presented here to show the concepts suitability for both liquid and solid motors.

Agena Engine

The 16,000-lbf Agena liquid rocket engine, Bell Model 8096, is constrained in length and diameter by the Titan second-stage interface. The fitting of a nozzle extension with GDS gives an area ratio of 74/1 compared with the existing 45/1 nozzle.

Figure 6 shows the GDS design for the Agena rocket engine. For this application, the GDS would be fabricated from 0.007-in.-thick C103 Columbium alloy. The Agena engine operates for a maximum duration of 240 s with a fuel rich boundary flow such that the GDS temperature will not rise

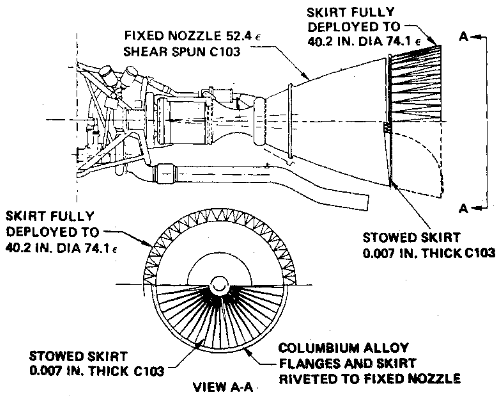

Fig. 6 Agena engine 74ϵ GDS.

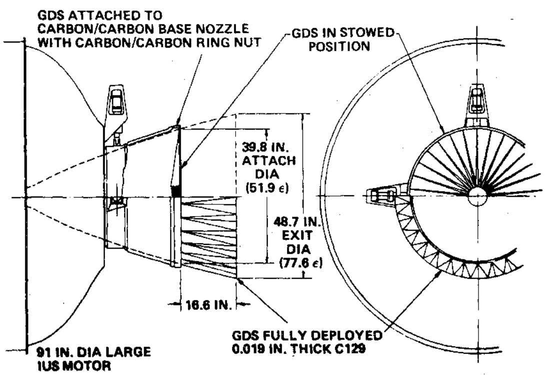

Fig. 7 IUS large motor GDS.

above 2200°F (without emissivity coating) well within the capabilty of C103 material. The overall nozzle contour approximates the ideal profile for 74/1 area ratio so that the GDS attaches at 33.8 in. diameter, an area ratio of 52/1 on the revised base nozzle contour. When deployed, the skirt forms a conical extension at 13.2 deg half-angle to an exit diameter of 40.2 in., 74/1 area ratio.

The start sequence of the Agena engine is relatively slow, approximately 0.2 s acid lead followed by ignition and a rise to 75% design chamber pressure in 0.10 s. Dynamic analysis gives a minimum deployment time of 0.067 s. The BATES motor GDS is in many respects a half-scale model of the design for the Agena, and the motor start transient displays similarities which make the BATES motor GDS tests a representative scale demonstration for this Agena design. The revised base nozzle is also fabricated from C103 Columbium alloy and the skirt will be attached to this with a simple riveted flange joint. Because the original 45/1 area ratio nozzle was a Molybdenum reinforced titanium alloy shell (a 17-year-old design), the new nozzle extension including GDS of 74/1 area ratio will be seven pounds lighter, and provide an improvement of 5.7 s in specific impulse. This yields a payload gain of 136 lb for a typical Agena spacecraft mission.

IUS Motor

The 60,000-lbf Interim Upper Stage (IUS) solid rocket motor is an attractive candidate for addition of a gas-deployed skirt, where stage length is constrained by the space shuttle hold size. The preliminary design of a GDS for the IUS large motor design described in Ref. 4 is shown in Fig. 7.

The design of the GDS for this motor follows the general design principles described previously. However, for this application, the GDS will operate at a temperature of about 3250°F (uncoated) in the attach region, and therefore the higher strength Columbium alloy C129Y was selected at a thickness of 0.0195 to meet the hoop load and thrust buckling criteria.

The stowed skirt is clamped to the 52/1 area ratio exit plane of the carbon/carbon base nozzle by means of a large carbon/carbon ring nut. This assembly technique has previously been demonstrated in the attachment of a metal EEC to a C4 development motor with a carbon/carbon nozzle.[3]

The minimum deployment time for this skirt is estimated to be 0.057 s, which is well under the predicted start transient for this motor of 0.107 s.[4] The skirt will initially deploy to a 13-deg half-angle while still cold but will rapidly heat up (<5 s) and fully deploy to the design half-angle of 15 deg and exit expansion ratio of 77.6/1. This GDS offers a potential performance gain of approximately 5.6 s specific impulse for a weight increase of 29.6 lb. This represents a net increase in synchronous orbit payload of 147 lb for the basic IUS with the GDS added to the large motor only.

Conclusions

The advanced development of a folded metal gas-deployed skirt has been successfully completed. This effort demonstrated a lightweight low-cost EEC of high intrinsic reliability. GDS application studies show significant performance gains (5 s min. ΔI_{sp}) for typical upper stage and spacecraft rocket motors. It was therefore concluded that the GDS concept is ready for operational development.

Acknowledgment

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References

[1]Carey, L., Dueringer, J., and Nixon, G., "Convoluted Nozzle Extension," *Journal of Spacecraft and Rockets*, Vol. 9, July 1972, pp. 485-486.

[2]Kobalter, G.F., "Development of Expandable Rocket Nozzles," JANNAF Propulsion Meeting, Chemical Propulsion Information Agency Publication 242, Vol. II, Nov. 1973, pp. 67-85.

[3]Carey, L. and Ellis, R., "Extendible Exit Cone Development for the C4 Third Stage Motor," *Journal of Spacecraft and Rockets*, Vol. II, Sept. 1974, pp. 624-630.

[4]Chase, C.A. and Hanford, D.R., "Solid Rocket Motors for the Interim Upper Stage," JANNAF Propulsion Meeting, Chemical Propulsion Information Agency Publication 280, Vol. III, Dec. 1976, pp. 513-530.