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Memorandum No. 269

March, 1963

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A COMPARISON BETWEEN SWIVELLING NOZZLES WITH SPLIT LINES UPSTREAM AND DOWNSTREAM OF THE THROAT

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General Electric Co., Cincinnati, Ohio, U.S.A., has reported successful firings with a new type of swivelling nozzle for solid propellant rocket motors. The dividing line (split line) separating the swivelling part from the fixed part of the nozzle is downstream of the throat. This nozzle is compared here with a conventional one with the split line upstream of the throat.

The main advantage of the new nozzle is the vectoring amplification factor of 1.5 which can be achieved. Other advantages claimed appear to be marginal and to apply to special applications only.

The main disadvantage is the fact that the exit cone or part of it is turned into the supersonic exhaust stream. The moveable cone and its leading edge are subject to very severe corrosion.

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1 INTRODUCTION

The Flight Propulsion Laboratory Department of General Electric Co., Cincinnati, Ohio, U.S.A., has reported<sup>1</sup> successful firings with a scale swivelling nozzle of a design somewhat different from the conventional ones developed elsewhere in the U.S.A. and by R.P.E. It would appear that the main difference lies in the position of the dividing line (split line) between the fixed and the moving portion of the nozzle, the split line being downstream of the throat in the new design and upstream in conventional nozzles. The two configurations are shown diagrammatically in Fig. 1.

It is claimed that the thrust vectoring system developed by the General Electric Co. (Fig. 2) offers a number of improvements and advantages over contemporary systems. The purpose of this memorandum is to compare both systems in the light of present knowledge at R.P.E.

2 SWIVELLING NOZZLE WITH SPLIT LINE UPSTREAM OF THROAT

Conventional swivelling nozzles including those tested at R.P.E. comprise four main parts:-

- (a) The stationary converging portion of the nozzle which is fixed to the motor end plate,
- (b) The moving (swivelling) part, essentially the throat section and the expansion cone,
- (c) The stainless steel bellows forming the flexible and gas tight seal between (a) and (b),
- (d) The gimbaling components.

The R.P.E. nozzle used here for comparison (Fig. 3) has a throat diameter of 2.8 inches and an expansion area ratio of 5 : 1. The nozzle is fitted to a 24-inch diameter solid cord plastic propellant test motor, burning at a pressure of 500 lb/sq in. for 38 seconds and then falling off to atmospheric pressure over a further period of 8 seconds and delivering a thrust of 4400 lb. The fully gimballed nozzle with one actuator arm each in the pitch and yaw plane weighs 41 lb.

When deflecting this type of nozzle the angle of the jet is the same as that of the nozzle. Since the maximum nozzle angle in pitch and yaw is  $\pm 6$  degrees, the maximum side thrust on the diagonal between the actuator arms becomes  $\sqrt{2} \times \sin 6 \text{ degrees} \times \text{axial thrust}$  or 14.8 per cent of the axial thrust.

The forces required to turn the jet in the subsonic region and those due to mechanical friction of the nozzle are considered small and neglecting these the control torque becomes equal to the bending moment of the bellows. In the case of external pressurisation of the bellows their stiffness decreases with increasing pressure. The control torque measured during static firings is about 24 lb-ft per degree nozzle deflection.

### 3 SWIVELLING NOZZLE WITH SPLIT LINE DOWNSTREAM OF THROAT

For direct comparison purposes the R.P.E. nozzle design with the split line downstream of the throat (Fig. 4) has the same throat dimensions and converging and diverging angles and fits the same test motor. The metal, refractory and insulation thicknesses have been estimated.

Contrary to the General Electric Co. design the nozzle is also provided with a stainless steel bellows. These, however, being in connection with a section downstream of the throat, have to withstand a considerably lower pressure and a somewhat lower temperature than the bellows in the conventional nozzle which have to cope essentially with motor pressure conditions. The split line is arbitrarily positioned at a point 1.75 inches downstream of the throat, where the area ratio is 1.4 : 1 and the gas has expanded to one quarter of the motor pressure, i.e. 125 lb/sq in.

The calculated weight of the nozzle is 43 lb. This is 5 per cent more than the actual weight of the conventional nozzle under comparison. Although some lightening of the new scheme may be achieved with a detailed design, the weight saving is likely to be small.

The relations between side thrust, nozzle angle and control torque are not quite so straightforward. Neglecting again friction, the control forces result from the stiffness of the bellows and the force required to turn the supersonic jet. The pressure acting on the bellows is 125 lb/sq in, as compared with 500 lb/sq in. for the conventional nozzle. This permits the use of a thinner gauge material for the bellows with a corresponding reduction in stiffness. At the same time, however, the reduction in stiffness due to the lower external pressure on the bellows is only small.

The forces required to turn the supersonic jet are quite substantial. However, by pivoting the exit cone a shock wave is produced on the side of the exit cone pivoted into the gas stream, and an expansion wave originates on the opposite side of the nozzle and General Electric Co. claim that this produces an effective thrust vector angle 50 per cent greater than the nozzle angle. Amplification factors in excess of 1.5 have, in fact, been obtained in testing.

The estimated torque required to deflect the jet one degree is 26 lb-ft. Taking account of the amplification factor the nozzle angle for this torque becomes  $\frac{2}{3}$  degree. The bending moment of the bellows has been calculated as 14 lb-ft for  $\frac{2}{3}$  degree. Thus the total torque for this nozzle is 37 lb-ft per degree jet deflection which is 50 per cent higher than the value for the conventional nozzle.

It should be remembered however that this high control torque value refers to a nozzle with a stainless steel bellows (Fig. 4), whereas the General Electric design (Fig. 2) shows instead a rubber bladder filled with hydraulic fluid. The bladder acts as a gas seal and, when divided into four sections, provides four actuators for positive and negative pitch and yaw deflection at the same time. It is understandable that the bladder presents considerable manufacturing difficulties but it does reduce the overall control torque requirements to about the same as that of the conventional nozzle. The General Electric nozzle in Fig. 2 swivels in one plane only but it can be designed for full gimbaling.

4 ADVANTAGES OF THE NEW DESIGN

Having described the differences in design and operation of the two nozzles under comparison we can now list the advantages of the new nozzle as these transpire from calculations and commonsense considerations.

- (a) Due to locating the swivel joint downstream of the throat vectoring amplification factors of 1.5 can be achieved.
- (b) This means that for equal side thrust values less nozzle movement is required, which would provide extra packaging space around the nozzle or reduce interference with adjacent exit cones in clustered nozzle systems.
- (c) Conversely for equal nozzle deflection angles 50 per cent larger thrust vector angles can be achieved which may be useful in booster applications.
- (d) Since the exit cone only is swivelled the mass moment of inertia is lower and actuation of the system should be rapid.
- (e) The downstream split line reduces the pressure in the bellows or rubber seal cavity to a fraction of the motor pressure, thereby reducing the sealing problems.
- (f) The converging part, being the same as that of a fixed nozzle, is shorter and lighter than that of a conventional swivelling nozzle. Our weight calculations, however, have shown that the total weights of both the nozzles under comparison when fitted with a metal bellows are only just comparable, whilst General Electric state that a nozzle with a rubber seal actuator, hydraulic fluid and extra steel shells is heavier than a nozzle actuated by external hydraulic actuators.
- (g) It has also been shown above that when a flexible rubber seal is used instead of a stiff metal bellows the control torque may be reduced to about that of a conventional nozzle with a bellows seal.
- (h) General Electric say that the incorporation of this seal actuator reduces the hydraulic pressure since the effective piston area is large and the reduction in pressure, it is claimed, results in a weight saving for piping and valves.

This is contrary to normal practice, at any rate in this country, where operating pressures of 3500 to 4000 lb/sq in. are used<sup>2</sup> in order to increase the stability and response and to reduce the weight of the system.

It can probably be safely assumed that the low actuator pressure of 300 to 400 lb/sq in. was forced on the design because either no rubber actuator of this type would stand a pressure of several thousand lb/sq in. or because a large effective piston area results from the choice of this type of actuator.

- (i) Since the throat is fixed this design is compatible with many of the nozzle cooling schemes being developed should any be required.

(j) General Electric claim that deposition of aluminium oxide presents no problem since the split line is close to the throat on the downstream side where the liquid globules have not expanded due to their higher density. This may be true but will probably have to be confirmed by tests.

Summing up, it is concluded that the main advantage of the system is that a thrust vector amplification factor of 1.5 can be achieved. Other advantages claimed appear to be only marginal and to apply to very special applications.

#### 5 DISADVANTAGES OF THE NEW DESIGN

In comparing the two schemes it is important also to list the disadvantages of the new nozzle and to assess the seriousness of the faults:-

(a) A nozzle of this design with a metal bellows is comparable in weight but requires a much higher control torque than the same conventional nozzle due to a large force needed to turn the supersonic jet in addition to overcoming the stiffness of the bellows.

(b) A nozzle with a rubber seal with a hydraulic actuator incorporated requires a comparable control force but it is heavier. In order to keep the hydraulic pressure and the stresses in the rubber bladder low a large actuator must be accommodated in a steel shell which is not required in other designs.

(c) Entry and throat erosion are likely to be similar to those in a conventional design. Exit cone erosion must be considered to be more severe since the exit cone is moved into the supersonic gas stream.

(d) The lip of the exit cone dipping into the gas stream is expected to get severe punishment.

(e) The nozzle efficiency is impaired by a loss due to the annular groove at the pivot joint and by the loss from vectoring the exit cone.

Summarising, it would seem that the main disadvantages are severe erosion of the exit cone and its leading edge, a slight increase in weight and a small loss in nozzle efficiency.

#### 6 CONCLUSIONS

A new type of swivelling nozzle with the split line downstream of the throat is compared with a conventional one with an upstream split line.

If the new nozzle is fitted with a metal bellows the weights are comparable but the control torque is augmented by about 50 per cent. Replacing the bellows with a rubber seal actuator, the control torques become comparable but the weight is increased. So, depending on the design, there is either an increase in weight or control torque.

The new design incurs a slight loss in nozzle efficiency resulting from the annular groove at the pivot joint and from turning the exit cone into the supersonic jet stream. The latter would also cause an increased erosion of the exit cone as a whole and in particular of the leading edge of the exit cone.

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The one outstanding advantage of the scheme is the vectoring amplification factor of 1.5 which can be achieved. Other advantages appear to be hardly better than marginal and apply to very special applications only.

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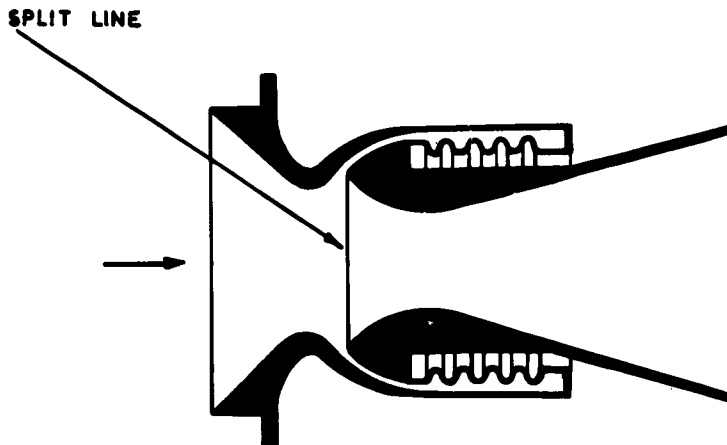
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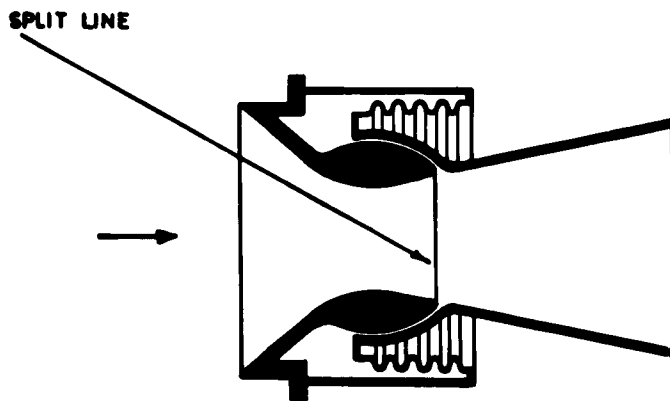
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UPSTREAM SPLIT LINE NOZZLE



DOWNSTREAM SPLIT LINE

FIG.1 DIAGRAM SHOWING UPSTREAM AND DOWNSTREAM SPLIT LINE ARRANGEMENT

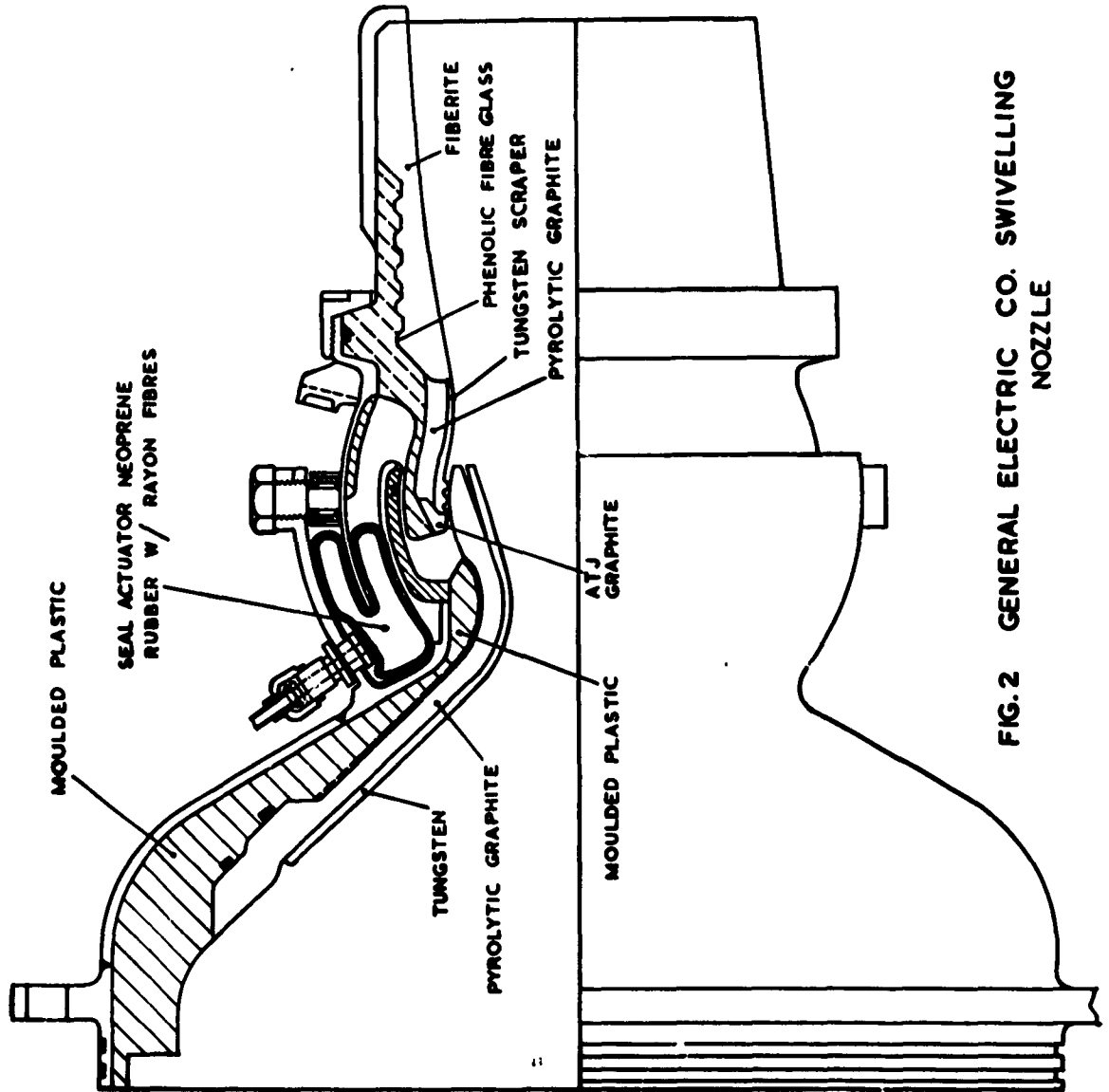


FIG.2 GENERAL ELECTRIC CO. SWIVELLING  
NOZZLE

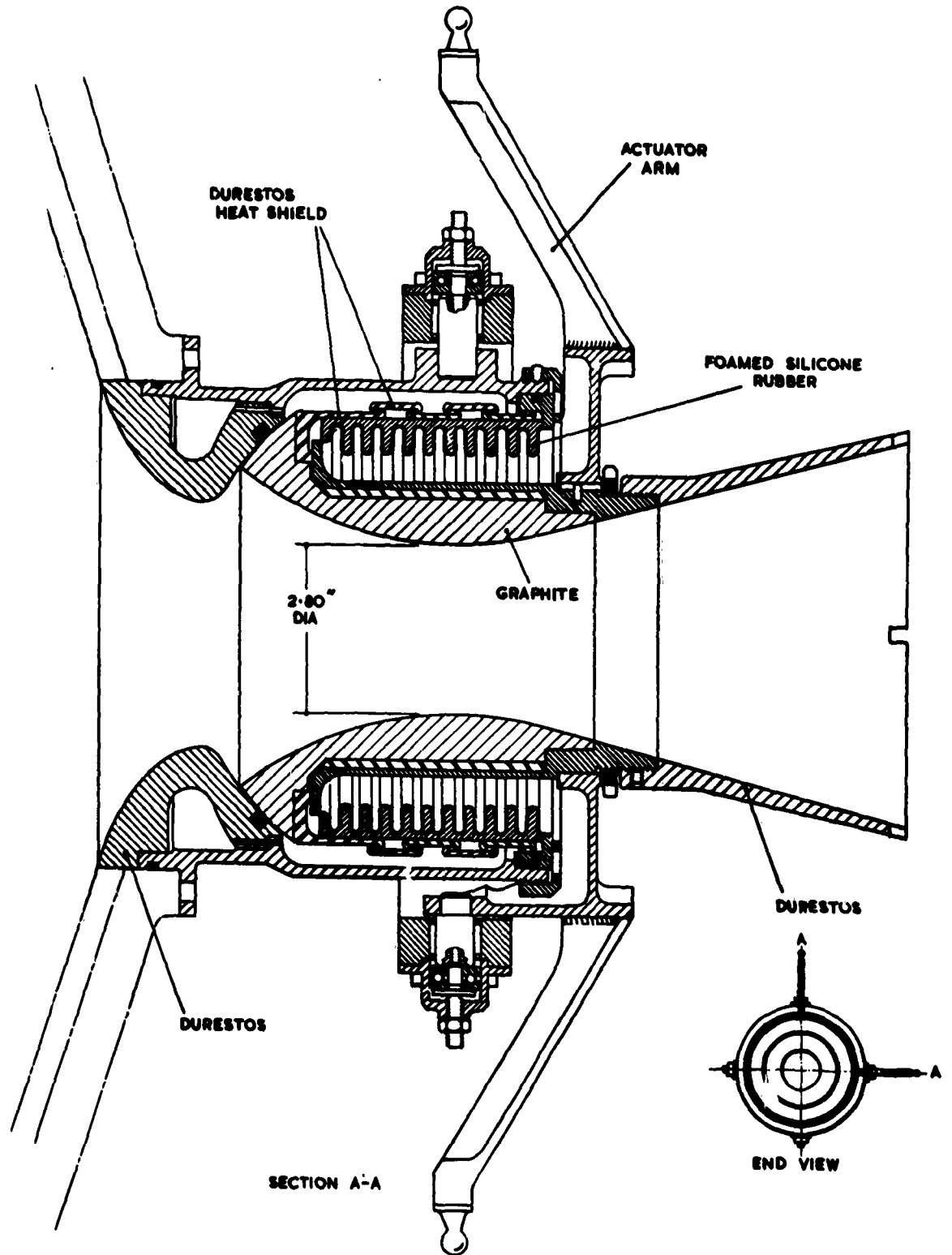


FIG. 3 R.P.E. SWIVELLING NOZZLE WITH UPSTREAM SPLIT LINE

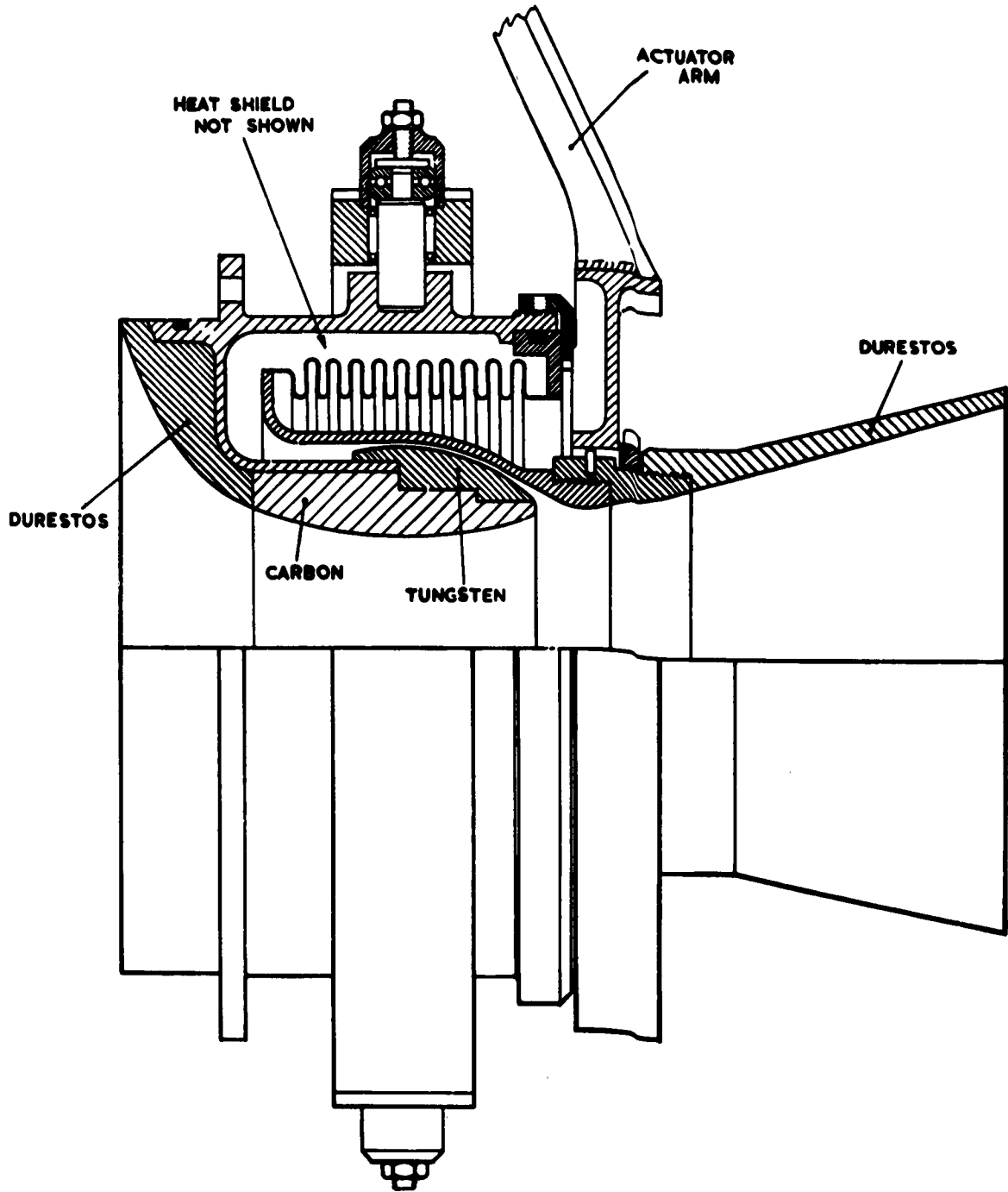


FIG. 4 R.P.E. SWIVELLING NOZZLE WITH  
DOWNSTREAM SPLIT LINE



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