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EXPERIMENTAL RESEARCH ON ELECTRIC PROPULSION  
NOTE V: EXPERIMENTAL STUDY OF A MAGNETIC FIELD STABILIZED ARC-JET

A. C. Robotti and M. Oggero

(NASA-TM-77474) EXPERIMENTAL RESEARCH ON N84-34266  
ELECTRIC PROPULSION. NOTE 5: EXPERIMENTAL  
STUDY OF A MAGNETIC FIELD STABILIZED ARC-JET  
(National Aeronautics and Space Administration) 13 p HC A02/MF A01 CSCL 20I G3/75 Unclass 22664

Translation of "Ricerche sperimentali sulla propulsione elettrica -  
Nota V: Studio sperimentale di un plasmagetto ad arco stabilizzato  
con campo magnetico", La Ricerca Scientifica, Year 33, Rendiconti A  
Vol. 3, No. 1, 1963 - Series 2, pp 28 - 35.



## STANDARD TITLE PAGE

1. Report No. NASA TM-77474		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Experimental Research on Electric Propulsion - Note V: Experimental Study of a Magnetic Field Stabilized Arc-Jet				5. Report Date June 1984	
				6. Performing Organization Code	
7. Author(s) Aurelio C. Robotti and Mario Oggero School of Aerospace Engineering, Turin Polytechnic				8. Performing Organization Report No.	
				10. Work Unit No.	
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94063				11. Contract or Grant No. NASW-3541	
				13. Type of Report and Period Covered Translation	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes Translation of "Ricerche sperimentali sulla propulsione elettrica - Nota V: Studio sperimentale di un plasmagetto ad arco stabilizzato con campo magnetico", La Ricerca Scientifica, Year 33, Rendiconti A Vol. 3, No. 1, 1963 - Series 2, pp 28-35.  104 750 7					
16. Abstract  This paper describes a number of experiments carried out on a magnetic field stabilized arc-jet, using nitrogen as a propellant.					
17. Key Words (Selected by Author(s))			18. Distribution Statement Unclassified-Unlimited		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 13	22.

EXPERIMENTAL RESEARCH ON ELECTRIC PROPULSION  
NOTE V: EXPERIMENTAL STUDY OF A MAGNETIC FIELD STABILIZED ARC-JET

A. C. Robotti and M. Oggero  
School of Aerospace Engineering  
Turin Polytechnic

1. Preface

In a previous Note<sup>1</sup> on the same subject, we described the ex- /28\*  
perimental results obtained with an electric arc rotating under the  
influence of a magnetic field in ambient air. The continuation of  
the research has been directed at gauging the possibility of practical  
use of this type of arc as a means of heating a working fluid, with  
a view toward possible astronautical applications.

The tests described herein were therefore carried out with a  
device similar to the above, but closed at the ends and equipped with  
a convergent-divergent type nozzle suitable for transforming the heat  
energy of the working fluid arc into the kinetic energy of the jet,  
which is the one which is of interest for purposes of propulsion.

2. Testing Device

Fig. 1 shows a schematic cross section of the test device: the  
chamber, which also includes the discharge nozzle, is of copper and  
is enveloped by a pressurized water-jacket; at its base it has the  
connections for the propellant gas and the pressure device; an insu-  
lating support on the outside of the brass jacket carries the winding  
that creates the magnetic field, consisting of 12 turns of series  
wound copper for the arc current.

A great deal of attention was given to the thermal stress borne

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\* Numbers in the margin indicate pagination in the foreign text.

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by the chamber due to the arc: contrary to expectation, the greatest stress is not on the nozzle but on the area struck by the arc, even though the latter may be rotating rapidly. It is therefore necessary to provide finning in this area in order to increase the heat exchange /29 surface.

The water-cooled central electrode is concave, a form offering the greatest stability among the various types previously studied. Here, too, the material used is copper.

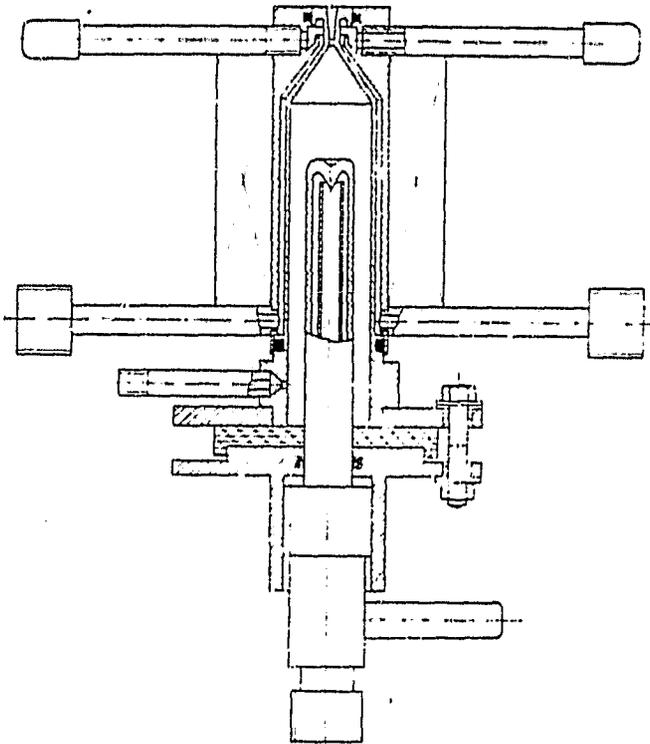


Fig. 1 - Schematic cross section of the jet.

In this series of tests, as in the preceding ones, the source of electrical energy was a metadyne with variable current controlled by the excitation.

The wiring and the plan for the cooling unit are also the same; the only difference is that the propellant in the present tests is nitrogen, which is supplied by a set of cylinders with reducer.

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Nitrogen was chosen so as to be able to experiment with a practically inert gas on the electrodes from the chemical point of view, without needing to have recourse to excessively costly rare gases or to hydrogen, which does not lend itself well to experiments in a closed environment. Compressed air, which was used previously in the tests in ambient air with the device without a nozzle, proved unsuitable inasmuch as it caused the formation of slight oxide crusts that clogged the nozzle from time to time, thereby affecting the results.

### 3. Measurement of Thrust

From the point of view of propulsion, the measurement of the thrust is fundamental inasmuch as it permits calculation of the unit's specific thrust and its electrical/kinetic yield, which are at the basis of every application of this kind.

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Elsewhere thrust is an entity that is very difficult to measure directly, especially when it is of very limited intensity due to many other parasitic thrusts (cooling water, feed gas) which can cause appreciable errors.

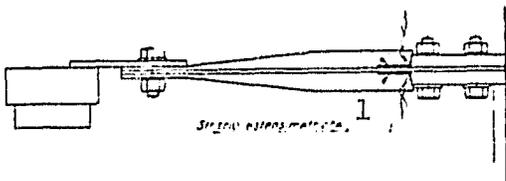


Fig. 2 - Device for measuring thrust.

(1) Extensimetric strips

We therefore resorted to indirect measurement, fixing the jet on a flat surface so as to make it deviate  $90^{\circ}$  and then gathering all of the variations of momentum.

The device is shown in Figure 2, while Figure 3 shows the wiring for the reading; the deflector is a small block of graphite held in a small bowl which in turn is attached to a thin plate; the sensitive parts are two strain gauges stuck on the thin plate and acting as two branches of a Wheatstone bridge. The bridge is completed by other external resistances and the imbalance is read on a very sensitive galvanometer. The device is calibrated with suitably arranged weights,

great care being taken to prevent the calibration from varying with the temperature, and for this reason we have to properly insulate the device from the possible projection of particles during operation. The calibration is always checked before and after each series of tests. The device is mounted at the side of the engine and is exposed to the remote-controlled jet at the appropriate time. While the thrust readings are being taken the graphite block is deteriorating rapidly, eroding at the center and developing a slight concavity; it is therefore changed after every two or three tests so as to avoid results that are affected by errors. This precaution in fact proved to be /31 excessive inasmuch as we experimentally proved that if the concavity did not reach very high values, the variations in thrust were very slight with reference to the block, and practically negligible.

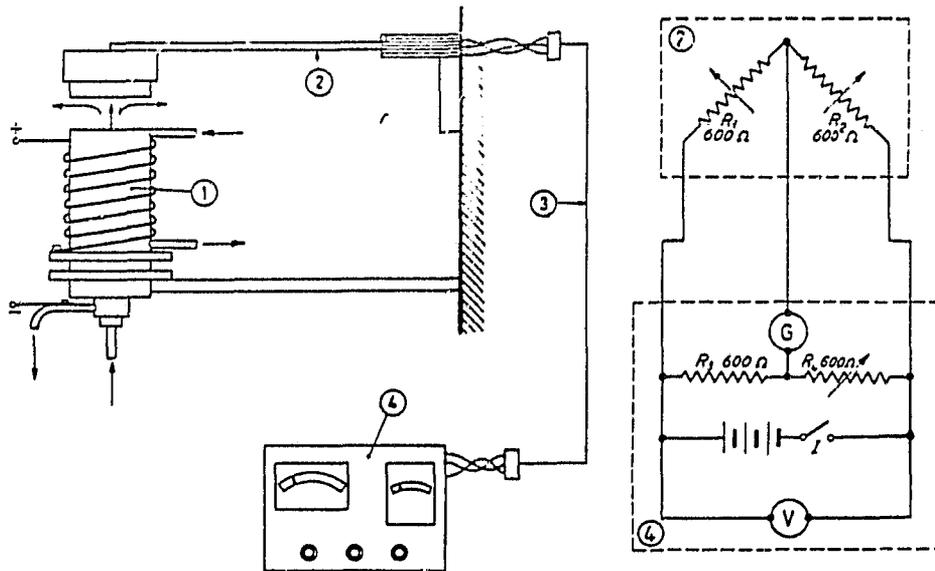


Fig. 3 - Thrust Detector Wiring Diagram. 1 = Jet; 2 = Sensitive Element; 3 = Screened Cable; 4 = Feeder Detector; V = Voltmeter; G = Galvanometer; I = Switch.

Great care was taken to see that the distance of the block from the nozzle remained constant for all of the tests and a preliminary calibration was also made to check the effect on the device due to attraction by the magnetic field (extremely weak) generated by the fixed windings carrying the current; but there was no noticeable effect.

Figure 4 shows the thrust detector during a measurement.

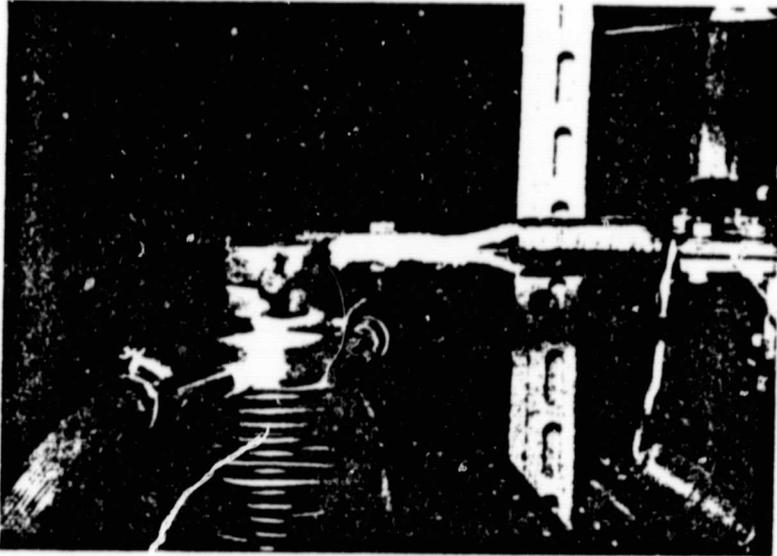


Fig. 4 - Device for measuring thrust in operation.

During the tests it is very interesting to study the motion of the arc in the chamber, but since direct observation is impossible with the present device, the very luminous cathode spot is observed indirectly, reflected on a white screen positioned at a suitable distance above the nozzle; this behaves like the aperture of a camera obscura and gives a rather clear image of the cathode spot, permitting its motion to be studied even when the device is under pressure and therefore closed.

#### 4. Test Procedure

The device is usually primed with a wire inserted between the two electrodes; when the circuit is closed the live wire vaporizes and primes the arc.

At first, when the rate of gas flow is nil, the arc rotates rapidly around the central electrode, which can be observed on the screen. Then, with the increase of gas flow and pressure in the chamber, the motion of the cathode spot becomes more irregular and

tends to stabilize at two or three points which appear more luminous. By using suitable goggles it is possible to discern the Mach waves distinctly if the chamber pressure is at least  $4 \text{ kg/cm}^2$ . The dart-shaped jet is 4 to 5 cm long; after that the zone where it mixes with the surrounding air begins, giving it the characteristic foxtail appearance. /32

The dart has considerable mechanical-thermal energy: It rapidly melts and vaporizes any metal that touches it, and even the graphite block for measuring thrust quickly becomes incandescent inasmuch as it is exposed to the jet, and if the reading is prolonged it is consumed, taking on a concave appearance.

## 5. Experimental Results

The principal aim of the present series of tests is to evaluate the arc-jet as a possible propellant. We therefore sought essentially to determine the parameters that are of interest for this purpose. The first object in particular of the study was specific thrust.

In this first investigation, however, we did not inquire into the maximum absolute value possible but instead investigated the behavior of the specific thrust with variation of the two independent variables available to the experimenter: the current and the rate of gas flow.

To this end it was necessary to operate with a possibly neutral gas with a well-defined chemical composition that would not react with the electrodes and not undergo alterations due to pressure and temperature (besides dissociation and ionization). Nitrogen was therefore chosen, essentially for reasons of cost and safety, even though the specific thrust obtained with it is nearly one third that of hydrogen with the same chamber temperature, because of the molecular weight.

Using the two variables, electric current and rate of gas flow, various series of tests were carried out on the gas flow/constant power

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ratio, with a view toward determining their effect on specific thrust.

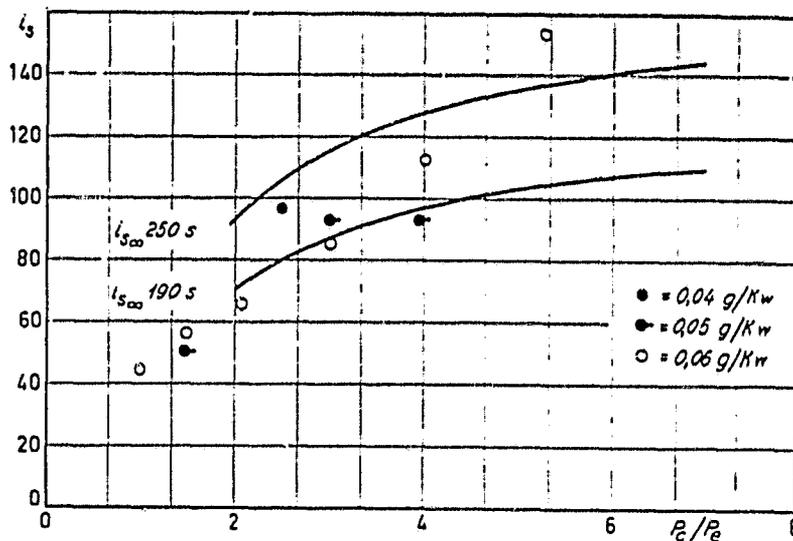


Fig. 5 - Variation of specific thrust and chamber pressure

The experimental results are given in Figures 5 through 7. In the diagrams the unbroken lines indicate the theoretical curves of the variation of specific thrust in relation to pressure, presupposing the use of the appropriate nozzle, for the two values of 250 s and 190 s for  $P_c/P_e = \infty$ .

## 6. Analysis of Results

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Examination of the Figure 5 through 7 diagrams immediately brings to the fore a very important fact, which is that the specific thrust, pressure being equal, is affected hardly at all by the gas flow/power supplied ratio. In fact, passing from a ratio of 0.04 g/kW to 0.09 g/kW, no noticeable improvement is seen.

It nevertheless must be noted that in regard to regularity of functioning the gas flow/power ratio does have appreciable importance inasmuch as the device, chamber pressure being equal, is much more stable electrically and in terms of pressure oscillation when the power supplied is increased.

This behavior can be explained if we consider the mode of functioning of the device. In the chamber there is an arc rotating at a certain velocity in a nitrogen atmosphere which, given the ratio between the cross section of the nozzle and that of the chamber, can be considered calm.

The cross section of the arc is very small compared to that of the chamber and therefore we can reasonably suppose that the greater part of the gas is not touched by the arc but is heated only by convection and radiation. Under these conditions the exchange of heat between the nitrogen and the arc is essentially a function of the electrical energy dispersed in the arc column.

An increase of current causes an increase in temperature in the gas column, resulting in a decrease in voltage inasmuch as the conductivity of the gas increases with the temperature, as is well-known. Consequently, the power dispersed in the arc column is nearly constant with variation of current, while the excess power is absorbed by the electrodes, which locally heat up more and therefore increase their resistance.

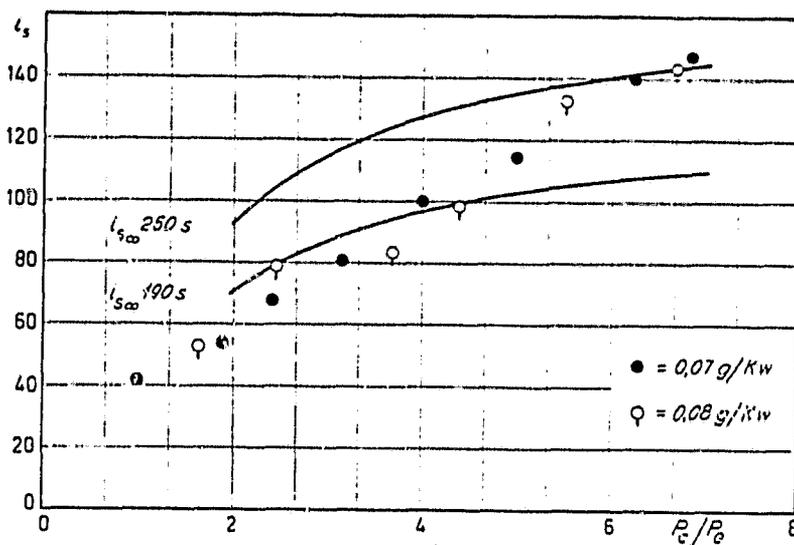


Fig. 6 - Variation of specific thrust and chamber pressure

Under these conditions it would be advantageous to work with the least possible current, corresponding exactly to that absolutely necessary for maintaining the arc. It must nevertheless not be forgotten that there are rather appreciable turbulences in the chamber which, if too close to the limit, can very easily cause the arc to break, as experience has shown.

Figures 5 through 7 indicate another interesting point: The specific thrust which at low temperatures is very low increases much more rapidly than might be expected, exceeding the corresponding value at 250 s in relation to infinite expansion (for chamber pressures greater than 6 kg/cm<sup>2</sup>). This behavior can in part be explained by taking into account the fact that the nozzle was designed for an expansion ratio of 6, so the jet becomes hyperexpanded with less than 6 atmospheres in the chamber. However, it is quite probable that another phenomenon of a different nature has come into play here.

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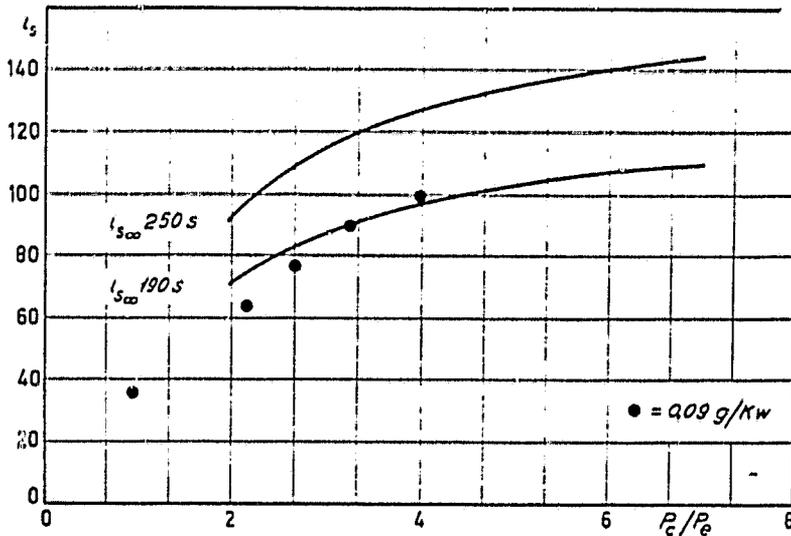


Fig. 7 - Variation of specific thrust and chamber pressure

We said that the gas is heated through exchange by convection and radiation between the arc column and the surrounding nitrogen. This exchange increases with the pressure and more heat is drawn; the arc reacts with an increase in voltage which (current being equal) is equivalent to dispersing more energy in the column of conductor gas.

Thus it is clear that while an increase in dispersed energy (chamber pressure being equal) increases only the losses in the copper, the greater power supplied goes only to heat the cooling water; while conversely the increase in absorbed energy caused by increasing the pressure goes effectively to heat the gas.

## 7. Conclusion

The abovementioned hypotheses represent an attempt to explain the arc's behavior under pressure with gas flow. There are many parameters which in this first series of investigations were negligible and on which perhaps the behavior of the arc-jet depends in an appreciable way.

The task of the next experiments will be to investigate these phenomena for the purpose of drawing some reliable conclusions.

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Special thanks is due Prof. Ing. S. B. Toniolo of the Istituto Galileo Ferraris, who made the necessary electrical equipment available, and to his co-worker Ing. A. Abete, who actively cooperated with the writers in carrying out the experiments described herein.

## REFERENCES

- (1) A. C. Robotti & M. Oggero: "Ricerche sperimentali sulla propulsione elettrica. Nota IV: Ricerche sull'arco elettrico rotante in campo magnetico in vista di una sua applicazione in propulsori spaziali" (Experimental research on electric propulsion. Note IV: Research on a rotating electric arc in a magnetic field in view of its possible application in space propellants), in Ric. sci., 32 (II-A), 20-27 (1962).

### SUMMARY

**Experimental research on electric propulsion. Note V: Experimental study of a magnetic field stabilized arc-jet.**

*(Original scientific paper)*

This paper describes a number of experiments carried out on a magnetic field stabilized arc-jet, using nitrogen as a propellant.

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