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(NASA-TM-77473) EXPERIMENTAL RESEARCH ON ELECTRIC PROPULSION. NOTE 7: ANALYSIS OF THE PERFORMANCE OF AN ARC-JET DRIVEN BY MEANS OF HYDROGEN AND NITROGEN (National Aeronautics and Space Administration) 17 p G3/20 11474

N85-14861
HC#A02/MF#A01
Unclass

EXPERIMENTAL RESEARCH ON ELECTRIC PROPULSION. NOTE VII.
ANALYSIS OF THE PERFORMANCE OF AN ARC-JET DRIVEN BY MEANS
OF HYDROGEN AND NITROGEN

Aurelio C. Robotti and Mario Oggero

Translation of "Ricerche sperimentali sulla propulsione elettrica. Nota VII: Rilievo delle prestazioni di un arc-oggetto operante con idrogeno e con azoto", La Ricerca Scientifica, Anno 35, Series 2, Rendiconti A, Vol. 8, No. 4, 1965, pp 894-901

STANDARD TITLE PAGE

1. Report No. NASA TM-77473		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle EXPERIMENTAL RESEARCH ON ELECTRIC PROPULSION. NOTE VII. ANALYSIS OF THE PERFORMANCE, OF AN ARC-JET DRIVEN BY MEANS OF HYDROGEN AND NITROGEN				5. Report Date July, 1984	
				6. Performing Organization Code	
7. Author(s) Aurelio C. Robotti and Mario Oggero				8. Performing Organization Report No.	
				10. Work Unit No.	
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108				11. Contract or Grant No. NASw 3542	
				12. Type of Report and Period Covered Translation	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				13. Type of Report and Period Covered Translation	
				14. Sponsoring Agency Code	
15. Supplementary Notes Translation of "Ricerche sperimentali sulla propulsione elettrica. Nota VII: Rilievo delle prestazioni di un arc-ogetto operante con idrogeno e con azoto", La Ricerca Scientifica, Anno 35, Series 2, Rendiconti A, Vol. 8, No. 4, 1965, pp 894-901 (A66-27097)					
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17. Key Words (Selected by Author(s))			18. Distribution Statement Unclassified and Unlimited		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 17	22. Price

EXPERIMENTAL RESEARCH ON ELECTRIC PROPULSION. NOTE VII:
ANALYSIS OF THE PERFORMANCE OF AN ARC-JET DRIVEN BY MEANS OF
HYDROGEN AND NITROGEN**,***

/894*

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1 INTRODUCTION

During the early days of research on arc-jets at this school, in 1960, designing and getting ready a hydrogen arc-jet presented considerable difficulties. Therefore, the initial research was performed using inert gases such as nitrogen, air and argon, which are of little propulsive interest, to obtain some preliminary experience.

The experimental results obtained during this first research phase were published in several notes [1-3].

They provided useful indications on the behavior of electric arc in the presence of magnetic and aerodynamic fields, and made it possible to determine the best electrode geometries, both with respect to their consumption and their heat exchange.

It was thus possible to continue with the design and testing of a new arc-jet, capable of using hydrogen as a propellant, with a

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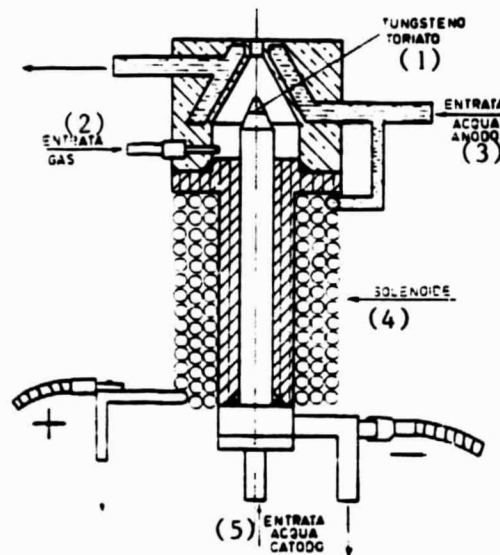
** This work was submitted by prof. Aurelio Robotti, Aerospace Engineering School, Polytechnic Institute, Turin (Italy)

*** This work was performed with the financial assistance of the CNR (Consiglio Nazionale delle Ricerche = National Research Center) in the context of the Project "Electrodynamic Propulsion Systems"

good probability of success.

Subsequently, and in order to establish a comparison with the results obtained for hydrogen, the same arc-jet was operated also with nitrogen.

2 EXPERIMENTAL DEVICE



KEY 1 Thoriated tungsten 2 Gas admission 3 Anode water admission 4 Solenoid 5 Cathode water admission

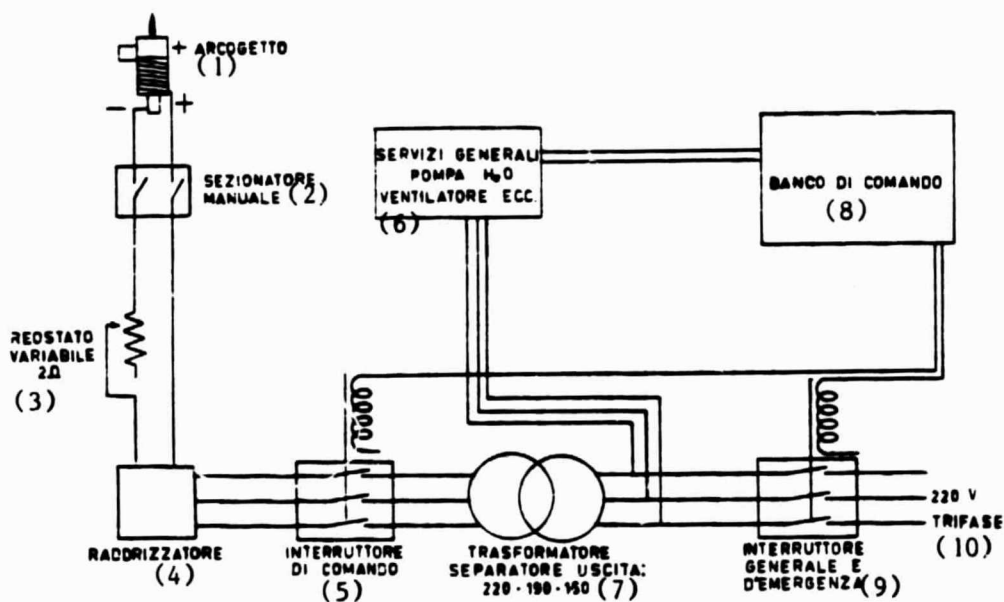
Figure 1 Hydrogen arc-jet schematic

The hydrogen arc-jet is shown in Figure 1, above: in comparison to previous models, designed for nitrogen and argon, the distance between electrodes is reduced to one third, to increase arc stability; hence the chamber dimensions are much smaller than those for the nitrogen and argon arc-jets. The central electrode, however, always has the same dimensions and is /895

exchangeable with those of the devices built earlier.

The arc is stabilized primarily by the vortex created by the feed gas, which is injected tangentially to the chamber; in addition, at the base of the arc-jet there is a winding through which the arc current flows, producing also an electromagnetic stabilizing effect that is especially useful during the initial transient, when the vortex is not efficient yet.

Electrode refrigeration is assured by water circulation, at a rate of 0.5 l/sec for the anode and 0.4 l/sec for the cathode. The winding that generates the magnetic field is also water-cooled.



KEY 1 Arc-jet 2 Manual cut-off 3 Variable resistor 4 Rectifier 5 Main switch 6 General services (water pump, fans, etc.) 7 Separating output transformer 8 Control console 9 General emergency switch 10 3-phase

Figure 2 General facility schematic

The general schematic for the supply is shown in Figure 2, above: direct current is provided from a silicon rectifier bridge, supplied by the 3-phase, 220 V line by means of a triple output transformer (220, 190 and 150 V), which makes it possible to choose the voltage best suited to the device and which functions as a separator between the arc circuit and the power line.

Refrigeration is of the closed loop type, with a 1 m reservoir that makes long-term tests possible, without noticeable water temperature increases. Circulation is assured by means of a pump with a maximum capacity of 5 l/sec and an effective range of 40 m.

All operations are controlled remotely by means of rotary keys; all commands are gathered on a single control console. The arc-jet is arranged in such a manner to avoid any danger in case of accidental gas releases.

3 INSTRUMENTATION

In addition to the usual electric measurements of voltage and current readings, the arc-jet is equipped with temperature sensors at the entrance and exit of the cooling loops. To this end, both thermocouples and thermoresistors have been used in different tests. Due to the small change in water temperature, the sensitivity of the thermocouple was increased by placing several junctions in series, with the cold joint placed in the water at the entrance, in order to read the temperature change directly.

Precision and repeatability of the two measuring methods are

nearly equal: the thermoresistors used in conjunction with a bridge are more sensitive but have a longer response time and hence their use should be limited to operating and "regime" tests, which are of longer duration. /896

Measurements of the water flow were performed with venturi meters introduced into the two discharge lines; the hydrogen flow, instead, is measured with a diaphragm flow meter, previously calibrated against a rotameter.

4 EXPERIMENTAL RESULTS

4.1 Hydrogen tests

The experiments performed with the new hydrogen arc-jet were designed to obtain a first group of analyses, readily interpreted on the basis of previously obtained results. To this end, a single variable was changed, and more particularly, we studied the behavior of the arc-jet when the gas flow was varied, keeping the current or the chamber geometry constant. In addition, we used a nozzle with a rather large diameter - approximately 4 mm - to be able to keep the arc pressure approximately constant and equal to atmospheric, over the entire field of measurements.

During this first series of tests we tried two current levels - 200 and 160 A - for both the hydrogen and the nitrogen tests.

In the case of hydrogen (Figure 3, below), the arc voltage tends to increase considerably, at a given current, with the gas flow; this voltage increase is accompanied by a directly visible change in arc geometry, during the test.

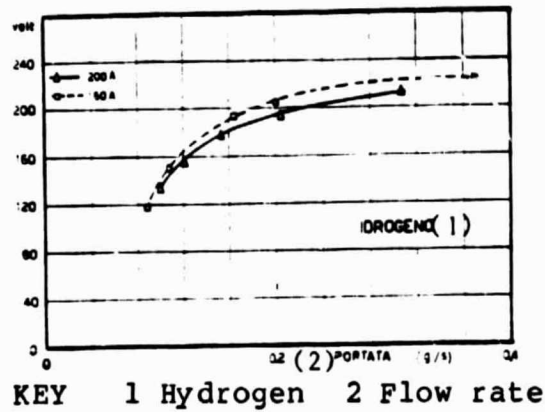


Figure 3 Voltage-mass flow in the hydrogen arc-jet

At lower flows, the electric arc strikes inside the chamber and the anodic foot rests near the nozzle's converging zone, as shown in Figure 4: this is confirmed by the readily visible marks to be seen in the chamber, at the end of the tests.

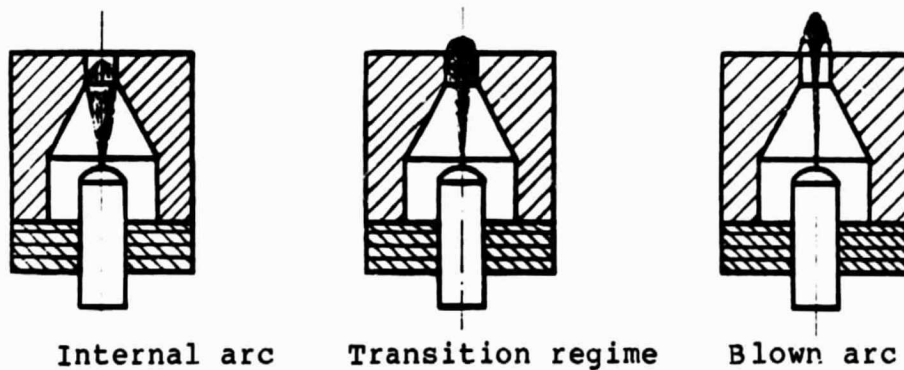


Figure 4 Arc configuration

As the flow rate increases, the arc rises to the top of the throat and for a given value stabilizes along the upper edge: in this position the arc can be seen directly, through the appropriate protection, appearing as a luminous core centered in the nozzle. Further increases in the flow rate lead to an external lengthening of the arc, as if it were blown, but the support position in the chamber remains unchanged, corresponding to the nozzle's outer edge.

The erosion of the nozzle's walls is closely related to arc geometry. For high flow rates, for instance, one can identify very well localized crater formations in the nozzle's end section, where the arc's foot rests for support.

When the current is reduced, the phenomenon of arc blowing tends to occur at lower flow rates: the voltages increase noticeably and the arc becomes unstable. For currents of the order of 140A, the arc becomes readily extinguished.

4.2 Nitrogen tests

The tests at 200A and 160A were repeated with nitrogen, operating at molar enthalpy levels of the same order of magnitude as those of hydrogen, to obtain the same amount of heat supplied to the gas, and hence as a first approximation and disregarding dissociation, the same mean gas temperature.

In the case of nitrogen, the arc voltage (see Figure 5, below) is lower than in the case of hydrogen, but retains one identical characteristic: also in this case it is possible to observe the arc's displacement as the flow rate increases, with the consequent external blowing for the higher values. However, for nitrogen the arc is much more stable and throughout the tests /898 it never extinguished.

5 CALORIMETRIC MEASUREMENTS

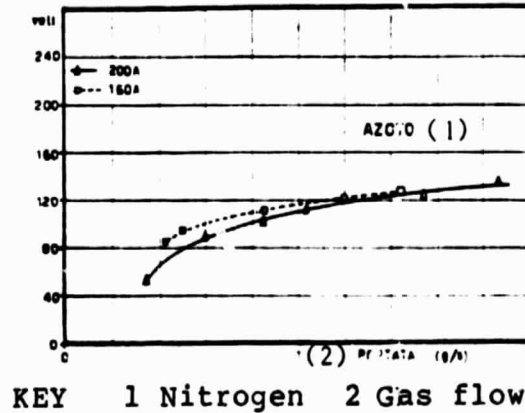


Figure 5 Voltage-mass flow curve for the nitrogen arc-jet

Temperature determinations at the entrance and exit of the individual cooling circuits made it possible to evaluate the heat loss at each electrode and hence, the yield loss due to heat transmitted to the walls

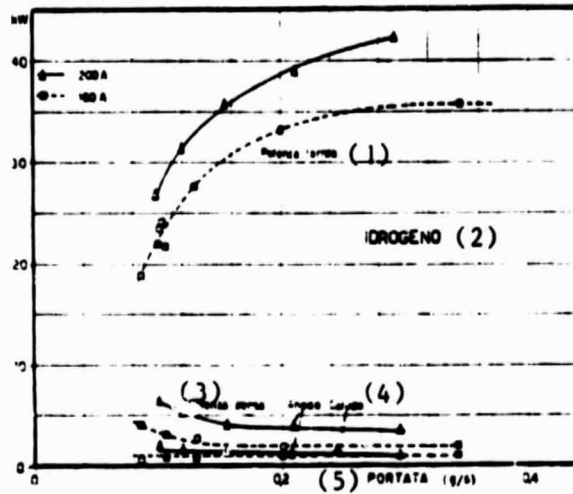
$$1 - \eta = W_p / W$$

where W = electric power supplied, $V.I$,

W_p = sum of the power losses due to the cooling of both electrodes

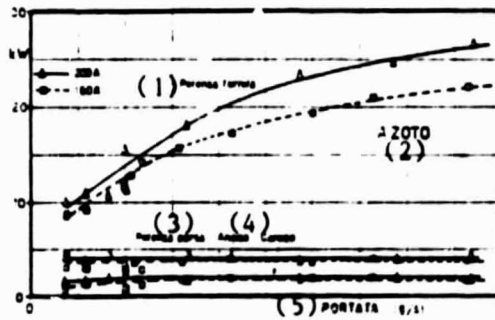
Note that η can as a first approximation be assumed to be equal to the yield of the conversion of electric power into the jet's thermal energy.

The heat loss at the two electrodes is shown in Figure 6, below,



KEY 1 Power supplied 2 Hydrogen 3 Power lost 4 Anode-cathode 5 Flow rate

Figure 6 Heat loss at the electrodes, hydrogen arc-jet



KEY 1 Power supplied 2 Nitrogen 3 Power lost 4 Anode-cathode 5 Flow rate

Figure 7 Heat loss at the electrodes, nitrogen arc-jet

for hydrogen and in Figure 7, above, for nitrogen. An analysis of these results elicits some comments regarding the heat exchange phenomena at the two electrodes.

5.1 Cathodic losses

Cathode heating is due primarily to the existence of a high temperature zone at the arc's foot, corresponding to the cathodic spot, where a local voltage drop can be observed, corresponding to the tension necessary to remove from the metal the thermoelectrons that constitute the ionized column. The cathodic voltage decrease is a function of the metal's nature, the arc current and the operating gas. Everything else being equal, it will be a decreasing function of the current, because with increasing current and hence, with increasing local cathode temperature - due to the Joule effect - there is a decrease in the energy needed to extract thermoelectrons. Hence, the power dissipated at the cathode should remain approximately constant as the current changes. In actual fact, the cathode is heated also by irradiation from the arc column, while the gas bathing it can produce a certain cooling effect. But such effects should be secondary.

Experimentally, these considerations were confirmed in the case of nitrogen, for which the power dissipated at the cathode is in fact nearly constant, as the power or the flow rate are varied. In the case of hydrogen, instead, there is an increasing loss with current, especially at the lower flow rates, while the changes at varying flow rates are negligible. This anomaly - which will be the subject of further research - is probably determined by the higher quantity of heat supplied to the cathode by conduction of the hydrogen arc, when it sparks completely within the chamber, at low flow rates.

5.2 Anodic losses

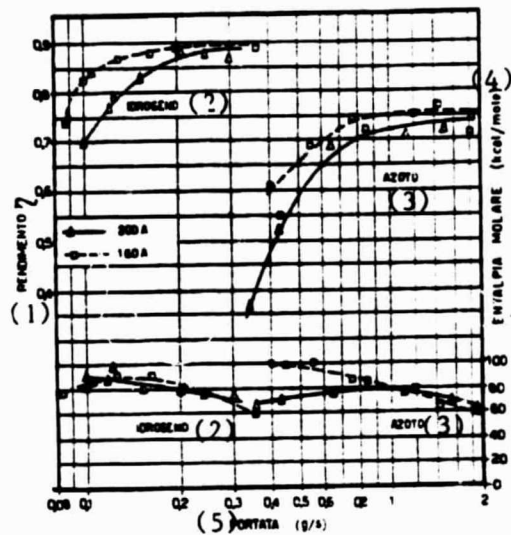
The heat exchange between chamber and arc is closely related to the gas' fluid dynamics characteristics, in the nozzle: at the anode, too, there is some power dissipation at the arc contact surface, corresponding to the cancellation of the thermoelectrons' kinetic energy, but this loss is far inferior to the heat transmitted by convection of the working gas. The heat exchange between gas and metal is an increasing function of the eflux; the presence of the vortex can however significantly change the results. /899

In practice, it is observed that in the case of nitrogen, the power dissipated remains approximately constant, if the current remains unchanged and the flow rate is increased, while for hydrogen it decisively decreases.

This anomalous behavior by hydrogen can be explained by means of a hypothesis similar to that used for the cathodic losses; one can in addition assume that the jet loses its homogeneity, as the flow rate increases, with a very hot core around the axis, surrounded by relatively cooler gas. This latter hypothesis would be confirmed by the considerable reduction in losses that accompany a decrease in current; this variation is much more modest for nitrogen. It is expected, however, that a continuation of the current experiments will also elucidate this point.

6 YIELDS

Figure 8, below, shows the conversion yields for the two gases as the current and the flow rate are changed: for hydrogen the yields are very high, approaching 90%, while for nitrogen they



KEY 1 Yield 2 Hydrogen 3 Nitrogen 4 Molar enthalpy
5 Flow rate

Figure 8 Yield curves

are closer to 80%.

The lowest values are observed for the lowest flow rates. They are justified not so much by higher gas temperatures - since the molar enthalpy is practically constant throughout - but because /900 under these conditions the arc burns entirely within the chamber and the arc voltage is very low. Therefore the ratio of the power supplied to the gas to that dissipated at the electrodes is lower.

As the flow rate increases, the arc blowing phenomenon already mentioned occurs. Consequently, the voltage increases and hence, the available power, while the electrode losses remain approximately constant (or decrease, in the case of hydrogen) due to the protective effect of the vortex, which thermally

insulates the ionized gas column from the walls and reduces it to the arc's extremes.

Given the considerable inhomogeneity of the gas jet at the exit of the arc chamber, for propulsive purposes it would be advisable to have a homogenization chamber ahead of the expansion nozzle. This was not done here, because at this time the main research objective was a study of the arc-jet's electrical characteristics under hydrogen and nitrogen operation, and the determination of the nature of the electrode losses.

The introduction of a mixing chamber, in fact, would considerably decrease the yield: suffice it to observe, in this context, the large differences between these values and those obtained previously [5] with arc-jets with a much larger arc chamber and a very uniform jet.

7 CONCLUSIONS

These research efforts - which practically complete the four year cycle of experimentation at this School - have shown the possibility of building an operational hydrogen arc-jet, under stable conditions and low electrode consumption. The arc-jet's thermal losses were evaluated under various conditions of usage and the thermal conversion yield was determined.

These results shall form the basis for a new cycle of experiments that will include the construction of a dynamometer stand and, as a second phase, setting up a vacuum chamber, in order to be able to complete the arc-jet studies with real thrust measurements and tests simulating space conditions.

SUMMARY In this note experiments are described using a new /901 type of arc-jet, characterized by composite electromagnetic and vortex stabilization and propelled by hydrogen and nitrogen in turn.

Attention was particularly directed to the electrical characteristics of the arc and the loss of heat through the electrodes (Authors' summary).

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