NUCLEAR ROCKET OPERATIONS
SACRAMENTO PLANT

REPORT NO. RN-NC-0013

THE USE OF THE HES 1-MEGAWATT ARC-HEATER
TO
HEAT HYDROGEN

NOVEMBER 1967

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~~THE~~ USE OF THE HES 1-MEGAWATT ARC-HEATER
TO
HEAT HYDROGEN

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ABSTRACT

Some problems related to the development of nuclear rocket engines may be studied experimentally if sufficient hot hydrogen can be produced. Tests have shown that a particular arc-heater, the Hyperthermal Environmental Simulator, can produce hydrogen at temperatures between 2800° and 3600°K. The arc consumes between 800 and 1200 kw of electrical power and maintains an energy conversion efficiency of about 40%. At maximum power the arc can produce varying amounts of hydrogen, depending on the temperature (e.g., 8 gm/sec at 3300°K and 13 gm/sec at 2500°K). There are fluctuations in power during arc operation, lasting about 0.1 second and causing the hydrogen temperature to fluctuate by as much as 50°K. The maximum arc power (1200 kw) is reached when the arc current becomes sufficient to cause rapid erosion of the tungsten cathode of the arc chamber. In these tests the temperature of the gas was obtained indirectly from energy balances performed for the arc chamber and the exhaust duct, and directly by an optical method in which the radiance of the gas was compared to that of a tungsten filament at a single wavelength, 5890 Å, the center of a sodium D-line.

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I. INTRODUCTION

The major problems of solid-core nuclear engines are caused by high temperatures of the propellant and structural materials. Some may be solved by small-scale testing in which samples of fuel elements, the core-support structure, nozzle wall, or a turbine blade are exposed to hot hydrogen. Useful experiments may be done only if sufficient hot hydrogen is produced, and this appears to be within the compass of a 1 MW arc-heater. The main purpose of the work to be described was to demonstrate that the arc-heater of the Aerophysics Laboratory Hyperthermal Environmental Simulator (HES), with a nominal maximum power of 1.2 MW, could produce sufficient hydrogen (about 10 gm/sec) at a temperature of about 3300°K (~ 6000°R), the maximum attainable in a solid-core engine.

A secondary aim was to demonstrate that the temperature of the hydrogen could be measured using an optical technique. This may be useful in experiments producing temperatures greater than 2800°K/5040°R, temperatures at which thermocouples are likely to disintegrate.

II. APPARATUS

Modifications have been made to the HES equipment, as shown in Figures 1 and 2*. No changes were made to the arc and plenum chambers. The cathode is constructed of tungsten pins brazed to the inner wall of a water-cooled copper cylinder, and the anode is a water-cooled copper body of conical shape, as shown in Figure 1. Overheating of electrodes is prevented by rotation of the arc in a cusp-shaped magnetic field, supplied by two opposed solenoids connected in series with the electrodes. Gas is injected with a swirling motion in the annulus around the cathode. The plenum chamber allows smoothing of temperature gradients produced by the arc, or admixture of cold gas to adjust the temperature to the value desired.

*See Description of the Hyperthermal Environmental Simulator, Aerophysics Laboratory Report, January 1967

Figure 1 - Schematic Diagram of HES Arc Apparatus and Test Section Used for Gas Temperature Measurement

Figure 2 - Arc Apparatus, Test Section, and Optical Bench

The gas flows then through a water-cooled copper chamber which is contained in a steel housing (see Figures 1 and 2). Two ports fitted with quartz windows allow measurements to be made of the spectral radiance and transmittance of the gas. The windows are kept clean by a small flow of nitrogen. The flow is choked in a nozzle at the bottom of the chamber, where cold nitrogen is injected at the minimum-area section both to cool the gas leaving the chamber and to control upstream pressure. A perforated tungsten cup promotes mixing of the two gases and the temperature of the mixture is measured by three chromel-alumel thermocouples. This measurement is made in a double-walled duct cooled with the same flow of water used to cool the copper chamber. At the level of the thermocouples in the gas, a portion of the water is diverted from the duct cooling jacket and its temperature measured with a chromel-alumel thermocouple. The water coolant mixes then with the gases, and the mixture passes to a stack where the hydrogen is burned in air.

In each test the following measurements were made:

A. Arc current and voltage were measured with galvanometers. The greatest errors were reading errors, caused by large fluctuations in current and voltage at frequencies greater than 1 kc/s. These fluctuations became greater as the current increased, reaching $\pm 20\%$ in the case of the current and $\pm 15\%$ in that of the voltage. The measured current and voltage may be in error from the true mean values of these quantities by as much as 5%.

B. The flow-rate of hydrogen to the arc and plenum chambers, and of nitrogen to the duct, were measured by choked orifices. Errors due to uncertainty in gas temperature and those incurred during calibration of pressure transducers and reading of the records should amount to no more than 3%.

C. The flow-rates in the two water-coolant circuits were measured with turbine flowmeters. Errors were caused by variations in flow during the run and uncertainty of the flowmeter calibrations, and amount to no more than 2%. In addition, in the coolant duct circuit there is a possible reading error of about 1%.

D. The temperatures of the nitrogen-hydrogen mixture in the duct, and the water flowing between the duct walls, were measured with chromel-alumel thermocouples. The temperature of the water leaving the arc and plenum chamber coolant jackets was measured with a platinum resistance thermometer. Reading and recording errors were no more than 2%. Radiation and conduction of energy from the thermocouples in the gas introduced an error which could be neglected (about 1°K). The greatest uncertainty in gas temperature measurement was caused by the differences among the readings of the three thermocouples in the gas, the highest and lowest temperatures differing by as much as 70°K in one instance.

E. The arc chamber pressure was read directly from a gauge, an accurate measurement not being necessary.

The temperature of the hydrogen leaving the arc plenum chamber was measured in three ways which will be compared later in Section III,B. Two of these depended on a gas enthalpy determination, and the third was an optical measurement performed as follows:

In the manner shown in Figures 2 and 3, optical benches were set up on either side of the arc-heater, having a line of sight through the ports in the copper chamber*. Radiation from a tungsten lamp filament is focused by a lens to give an image at the center of the chamber, and collected by a lens on the other side which focuses the radiation onto the inlet slit of

*The method is described in Spectroelectric Methods for Measuring Combustion Gas and Particle Temperatures, J. M. Adams and L. Cann, Aerojet-General Technical Paper 139, June 1964

Figure 3 - Schematic Diagram of the Optical Bench

a monochromator. A rotating chopper interrupts the light from the lamp, so the monochromator receives alternately radiation from the gas alone, and then radiation from the gas and the lamp.

The monochromator is adjusted, with the aid of a sodium lamp, to scan continuously a $10 \text{ \AA}$ - wide band of wavelengths, so the upper limit of the scan just overlaps the center of the sodium line at $5890 \text{ \AA}$. Light from the exit slit of the monochromator passes to a photomultiplier, the output signal from which is amplified and recorded. The reading and recording errors are no more than 1%.

The arc chamber was given a thin coating of saturated sodium iodide solution, which was sufficient to make the heated hydrogen a strong emitter at the wavelength of the sodium D-line at $5890 \text{ \AA}$. One coating was sufficient for up to five runs.

The speed of the chopper was adjusted so that the sodium line was scanned by the monochromator four times in each chopping cycle. The resulting oscillograph trace of the photomultiplier current is shown in Figure 4.

As will be shown later, the measurement of temperature depends only on ratios of the deflections of the oscillograph traces, on the brightness temperature of the lamp filament, and on the transmissivities of the lens and window on the lamp side of the arc-chamber (see Figure 3). These transmissivities were measured and found to be 0.87 and 0.90, respectively. The lamp-filament brightness temperature during the run was determined from the average of the deflections of the trace immediately before and after the run. This deflection was calibrated before and after the run by measuring the filament brightness temperature with an optical pyrometer over a range of filament currents. The scatter of the measured values about the calibration curve drawn through them caused an uncertainty in the brightness temperature of $\pm 5^\circ\text{K}$.

Figure 4 - Typical Current Signal from the Photomultiplier

III. RESULTS

A. OPERATION OF THE ARC

The arc was started in a flow of nitrogen, which was gradually replaced by hydrogen until steady operation was achieved with hydrogen alone at an electrical power level of about 700 kw. The arc current and power were then increased gradually, and simultaneously the mass flow-rate of hydrogen was raised in an attempt to maintain a constant gas temperature. Several plateaus of steady operation were maintained, during which optical observations were made. Sixteen runs were made, of which the first twelve were devoted to proving the techniques of measurement and instrumentation.

It was observed that periods of smooth operation could be achieved, when current and voltage fluctuated at high frequency (>1 kc/s) by approximately $\pm 10\%$. Such a frequency is too high to cause measurable fluctuations in gas temperature. This condition was obtained when the electrical power was less than about 1000 kw and the current less than about 700 A. However, as the power was raised from 1000 to 1200 kw, the amplitudes of the current and voltage fluctuations increased to as much as $\pm 20\%$ and $\pm 15\%$, respectively, interspersed with spikes of a magnitude too great for the galvanometer to record accurately. In addition, there was a change in the manner of arc operation, whereby the current changed little as the power was raised from 1000 to 1200 kw, and the arc voltage rose by 200 v or more (see Table 1). There was a corresponding increase in arc efficiency.

In the first run in which reliable measurements were made (Number 13) the thermocouples in the gas showed at all power levels a smooth trace punctuated by short, random pulses of duration about 0.1 second, during which the temperature fell by as much as 50°K . This means that the arc faltered for a moment, causing the hydrogen temperature to drop by approximately the same amount (up to 50°K). These pulses became more frequent as the electrical power was raised, and were more frequent during succeeding runs.

TABLE 1

MEASUREMENTS OF THE MAJOR ARC OPERATING PARAMETERS

<u>Run</u>	<u>Current</u> <u>A</u>	<u>Voltage</u> <u>V</u>	<u>Electrical Power</u> <u>kw</u>	<u>Mass Flow</u> <u>of Hydrogen</u> <u>gm/sec</u>	<u>Chamber Pressure</u> <u>psi</u>
13	663 $\pm$ 60	1307 $\pm$ 160	865	4.34	---
	685 $\pm$ 80	1400 $\pm$ 150	959	4.95	275
	768 $\pm$ 80	1465 $\pm$ 200	1125	5.84	---
	720 $\pm$ 150	1665 $\pm$ 200	1200	6.41	---
14	666 $\pm$ 60	1264 $\pm$ 140	842	4.16	---
	736 $\pm$ 100	1387 $\pm$ 130	1020	5.76	270
	763 $\pm$ 130	1630 $\pm$ 200	1243	7.71	---
15	660 $\pm$ 65	1300 $\pm$ 120	858	4.45	230
	644 $\pm$ 70	1350 $\pm$ 120	870	4.45	230
16	590 $\pm$ 50	1400 $\pm$ 150	825	7.55	255
	652 $\pm$ 50	1360 $\pm$ 125	885	7.60	255

The increase in severity, as the electrical power is raised, of both the high-frequency fluctuations and the negative pulses in power and hence in gas temperature, is related to changes at the cathode surface which result in melting and loss of tungsten. After run Number 14, in which the most severe fluctuations were observed at the highest power level (1200 kw), it was discovered that several of the tungsten pins had been removed completely. In all runs, the loss of tungsten, copper, and brazing material from the cathode caused a fine black deposit upon the interior surfaces of the copper chamber and the duct.

Some measurements of the major operating parameters during the last four runs are shown in Table 1. The arc efficiency, η , was obtained in two ways, by making an energy balance firstly in the arc and plenum chambers, and secondly in the duct:

$$\eta_1 = \frac{P_e - P_{c1}}{P_e}, \quad (1)$$

$$\eta_2 = \frac{P_{c2} + P_d}{P_e}, \quad (2)$$

where:

P_e	= electrical power, .
P_{c1}	= power absorbed by the arc and plenum chamber coolant,
P_{c2}	= power absorbed by the duct coolant, and
P_d	= enthalpy flux in the exhaust duct.

The enthalpy flux in the exhaust duct is obtained from measurements of hydrogen and nitrogen flow-rates, and the mean gas temperature in the duct. The two sets of efficiencies are compared in Table 2. There is a discrepancy between these two sets, which is due probably to an overestimation of the electrical power, which would cause η_1 to be higher and η_2 to be lower than the true

TABLE 2

MEASUREMENTS OF THE ARC EFFICIENCY BY TWO METHODS

<u>Run</u>	Electrical Power kw	Arc Efficiency %	
		<u>From Arc Chamber Energy Balance</u>	<u>From Duct Energy Balance</u>
13	865	40.3	35.6
	959	43.7	38.1
	1125	49.3	39.7
	1200	54.3	41.8
14*	842	43.5	---
	1020	52.9	---
	1243	62.0	---
15	858	44.3	37.4
	870	45.1	36.9
16	825	46.8	39.6
	885	44.3	37.8

*Thermocouples in the duct were damaged.

value. The true mean power may well be different from the product of the arbitrarily determined mean values of the fluctuating current and voltage, each of which may be in error by as much as 5%.

B. MEASUREMENT OF THE GAS TEMPERATURE

Gas temperature was measured in three ways. In two of these it was derived from measurements of the gas enthalpy, obtained by dividing the hydrogen mass flow-rate into the power absorbed by the hydrogen in the arc chamber. This latter quantity could be obtained from energy balances made firstly in the arc and plenum chambers, and secondly in the duct.

The third way was by optical measurement. Three oscillograph deflections must be measured, that due to the lamp alone D_o , that due to the gas alone D_1 , and that due to the gas and the lamp D_2 , as shown in Figure 4. These deflections may be related as follows to the gas properties, the optical characteristics of the system, and the lamp brightness temperature:*

$$D_o = \frac{k \tau}{\lambda^5 \left[e^{c/\lambda T_b} - 1 \right]}, \quad (3)$$

$$D_1 = \frac{k \epsilon_g}{\lambda^5 \left[e^{c/\lambda T_g} - 1 \right]}, \quad (4)$$

$$D_2 = D_1 + (1 - \alpha_g) D_o, \quad (5)$$

where

- k = a constant of the system,
- τ = transmissivity of the window and lens on the lamp side of the chamber,
- λ = wavelength of the radiation observed, $5893 \text{ \AA}$,
- c = a constant, $1.4388 \text{ cm } ^\circ\text{K}$,

*AGC Technical Paper 139, op. cit

$$\begin{aligned}
T_b &= \text{lamp brightness temperature,} \\
T_g &= \text{gas temperature,} \\
\epsilon_g &= \text{gas emissivity, and} \\
\alpha_g &= \text{gas absorptivity.}
\end{aligned}$$

As the gas emissivity is equal to its absorptivity, equation (5) gives directly an expression for the gas emissivity:

$$\epsilon_g = \frac{D_o + D_1 - D_2}{D_o} . \quad (6)$$

Therefore, the gas temperature may be derived from equations (3) and (4):

$$T_g = \frac{T_b}{1 - \frac{\lambda T_b}{c} \log \frac{\tau D_1}{\epsilon_g D_o}} \quad (7)$$

Unfortunately there are fluctuations in gas temperature and/or emissivity which cause fluctuations in the photomultiplier signal, as shown in Figure 4. Therefore, the deflections were averaged over 20 to 30 scanning cycles of the monochromator. These fluctuations and the uncertainty in the lamp brightness temperature ($\pm 5^\circ\text{K}$) are the major sources of error.

The results of these three methods of temperature measurement are shown in Table 3. An analysis of the possible errors in these values has been made, based on the estimates given in Section II of the errors in measurements which are used to deduce the temperature. The possible errors in temperature deduced from the arc chamber and the duct energy balances are given in Tables 4 and 5, respectively. The temperatures obtained from the arc chamber balance are consistently higher than those obtained from the duct balance (see Table 3), by an amount between 150° and 300°K . Except in the case of the electrical power measurement, the errors shown in

TABLE 3

MEASUREMENTS OF THE TEMPERATURE OF THE HYDROGEN
LEAVING THE PLENUM CHAMBER

<u>Run</u>	<u>Electrical Power kw</u>	<u>Gas Temperature °K</u>		<u>Optical Measurement</u>	<u>Gas Emissivity</u>
		<u>From Arc Chamber Energy Balance</u>	<u>From Duct Energy Balance</u>		
13*	865	3690	3535	-	-
	959	3755	3585	-	-
	1125	3885	3630	-	-
	1200	3960	3655	-	-
14†*	842.	3795	-	-	-
	1020	3865	-	-	-
	1243	3940	-	-	-
15	858	3755	3530	3300	0.55
	870	3765	3530	3245	0.67
16	825	3070	2820	3140	0.56
	885	3090	2850	3300	0.30

*Optical measurements unsatisfactory.

†Thermocouples damaged.

TABLE 4

POSSIBLE ERRORS IN HYDROGEN TEMPERATURE DEDUCED FROM THE ARC AND PLENUM CHAMBER ENERGY BALANCE, AS A RESULT OF ESTIMATED ERRORS IN MEASUREMENT OF ELECTRICAL POWER, THERMAL POWER REMOVED BY THE COOLANT, AND MASS FLOW-RATE OF HYDROGEN

<u>Quantity Measured</u>	<u>Electrical Power</u>	<u>Thermal Coolant Power</u>	<u>Mass Flow-Rate of Hydrogen</u>
Error in this quantity %	5	4	3
Resultant temperature error, °K	100-170	30 - 60	30 - 45

TABLE 5

POSSIBLE ERRORS IN HYDROGEN TEMPERATURE DEDUCED FROM THE DUCT ENERGY BALANCE, AS A RESULT OF ESTIMATED ERRORS IN DUCT GAS TEMPERATURE, MASS FLOW-RATE OF HYDROGEN, MASS FLOW-RATE OF NITROGEN, AND THERMAL POWER REMOVED BY THE DUCT COOLANT

<u>Quantity Measured</u>	<u>Duct Gas Temperature</u>	<u>Mass Flow-rate of Hydrogen</u>	<u>Mass Flow-rate of Nitrogen</u>	<u>Duct Coolant Thermal Power</u>
Error in this quantity	50°K	3%	3%	5%
Resultant temperature error, °K	30-60	30	20-30	10

Tables 4 and 5 should be random and, since these errors are the maximum values thought possible, it is unlikely that they are the cause of this consistent discrepancy in temperature. It is due probably to a repeated overestimation of the electrical power, for reasons which were discussed earlier with regard to discrepancies between arc efficiency measurements. Therefore, the duct energy balance is thought to give the most accurate measurement of the mean temperature of the hydrogen leaving the plenum chamber, for it does not rely on a measurement of electrical power. The values quoted in Table 3 are reliable to within $\pm 50^{\circ}\text{K}$.

The temperatures measured by the optical method do not agree well with those obtained by means of a duct energy balance (see Table 3). In run Number 15, the optically measured values were lower by 230 and 285°K. In this run, no hydrogen was introduced to the plenum chamber downstream of the arc and, therefore, the gas passing the windows should have a hot core due to the method of arc heating and to cooling at the chamber walls. Therefore, as the gas emissivity is high (~ 0.6 , Table 3), the mean temperature measured optically is too low, because it is biased toward the temperatures of the cooler outer layers.

In run Number 16, the optically measured temperatures were greater than the values deduced from a duct energy balance by 320° and 450°K (see Table 3). In this run, cold hydrogen was mixed in the plenum chamber with the arc-heated hydrogen, which had temperatures of 3380° and 3480°K in the two conditions represented in Table 3. The hotter regions would be richer necessarily in sodium, for the sodium is added in the arc, and, therefore, it is the temperatures of these regions toward which the optical measurement would be biased.

These conclusions should be treated with some reservation. The major error in the optical measurements was caused by fluctuations in gas radiance and transmittance, shown in Figure 4 on a typical record of the

photomultiplier current, produced by fluctuations in gas emissivity and/or temperature. In run Number 15, the lamp temperature was 2600°K, much lower than the mean gas temperature of 3500°K. As a result, the deflection D_0 in Equation (6) was much smaller than D_1 and D_2 , causing the measured value of the emissivity to be sensitive to the readings of D_1 and D_2 .

The resultant uncertainty in the value of gas emissivity places the value (with 95% confidence) between the broad limits of 0.337 and 0.773. The resultant 95% confidence interval about a mean gas temperature of 3600°K is 226°K. Although this represents a large, relative uncertainty in the time-average gas temperature, it is possible that most of the interval, due to actual temperature fluctuations of the arc, may be discerned through a detailed regression analysis of the data. However, such a statistical analysis requires a larger number of measurements than was made in these tests.

In run Number 16, the lamp temperature was raised to 2700°K and the mean gas temperature reduced to about 2850°K. Despite this improvement, fluctuations in gas radiance caused the uncertainties in the measurements of gas emissivity and temperature to be as great as in the previous run.

IV. SUMMARY AND DISCUSSION

It has been shown that the Hypothermal Environmental Simulator arc-heater may be employed to heat hydrogen to a temperature as high as 3650°K. The efficiency of the heater may be maintained at about 40% as the electrical power is raised from 800 to 1200 kw. The temperature of the hydrogen produced may be adjusted to lower values (e.g. between 2500 and 3500°K) by dilution in the plenum chamber of the arc-heated gas with cold hydrogen. Table 6 shows the amount of hydrogen which may be produced at a number of temperatures in this range, when the maximum electrical power, 1200 kw, is used. The maximum pressure attained by the hydrogen was 270 psia, but this limit was set only by the size of the orifice choking the flow in the copper chamber.

The current and voltage fluctuate at frequencies greater than 1 kc/s with an amplitude of +10% at a modest electrical power (800-1000 kw), but these fluctuations increase to +20% and +15%, respectively, at higher powers (1000-1200 kw). Such fluctuations are too fast to produce perceptible variations in gas temperature. In addition, there are random negative pulses in power, which cause the hydrogen temperature to drop by as much as 50°K over a period of 0.1 second. These fluctuations and pulses become more severe as the power is raised and, when the electrical power is greater than 1000 kw, are associated with melting and loss of tungsten from the cathode. As a result, surfaces exposed to the flow of hydrogen from the arc chamber become covered with a fine black layer containing tungsten and copper. Modifications will be made to the arc-heater to obtain smoother arc operation and to reduce damage to the cathode at electrical powers greater than 1000 kw.

Optical measurements of gas temperature differed from those obtained from a duct energy balance by an amount between -285°K and +450°K. This discrepancy was due probably to temperature gradients in the gas, to incomplete mixing of hot and cold hydrogen in the arc plenum chamber, and to errors in emissivity measurements caused by fluctuations in gas emissivity and/or temperature. Improvements would be obtained by mixing thoroughly the gas in the arc plenum chamber and controlling the addition of sodium to the gas in the arc.

TABLE 6

THE FLOW-RATE OF HYDROGEN WHICH MAY BE PRODUCED BY THE HES ARC-
HEATER OPERATING AT 1200 KW (ARC EFFICIENCY = 40%)

<u>Hydrogen Temperature</u>	<u>Mass Flow-Rate gm/sec</u>
°K	
2500	13.3
2700	11.9
2900	10.5
3100	9.2
3300	8.0