# Automatic Control System of the AMICOM 8000-kw Plasma Facility

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**A description is given of the control system for the MICOM 8000-kw plasma facility. This includes a set of six 65-kw, 3-phase, phase-controlled thyristor amplifiers which, together with control and digital multiplexing components, regulate the field currents of the six power generators in the plasma facility. Problems encountered in the design of the control system were related to the establishment of stability, accuracy (2%) and speed of response (system time constant ≈0.13 sec) in the facility. Sufficient details are given to permit a working understanding of the system's structure and design concepts.**

## Introduction

THE Army Missile Command's 8-mw plasma facility at Redstone Arsenal, Ala., is an electric arc-driven wind tunnel, capable of simulating parameters of high-altitude, high-velocity flight, and those resulting from rapidly changing altitude and velocity, as with a re-entry body.[1] It has the capability to control the plasma velocity, pressure, temperature, and duration relative to the test specimen. Automation is required to control these variables as well as to protect the personnel and the installation.

The facility has been used chiefly for studies of stagnation-zone thermodynamic properties of objects in simulated flight at altitudes from 300,000 ft down to 150,000 ft[4] and of the radio "blackout" problem during re-entry. This article describes the principles of operation of the control system referred to in earlier publications,[2-4] and shows how problems encountered were solved. The latest form of the system is presented in sufficient detail to give a working understanding of its structure for possible further application by others of its principles and design concepts.

## Plasma Jet Facility Equipment

The facility is operated as a "blowdown" wind tunnel (Fig. 1) with a 10,000-$ft^3$ vacuum tank attached.[5] Cooling water circulated under pressure is used to cool the plasma jets, plenum, nozzle, and current-measuring shunts. Approximately 1100 gal/min of water at 300 to 500 psig is required.

For plasma generation, air is introduced at ambient temperature and at a programed mass flow rate into 6 electric arcs (Fig. 2). Plasma leaves the arc chambers and flows through a plenum and out through the nozzle.[4] Stagnation temperature as high as 5500°K and a velocity as high as 5 km/sec are obtained in the test section. The magnetic coils cause the arc to rotate rapidly. This rotation prevents excessive local heating of the electrodes. The magnetic field also causes the arc to follow a spiral path much longer than the distance between electrodes; this increases the voltage of the arc, allowing operation at higher power for a given current and permitting better use of the capabilities of the power plant. The magnetic field gradient in the region of the maximum diameter of the central electrode causes the arc discharge to occur there rather than on the smaller diameters, where damage could occur. In addition, the incremental resistance of the arc, which without the magnetic fields is negative, is made less negative, or even positive when the intensity of the field is sufficient, and stable control of the arc becomes easier. The inductance (≈1 mh) that is introduced in the current path is small enough not to impair the action of the power controls, but large enough to prevent most of the inherent instability of a sustained arc. The combined effects of the inductance and the increased incremental resistance reduce or eliminate the need for ballast resistance in series with the arc.

A consideration in planning this facility was the availability of six dc generators, each capable of delivering up to 2 Mw at 600 v, and with output inherently low in ripple content. The generators are driven by three 1500-hp synchronous motors, each driving two generators on a common shaft. The motors can be forced to 6000 hp each for 1 min. The power installation also includes rotary and solid-state exciters for the field windings of the motors and generators, manual controls, and a saturable-core mobile substation which limits maximum power to about 24 Mw. From the generators, the current is conducted through 500-MCM copper cables to the plasma heaters. The insulation of the cables will withstand the heating from continuous passage of rated power for 2 to 3 min. The generators are driven at a constant speed, and the output is regulated by varying the excitation of the fields. To provide a more rapid response and due to the inherently slow response of the fields to changing signals, voltages considerably above rated values (forcing) must be applied by the power amplifiers which excite the field windings.

## Automatic Control of Power to Arcs

The most rapidly changing operation of the facility calls for programs of electrical power and mass flow rate of air that double every ≈1.2 sec (Fig. 3) with a desired maximum deviation less than 0.5%.

### Use of Simulation and Low-Power Trials in Development

In the process of designing and testing the power control system, simulation techniques and low power were used first. The low power was used to avoid damage to the equipment

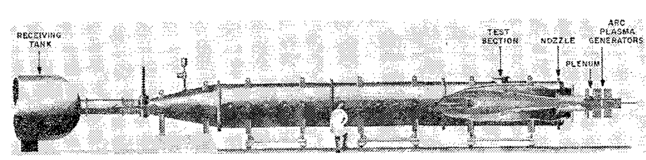


Fig. 1 The MICOM 8-mw wind tunnel (artist's drawing).

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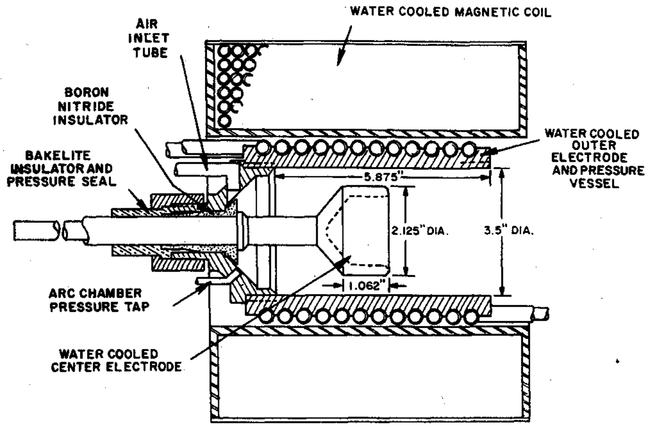


**Fig. 2 Electric arc plasma generator.**

during preliminary tests, so the maximum power was limited to ≈100 kw. Tentative control system configurations were first applied to an operating 75-kw prototype plasma generator. Also, analog computer simulations of trial controllers were used in conjunction with simulated fixed elements of the facility as it would finally take form.[6–9] The computer was a Reeves REAC Model C400.

The aforementioned procedures yielded useful information throughout the developmental stages.[10–11] For example, these techniques showed the degree of forcing of the generator field excitation (meaning application of field voltage above that required for normal steady-state generator output) that would be required to provide the time rates of power change in anticipated programs, such as re-entry phenomena studies. It was found that voltages as much as 15 times the rated voltages would have to be applied to the fields if the most rapid programs were to be followed.

Frequency-response tests performed while one of the actual generators was being used as a fixed element in the simulations indicated that only small phase-lead and phase-lag compensation was needed in the controllers, and that a sampled-data system could be used if desired. These tests showed also that a 360-Hz ripple going to the generator field, such as could be expected if a three-phase thyristor-type of power amplifier were used, would result in a generator output voltage ripple of less than 0.02 v (on 600 v d.c.) at full excitation. The inductance of the generator field windings (≈3h), detrimental as it is in slowing down the attempted rapid changes in power level, is effective in filtering out most of the ripple. The ripple appearing in the generator voltages that was attributable to the amplifiers was found to be at least 60 db below that present in the exciting current.

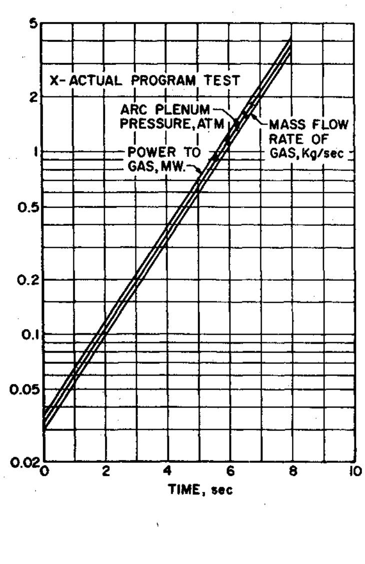


**Fig. 3 Exponential programs of power, plenum pressure, and air flow for re-entry simulation, with experimental tests points along pressure line.**

It was also found during the simulations[10–11] that forcing the generator fields more than 5 times with exciting power limited by feedback alone resulted in instability or oscillations about the limiting point. To reach the required forcing level it was necessary to use a series resistor. If a forcing of the generator fields approaching 15 times were to be used, the total power consumption and building transformer capacity would be the only remaining considerations limiting the design. It was decided that it would be best to use the maximum capabilities of the available thyristors in terms of both voltage and current. No likelihood of instability would then be involved, and the safest means of forcing would be in effect. (Safe current limiting can be achieved by means of a series resistor, which, when it limits the current, also serves to shorten the time constant by the amount of the $R$ it contributes to the $L/R$ figure.)

### Power Control System

A feedback system is used to control the power to the plasma arcs (Fig. 4). When the system is being used for re-entry simulation the reference input varies exponentially with time; in steady-state runs the reference is held constant. The chamber or plenum pressure $P_c$ (the pressure of the plasma just upstream of the throat) is measured by a pressure transducer, whose output voltage is used as the feedback in the main (or pressure) control loop.

The $P_c$ feedback voltage is compared with the reference signal that is produced by a programed device [desired $P_c(t)$]. The $P_c$ error signal and the reference are added together, with adjustable weightings, or gains, and used to drive the arc current controller, changing the arc power to produce the $P_c$ demanded by the program. The partial use of the reference together with the error signal improved stability; this was done in the current controller as well as the pressure controller.

Power for the field excitation of each generator, the means noted earlier by which power output from the generators is regulated, is obtained from a 65-kw power amplifier. Resistance is added in series with the field windings to shorten the time constant of the generator field by a factor of almost 11, the amount of field forcing chosen to make the generator outputs approximate the fastest re-entry-simulation programs. The factor of ≈11 resulted as a compromise after considering cost, available line voltage, field insulation capabilities, and the quantity of power that had to be wasted. The time constants of the generators in response to large excursions without forcing are ≈1.3 sec up and ≈1.8 sec down.

The power amplifier design is based on the use of a three-phase thyristor bridge configuration. Variations in the output are accomplished by a gate drive that varies the conduction angle of the thyristors in proportion to a dc signal. The gate drive is commercially available (Sprague Electric Co., Model V56732-EF-230/460-3).

Because of the rather high inductance of the control windings of the gate drives, a signal of 100 v is used to furnish the 1.2 v required as input to the gate drives. The difference is dissipated in a resistor. This brings the time constant of the gate drive down to ≈8 msec, which is the least possible with a 60-Hz supply. The 100-v signal is obtained from a programable power supply, also commercially available (Deltron, Inc., Model FCD100-0.24), which is connected for electrical input, so that it amounts to a 20-kHz d.c. amplifier. It receives an input signal of 0 to 20 ma (0 to 5 v). The programable power supply was chosen for this use because of its relatively low cost as compared to an operational amplifier with associated power supplies, and because only one output polarity is required.

The three-phase thyristor bridge contains six thyristors instead of the frequently-encountered three together with three "free-running" diodes. This is done for wider continuous range of bridge conduction angle at its lower end

(30° cutoff instead of 60°). The thyristors (General Electric C150P) are rated to conduct 110 a rms and to withstand repetitive peak forward and reverse voltages of 1000 v. They are protected from damaging transient conditions by R-C networks and voltage-limiting diodes. The bridges supply 0–648 v d.c. to each generator at 0–100 a. The ten field-pole windings of each generator, all of which were in series, were rewired to place the five north poles in parallel with the five south poles. This was done to match the voltage and current of the thyristors and to avoid voltages too high for the insulation of the field coils. Equal current in individual poles was maintained by the forcing resistance in each parallel path. The resistors are 11.76-Ω, 30-kw, each, mounted in the cooling-air duct of each generator.

Power from three 150-kva, 480/480 v transformers, one for each phase, to each power amplifier, is connected and disconnected by a Size-3 contactor. The output of the power amplifier remains connected to the field through the field-forcing resistors. A diode connected across the resistor-field combinations permits decay of the energy stored in the field when the excitation is turned off; the decay is accelerated by the forcing resistors. This downward response is very nearly the same as that for a downward change in actuating signal with forcing.

The output voltage of each generator, reduced to a suitable level by a voltage-dividing resistor network, is fed back to a control winding of the gate drive unit, with polarity opposite to that of the actuating signal. This serves to linearize the generator output in terms of the gate-drive input.

### Digital Multiplexing and Distributing of Control Signals

Cost saving is the chief advantage of multiplexing, that is, of using digital logic modules to make fewer analog components necessary by using each of them sequentially for more than one function. The plenum-pressure controller and the arc-current controller, containing four and six operational amplifiers (Zeltex, Inc., Model 116), respectively, are used for more than one function. Digital logic circuits,[12] analog-to-digital and digital-to-analog converters, and solid-state switches (built in this laboratory) are used to select the reference, actuating, and feedback signals associated with each of the six power generators and to route these signals in turn to the proper shared controller. Each of the controllers performs the actions assigned to it as shown in the block diagram of Fig. 4, but is switched to control six power systems, including the one shown.

The solid-state switches are represented by blocks labelled SW in Fig. 5. Two modes of operation are available: a plenum pressure control (i.e., enthalpy control) and a current control. With the system operating in the plenum-pressure control mode, one pair of switches connects the selected plenum pressure reference (either the output of the mass-flow-pressure transducer or a steady reference source) to the plenum pressure controller. The reference is compared with the feedback signal from the plenum pressure transducer, the output of which remains continuously connected to the controller and is adjusted for the desired plenum pressure (or enthalpy) level. Another switch at the proper time in a scan connects the output of this controller to the analog-to-digital converter ($A/D$), where it is converted to binary form. It is then stored in a digital-to-analog-converter ($D/A$) "memory" for use as reference for the arc current controller. Arc current feedback signals from the six current-measuring shunts are sampled by six switches in the same scan cycles and compared in sequence by the arc current controller with the arc-current reference being stored in the memory. Output signals from the arc-current controller, for each arc current in turn, are switched, converted, and stored in six additional $D/A$ memories, one for each arc. Analog actuating signals are delivered from these six memories to the respective

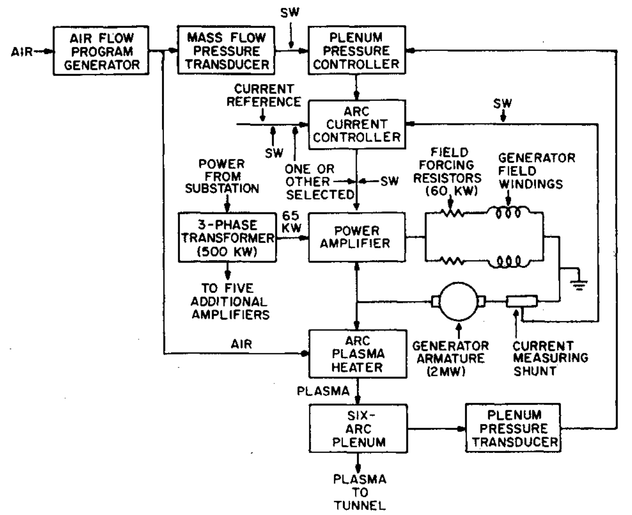


**Fig. 4 Block diagram of facility with automatic controls, showing flow of air, plasma, power, and control signals. "SW" indicates signals that are digitally multiplexed.**

actuating amplifiers and thyristor power amplifiers to bring the arc currents to the demanded level, resulting in the desired plenum pressure.

Operation in the arc-current control mode is similar to that for plenum pressure control with the arc-current reference being obtained from a steady source instead of from the plenum pressure controller. Control modes are selected at a controller setting panel, which has push buttons for setting initial states of flip-flops in the digital circuits before firing the arcs and potentiometers for adjusting starting generator voltages and steady-state operating levels. The voltages for starting the arcs may be different from those in the closed-loop condition.

A digital clock (oscillator) and a binary counter, together with digital logic circuits (AND and OR gates, flip-flops, inverters, etc.[12]) control the $A/D$ converter and the solid-state switches, which scan the inputs and outputs of the controllers and the current-measurement and memory signals. The clock operates at a frequency of $\approx$200 kHz. The conversion rate of the $A/D$ converter is $\approx$12 kHz. The sampling rate per arc heater is $\approx$660 sec$^{-1}$.

### Programing the Flow of Air

The mass flow rate of air to the arc heater is determined, e.g., in programs increasing exponentially with time, by pro-

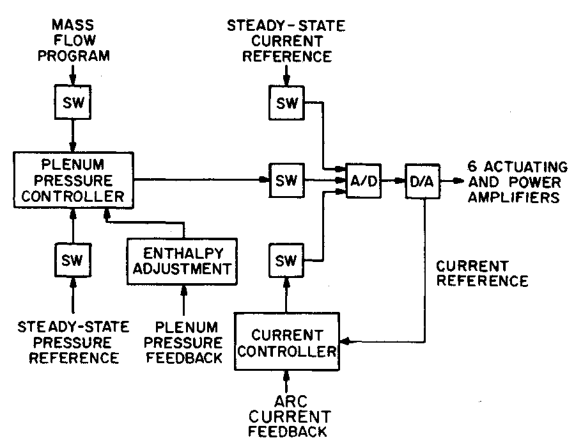


**Fig. 5 Simplified block diagram of the digital multiplexing applied to the plenum-pressure and current controllers. Solid-state switches, labelled "SW," select signals in properly timed sequence. "Arc Current Feedback" denotes six current signals sequentially switched.**

gramed pressure and the throat area of an orifice in the line feeding each heater. Air is supplied (at 900–3500 psig) to the air program generator, which consists of a cascaded sequence of six dome-controlled pressure regulators and a manifold to which the lines containing the orifices are connected.[13,14] (Exponential and other than exponential functions can be generated when desired, by adjusting the initial-condition and dome-pressure-rate valves; any monotonic function of time may be generated in terms of pressure if it can be represented sufficiently by a six-term power series expansion with positive integral exponents and coefficients.)

Steady-state tests are made by supplying air directly to the orifices of the arc heaters at a pressure corresponding to the desired mass flow rate.

## Conclusions

The system used to control multiple high-power rotary generators and arc heaters operates successfully with over-all accuracy of programed parameters within 2%. Digital multiplexing applied to sharing of control elements proved reliable and accurate (0.5%). Improvement of the response time of the generators was limited to a factor of 11 instead of the needed 15, mainly because of generator field insulation capabilities. This restricts application only in the most rapidly changing re-entry simulations. The thyristor amplifier design was found very satisfactory in this configuration, which has no problems from inductive loads. The techniques used suggest a general applicability, particularly to higher-power arc jets, powered either by motor-generator sets or polyphase transformers.

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