about 50% larger than the maximum velocity without electric acceleration, $\bar{u}_{max} = [(\gamma + 1)/(\gamma - 1)]^{1/2} = 2.45$.

Dimensionless distance $\xi = 4.53$ or for $\sigma = 200$ mho/m = const and $B_y = 10{,}000$ gauss, $a_1 = 1200$ m/sec, $p_1 = 10$ atm, and $x = 1.87$ m; at $B_y = 20{,}000$ gauss, $x = 0.47$ m. At $K = 0.1$ and $\xi = 4.2$, $\bar{u}_2 = 3.2$, $a_2 = 1.4$, and $u_{max} = 4.47$. At $K = 0.5$ and $\xi = 3.95$: $\bar{u}_2 = 6.5$, $a_2 = 2.6$, and $u_{max} = 8.7$.

Automatic Control Systems for Ion Engines

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Contact Engine System

The contact engine control system performs the following tasks: 1) upon command, starts up the engine and brings it to a predetermined level of operation, 2) maintains thrust at a predetermined level and controls ionizer temperature according to a criterion to be described, and 3) upon command shuts down the engine.

The start-up sequence is very simple; at $t = 0$, power is applied to feed system heaters and to the ionizer heater. When feed system and ionizer reach operating temperature, engine operation is begun by applying high voltage to the engine and closing the thrust stabilization feed-back loop. Since the engine operates at a fixed positive accelerating potential, the thrust produced is determined by the value of ion beam current. The thrust control loop operates by measuring the beam current, which is taken to be the algebraic sum of the currents from the positive and negative high-voltage power supplies, comparing this measurement with a reference signal, amplifying the difference, and applying it to the controlling element of the cesium vapor feed system.

To protect the engine against damage from excessive accelerator electrode drain currents, the constraint that accelerator current not exceed some reference value has been incorporated into the beam-current control loop. If the accelerator current exceeds the reference value, a signal proportional to the difference is introduced into the loop. This decreases the beam current, which in turn decreases the accelerator drain current. The result is a control loop that stabilizes beam current at a reference value or at a value that results in a predetermined value of accelerator drain current, whichever is smaller.

Mild sparking in the engine can be tolerated by the power supplies and does not appear to be damaging to the engine. Larger discharges activate the power supply overload detectors, which turn off both supplies for a few tenths of a second and then turn them both back on again. If repetitive overloading occurs, the supplies and the vapor feed are turned off for about a minute and then turned back on.

Optimum control of the ionizer temperature involves a compromise between competing factors. If the ionizer temperature is too high, radiated power losses are excessive. If the ionizer temperature is too low, other power losses begin to be important, and long-term stable operation is jeopardized. Thus it is important to maintain ionizer temperature at an "optimum" value derived according to some predetermined criterion.

Such a criterion can be based on the relation between ionizer temperature and the neutral efflux, i.e., that portion of the cesium fed into the ionizer which escapes without having been ionized. The neutral efflux-ionizer temperature relation is characterized by a very steeply rising part, a "knee," and a relatively flat part. Optimum operation occurs in the vicinity of the knee; on the low-temperature side, the neutral efflux is excessive, and on the other, excessive heater power is required to produce a slight additional decrease in neutral efflux. The function of the control system is to keep the engine operating at the knee of the curve. In the system that has been built and tested, the operating point is defined by a value of the derivative of neutral efflux with respect to temperature.

The derivative is determined by square wave modulating the ionizer heater power and making measurements on the resulting varying neutral efflux signal. Because of the fluctuations such as engine sparking, this signal is relatively noisy, making it necessary to take care in making measurements of signal amplitude. The system developed makes use of synchronous detection; a block diagram of the control loop is shown in Fig. 1 and typical waveforms are shown in Fig. 2. The neutral detector output (waveform 1 of Fig. 2) consists of a background level upon which is superimposed the variation due to ionizer temperature modulation. The modulation period is 80 sec and the thermal time constant of the ionizer, the dominant time constant in the system, is about 300 sec. The inverter produces the waveform 2 by inverting half of each cycle. At $t = 0$ (shown in waveform 7) the integrator is reset to zero and starts integrating to produce waveform 3. By integrating over the period indicated, the integrator output at $t = t_2$ is the integral of the absolute value of the alternating component of the neutral detector signal, less a fixed amount, which is the integral of the reference signal. Any noise appearing in the neutral detector signal is now integrated and produces much smaller output fluctuations. Furthermore, pairs of noise pulses occurring during the two halves of the integration cycle tend to cancel. At $t = t_2$, the sampler transmits the integrator output (waveform 3) and the compensator output (waveform 6) to the hold circuit (waveform 4), which produces output (waveform 5). The compensator output adjusts to equal the new level of the hold-circuit output during the next cycle, thus acting as a storage unit, enabling the control loop to regulate with zero steady-

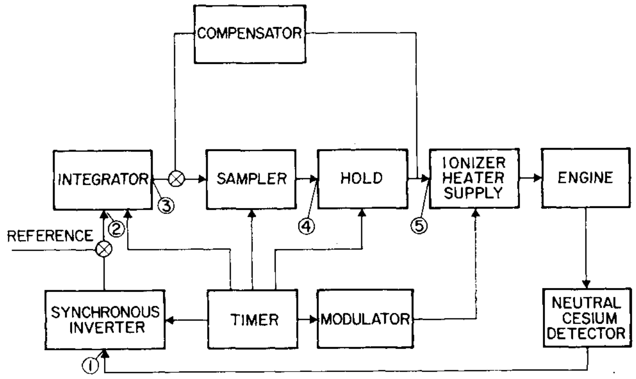

Fig. 1 Ionizer temperature control loop.

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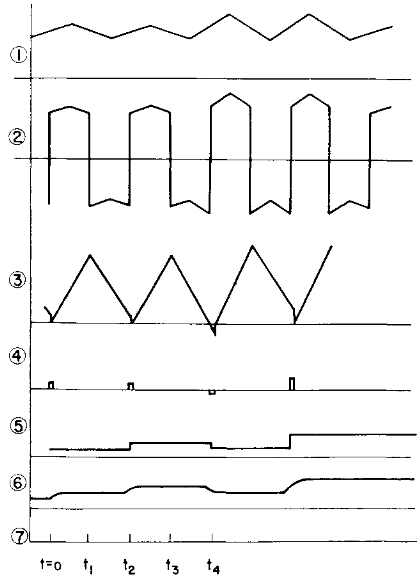

Fig. 2 Waveforms in synchronous detector.

state error. The integrator is reset and the process repeated, producing another output signal at $t = t_4$.

This output is used to control the mean power delivered to the engine ionizer heater. Thus the loop acts to stabilize the amplitude of the neutral efflux variation at a predetermined value. Since the periodic variation in ionizer temperature is approximately constant, this is equivalent to stabilizing the derivative of neutral efflux with respect to ionizer temperature.

Successful tests of the complete system have been carried out. Perturbations have been introduced into the control loops and satisfactory response observed. A completely automatic 24-hr engine test was also conducted in which all parts of the system performed as expected. As the run progressed, both neutral efflux and ionizer temperature decreased, demonstrating the desirability of using an optimizing type of ionizer temperature control.

Electron Bombardment Engine System

The electron bombardment engine control system performs the following tasks: 1) upon command, starts up the engine and brings it to a predetermined level of operation; 2) maintains thrust at a predetermined level; 3) maintains discharge chamber current at a value linearly related to the ion beam current; 4) upon command shuts down the engine.

The start-up sequence for the bombardment engine is somewhat more complicated than it is for the contact engine; for each, the procedure is basically one of bringing engine components to operating temperature. The bombardment engine, however, is not directly heated but is maintained at operating temperature by energy dissipated in the discharge chamber, and cannot be brought to operating temperature merely by applying power to a heater. The sequence proceeds as follows: When the start command is given, the feed system solenoid valve is opened, and the neutralizer, magnet, cathode heater, and feed system heaters are turned on. After a preheat period of about 18 min, the feed system is ready for operation. A preset voltage is applied to the discharge chamber, and a feed-back loop is established which controls cesium vapor feed rate to maintain a fixed value of discharge chamber current. The power dissipated in the chamber raises the temperature of the engine to a minimum operating level of about 80°C in 16 min. At the end of the second preheat period, the feed system vaporizer is de-energized for 2 min to allow the cesium concentration in the engine to decrease before the application of high voltage. At the end of the cleanup period, high voltage is applied, and the two feedback loops are closed in their normal operating configuration. High-voltage sparking is handled as described in the contact engine system section. The beam control loop is set to produce about one-half the final required beam current. The transition from half to full beam is made in a series of nine steps at 2-min intervals. This gradual approach to full operation has been found to produce smooth and reliable operation. Throughout the start and stop sequences and all automatic operation, the cathode heater is interlocked with arc current; whenever the arc current is greater than 20 amp, ion bombardment maintains the cathode at operating temperature and the cathode heater is turned off. When arc current drops below 10 amp, the heater is turned on again.

The shutdown sequence is as follows: When the stop command is given, the beam control loop turns off the feed system vaporizer, decreasing beam current to about 20% of full value in 1 min. At this time, the arc power supply is turned full on, so that the cesium remaining in the engine will be ionized and extracted as ions. As the cesium is exhausted, the discharge current drops and the cathode heater is re-energized. After a few minutes, the discharge extinguishes and ion production ceases. Shortly thereafter all power is removed from the engine. It is relatively free of cesium and ready for a smooth restart.

A block diagram of the control system in its normal operating configuration is shown in Fig. 3. The first control loop is essentially the same as its counterpart in the contact engine system. Transient responses of the loop are primarily determined by the thermal response of the vaporizer. In order to produce smooth transient response, it was found necessary to add a compensating network to the loop.

The arc-control loop acts to maintain arc or discharge current at a value linearly related to the ion beam current. As shown, this is accomplished by comparing arc current with beam current and an offset signal and using the difference to control the arc power supply. The beam-current/arc-current relationship was chosen so that, as beam current varies, the energy efficiency of the engine remains very nearly constant.

The control system was tested with the engine and feed system by conducting 10 successful consecutive start-up-run-shutdown sequences. All cycles were completely automatic, the only operator action being the initiation of each start-up and shutdown.

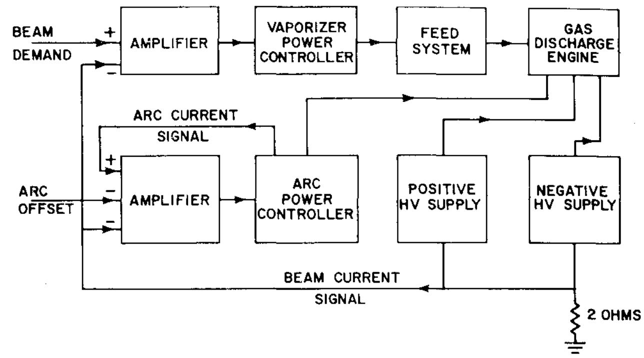

Fig. 3 Electron bombardment engine control system.