CONTROL OF SECONDARY-SODIUM FLOW IN EBR-II

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ABSTRACT

Control of secondary-sodium flow in EBR-II has been the most difficult and time-consuming operation performed by an operator. A very small change in flow directly affects the temperature of the primary coolant, which must be held within very close limits. Flow control was affected by changes in ambient temperature and perturbations on the power system and was complicated by the time lag between the primary- and secondary-sodium systems. The addition of a limited automatic flow-control system has minimized the operator-performed functions by essentially eliminating the adverse effects of changes in ambient temperature and perturbations on the power system. The remaining operator function is to match the secondary-sodium flow to the temperature of the primary coolant and to switch to automatic control for continuance of the match. The flow-control system is composed of commercially manufactured components carefully matched and interconnected to satisfy a complicated and complex control requirement.

I. INTRODUCTION

The secondary sodium system in EBR-II is a closed loop of liquid sodium that transfers heat from the primary sodium system to the steam system. With the reactor operating at any given power level, the temperature of the primary coolant sodium is controlled by flow of the secondary sodium. Therefore, it is important to have a reliable, stable means of controlling flow of the secondary sodium.

Figure 1 shows the flow path of the secondary sodium. Secondary sodium is pumped through the closed loop by an ac electromagnetic (EM) pump powered by one of two power supplies. The normal power supply is a 350-kW, 3-phase motor-generator (M-G) set. Auxiliary power for the pump comes from an autotransformer, which is used only for low flow rates at standby. Drift-free control with the normal supply is essentially impossible to achieve near zero flow (1/2 to 1% of full flow).

The amount of normal power supplied to the pump is controlled by controlling the current in the field windings of the generator. The drive motor of the M-G set is a 500-hp, 3-phase, 2400-V induction motor which has a full-load speed of 1185 rpm. Whenever the normal power supply is used, the motor rotates at about 1185 rpm. Therefore, the output power of the generator depends solely on the amount of field current supplied to the generator. Control of the field current is the subject of this report.

Originally, field current was supplied by an amplidyne, which was in turn controlled by a thyatron controller. However, this system proved unsatisfactory, mostly because of instabilities at low flow rates. Another scheme was substituted for controlling the amplidyne, but the major problem was the unpredictable output of the amplidyne itself. Therefore, a motor-driven autotransformer and a rectifier bridge were installed in 1964. Figure 2 shows how this system was arranged. A switch on the control-room console allowed an operator to drive the autotransformer and, consequently, change the field current from zero to maximum with continuously variable control. This system was used until September 1970.

The most significant problem with the motor-driven autotransformer was a lack of fine control. When the operator momentarily closed the raise-lower switch, the field current would change either too much or practically not at all. With the reactor at full power, a small change in field current will produce a significant change in primary-sodium temperature. Consequently, the operator had to monitor primary-sodium temperature carefully, and a stable secondary-sodium flow rate was difficult to achieve. In addition, since the flow control was open loop, a change in ambient temperature or line voltage caused a change in flow unless the operator compensated for the conditions. The overall result was a system that, although operated safely and reliably for many years, required considerable attention from the operators.

Fig. 1. Flow Path of Secondary Sodium

Fig. 2. Control of Generator Field Current with Motor-driven Autotransformer

In September 1970, a test system (see Appendix A) was installed as shown in Fig. 3. A Lambda Model LB704-FM-0V dc power supply replaced the autotransformer and rectifier bridge. One of the possible ways to control the output of the Lambda power supply is by external-resistance programming. Therefore, a motor-driven potentiometer was used to control the output of the power supply and, consequently, the field current of the generator. The control scheme was very similar in operation to that of the motor-driven autotransformer, except that the Lambda power supply provided the important capability of a closed-loop control system if desired later in the test program.

With the new Lambda power supply in an open loop, some of the old problems still existed. Although it was possible to make finer adjustments than had been possible with the autotransformer, the field current still tended to change too much or too little when the raise-lower switch was closed. Also, because control was still open loop, changes in temperature required the operator to make periodic adjustments to maintain a constant flow.

A closed-loop system, incorporating negative feedback, was investigated and found to be feasible. After some preliminary bench-testing, the

Fig. 3. Control of Generator Field Current with Lambda Power Supply and Motor-driven Potentiometer

system was assembled and installed as a test (see Appendix B). About two months of successful operation demonstrated the advantages of the new control system, so it was installed as a plant modification.

The balance of this report describes some aspects of the new control system. Section II describes the operating principles and characteristics of the components in the system. Section III discusses the initial installation and checkout of the system, and Section IV includes some comments about the new M-G set that is used in the system.

II. THE CONTROL SYSTEM AND ITS COMPONENTS

A. General

Figure 4 is a block diagram of the present secondary-sodium flow-control system, shown in the automatic mode. There is also a manual mode in which an operator raises or lowers flow by depressing a pushbutton,

Fig. 4. Block Diagram of System for Automatic Control of Secondary-sodium Flow

thereby overriding the flow signal. The differences between automatic and manual control are discussed in Section II.I.2.

In the automatic mode, a signal from the permanent-magnet (EM) flowmeter is amplified, with a standard millivolt-to-current (MV/I) amplifier, and compared to a signal that represents the desired flow (setpoint). If the actual and setpoint flow are not equal, an error signal is generated which, after amplification, changes the field current of the generator of the M-G set in a direction to bring the actual and setpoint flows closer together. Therefore, any perturbation that causes actual flow to change will be compensated for automatically by the controller to return the flow to the setpoint value.

Figure 5 is a more detailed diagram of the secondary-sodium flow-control system. Each component will be considered below, along with a discussion of how the individual components combine to perform the intended function.

B. Flowmeter

The flowmeter is a permanent-magnet (EM) type that generates a voltage of about 53 mV at 100% (about 6000 gpm) flow. Figure 1 shows the location of the flowmeter relative to the pump in the system. The flowmeter is on the second floor of the east wing of the sodium boiler plant. Its specifications are in Section 1 of Appendix C.

C. Filter

An RC (resistance-capacitance) low-pass filter is installed in the flowmeter signal path in the cable-routing room to reduce noise both from the flowmeter itself and from pickup along the line. The time constant of the filter is 0.3 sec. This time constant is high enough to eliminate most of the noise but, because of the large inertia in the secondary sodium, does not affect normal response.

D. Flow Amplifier (EMF Transmitter)

From the filter, the signal is interconnected with the input of the amplifier, an L & N M-line EMF transmitter in the cable-routing room. This

Fig. 5. Detailed Diagram of Secondary-sodium Flow-control System

device generates an output current across a resistor that is directly proportional to the input voltage. Because it converts a voltage to a current signal, the EMF transmitter is frequently called an MV/I (millivolt-to-current) amplifier. Specifications of the MV/I are in Section 2 of Appendix C. The MV/I is designed and aligned to produce an output of 0-4 mA for an input of 0-53 mV.

E. Alarm Unit

The MV/I output feeds several components in a series string (often referred to as a current loop). One is the alarm unit, a Rochester Model ET-215K electronic trip (or monitor) designed to sense a voltage level and actuate a bistable trip when the level is greater or less than a setpoint voltage. In this application, the monitor actuates when the flow is less than 0.5% of full flow. Upon trip, an annunciator in the control room alerts the operator to the low-flow condition. The monitor automatically resets when flow is greater than about 1.5% of full flow. The specifications of this monitor are in Section 3 of Appendix C.

F. Flow Recorder

Another component in the output current loop of the MV/I is the flow recorder, which is mounted on the console in the control room. The recorder, an L & N Speedomax H, Model S, has an input range of 0-10 mV. It is the instrument normally depended upon by an operator for reading secondary-sodium flow. To provide an expanded range for low flow, a switch and two resistors are used as shown in Fig. 5. With the switch open (expanded mode), full scale on the recorder corresponds to 10% of full flow. With the switch closed (normal), full scale is 100% flow. Specifications for the recorder are in Section 4 of Appendix C.

G. Flow Indicator

The MV/I also feeds an indicator on the secondary-system control panel in the west wing of the sodium boiler building. This indicator is a GE Model 8DB, 0-50 μ A meter with an internal resistance of about 11,500 Ω . The meter face is calibrated for 0-100% flow in 270° of movement.

H. ADL (Automatic Data Logger)

The output string of the MV/I includes a 5- Ω resistor across which is developed 0-20 mV for 0-100% flow. This voltage is one of the analog signals sampled periodically by the ADL in the control room. The channel used is module 2, channel 01.

I. Flow Controller

1. General

The remaining component in the MV/I output current loop is a solid-state L & N 420 current-adjusting type (CAT), fast-process (minimum filtering employed), two-mode controller. Figure 6 shows a block diagram of this controller, and Fig. 7 identifies the front-panel controls and indicators. Specifications are in Section 5 of Appendix C.

2. Basic Operation

a. Automatic Mode

The automatic mode of operation of the 420 controller is the operating mode during which negative feedback is used to maintain a constant flow of secondary sodium. This feature is the significant difference between present and past types of secondary-sodium flow control.

Input to the controller is the 0-4 mA dc signal from the MV/I. On the terminal block of the controller case, this current is programmed through a 1133- Ω resistor, and the resulting voltage is one input to a resistive voltage comparator inside the controller. The other input to the comparator is derived from the sliding contact on a potentiometer, one end of which is grounded and the other end of which is held at a positive potential. The potentiometer-controlled circuit is the setpoint circuit an operator adjusts to select the desired flow.

The comparator output is the algebraic sum of the input voltage and the setpoint voltage. The input signal is grounded on the positive side; therefore, if the input voltage (input current x 1133 Ω)

Fig. 6. Block Diagram of Flow Controller

Fig. 7. Front Panel of Flow Controller

is equal in absolute value to the setpoint voltage, the output of the comparator will be zero. With a constant setpoint voltage, if flow increases, thereby producing a larger negative input voltage, then the output of the comparator will go negative because the algebraic sum is negative. If flow decreases, the comparator output will swing positive by an amount equal to the difference between the absolute values of the controller input and the setpoint. This difference is called the error signal.

The error signal is amplified in the control amplifier, which also has inputs from control-panel adjustments, as discussed below under "Manual Mode." The control amplifier is a solid-state operational amplifier. A feedback signal from the controller output is used to adjust the gain of the amplifier.

From the control amplifier, the conditioned error signal is programmed through contacts controlled by mode (automatic or manual) into the output control amplifier, which contains a field effect transistor (FET) and driver transistor. This amplifier section supplies the necessary power amplification and converts the output to a 0-5 mA signal for loads of 2000 Ω or less. A negative error signal will lower the controller output, but the output will never go below zero. A positive error signal will increase the controller output, but the output is limited to just over 5 mA.

b. Manual Mode

In addition to the automatic control mode in which the output is proportional to the difference between input and setpoint, the controller has a manual mode in which the controller output is changed by closing a "raise" switch or a "lower" switch. In this mode, the controller output is not affected by the flow signal and will not change unless one of the switches is closed. The manual-mode output signal is controlled by switch operation which applies a dc voltage to the gate of the FET in the output control amplifier. The gate is connected to ground through a capacitor that determines, along with a resistor, the rate at which the controller output will change when the raise switch or lower switch is closed. Closing the raise switch puts a positive charging voltage on the capacitor, and closing the lower switch applies a negative voltage. The rate of

increase or decrease of the controller output is exponential, and the time constant is the same in both directions. The controller, as received from the manufacturer, had a time constant of about 17 sec for a change from zero to full output. This is too fast for use with the secondary-sodium pump; therefore, the charging capacitor was modified to provide a time constant of about 100 sec.

If neither the raise switch nor the lower switch is closed while the controller is in the manual mode, output of the controller will either remain constant or very slowly change because of leakage in the capacitor. In general, however, the controller is switched into the automatic mode shortly after desired flow is reached, so a small leakage in the capacitor is not a significant problem. In the automatic mode, the capacitor stays charged at the output voltage of the control amplifier, so the output does not make a step change when transfer is made from automatic to manual. In automatic, the resistor that controls the rate-of-change of output during the manual "raise" and "lower" is disconnected; therefore, the capacitor does not introduce a significant damping of the output.

c. Controls

Figure 7 shows the location of each of the front-panel controls. The three switches--lower, automatic, and raise--are interlocked so that only one switch can be engaged at a time. Both the raise switch and the lower switch are momentary contact and must be held depressed to raise or lower flow. Depressing the automatic switch puts the controller in automatic until either the raise switch or lower switch is depressed, an action which mechanically opens the automatic switch. The automatic switch then has to be depressed again to go into automatic; otherwise, the controller will stay in manual. A light in the pushbutton of the automatic switch is on when the controller is in automatic and off when in manual. If an operator desires to return from automatic to manual without raising or lowering flow, he can briefly tap the raise switch or lower switch, thereby mechanically releasing the automatic switch without actually closing the raise or lower contacts.

The remaining front-panel control is for the potentiometer that establishes the setpoint voltage. The potentiometer dial is calibrated from 0 to 100%, and the setpoint is continuously variable over the

full range of control. The knob is connected to the potentiometer through a vernier, which allows for a very small incremental change in setpoint. Approximately 5-1/2 turns of the knob covers the range of 0 to 100%.

There are two panel meters on the front panel. The lower meter (output meter) is calibrated from 0 to 100% and shows percentage of full output current of the controller. This 0-1 mA meter is shunted by a 20- Ω potentiometer for adjustment for full-scale deflection of the meter at 5-mA output of the controller.

The upper meter (deviation meter) on the front panel has a range of -25 mA to +25 mA. This meter is connected to the output of the comparator and indicates the relative difference between the controller (variable) input and the setpoint. The meter has equally spaced gradations across its scale. Experience has shown that each gradation corresponds to a difference of about 0.8% between setpoint and actual flow. The most important function of the deviation meter is to allow an operator to adjust the setpoint so that transfer from manual to automatic does not produce a step change in the controller output.

In addition to the front-panel controls, there is an internal control panel which is reached by pulling the controller forward out of its case. This panel contains three potentiometers and an 18-position rotary switch.

One of the potentiometers, labeled "Proportional Gain," adjusts the gain of the feedback loop. If the gain is too low, the flow will very slowly approach the setpoint with an overdamped characteristic. If the gain is too high, flow will oscillate about the setpoint and may become completely unstable. With the correct gain, flow will approach the setpoint with a critically damped characteristic.

Another potentiometer, called "Lag," is part of a low-pass filter on the controller error signal. Used only for a noisy input signal, the lag control adjusts the response of the controller to a change in input signal. For this application, the lag time is set at zero ("off" position).

The third potentiometer, the "Maximum Current Adjust," is in series with the controller output. Maximum output current is factory-adjusted to be 5.4 mA for a 2000- Ω load. However, if a different load resistance is used, the maximum current adjust must be reset if 5.4 mA is

still the desired maximum output current. This control was set during check-out, and the knob was removed to prevent accidental raising or lowering of the maximum output of the controller.

The 18-position rotary switch, labeled "Reset Action," has the effect of limiting the rate-of-change of the controller output. It is used in conjunction with the proportional gain to achieve the desired controller response to a change in setpoint or input signal. Too high a setting of the reset action causes cycling of the output above and below the setpoint. Too low a setting causes sluggish response. The instruction manual for the controller gives detailed instructions and precautions for setting the proportional gain and reset action.

3. Modifications

Two modifications of the controller were made to adapt it for use on flow control of secondary sodium. The first, discussed earlier, was changing the capacitor in the gate circuit of the output control amplifier to limit the rate-of-change of output during manual "raise" or "lower." The rate-of-change is limited to prevent a strain on the secondary-sodium pump. The capacitor was changed from 2 to 12 μ F, thereby increasing the time constant of manual increase and decrease from about 17 to about 100 sec.

The second modification was made to prevent an operator from placing the controller into automatic when the error signal is large. Without this protective circuit, the controller would attempt to zero the error signal by forcing the pump to change at a rate that could place unnecessary strain on the pump. The modification interlocks the controller out of automatic if the voltages equivalent to flow and setpoint differ by more than 5%. If actual and setpoint flow voltages differ in either direction by more than 5%, the controller will automatically transfer to manual and cannot be returned to automatic until the difference (deviation) voltage is less than 5%.

Figure 8 is a diagram of this modification. Before the modification, two terminals, 4 and 5, on the controller case normally were shorted with a jumper. If the input circuit was broken, a relay inside the controller, which determines controller mode (automatic or manual), would deenergize and place the controller in manual. For the modification, the

Fig. 8. Modification of Deviation Meter of Flow Controller

jumper was removed, and leads were run to relay contacts on an Assembly Products Incorporated (API) Model 630K meter with a range of -50 to $+50 \mu\text{A}$. This meter has both high and low setpoint controls.

Inside the controller, two new leads were connected in such a way that the API meter could be connected in series with the deviation meter. Contacts on the API meter, as shown in Fig. 8, were chosen so that if the indication on the API meter is between the setpoints, both sets of contacts are closed. If the indication is below the low setpoint or above the high setpoint, one set of the contacts will open and transfer the controller to manual. The setpoints were adjusted so that a trip (contacts open) would occur if the voltages equivalent to actual and setpoint flow are different by more than 5%. For example, if the setpoint is at 50%, the actual flow must be between 45% and 55% for the controller to be in automatic. When the controller is in manual, flow can be changed only with the raise switch or lower switch.

J. Kepeco Power Supply

Output of the L & N 420 controller is limited to about 10 V (e.g., 5 mA into a 2000-Ω load). If the load resistance is higher, the controller

output current will drop to maintain about 10 V maximum. The Lambda power supply used to provide power for the field of the generator of the M-G set can be programmed to produce a maximum output/input ratio of 1 (1 V output per 1 V input). Since the field voltage at 100% flow is more than 50 V, the controller output is amplified approximately five times before being fed to the Lambda. The amplifier used for this purpose is a Kepco Model OPS 72-0.3B (C) operational power supply. Specifications for this unit are in Section 6 of Appendix C.

The Kepco power supply combines a high-gain operational amplifier and programmable power supply. External input and feedback resistors are used to control gain. Figure 5 shows how the Kepco power supply is connected to the L & N 420 controller. The current output of the controller is connected through a 2.4K resistor to produce about 0-10 V. The input resistor to the Kepco amplifier is 9.1K, and the feedback resistance is a 50K potentiometer. The potentiometer is set at about 45K, a setting that produces a gain of about 5 in the Kepco supply. Therefore, a 0-10 V input generates a 0-50 V output.

K. Lambda Power Supply

The Lambda Model LB-704-FM-0V programmable power supply is all solid-state and can supply 50 A at 0-60 V. Field current for 62.5-MWt reactor power is 24 A at 46 V. Section 7 of Appendix C gives the specifications of the Lambda supply.

The Lambda supply has both an adjustable current limit and an adjustable overvoltage trip. The overvoltage trip will open a circuit breaker and completely deenergize the supply if the output voltage exceeds the set-point. The trip is intended to protect the supply from voltage transients that could be generated in the load and to protect the load from excessive voltages if the internal voltage regulator of the power supply fails.

As mentioned above, the Lambda is wired for 1:1 voltage programming (i.e., the output voltage equals the input voltage). However, the Lambda can also be programmed by a resistance across the input terminals. To program in this way, the Lambda sends a current of about 5 mA into its input and uses the voltage generated to control the output. For use with the Kepco supply, it was necessary to load the Lambda with about 200 Ω .

Without the added resistance, the Lambda output would never go below 1.2 V, because the output resistance of the Kepco [from (-) out to (+) out, which is the direction of the position feedback current from the Lambda] is about 250 Ω . With the 200- Ω load, the Lambda will go down to about 0.6 V. Interlocking through the "at minimum" trip (see Sec. II.M) requires as low a repeatable voltage as possible. Of course, a lower Kepco resistor would allow an even lower Lambda minimum voltage, but it would also load the Kepco excessively.

L. M-G Set

Output from the Lambda power supply is the field current for the generator of the M-G set. The generator is driven at a constant speed of about 1185 rpm. Generator output is 3-phase, ac power, which is about 240 kW when the reactor is at full power. Specifications are in Section 8 of Appendix C.

M. "At Minimum" Trip System

The voltage output of the Lambda is monitored by the system shown in Fig. 9. The monitors are EG&G Model 3096, which can be adjusted to trip (deenergize a relay) at an input voltage between 0 and 10 V. Two monitors are used for redundancy: if one fails, the other will perform the trip function. The monitors are similar to the type used in the nuclear instrumentation for reactor protection.

The purpose of the "At Minimum" system interlock is to prevent switching the pump from normal (M-G set) power to auxiliary power, or from auxiliary to normal, unless the normal power supply is at some minimum level. This prevents suddenly applying a large amount of power to the secondary pump. The interlock level is set at 2 V.

N. Secondary-sodium Pump

Secondary sodium is pumped by an ac, electromagnetic, linear induction pump, a totally enclosed unit designed to circulate 6500 gpm of 700°F sodium at a 53-psi head. Pump flow is continuously variable from 0 to 100%. Section 9 of Appendix C gives the specifications of the pump.

Fig. 9. "At Minimum" Trip System

O. Capacitor Banks

The power factor of the pump is 0.3. To improve this somewhat, six banks of capacitors, each bank containing between eight and 12 capacitors, are connected between phases of the pump power supply. The capacitors are oil-filled and are rated at 1340 kVAR per bank. The corrected power factor is about 0.9.

III. INSTALLATION AND CHECKOUT

A. Preliminary Testing

To verify the overall concept of automatic control of secondary-sodium flow, a system was set up as shown in Fig. 10. Testing with this setup also provided important information concerning operation of the controller, especially the effects of changes in the proportional gain and reset action.

Output of the Lambda drove a small rotating inverter that contained a dc drive motor (0-28 V) and an ac generator. Output of the generator was transformed down, rectified and filtered, and then divided to yield an output of 4 mA at 28 V on the dc drive motor. The divider output was the controller input. Output of the controller drove the Kepco, which in turn drove the Lambda supply.

The inverter-transformer-rectifier-divider system simulated to some extent the M-G set-pump-flowmeter action in the real secondary-sodium system. If the inverter started to speed up, the controller would generate an error voltage signal and lower the output of the Lambda until the actual speed was matched to the setpoint voltage. During this phase of testing, the controller was modified as discussed in Section II.I.3.

B. Initial Test of Installed System

1. General

In November 1970, the secondary-sodium flow-control system was connected as shown in Fig. 5. In addition, a six-pen Brush Mark 260

Fig. 10. Block Diagram of Setup for Preliminary Testing of Automatic Flow-control System

recorder was set up to record (1) flow of secondary sodium, (2) field current of the generator, (3) field voltage of the generator, (4) outlet temperature of generator cooling air, and (5) temperature of the capacitor bank. The EG&G trip monitors were not used, but an API 0-2 V dc voltmeter with adjustable trip point performed the "At Minimum" function during the test.

The Lambda and Kepco power supplies were mounted in the west wing of the sodium boiler building. The Lambda was placed in an enclosed frame with cooling ducts just below the Lambda power supply that was used in testing in September 1970 (TST 60-70, Appendix A). The Kepco was installed in the frame between the two Lambdas. The 420 controller was placed on top of the console in the control room and fastened down with a bracket.

The first system type of problem encountered was a grounding problem. By attaching the controller case to the console, the controller was grounded at the plus input to the controller. The secondary-flow recorder happened to be grounded on one input; therefore, the MV/I output simply bypassed the controller. The situation was quickly remedied by repairing (ungrounding) the recorder.

Appendix B contains details of the test procedure (TST 66-70) that was carried out after the system was installed and checked for grounds and continuity. During the test, the system performed as expected.

2. Test Procedure

Item 12 of Appendix B lists the steps that were carried out during the test. The results for each step are summarized below:

12.1 Everything was normal and as expected.

12.2 The "At Minimum" light functioned normally.

12.3 The transfer was accomplished as usual.

12.4 The transfer was normal.

12.5 When the normal power supply went above about 2 V, the "At Minimum" light went out.

12.6 The transfer did not occur. This showed that the "At Minimum" circuit was functioning as desired, so that transfer to normal power supply cannot be accomplished if the power supply is not "At Minimum." (Note: For this part of the test, ac power for the controller was taken from one of the recorders on the console. Otherwise, the Lambda output could not have been raised above the "At Minimum" while on auxiliary power.

12.7 The "At Minimum" light came on as expected.

12.8 The transfer was normal.

12.9 The pump was tripped from the boiler plant.

12.10 The start was normal.

12.11 The flow continued to increase after the "raise" switch was released. This is as expected, since there is considerable inertia in the secondary sodium. The flow did not shift after it leveled at 10%.

12.12 The flow did not change, which showed that the deviation meter was adjusted properly.

12.13 As before, the flow remained constant after leveling out.

12.14 The automatic switch did not engage, which showed that the deviation circuit that sets the $\pm 5\%$ limits was operating.

12.15 The new flow was 15.5%, which indicated that the automatic controller had come on at 4.5% from the setpoint. Although the desired setting is 5%, the 4.5% was considered close enough.

12.16 As expected, the flow did not change.

12.17 This time the difference was 3.5%. Again, it was decided not to adjust any settings to move this closer to 5%.

12.18 Figure 11 shows the plot (flow versus time) of the data for manual increase of flow. Again, we see the inertia of the sodium having an effect.

Fig. 11. Flow vs Time for Manual Increase of Flow during Test

12.19 Some drift of the controller in manual was noted here. Unless a steady value had not been reached, the most likely cause of this drift was a slightly leaky capacitor. The controller will normally be in automatic, in which case there is no drift.

12.20 Figure 12 shows the data for manual decrease of flow. The rate of decrease is high enough for an anticipatory shutdown.

12.21 The difference was 5.5%. It is not too surprising that the exact limits of deviation beyond which the controller is out of automatic would change because of nonlinearities and a certain amount of non-repeatability of the setpoints of the API meter. This should not be a serious problem.

12.22 The limit here was 3%. See above comments.

12.23 The step was carried out, but the data were inadvertently unrecorded.

12.24 The purpose of this step was to calibrate the setpoint indicator and the controller output meter. The setpoint indicator was reasonably close to the recorder flow. The controller output meter was less accurate because, although the controller output is linearly related

Fig. 12. Flow vs Time for Manual Decrease of Flow during Test

to field volts, the relationship between field volts and secondary-sodium flow is not perfectly linear. The controller output is not linear with flow and cannot be calibrated using the linear scale on the meter. This is not a serious problem; the controller output meter is not used as a flow indicator.

12.25 The purpose of this step was to determine the maximum rate of flow decrease using the setpoint and automatic control. The rate was found to be not much faster than that for manual decrease and to depend on the skill of the operator.

During the test, the current limit on the Lambda power supply was set at about 25 A, which is about 1 A above the normal operating point for 62.5 MWt. This ensures that an up-scale failure of the controller will not produce more than about 95% secondary-sodium flow. The overvoltage trip on the Lambda, which is intended to protect the Lambda from transients on its output, was set at 60 V.

After the steps in Item 12 of TST 66-70 were completed, the system was considered to be operating as desired, and it was decided to try the new system for normal reactor operations.

During the approach to power for the next run, a temporary loss-of-flow signal occurred at about 50 MWt. The indicated (not actual) flow dropped to zero and then rose to the original level. This occurred several times at irregular intervals. The controller was in automatic and tried to control for the variations, but went out of automatic several times. The operator put the controller in manual, but the flow signal continued to swing for about a minute. When the recorder settled down, the flow was returned to the desired level and placed in automatic by the operator. From that point on, the system has been normal.

The most likely cause of the loss-of-flow signal is associated with the Brush recorder. It is possible that one side of the flow signal became grounded somehow (possibly through the recorder) for a moment and caused the flow signal to bypass the controller. There was no easy way to verify this without taking a chance on causing it again. As soon as the needed data were collected, the Brush recorder was removed from the system.

Except for the above problem, the system was used with little difficulty during the next run. A breaker in the secondary-sodium system tripped and caused an indirect reactor scram during the test run, but no evidence was ever found that the flow-control system was in any way responsible. The automatic mode of control did correct the flow drift seen with earlier systems and almost eliminated the need for adjustment after full power was reached.

After one run with the control system as a test, the system was made a permanent installation as Plant Modification No. 366.

IV. PERFORMANCE SINCE INSTALLATION

A. General

Since the automatic flow-control system for secondary sodium was permanently installed, no difficulties worth mentioning have been encountered. Some initial adjustments of proportional gain and reset action were made for optimum performance, but overall the system has been

very predictable and stable. The special operating procedure used by operators of the system has been incorporated in the EBR-II Operating Instructions as part of Division V B of Vol. 2.

B. Controller Failure Mode

In automatic control, the controller could fail to increase or decrease the pump output, depending on the particular controller failure. In either case, the automatic transfer circuit described in Section II.I.3 will transfer the control to the manual mode of control with an error of approximately 5% flow. Normal secondary-sodium flow at rated reactor power is approximately 90% of full flow; therefore, the failure is controlled within safe limits and requires only operator action to correct it.

C. Improved M-G Set

The M-G set that had been in service since the reactor was built was replaced after the flow-control system was installed. The new M-G set performs exactly the same function as the old, but uses a brushless generator and improved drive motor. The old set had begun to make a noise that apparently was caused by a worn bearing in the generator. The old motor and generator were removed, overhauled, and stored as spare parts.

The generator of the new M-G set requires a much lower field current for any given flow. For full-power flow, for example, the old generator required about 24 A and the new generator requires only about 2.5 A. This lower current requirement showed the need for a slight change in the control system. When the new M-G set was installed and tested, the Lambda power supply was found to be unsatisfactorily regulated at a low output (which before was never used). Also, at 2.5 A, it was difficult to set the current limit, which has a range of 0-60 A.

Figure 13 shows the modification made to correct this problem during checkout of the new M-G set. An 11- Ω resistor was added in series with the generator field so that the output voltage of the Lambda was raised above the level where regulation becomes unsatisfactory. This did not change the current drawn from the Lambda for any given flow.

Fig. 13. Modification for New M-G Set

A Lambda power supply with a lower output voltage (0-20 V) and lower current rating (0-6 A) but identical in regulatory and programming circuitry has replaced the original power supply. The new power supply is sized to satisfy the generator field requirements. Because the new supply is sized properly, the control characteristics of the entire control system are more responsive to system characteristics.

APPENDIX A

EBR-II Test Procedure No. TST 60-70

1. Title

Installation and Test of New Static Power Supply for the Secondary Sodium AC-EM Pump Alternator Field Excitation

2. Purpose

The purpose is twofold:

- 2.1 To replace the existing static power supply for the alternator field excitation with a power supply having improved performance.
- 2.2 To run performance tests on the operation of the main secondary AC-EM pump with the new alternator field excitation supply.

3. Discussion

3.1 The ac alternator output to the AC-EM pump is controlled by varying the excitation field of the alternator. The variable power to the exciter field has been supplied by a variable transformer and rectifier controlled from the control room. The control has been coarse and subject to ambient-temperature changes, system-voltage perturbations, and equipment conditions. This test will provide for a control that will be infinitely adjustable, well regulated for line perturbations, and with the capability of automatic regulation.

4. Supplementary Procedures

4.1 SA 3-69, "EBR-II Electrical System - General Safety Requirements for Maintenance or Installation"

4.2 EBR-II Operating Instructions, Division II B, "Normal Plant Operation," and Division V B, "Secondary Cooling"

4.3 Work Plan IC-24-70

5. Industrial Safety

5.1 All phases of removal of the old power supply and installation of the new supply shall be in accordance with Safety Procedure SA 3-69.

6. Preparatory

6.1 Shop-test static power supply for load and voltage characteristics. Determine failure modes.

6.2 The new power supply shall be bench-tested under simulated full load range as imposed by the alternator field excitation compatible with normal pump operation. This test is to be made at the ambient temperature that will prevail during normal operation. Temperatures of selected critical components are to be measured.

7. Plant Conditions

7.1 The plant will be in a shutdown condition with the primary-tank and secondary-sodium systems isothermal at 560 to 580°F.

8. Installation

8.1 The power supply is to be installed as specified in Work Plan IC-24-70 and connected in accordance with the drawings included with the work plan.

8.2 Check all installed wiring for continuity and polarity, and ground-test all installed wiring at 500 volts.

8.3 Install test instrumentation as shown on Sketch SK IC-24-70.

9. Performance Test Limitations

CAUTION: During the performance tests on the pump with the new alternator field supply installed, care must be exercised not to exceed maximum pump flow, pump current, and other parameter maximums as listed in 9.1 through 9.5.

9.1 96.5% indicated flow (5680 gpm)

- 9.2 1476 amperes pump current
- 9.3 527 amperes generator current
- 9.4 36.6 amperes generator excitation
- 9.5 3% per second rate-of-change of secondary flow in the increasing direction.

10. Performance Test of Pump with New Alternator Field Supply Installed

10.1 Operate the secondary main EM pump in the forward direction at 8% indicated flow until the primary and secondary systems are isothermal within 10°F.

10.2 Using normal procedures, start the secondary-pump M-G set and place the secondary pump on its normal power supply. (If secondary flow changes more than 5%, trip the pump and consult the test engineer before further action is taken.)

10.3 Operate the pump in the forward direction as requested by the test engineer to determine proper operation of the pump and control system. Do not hold the control switch continuously in the increase direction for more than 3 seconds until steps 10.4 through 10.6 have been satisfactorily completed.

10.4 With secondary flow initially at 5%, hold the control switch continuously in the increase position until flow is 30%. Measure the time required to increase secondary flow to 30%. This time should be about 15 seconds, but must not be less than 8 seconds. If time is less than 8 seconds, corrective action must be taken before proceeding.

10.5 Reduce secondary flow to 5% and stabilize.

10.6 Again hold the control switch in the increase direction until secondary flow increases to 80%. Measure the time required for the secondary flow to increase to 80%. This time should be about 45 seconds, but must not be less than 25 seconds.

10.7 Return flow to 5% by continuously holding the control switch in the decrease direction. Measure the time required for the secondary flow to decrease from 80% to 5%.

10.8 Operate the pump as requested by the test engineer to determine operating characteristics of the control system.

10.9 Using normal operating procedures, return secondary pump to the auxiliary power supply.

11. Record Following Data:

- 11.1 Verification of raising flow to 96.5%
- 11.2 Pump current at 96.5% flow
- 11.3 Alternator current at 96.5% flow
- 11.4 Alternator excitation at 96.5% flow
- 11.5 Percent flow change per second

APPENDIX B

EBR-II Test Procedure No. TST 66-70

1. Title

Checkout and Test of New Automatic Secondary Sodium Flow Control System

2. Purpose

2.1 To determine the characteristics of a new secondary sodium flow control system that features automatic regulation of the AC-EM pump to maintain desired flow rate.

3. Discussion

3.1 At present, secondary sodium flow is controlled by remote adjustment of a potentiometer which controls the power to the field of an ac alternator. Output of the alternator provides power to the AC-EM pump for pumping the secondary sodium. The potentiometer is driven by a motor which is remotely controlled by a switch located on the main console in the control room. However, due to site voltage fluctuations and environmental variations, secondary flow will vary and must be readjusted by the operator.

The automatic controller uses the flow signal as a reference or setpoint. The output of the controller, which functionally replaces the potentiometer, is proportional to the difference between actual flow and desired flow. If the actual flow changes and the setpoint is not changed, the controller automatically returns the flow to the setpoint level. For major changes in the flow rate, the controller has a manual control mode in which flow can be increased or decreased at a fixed percentage rate of existing flow, with the additional provision of a reduced rate-of-change in the range of maximum flow control. All controls are located on the main console.

In the automatic mode, if the actual flow and setpoint differ by more than 5% the automatic mode is automatically disabled. The controller will then respond only to manual adjustments until the difference with respect to the setpoint is less than 5%. This will prevent a large, rapid rate-of-change of flow by the automatic control system.

4. Supplementary Procedures and Documents

4.1 TST 60-70, "Installation and Test of New Static Power Supply for the Secondary Sodium AC-EM Pump Alternator Field Excitation"

4.2 SA 3-69, "EBR-II Electrical System - General Safety Requirements for Maintenance or Installation"

4.3 EBR-II Operating Instructions, Division II B, "Normal Plant Operation," and Division V B, "Secondary Cooling"

4.4 Work Plan IC-52

4.5 RDT Standard C16-1T

5. Industrial Safety

5.1 All phases of the work in modifying the old system and installing the new equipment shall be in compliance with Safety Procedure SA 3-69.

6. Hazards Considerations

The proposed secondary flow control system actually enhances safety of operation since it will automatically regulate secondary flow to maintain constant flow and effect more uniform control of the bulk sodium temperature.

The reliability of the proposed equipment is equal to or better than the existing equipment. The possibility of loss of control of the input to the alternator field is no greater than with the existing equipment.

7. Plant Conditions

7.1 The plant shall be at standby during installation of the new controller.

7.2 For the first part of this test, the plant will be shut down, with approximate isothermal conditions at 580°F existing between the primary and secondary systems.

7.3 For the operational performance of the new control system, the plant is to be operating at normal-power-level conditions.

8. Preparatory

8.1 The automatic control components have been assembled in the shop and their characteristics determined using a rotating inverter (M-G set) to provide a simulation for the pump-flowmeter interaction.

8.2 Failure modes and consequences thereof will be determined and evaluated on the basis of the requirements of Standard C16-1T.

8.3 The new control system is to be installed in accordance with Work Plan IC-52 and connected as shown on the attached schematics, Figs. A.1 and A.2.

8.4 The power-supply output current shall be adjusted to limit the current to 36 amperes and output voltage to 56 volts.

9. Checkout

9.1 The new control system has been completely bench-tested as required by step 8.1 prior to installation.

9.2 Check all installed wiring for continuity and polarity, and ground-test with 500-volt megger.

9.3 Install test instrumentation and connect as shown on Figs. A.1 and A.2.

9.4 The output of the Lambda No. 2 power supply is to be adjusted to limit output maximum current to 36.5 amperes.

10. Performance Test Limitations

CAUTION: During the performance tests on the new flow control system, the limits stated in this section are not to be exceeded.

10.1 96.5% indicated flow (5680 gpm)

10.2 1476 amperes pump current

Fig. A.1. Functional Diagram of Test of Control of Secondary-sodium Flow

Fig. A.2. Miscellaneous Wiring Details for Test of Control of Secondary-sodium Flow

- 10.3 527 amperes generator current
- 10.4 36.6 amperes generator field current
- 10.5 3% per second rate-of-change of secondary flow in the increasing direction

11. Data Requirements

- 11.1 Record data as required by tests in section 12.
- 11.2 A multi-pen oscillograph is to be installed to record the following parameters during the tests required by this procedure:

- Secondary Flow
- Flow Control Switch Position
- Alternator Field Current
- Alternator Field Voltage
- Alternator Cooling Air Temperature Out
- Capacitor (Power Factor Correction) Temperature

12. Performance Test of the New Flow Control System - Reactor Shut Down and with Isothermal Conditions in the Primary and Secondary Systems

12.1 Using normal procedures, start the secondary pump with power supplied by the alternate power supply, using the procedures for operation with the alternate power supply starting on page V B-17 of the EBR-II Operating Instructions.

12.2 Adjust secondary flow until the "At Minimum" light comes on.

12.3 Using normal procedures, transfer the secondary pump to normal power supply.

12.4 Transfer the pump to alternate power supply.

12.5 With normal power supply on but not connected to the pump, increase the alternator excitation to 3 volts.

12.6 Attempt to switch the pump from the alternate to the normal power supply. This should not be possible.

12.7 Decrease excitation of alternator to "0" volts. The "At Minimum" light should come on.

12.8 Transfer the pump to the normal power supply.

12.9 Trip the pump off the power supply by simulation of a reactor scram.

12.10 Restart the pump using normal procedures.

12.11 With the new controller in manual mode, using the manual switch increase flow to 10% and release switch. Observe the flow and note any changes in flow that occur after the switch is released.

12.12 Adjust the setpoint control until the deviation meter is nulled (center of scale). Push the automatic switch and note flow change.

12.13 Manually raise flow to 20%. Again note change in flow after raise switch is released. Readjust flow to 20% using manual switches if necessary.

12.14 With the setpoint still in the 10% setting, push the automatic switch. If the flow changes, consult with the test engineer before proceeding.

12.15 With the automatic switch still depressed, slowly raise the setpoint until the automatic function engages (noted by decrease in flow and by a light in the automatic switch lighting). Note the new flow after the deviation meter nulls.

12.16 Using the manual raise, set flow at 20%, then set the setpoint control to 30%. Push the automatic switch, and if the flow changes, consult with the test engineer.

12.17 With the automatic switch still depressed, slowly decrease the setpoint until the automatic function engages.

12.18 Manually decrease flow to 5%. Then manually increase flow to 80%, noting the time elapsed at each 10% interval.

12.19 Upon reaching 80% flow, release the raise switch and note if flow changes.

12.20 Using the manual decrease, lower flow to 5%, noting the time elapsed at each 10% interval.

12.21 Raise flow to 75%. Adjust setpoint to 65%. Push the automatic switch and consult test engineer if the flow changes. Slowly raise the setpoint until the automatic function engages.

12.22 Manually readjust flow to 75%, setpoint at 35%. Depress automatic switch. If automatic function engages, see the test engineer. Otherwise slowly decrease setpoint until automatic function engages.

12.23 Manually readjust flow to 80%. Adjust setpoint so that deviation meter is nulled. Depress the automatic switch. Then, under guidance from the test engineer, slowly move the setpoint until the setpoint is at 80%, if moving the setpoint is necessary.

13. Performance Test of Flow Control System - Reactor at Power

13.1 If the new flow control system has performed satisfactorily during the previous tests, subject to the approval by the Operations Manager it may be used for control of the secondary system during normal operation at power. The test engineer is to be notified if any anomalous performance occurs.

Note: Procedures for operation of the secondary pump during power operation of the plant will be required.

APPENDIX C

Specifications

1. Flowmeter

Manufacturer	Mine Safety Appliance Research Corp.
Type	Permanent-magnet (EM)
Output signal	≈ 1.0 mV per 100-gpm flow
Linearity	$\pm 1\%$ of nominal flow
Flow direction	Horizontal
Aging	Permanent magnet is normalized at or above ambient conditions and does not depreciate in flux level more than 1% in five years and not more than 2% in 10 years
Material in contact with sodium	Type 304 stainless steel
Maximum flow-measurement range	0-8000 gpm
Nominal flow range	0-6000 gpm
Temperature range of sodium	200-1000°F
Maximum pressure	53 psig
Magnet strength	508 gauss
Piping size	12-in. diameter, Schedule 10
Maximum dimensions of meter	Width 23 in., height 18 in., length 26 in.
Weight	875 lb

2. EMF Transmitter (MV/I)

Manufacturer	Leeds and Northrup
Model	M-line
Range of input	Any dc range between limits of -60 mV and +60 mV having a span between 5 mV and 60 mV
Range of output	0-4 mA or 1-5 mA dc with a 500-2500 Ω load 0-10 V at 1 mA or 2.5-12.5 V at 0.1 mA

Accuracy rating

Basic limit of error for any combination of rated operating conditions

$$\pm \left[0.5\% \pm \left(0.07 \frac{\text{suppression}}{\text{span}} \right) \right] \% \text{ of input span}$$

Rated conditions

Source resistance	0-2000 Ω
Load resistance	500-2500 Ω
Line voltage	110-125 V
Ambient temperature and humidity	59-104°F, 10-90% relative humidity
Line frequency	60 $\pm$ 2 Hz, or 50 $\pm$ 2 Hz

Interference effects

(The additional limits of error indicated must be added to the basic limit of error.)

Transverse interference 40% of span $\pm$ 0.1% additional error

Common-mode interference at input circuit
When source resistance is between 0 and 100 Ω , a common-mode interference of 5 V rms at the rated temperature and humidity conditions can produce an additional error of $\pm 0.5(5/\text{span})\%$. When source resistance is 2000 Ω , this level of interference can produce additional error of $\pm 1.0(5/\text{span})\%$ of input span

Common-mode interference at output circuit

When source resistance is between 0 and 2000 Ω , a common-mode interference of 5 V rms at rated temperature and humidity conditions can produce an additional error of $\pm 0.5(5/\text{span})\%$ of input span

Maximum response time

1.5 sec for 99% of span
0.4 sec for 63.2% of span

Zero shift

Less than 1% per year

Physical characteristics

6 x 6-1/8" front panel; 23" deep
Weight is 20 lb

3. Alarm Unit

Manufacturer

Rochester Instrument Systems, Inc.

Model

ET-215K

Input signal	0-4 mA dc
Input resistance	400 Ω
Output signal	SPDT contacts rated 10 A at 117 V ac noninductive
Trip adjustment	(a) 0-100% continuously adjustable by means of calibrated potentiometer (1%) (b) Fine trip calibration for calibrating the dial
Fixed deadband	Less than 1% of span (20 mV)
Response time	15 msec for relay
Trip-point stability and drift	$\pm 0.5\%$ of span at room temperature $\pm 1.0\%$ of span for temperature range of 32-120°F
Repeatability	$\pm 0.1\%$ of span
Power input	117 V ac $\pm 10\%$, 60 Hz, 4 W
Power-supply effect	Less than $\pm 0.5\%$ of span (double-Zener regulated)
Controls	Calibrated dial for trip set (1%) Fine calibration

4. Flow Recorder

Manufacturer	Leeds and Northrup
Model	Speedomax H, Model S
Type	Indicating recorder (strip-chart record). Employs an electronic amplification of unbalance and a reversing motor to effect balancing action
Measuring circuit	DC potentiometer
Range span	0-10 mV
Accuracy rating	$\pm 0.3\%$ of electrical span where suppression ratio (SR) is 2 or less; $\pm 0.3 + 0.1\%$ (SR-2) of electrical span where suppression ratio is greater than 2. (Suppression ratio = low end of span, in mV, divided by span, in mV)
Deadband	0.15% of span
Span step-response-time rating	5 sec nominal, full scale
External-circuit-resistance rating	For rated performance, 2500 or 15,000 Ω , depending upon amplifier selected

Record	Continuous line, 6-1/2" calibrated width
Indicating scale	Straight, 6-1/2" calibrated width
Chart speed	Any standard single-speed or switch-selected two-speed combination
Measuring-circuit current source	Supplied by ac line, rectified, and regulated by Zener-diode circuit
Power requirements	120 V, 60 or 50 Hz, as specified Power consumption 40 VA
Case	Gray, cast aluminum, 12" (h) x 11" (w) x 13" (d)

5. Flow Controller

Manufacturer	Leeds and Northrup
Model	420 current-adjusting type (CAT), fast process, 2-mode with lag
Input signal	0-4 mA dc
Setpoint	
Range	0-4 mA
Stability	Line (107 to 127 V ac) - 0.2% Temperature -0.1%/30°F
Adjustment resolution	0.15%
Accuracy	0.5% (rms)
Input error signal to control amplifier	±2 V dc maximum span with transmitter and setpoint signals at opposite extremes. With proportional gain of 1, a 2-V dc span full-strokes the output
Amplifier frequency response	< 3 dB down at 1 kHz
Control functions	
Proportional gain	0.2 to 30
Reset	0.15 to 400 rep/min
Lag	0 to 30 sec
Control-point stability (including setpoint circuit)	
Line voltage	±0.4%
Temperature	20 rep/min ±0.7%
Humidity (10 to 90% at 40°C)	20 rep/min ±1.3% 0.2 rep/min ±4.3%

Output	0-5 mA dc into 0-2700 Ω load, with 2940- Ω feedback resistance
Auto-manual switching	Pushbutton switching between automatic and manual control modes. Lamp behind white pushbutton indicates automatic mode when lit and manual when out. Automatic operation is initiated by depressing the white pushbutton. Manual operation initiated by depressing yellow or red button; the output current increases when the red button is depressed and decreases when the yellow button is depressed
Manual-mode maximum drift rate (no buttons depressed)	Toward full output at 1/2%/hr at 25°C and 50% RH Toward 50% output at 1%/hr at 40°C and 90% RH Toward full output at 2%/hr at 60°C and 90% RH
Power requirements	107-127 V ac, 50 or 60 Hz, 14 VA
Spark-proof disconnect	A reed switch-magnet combination removes the ac line voltage from the controller before the chassis is disconnected, to eliminate a possible spark
Maximum current adjustment	Factory-set adjustment limits maximum output current to 5.4 mA into a 2000- Ω load or 21.6 mA into a 500- Ω load. Readjustment is necessary for other loads or to other maximum outputs. Low limit is always 0 mA
Temperature	
Operating	0-60°C
Storage	30-80°C
Relative humidity	90% for temperature up to 40°C and not more than 300 gr/lb of dry air
Dimensions	
Overall panel space	3-1/2 x 7"
Chassis depth	15-1/2"
Case depth	20"

6. Kepco Power Supply

Manufacturer	Kepco, Inc.
Model	CPS 72-0.3B (C)
Input requirements	105-125 V ac or 210-250 V ac, 50-440 Hz, single-phase, 0.40 A maximum
Ambient temperature	-20°C to +65°C maximum
Storage temperature	-40°C to +85°C maximum
Isolation	500 V maximum (dc or peak-to-peak) may be connected from chassis to either output terminal
Internal reference supplies	Precision regulated Zener sources of plus and minus 6.2 V (nominal) are provided internally and ter- minated at the rear as well as the front panel binding posts. The Zener reference sources are tem- perature compensated and optimized for stability for a load current of 1 mA
Reference specifications	
Stability	Less than 0.005% variation over 8 hr at constant line, load, and ambient temperature
Temperature coefficient	Better than 0.005% per °C
Regulation	Less than 0.0001% variation from the line changes over the range of 105-125 V ac or 210-250 V ac
Output range	0-72 V, 0-0.3 A
Output impedance	0.008 Ω dc
Input, inverting	DC or ac voltage or current signals. <u>Positive</u> input signal will produce <u>negative</u> output, both with respect to the <u>common</u> terminal
Input, noninverting	DC voltage or current signals only. <u>Negative</u> input signal will produce <u>negative</u> output, both with respect to the <u>common</u> terminal. (Maximum input voltage approximately -8 V)
Common terminal	The positive error-sensing terminal (normally linked to the positive output) represents the reference line common to inputs and output, to which all signals and dc voltage are referred

Slewing rate (programming speed)	1 V/ μ sec
Output ripple and noise	< 0.01% of peak output or 3 mV, whichever is greater
Transient response	
Voltage mode (for step load current)	Recovery is an exponential with a 50- μ sec time constant
Current mode (for step load voltage)	Recovery takes place at the specified slewing rate
Capacitive loading	0.001 μ F maximum. A variable dc stability control (lag network) and an adjustable feedback capacitor are provided to operate into a limited range of load conditions
Open-loop dc gain	< 0.5×10^6 V/V

7. Lambda Power Supply

Manufacturer	Lambda Electronics Corp.
Model	LB-704-FM-0V
DC output	0-60 V, 0-50 A at 40°C or less
Regulated voltage output	
Regulation (line)	0.05% plus 6 mV for line variations from 187 to 229 V ac or from 229 to 187 V ac
Regulation (load)	0.1% plus 10 mV for line variations from 0 to full load or from full load to 0
Remote programming	
External resistor	Nominal 200 Ω /V output
Programming voltage	One-to-one voltage change
Ripple and noise	10 mV rms with either positive or negative terminal grounded
Temperature coefficient	Change in output voltage less than 0.03% + 0.5 mV/°C
AC input	208 $\pm$ 10% V ac, 57-63 Hz, 3-phase $\pm$ 10% maximum phase unbalance, 4-wire. Input power = 3.75 kW, PF = 0.80

Overload protection	
Thermal	Thermostat, resets automatically when over-temperature condition is eliminated; circuit breaker S1 must be manually reset to ON position to apply input power
Electrical	
External	Adjustable, automatic, electronic current-limiting circuit, settable to 110% of rated current; limits output current to preset limit for protection of load and power supply when external overloads and short circuits occur
Internal	Primary circuit breaker protects against internal circuit failure. Overload of the supply does not cause circuit breaker to actuate
Input connections	Heavy-duty terminal block on rear of chassis
Output connections	Heavy-duty terminal block with 1/2" x 20 studs on rear of chassis; separate terminal block for series and parallel connections
Operating-ambient temperature range and duty cycle	Continuous duty from 0 to 71°C ambient with corresponding load-current ratings for all modes of operation
Controls	
DC output controls	Coarse and fine voltage controls and coarse and fine current controls permit adjustment of dc output; located on front panel of all models
Remote sensing	Provision is made for remote sensing to eliminate effect of power-output-lead resistance on dc regulation for up to 5 V in each leg
Power	Panel-mounted circuit breaker and indicator light for all units. The circuit breaker controls application of input power to the supply. On units with OV protection circuit, overvoltage condition causes the breaker to trip. When breaker is in the ON position, the red ON indicator lamp glows

Physical data

Size	7" (h) x 19" (w) x 18-1/2" (d)
Weight	185 lb

8. M-G Set

Induction motor

Manufacturer	General Electric
Model	5K26344
Horsepower	500
Type	K
Code	G
Frame	6344YS
Number	TS8323382
Voltage	2300, 60-cycle
Phase	3
Temperature rise	40°C
Full load current	111 A
Full load speed	1185 rpm

Generator

Manufacturer	General Electric
Model	5SJ1712A24
Kilowatts	350 with 0.8 power factor
Type	ATI
Frame	974Y
Serial No.	VS8273791
Voltage	480, 3-phase, 60-cycle
kVA	438
Amperage	527
Speed	1200 rpm
Excitation	125 V, 36.6 A
Stator temperature rise	50°C
Rotor temperature rise	80°C

9. Secondary-sodium Pump

Manufacturer	General Electric
--------------	------------------

Model	5 Ky 449 AA 1
Ratings	
Flow	6500 gpm
Pressure	53 psig
Efficiency	43%
Power factor	30%
Pumped fluid	700°F sodium
Power requirements	480 V, 3 phase, 60 cycle, 336 kW
Characteristics	
Synchronous flow	8425 gpm
Resistance of pumped fluid	8.12 $\mu\Omega$ /in.
Number of poles	8
Phase sequence	1, 2, 3
Duty rating	Continuous
Hot-spot temperature	200°C
Heater requirements	
Voltage	220, single-phase
Power	10 kW
Stator coolant requirements	
Coolant	Water
Flow	30 gpm
Pressure	25 psi per 2 stators in series
Inlet temperature	95°F (maximum)
Physical characteristics	
Width	64-1/8"
Length	124-11/16"
Height	42"
Weight	18,500 lb