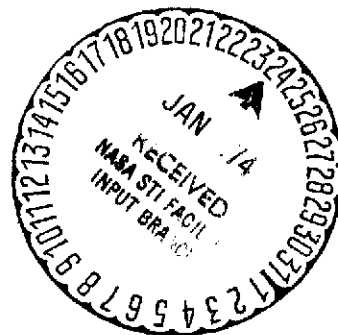2 mil

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Nuclear Electric Propulsion Reactor Control Systems Status

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Preface

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

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Abstract

This report describes and summarizes the thermionic reactor control system design studies conducted over the past several years for a nuclear electric propulsion system. The relevant reactor control system studies are discussed in qualitative terms, pointing out the significant advantages and disadvantages, including the impact that the various control systems would have on the nuclear electric propulsion system design. A recommendation for the reference control system is made, and a program for future work leading to an engineering model is described.

Nuclear Electric Propulsion Reactor Control Systems Status

I. Introduction

This report describes and summarizes the thermionic reactor control system design studies conducted over the past years for a nuclear electric propulsion (NEP) system. By reviewing the literature, starting with the initial analog studies at the Jet Propulsion Laboratory (Ref. 1) and continuing to the present control system design work (Ref. 2), a great deal of the confusion as to the current control status should be eliminated. The confusion exists mainly because the efforts to date have been largely independent, and preliminary design investigations have employed somewhat unrelated control philosophies (Refs. 3 to 5).

The intent of this review is to discuss the relevant control system studies, pointing out significant advantages and disadvantages, but avoiding emphasis on the design details that are of interest only to a control engineer. The approach used is: (1) to expand the knowledge of cognizant persons interested in the thermionic reactor control system design, (2) to summarize the overall progress in the area of control for those persons responsible for and involved in the development of a thermionic reactor power system, and (3) to provide a reference for future and continuing work in the control design synthesis of a NEP system.

II. NEP System Description

Since this report is concerned with the reactor control system design status for a nuclear electric propulsion system, a logical first step is the description of a reference
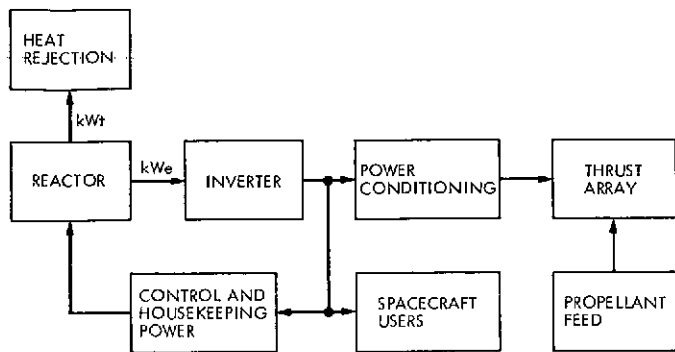
Fig. 1. Schematic of nuclear electric propulsion system

NEP system (Refs. 6 to 8). The NEP system is currently being considered as a candidate for a variety of space applications ranging from geocentric to deep-space missions (Refs. 9, 10). From NEP control system standpoint, it is not important at this stage of development to specify what the mission is. Regardless of the application, the basic requirement for the electric propulsion subsystem in any space vehicle will be to furnish thruster power plus auxiliary power.

To satisfy the objectives of this report, the description of the NEP system will include only those details pertinent to the control system formulation. Thus, instead of a hardware or component description, only those features which are important in a control system analysis are described. A typical NEP system configuration is shown in the block diagram (Fig. 1).

The proposed thermionic reactor is an assemblage of many individual thermionic-fuel elements (TFEs), constructed by series connecting individual thermionic converters (the so-called flashlight configuration) and enclosing them in a cylindrical metal sheath. Each TFE also has a cesium reservoir at one end, designed so that the ambient gas temperature at full power operation is maintained on the low side of optimum operating temperatures by heat conduction from the reactor core. Additional, more precise, temperature regulation is provided by electrical trim heaters. (A cross-sectional diagram of an F-series converter, currently being tested, is shown in Fig. 2.) The reactor core is surrounded by both axial and radial neutron reflectors; however, the radial reflectors are segmented and equipped with drive motors which rotate the segments away from the reactor periphery. A single loop of liquid metal connects the reactor core with the heat rejection subsystem. The waste thermal energy is transported by the coolant from the core zone to a radiating surface (possibly constructed from heat pipes) where
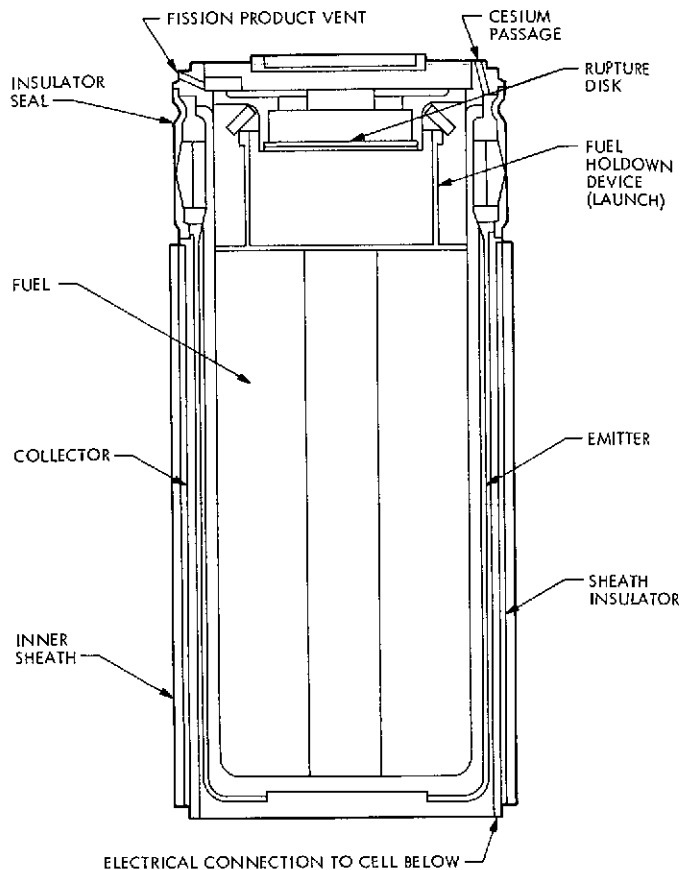
Fig. 2. Cross-sectional view of an F-series thermionic converter (Ref. 29)

it is rejected to space. The coolant flow is maintained by a doubly wound electromagnetic (EM) pump which consumes the major portion of reactor electrical power allocated for control and housekeeping chores.

The power conditioner (PC) subsystem contains the necessary electronic components and circuitry for processing the "raw" TFE electrical power and converting it to the voltages and currents required by the thrust subsystem and other spacecraft users. Since the TFE is inherently a low-voltage high-current DC power source and the PC output power requirements range from high-voltage DC to low-voltage AC, the PC design is quite complex and a variety of configurations have already been proposed (Refs. 11, 12). A detailed discussion of these power conditioner designs is beyond the intended scope of this report.

The PC design depends upon, among other system constraints, the electrical interconnections between the reactor TFEs and the PC inputs. To improve the PC efficiency,

two or more TFEs could be series connected to form a "TFE module" having a higher PC input voltage. However, a TFE module consisting of many TFEs would raise the PC input voltage, but it would increase the probability of collector-to-cladding insulator voltage breakdown. The resultant TFE module would also reduce the power source reliability because an open-circuit failure of any one TFE would mean the loss of all TFEs in the series string. Furthermore, series-stacking the TFEs complicates the mechanical layout of the power source, as TFE leads would penetrate both reactor ends and some TFEs would have to be isolated from the reactor ground. A power conditioner study by Macie (Ref. 12) has shown also that for PC input voltages above 40 V, the improvement in PC efficiency is minimal. On the other hand, reliability considerations and temperature limitations on the PC electrical components favor one PC input per TFE module. Lower input voltage means a larger number of TFE modules for a given power level. This results in more PC modules and consequently higher power processing costs and weight.

A tradeoff study in the area of TFE interconnections would be very helpful in defining the optimum TFE module configuration. The interconnection scheme should ensure a high operating reliability against possible TFE open- and short-circuit failures and a minimum weight and efficiency penalty in PC hardware.

The PC design studies currently under investigation use the concept of a high-voltage bus formed by connecting the DC-AC power inverter outputs in series or parallel (if the bus is DC, the inverter outputs are rectified before generating the bus voltage). However, with the stipulation that reactor load changes or fuel element degradations should be shared equally by all TFE modules, the series connection seems preferable. With the parallel connections, each PC/TFE module could conceivably compete for any power loss or demand and thus propagate a succession of PC/TFE failures.

The thrust subsystem consists of the thruster array, propellant tanks, propellant feedlines, mag-amp controls for the ionizing arc, accelerators, vaporizers, heaters, etc., and other structural components. The thruster design has been treated in more detail by the solar-electric propulsion literature (Refs. 13, 14). This technology will hopefully be compatible with the NEP project requirements and the complete thrust subsystem design concept including controls will be duplicated and incorporated into the NEP system. The number of thrusters in the array and/or the individual thruster diameter might possibly be in- creased to accommodate NEP missions requiring much higher power levels. The NEP reactor control system, integrated with this type of subsystem, would be responsible for the regulation of a high-voltage bus and for matching the load power demands of the thrust subsystem and other spacecraft users.

III. NEP Control System Parameters

The NEP system described above has, from a reactor control standpoint, the adjustable parameters or driving-force inputs described below. These inputs are regulated in the closed-loop configuration by feedback information and external references, and are used to maintain prescribed operating conditions or make programmed changes in the system state.

First, the radial reflector segments can be moved to regulate the amount of neutron leakage from the reactor core. By varying the neutron leakage, the neutron power density can be raised or lowered. The rate of change in neutron power is determined by the number of degrees the segments are rotated per unit time. This so-called reactivity input is used to adjust the thermal energy delivered to the thermionic converters and to compensate for normal loss of fissile material due to fuel burnup. Since the thermionic reactor is physically small in size (approximately 75 liters) for electrical power requirements in the 100-kW range, and the fission energy spectrum is fast (neutron generation time $\cong 10^{-7}$ s), the neutron density will respond almost instantaneously to reflector rotations.

Another control in the NEP reactor system is the use of power inverters that can be used to regulate the TFE module output power. This regulation is obtained by electronically varying the commutation angle (producing changes in the load power factor) in a half-wave blocking converter or resonant circuit inverter or the chopping angle (conduction time) in a push-pull inverter. The use of the inverter in the control function is possible due to the uniqueness of direct energy conversion devices such as the thermionic converter. This unconventional feature concerns the direct power coupling between the thermionic reactor and the electric load which is different from the conventional power source. In the conventional source, the electric current is produced outside the reactor and is separated from the thermal power by a coolant transport delay time. In the thermionic reactor, over 50% of the fission energy is transported from the fuel to the coolant by the flow of electrons across the converter

emitter-to-collector gap. Therefore, variations in converter current can be used to vary the operating conditions in the thermionic reactor. If the TFE converters are operating at sufficiently less than maximum power for a particular set of reactor emitter temperatures, then the neutron power density could be increased to compensate for the loss of some TFE modules and/or a fractional increase in load power demand.

Another variable in the control system is the cesium reservoir pressure. The pressure is regulated by controlling the joule heating in the reservoir trim heaters (Ref. 15). Long-term degradations such as fuel burnup and accumulative TFE failures can be offset by initially operating the TFEs at an over-optimum cesium gap pressure versus reduced neutron power. Then as the reactor electrical power decreases, the operating efficiency can be continually improved by decreasing the cesium pressure to a more optimum value. Also, to compensate for the power distribution across the core, the pressure in each reservoir could be adjusted independently to flatten the electrical power generation or to ensure the same stability margin for each TFE against thermionic burnout. This would mean, unfortunately, an electrical efficiency penalty, because the power matching or stability margin would have to be referenced with the operating characteristics of those TFEs on the reactor core periphery.

The final important control parameter in the NEP reactor system is the coolant mass-flowrate which transports heat from the core to the radiator. The coolant flowrate is adjusted by varying the current in the windings of the EM pumps. The coolant flowrate regulates the temperature drop across the reactor core and prevents excessive centerline fuel temperatures which could cause fuel melting and subsequent TFE failures. Also, by programming coolant mass-flowrate changes in conjunction with large neutron thermal power variations, thermal shocks on the collector trilayer insulation or large drops in coolant temperature across the reactor core could be reduced.

The implementation of the regulatory capabilities discussed above into the closed-loop control system will be shown in greater detail when the individual control studies are discussed.

IV. Control System Design Requirements

Early analog studies (Refs. 1, 16) indicated an active feedback control system is necessary to prevent large

excursions in some system variables due to nominal plant perturbations. This dynamic behavior exists because the temperature reactivity feedback mechanisms are very weak and electrical load variations are thermally coupled to the reactor converter array. The temperature-reactivity coefficients are small because: (1) the reactor energy spectrum is hard, hence the resonance absorption is reduced, (2) the positive prompt Doppler coefficient of the highly enriched fuel tends to offset the negative Doppler coefficient associated with the tungsten emitter, (3) the fuel is segmented into the individual converters, so expansion changes affecting the fuel density and core size are inherently small, and (4) the delayed reactivity coefficient for the outer TFE sheath is designed to be low, since its thermal expansion has to be comparable to that of the collector insulation material to prevent cracking.

Before examining the various reactor control system studies, a discussion of the reactor control system philosophy and the pertinent design constraints might be helpful.

A. Control System Functions

The control system has basically three tasks: (1) to provide programmed steady-state spacecraft power during the mission, (2) to provide corrective action for degradations or failures within the reactor power subsystem, and (3) to match reactor electrical power output with variable load demands from the thrust subsystem or spacecraft users. The first requirement deals with operational mode changes such as startup, thrust-to-coast, coast-to-thrust, reactor scram, etc. Tasks 2 and 3 are essentially the same in the sense that they perform regulatory duties. However, the reactor control system has to be designed to be sensitive to internal perturbations as well as those external to it. Examples of internal degradations and failures would be neutron power drifts due to fuel burnup and TFE module short- or open-circuits caused by a loss of cesium pressure or emitter-to-collector contact. The varying load demands, for example, would result from random thruster outage or the startup of various onboard scientific experiments.

Designing a reactor control system which will perform all three tasks is physically possible only in a limited sense. Obviously, given an excessive TFE failure rate or unlimited load power demands, it would be impossible to provide or maintain the necessary reactor electrical power. Also, the control system must not exhibit any instabilities where corrective actions might propagate additional failures or neutron power level changes might generate excessive feedback which causes unstable oscil-

lations. Therefore, the control system must be designed to comply with a set of design constraints and be equipped with backup logic to prevent self-destruction.

B. Design Constraints

The design constraints consist of a set of various component and system performance limits or procedural rules which provide guidelines for formulating the feedback control law and the associated operational logic. The NEP reactor subsystem is currently in a component test and evaluation stage. The main efforts are directed toward the design and fabrication of a thermionic fuel element which will function at nominal operating conditions for 20,000 full-power hours. Since the thermionic reactor is modular, the demonstration of a reliable TFE would predict, with a reasonable certainty, the successful operation of the reactor.

At this time, preliminary test results (Ref. 17) indicate that fuel-emitter volumetric swelling resulting in converter short-circuit is the main failure mechanism. The control system cannot prevent losses due to poor fabrication techniques; however, it can protect against excessively high fuel and emitter temperatures and can retard fuel and emitter thermal cycling. Another failure mechanism is insulator voltage breakdown and/or loss of cesium pressure which leads to converter open circuit. By limiting the thermal shock on the collector tri-layer and also designing an inverter that can accept low TFE module output voltages, the control loop may prevent an accumulation of converter failures.

The reactivity insertion rate should be limited to a value that precludes fuel melting. This means that the maximum reactivity insertion rate should be less than a rate which would cause melting fuel temperatures; otherwise the shutdown system can override the excursion. A limiter on the reactivity insertion rate would protect the reactor against large reactivity feedback signals demanding more thermal power. The actual limit is dependent upon the neutron power which trips a "scram" and the number of reflector segments reserved for the shutdown capability. Heath (Ref. 18) determined that for four backup segments out of 18 and a 125% full power trip point, the maximum rate of insertion is approximately $0.10/s. The practical limit may be somewhat lower because of reliability specifications on how fast the segments can mechanically be rotated.

In order to improve the lifetime of the reflector bearings, a deadband about a desired neutron thermal power in which no reactivity control is initiated should be built into the control system to prevent control drum chatter. The control strategy therefore requires that sudden small changes in load power be corrected by the power conditioner and only slow, predictable variations in load power be taken care of with reactivity control. Data and specifications from the SNAP 10A control drums may be good estimates for the NEP reactor system.

Because load changes are reflected directly into the reactor core and the dominant heat-transfer mechanism for the emitter surface is the electron flow across the converter gap, the diode current should be a regulated or controlled variable to prevent converter "overheating." Furthermore, from a power conditioner design standpoint, the collection of electrical power should be accomplished with reliable electrical interconnections which ensure that: (1) all remaining TFE modules equally share the loss of any one TFE module, and (2) load power changes are shared proportionately by all operating TFE modules.

The coolant mass-flowrate should not experience large accelerations by the EM pumps because coolant surges and pressure shocks might exert stresses on the TFEs, which would cause bowing or internal cracking. The heat rejection system has to be designed so that coolant loop delay instabilities do not exist. These instabilities are discussed by Heath (Ref. 19). This type of instability, fortunately, is quite easily avoided by proper design of the heat rejection subsystem.

Next, the cesium reservoir temperature control should be capable of maintaining a sufficient stability margin to prevent thermionic burnout. The phenomenon of thermionic burnout discussed by Shock (Ref. 20) is caused by increasing the emitter surface heat flux until cesium desorption occurs. This loss of cesium coverage increases the emitter work function and forces the converter to operate at considerably higher emitter temperatures in order to maintain the same electrical power output at a fixed converter voltage. The cesium desorption point for a given voltage can be moved to higher emitter heat fluxes and higher emitter temperatures by increasing the cesium reservoir temperature. By increasing the cesium reservoir temperature, the point of maximum electrical power is also increased, allowing higher current densities for a constant diode voltage. Since the TFEs are assumed to have noninsulated cesium reservoirs, the reactor tends to stabilize itself for increased power demands. However, because the time constant for heating the cesium gas by heat conduction from the reactor core is much larger than the time constant for increased heat flow to reach the emitter surface, an active control loop coupling the

reservoir temperature to the reactor power seems necessary (Ref. 21). This reservoir control should be capable of regulating the cesium temperature within $\pm 2\,^{\circ}C$, since the converter I-V characteristics are very sensitive to reservoir temperature changes (Fig. 3).

Finally, the reactor control system should not make a significant contribution to the total propulsion subsystem weight or, in other words, should be designed for minimum weight. It should also be as simple as possible in order to increase reliability but able to maintain operating power levels for the mission duration without compromising lifetime or power efficiency.

With this control philosophy and important design constraints, each of the reactor control studies will be reviewed in a somewhat chronological order.

A brief explanation of the terms "average converter emitter temperature," "average TFE emitter temperature," and "average reactor emitter temperature" might assist the reader's understanding. A distribution of emitter temperatures within the reactor core results from the non-uniform axial and radial neutron power generation (fission

heat sources). Because the various control system design studies are dependent on lumped parameter mathematical models, a nomenclature problem for the various average temperatures could easily exist.

An average converter emitter temperature is defined as that emitter temperature corresponding to a converter output voltage and current density which, when multiplied by the surface area of one converter equals the measured output power from that converter. An average TFE emitter temperature is defined as the emitter temperature corresponding to a converter voltage and current density which, when multiplied by the surface area of one converter times the number of converters per TFE equals the measured output power from that TFE. An average reactor emitter temperature is also defined as the emitter temperature corresponding to a converter voltage and output current density which, when multiplied by the surface area of any one converter times the number of converters in the entire reactor, equals the measured output power from the reactor core.

These definitions will be implied in the next sections whenever a particular average emitter temperature is discussed or mentioned.
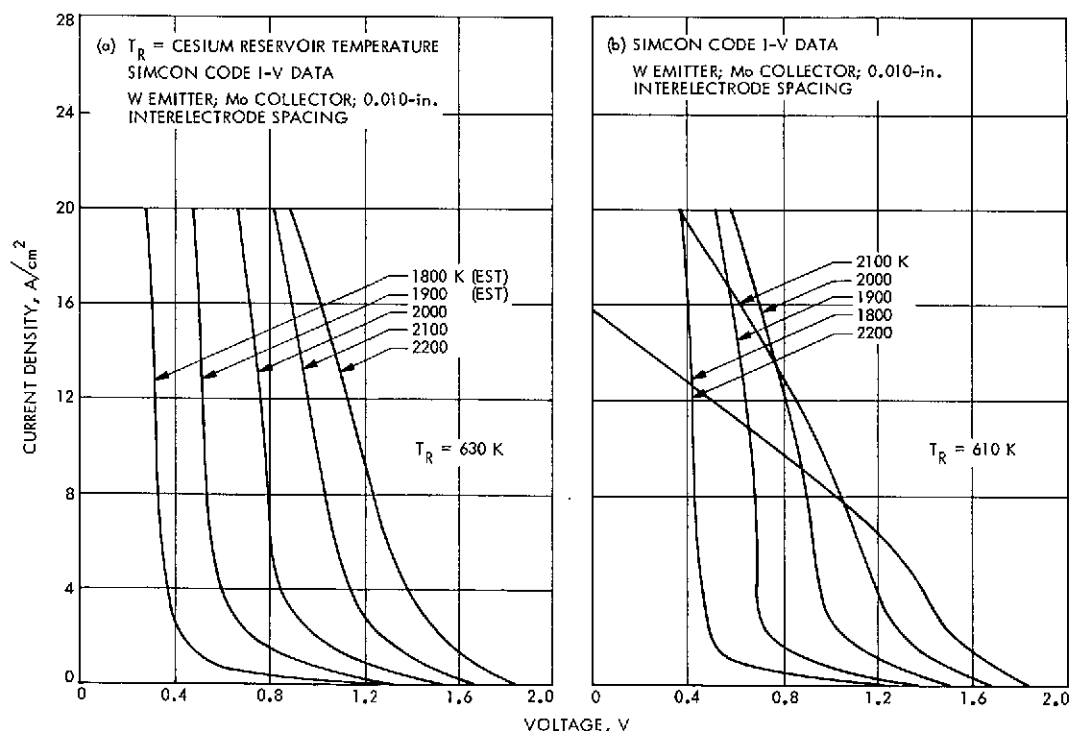

Fig. 3. Converter I-V characteristics for cesium reservoir temperatures:
(a) $T_R = 630$ K and (b) $T_R = 610$ K

V. Constant Voltage Control

Early efforts in formulating a closed-loop control system employed the concept of regulating the reactor system to provide a constant TFE output voltage to the power conditioners. The philosophy was that a regulated reactor voltage would simplify the power conditioning requirements. An unregulated output voltage would make it necessary for a power conditioner to operate over a range of TFE module voltages.

The constant-voltage control study by Weaver, Gronroos, et al. (Ref. 3) represents the first preliminary investigation into the design problem of a closed-loop thermionic reactor control system. The study used the modern control techniques of state-variable feedback. The system mathematical description consisted of a lumped-parameter spatially averaged nonlinear model with a Richardson-Dushman type of equation fitted to experimental data to predict the converter electrical characteristics. Only a single converter description was used in the system model, and, therefore, no power conditioner circuitry or TFE interconnections were assumed.

By simulating the system model on an analog computer, the dynamic behavior was investigated for various step perturbations in electric load and external reactivity. The resultant reactor controller (Fig. 4) varied neutron power density to counterbalance electric load changes and keep the converter voltage constant. The nonlinear time responses for various system state variables resulting from a 33% load drop are shown in Fig. 5. The feedback to the controller generated very large reactivity insertion rates, and therefore a limiter was included in the control system restricting the reactivity insertion rate to something less than $0.10/s. Nonlinear results with the limiter indicated a substantial improvement in the neutron power response without a gross impairment in the diode voltage change (Fig. 5).
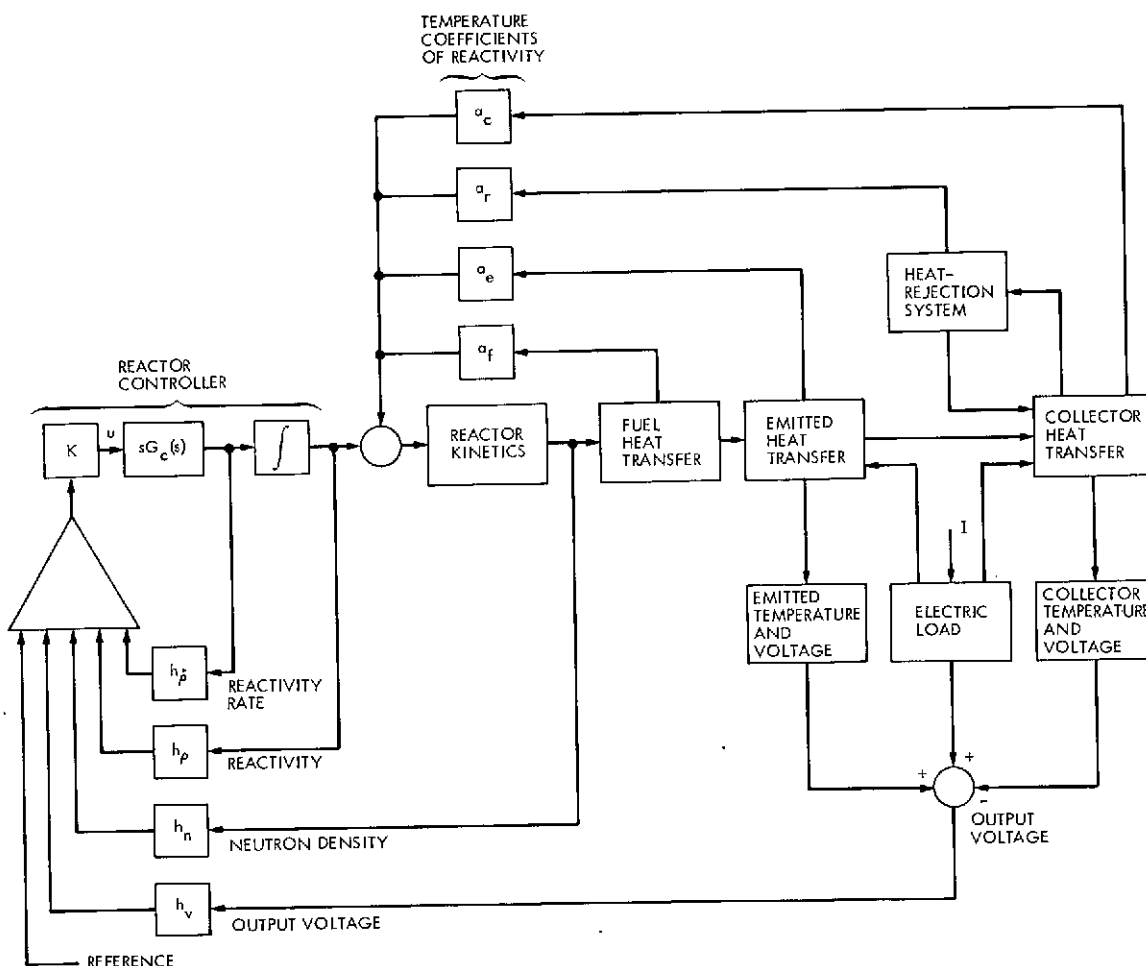

Fig. 4. State-variable feedback design of thermionic reactor controller (Ref. 3)
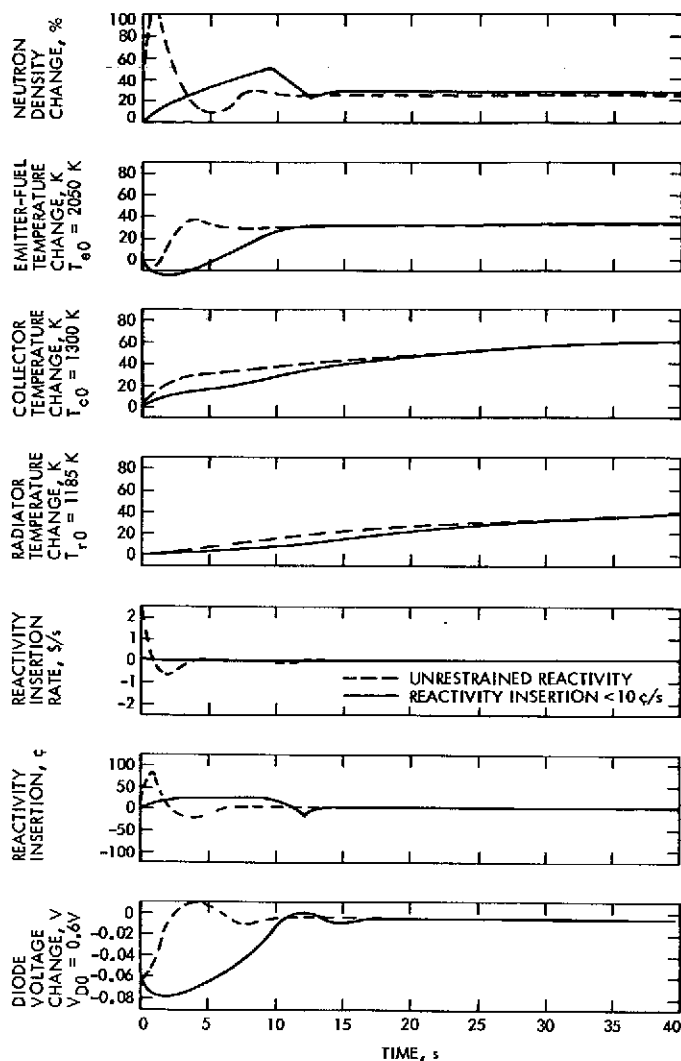
Fig. 5. Time response of closed-loop nonlinear system to a 33% load increase with constant converter voltage control (Ref. 3)

The study concluded that constant TFE module output voltage control was a feasible control mode and that, theoretically, state-variable feedback was applicable in the control system design. However, the control system had several inherent disadvantages and deficiencies which were left unresolved.

Because of the reactor temperature distributions in the core, and since each TFE is constructed from a number of individual converters, it is not readily apparent how one should generate certain feedback signals in the closed-loop system. If for example, an average emitter temperature for the entire core is used to feed back state information to the reactivity controller, the weighting method for obtaining this average temperature estimate must be specified and also the effect of neutron power changes on those TFEs operating at either higher or lower emitter temperatures has to be determined. On the other hand, if an average emitter temperature for each TFE is included in the feedback loop, increased weight and reduced reliability problems may be incurred due to the additional devices for measuring each TFE state. Also, since various state variables in the mathematical model such as fuel and emitter surface temperatures are not physically accessible or available for measurement, problems associated with state estimation and measurement correlation for predicting the true average TFE temperatures poses additional problems in the actual hardware implementation. The feedback loop is very complicated, and consequently would be very difficult, in reality, to construct or fabricate.

Heath (Ref. 22) and Vogel (Ref. 23) performed subsequent control studies also with the control constraint of constant converter output voltage. Both studies are similar in the sense that they have two feedback loops. One regulates the neutron power level either to prevent energy production in excess of that demanded by the load or to maintain an externally set desired reference power level. The other varies the neutron power level to match heat generation with the electrical power demands required to maintain constant load voltage. A schematic of the basic control scheme is illustrated in Fig. 6.

Sawyer (Ref. 4) subsequently investigated the transfer functions proposed by Heath and arrived at the relationships indicated on Fig. 7. The optimum value for the time constant τ_1 was found to vary with the particular load change, and, consequently, that value corresponding to a complete load drop was used in the dynamic analysis of the control system. The system was then programmed on an analog computer using basically the same model used by Gronroos, et al., (Ref. 24) except the I-V characteristics for an average converter were predicted by the simple linear relationship:

$$V_c = -0.97 + 1.125 \times 10^{-3}\, T_E - 1.25 \times 10^{-3} I_c$$

(1)

where V_c is the converter voltage in volts, I_c is the converter current density in amps/cm^2, and T_E is the average emitter temperature in kelvins. The model was again only a single converter description. Transient results for a complete load drop are presented in Fig. 8. An analysis of the load drop response is more easily understood if the characteristics of the constant voltage control system are examined in more detail.
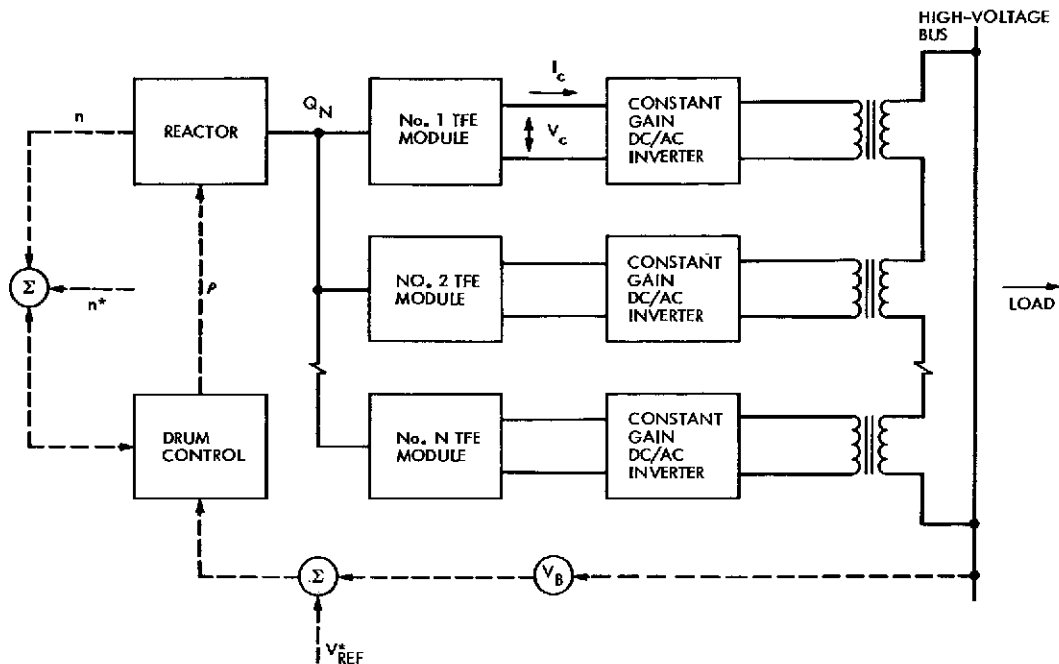
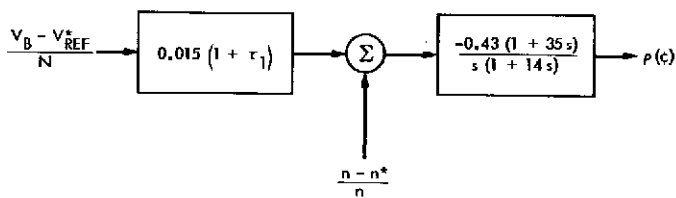**Fig. 6. Block diagram of constant voltage control scheme**

Fig. 7. Voltage error-to-reactivity feedback transfer functions

Three idealized characteristic curves are shown in Fig. 9 for a load power drop with the constant voltage control system. In Fig. 9b, the load power drop is shown as an increase in equivalent load impedance, and therefore, the load line shifts from R_i to R_f. The decrease in load current follows a line of constant emitter temperature because the load power drop occurs almost instantaneously, in times very small, compared to the emitter temperature time constant. Because the power conditioner is assumed to have constant voltage gain, G, the same response occurs on the converter I–V curve in Fig. 9(a). The neutron power density also has not yet had time to respond, so the operating point in Fig. 9(c) falls from 1 to 2 along a vertical line. The drop in load voltage, however, generates feedback to the reactivity controller which decreases the neutron power density causing the trajectory in Fig. 9(c) to move from point 2 toward point 3. The

reduction in neutron power reduces the converter and load current in Figs. 9(a) and 9(b), respectively, along their constant load lines until the new equilibrium point 3 is reached. There the load voltage is again equal to the reference value and the transient behavior dies out.

In a general analysis, several main deficiencies exist in the studies involving constant voltage control schemes. In all cases, the load voltage deviates from the reference voltage for a considerable portion of the transient, and the emitter temperature varies significantly as a function of the load power demand. The system models based on a Richardson–Dushman I–V description for the converters are susceptible to the criticism that they are too inaccurate and, therefore, do not induce confidence or support for the dynamic results. Subsequent theoretical considerations indicate the constant diode voltage control mode may result in thermionic burnout for large sudden load power demands. Although the time response curves in Fig. 8 are for a load power drop, it is apparent that the steady-state emitter temperature after the transient is different from the equilibrium emitter temperature before the transient. For a load power increase, this steady-state emitter temperature could possibly be high enough to cause thermionic burnout if the converter is to operate at voltages existing before and after the transient. Since
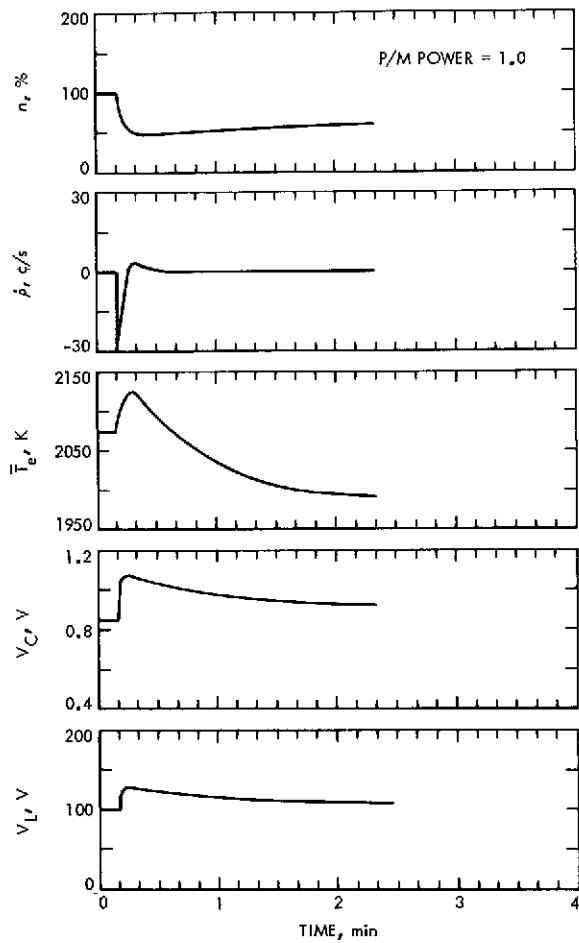
Fig. 8. Complete load drop responses with constant converter voltage law (Ref. 2)

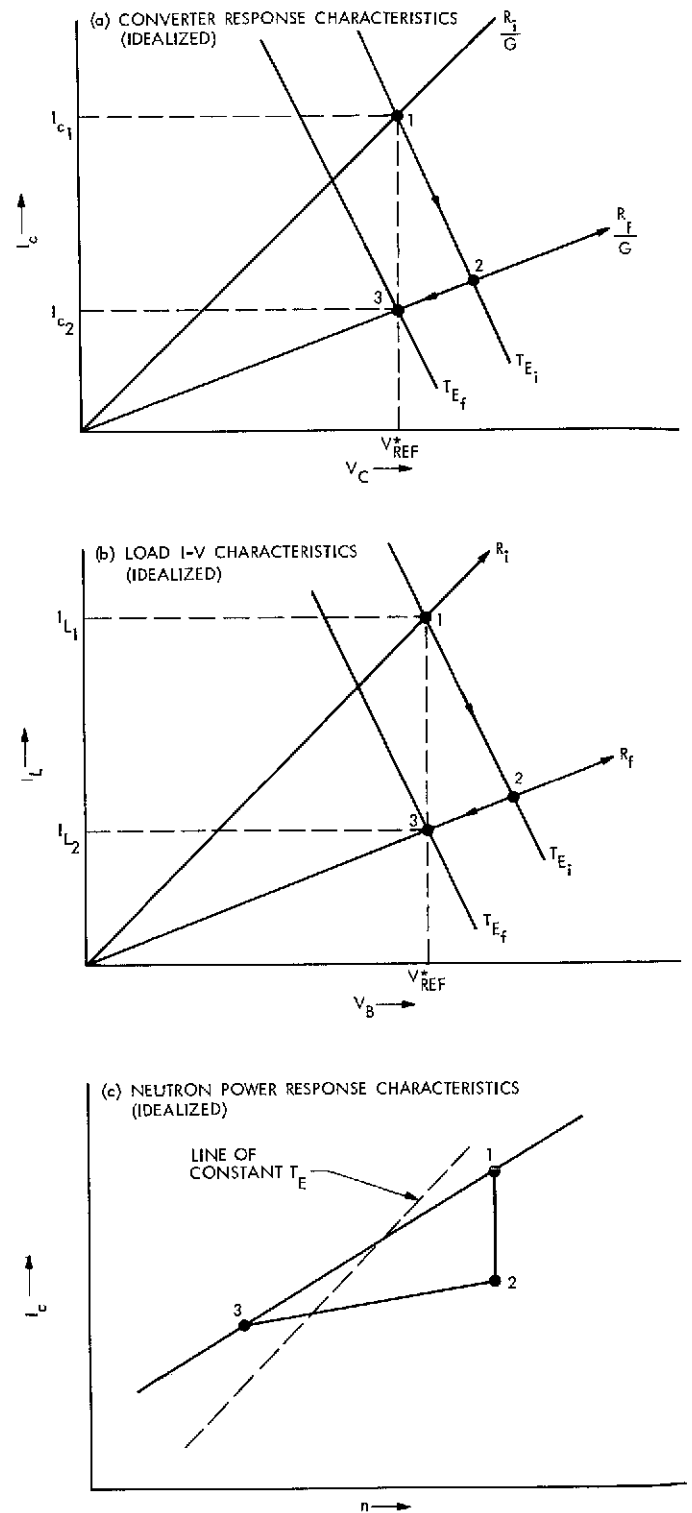(a) CONVERTER RESPONSE CHARACTERISTICS (IDEALIZED)

(b) LOAD I-V CHARACTERISTICS (IDEALIZED)

(c) NEUTRON POWER RESPONSE CHARACTERISTICS (IDEALIZED)

LINE OF CONSTANT T_E

Fig. 9. Ideal response trajectories for partial load drop with constant diode voltage control law

power conditioners can be designed which will maintain a regulated output voltage for a range of input voltages, a constant diode voltage is not a stringent requirement. Instead, a better design philosophy would be to program the reactor response for a control law that would prevent such instabilities as thermionic burnout and let the power conditioner provide any necessary voltage regulation.

VI. Constant Emitter Temperature Control

The concept of a constant converter voltage control scheme was abandoned in favor of a scheme which included power conditioners for maintaining a regulated high-voltage bus and provided active control for preventing emitter temperature thermal cycling (Ref. 15). The primary impetus being that results of converter tests (Ref. 17) indicated fuel-emitter thermal cycling could

cause warping or cracking of the emitter surface and ultimate failure due to electrical shorting of the emitter and collector surfaces. Furthermore, if the control law could hold the converter current constant, the possibility of thermionic burnout would be precluded.

Wilkins and Peck (Ref. 5) were the proponents of such a control scheme and are credited with a preliminary control system design which maintained identical steady-state reactor emitter temperatures before and after load variations. Their system model was similiar to that used by Gronroos, et al. (Ref. 24) with the important exception that the thermal and electrical performance characteristics of the converters were predicted with the digital computer program SIMCON (Ref. 25).

A block diagram of the constant emitter temperature control scheme is illustrated in Fig. 10. Instead of feed-
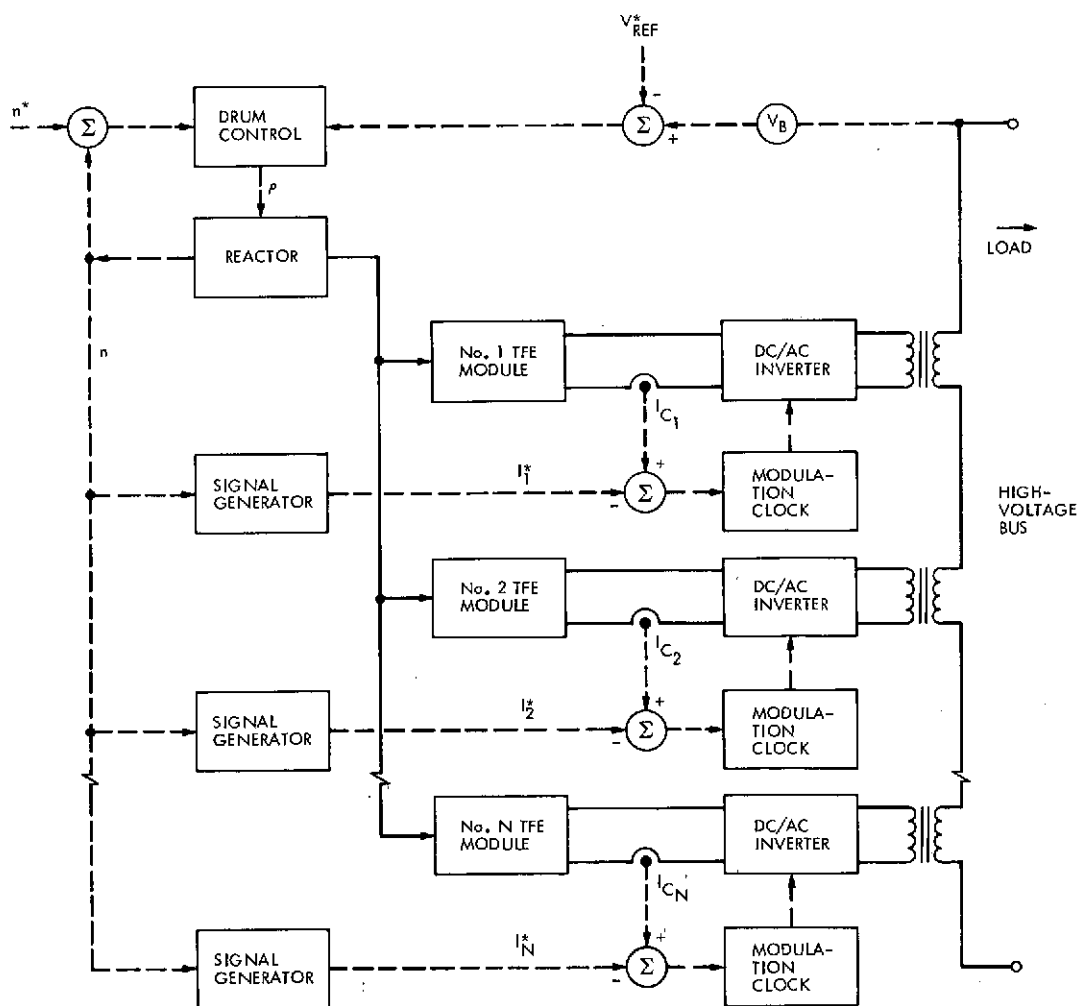

Fig. 10. Block diagram of constant emitter temperature control scheme

back, which included various reactor core temperatures, only the variations in load voltage and neutron power density were used in the closed-loop control law. The power conditioner modules are ideally represented as variable gain power regulators where the load voltage is proportional to the TFE module output voltage times the regulator gain ($V_L = GV_c$). Even though the TFE emitter temperatures are inaccessible for direct measurement, they can be regulated indirectly because of the inherent emitter temperature dependance upon two measurable parameters: neutron power density and TFE current density. For a constant average TFE emitter surface temperature, there exists an approximate linear relationship between the TFE current and the neutron power density. Therefore, from a control system viewpoint, if the TFE electrical current and the reactor neutron power density satisfy a linear relationship, where

$$I_{c_j} = A_j + B_j f_j n; \qquad j = 1, 2, \cdots, N, \qquad (2)$$

then the emitter temperatures in the jth TFE module should remain approximately constant. In Eq. (2), A_j is the intercept and B_j is the slope of the linear relationship, and f_j is the fraction of the total reactor thermal power which appears in the jth TFE module. Dependent upon the desired distribution of emitter temperatures in the reactor core, the signal generator for each TFE module power regulator would be adjusted to a set of constants corresponding to the average TFE emitter temperature desired for that module. That is, a reference TFE current, I_j^*, for the jth TFE module would be synthesized, and the actual TFE current, I_j, is then regulated by the PC inverters until I_j equals I_j^* at steady-state conditions.

The important characteristics of the control system operation for a load power drop can be illustrated with the three idealized curves of Fig. 11. The power drop on the high-voltage bus appears as an increase in load resistance and, therefore, the load shifts from R_i to R_f in Fig. 11(b). Since the power conditioner cannot store or dissipate energy, the operating point on Fig. 11(b) instantaneously moves from point 1 to point 2 along the constant power line. Since the neutron power density has not had time to change, the reference current, I^*, remains constant at the value before the partial power drop occurred. However, since the load current (I_L) decreases along the constant power trajectory from points 1 to 2, the TFE module current tends to follow it. However, the error signal (I_c-I^*) generated when I_c follows I_L adjusts the power regulator gain with electronic speed such that the TFE module load line in Fig. 11a stays fixed
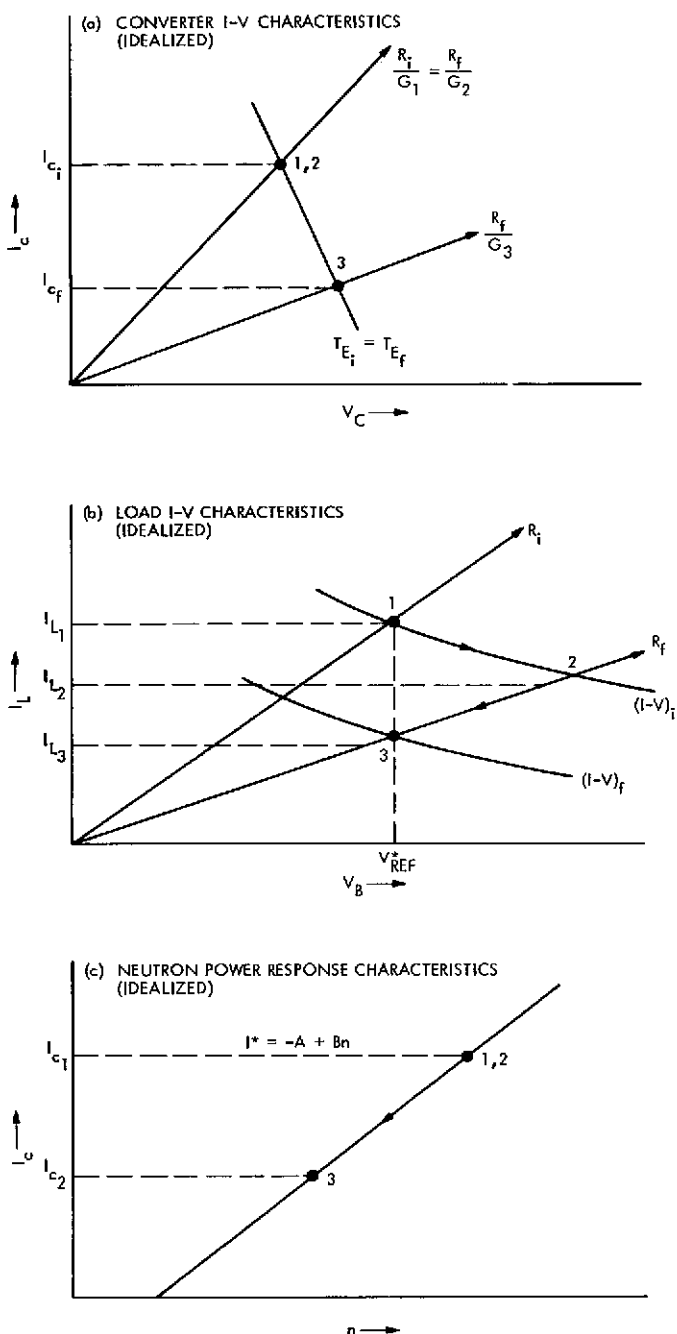
Fig. 11. Ideal response trajectories for partial load drop with constant diode voltage control law

($R_1/G_1 = R_2/G_2$). Therefore, I_c remains essentially constant and the operating point in Figs. 11(a) and 11(c) does not move. The almost instantaneous change in load voltage is fed back to the reactivity control drives, and after a short delay, the neutron power density begins to decrease. Since the reference converter current is proportional to the neutron power level, I^* also begins to

decrease. The error signal (I_C-I^*) then adjusts the power regulator gain so that the converter I-V characteristics move ideally from point 2 in Fig. 11(a) along the line of constant emitter temperature to point 3. The trajectory is supposed to move along the line of constant emitter temperature because the change in I^* is programmed with n to provide this control feature. The neutron power continues to decrease until the load voltage is again equal to the reference V_L^* as shown in Fig. 11.

The response of the system model to an 80% step reduction in load power demand is illustrated in Figs. 12 and 13. Actual transient results indicate that the emitter temperature does not remain constant for neutron power changes. The reason is the linear relationship between neutron power and converter current for a constant emitter temperature is valid only for static equilibrium power levels. Consequently, because of the time delay for heat to flow from the fuel volume to the emitter surface, the effects of neutron power variations are not felt instantaneously on the emitter surface. However, the TFE current is electronically coupled to the neutron power, and therefore the compensating effect of TFE current on the emitter surface temperature for neutron power level changes occurs immediately. The net result is that the emitter temperature will not remain constant during neutron power transients because of the finite fuel-volume heat capacity.

In contrast to the control system for constant converter voltage, the steady-state emitter surface temperature will return to the equilibrium emitter surface temperature that existed before the transient.

An additional undesirable feature of the control system resulting from instantaneous load power demands or step changes in load resistance are load voltage spikes. The spikes occur because the constant power lines (see Fig. 11b) are quite flat, and, therefore, the load voltage is very sensitive to load line changes. In Fig. 13, the peak of the voltage spike occurs at approximately 2.5 times the equilibrium load voltage.

Two proposed alterations were introduced to eliminate these unwanted characteristics of the constant emitter control system. Emitter surface temperature transients were retarded by introducing a time delay in the signal generator. This has the advantage of delaying the cooling or heating effect of TFE current to match the thermal time constant for heat flow changes on the emitter surface
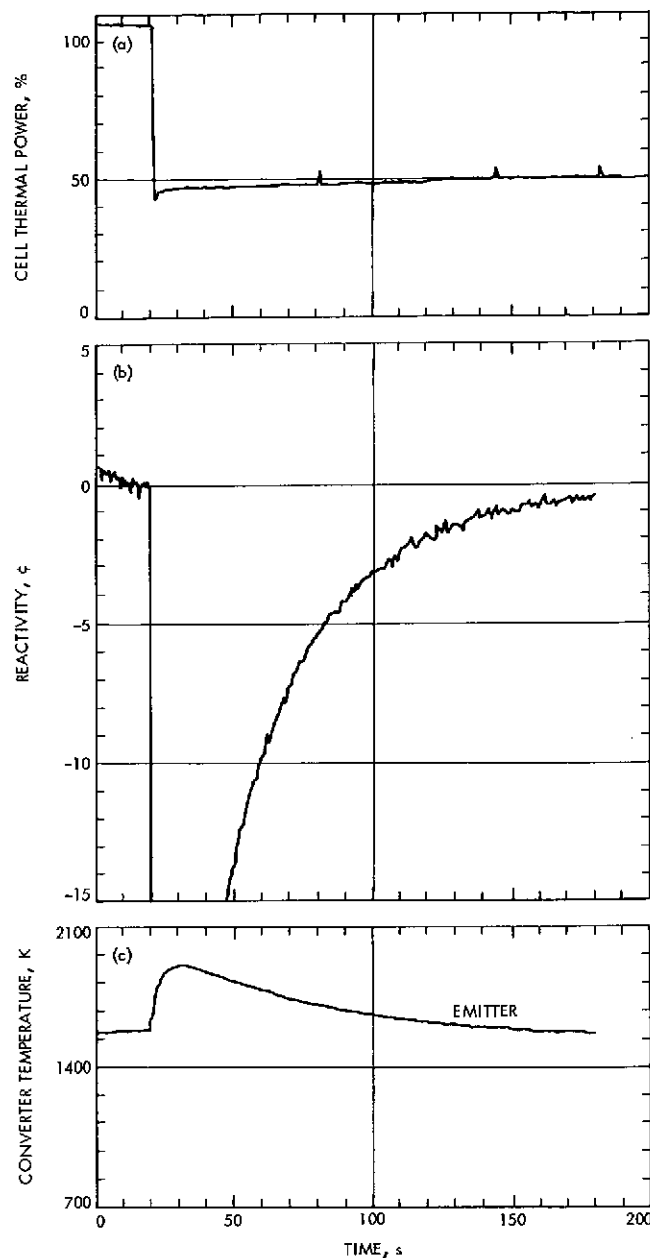
Fig. 12. Closed-loop thermal and neutronic response to step decrease from 100 to 20% in load power demand (Ref. 15)

due to neutron power increases or decreases. Analog computer results by Sawyer (Ref. 4) indicate the emitter temperature remains almost constant during the entire portion of the transient. Second, the reduction of load voltage spikes is accomplished by simulating the neutron power changes electronically. In this way, the TFE currents are regulated with electronic speeds and the voltage spike is reduced and smoothed out. A possible schematic diagram incorporating this modification into the system
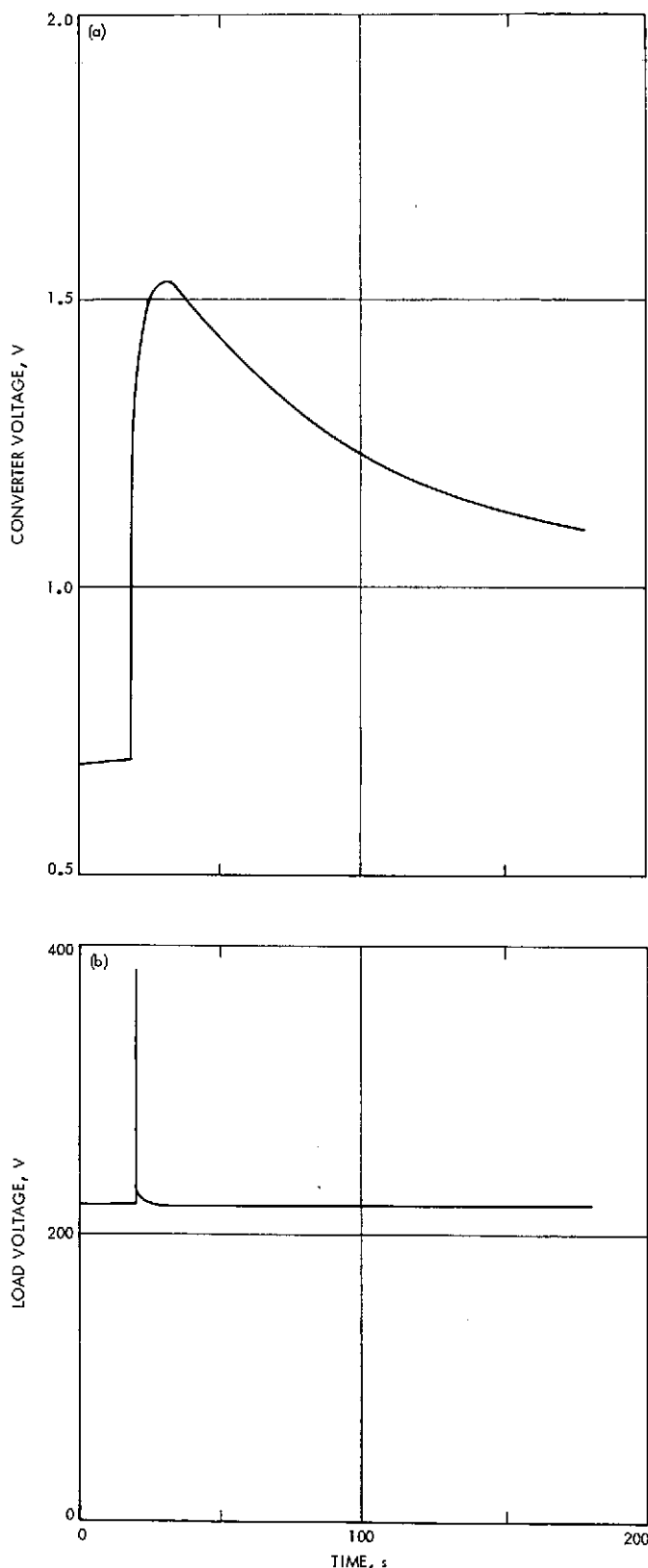
Fig. 13. Closed-loop electrical response to step decrease from 100 to 20% in load power demand (Ref. 15)

representation of Fig. 10 is shown in Fig. 14. Equation (2) is now expressed as a function of a pseudo-neutron power level where

$$I_{0_j} = A_j + B_j f_j S, \qquad j = 1, 2, \cdots, N,$$

$$\dot{S} = v_2 n^* (V_L - V_L^*)/V_L^* \qquad (3)$$

$$\dot{\rho} = -v_3 [n - (S + \tau \dot{S})]$$

and n^* is rated neutron power, S is the pseudo-neutron power level, v_2, v_3 and τ are general control-law constants. The addition of rate feedback to the reactivity controller has the advantage that neutron power can lead TFE currents for slow load power variations. The constant v_2 is critical in specifying how fast the TFE currents will respond to load changes. The effect of decoupling the TFE current from the actual neutron power level means the power regulator adjusts the converter electrical power to correspond with the load power demand.

For the assumed method of voltage regulation, the elimination of emitter temperature transients and the reduction of voltage spikes are incompatible in the sense that decreased voltage spikes mean increased emitter surface temperature transients, and decreased emitter temperature variations mean broader larger voltage spikes. The control system, however, does provide sufficient regulation of both load voltage and TFE emitter temperatures within tolerable bounds for large changes in the load power demand. The control system is also modular in nature, and, therefore, TFE failures and degradations are not catastrophic to system operation. In contrast to the constant voltage control system, the constant emitter temperature control system treats each TFE module as a nonuniform entity. Furthermore, dependent upon the electrical configuration of the TFE and the power conditioner modules used to form the high-voltage bus, load power demands can be shared equally by the operating TFE modules.

The main criticism of the constant emitter control scheme is that electrical load power changes are obtained by alterations in the neutron power through reactivity control versus moving to another power point on the converter I–V curves. Also, by using either a pseudo or actual neutron power level to generate a reference TFE current, the problem of tuning the signal generators becomes critical. Care must be exercised because, if the reference TFE current is generated poorly, the resultant emitter temperature at equilibrium may be high enough, depending upon operating conditions, to force thermionic burnout. To illustrate this point, consider the typical I–V
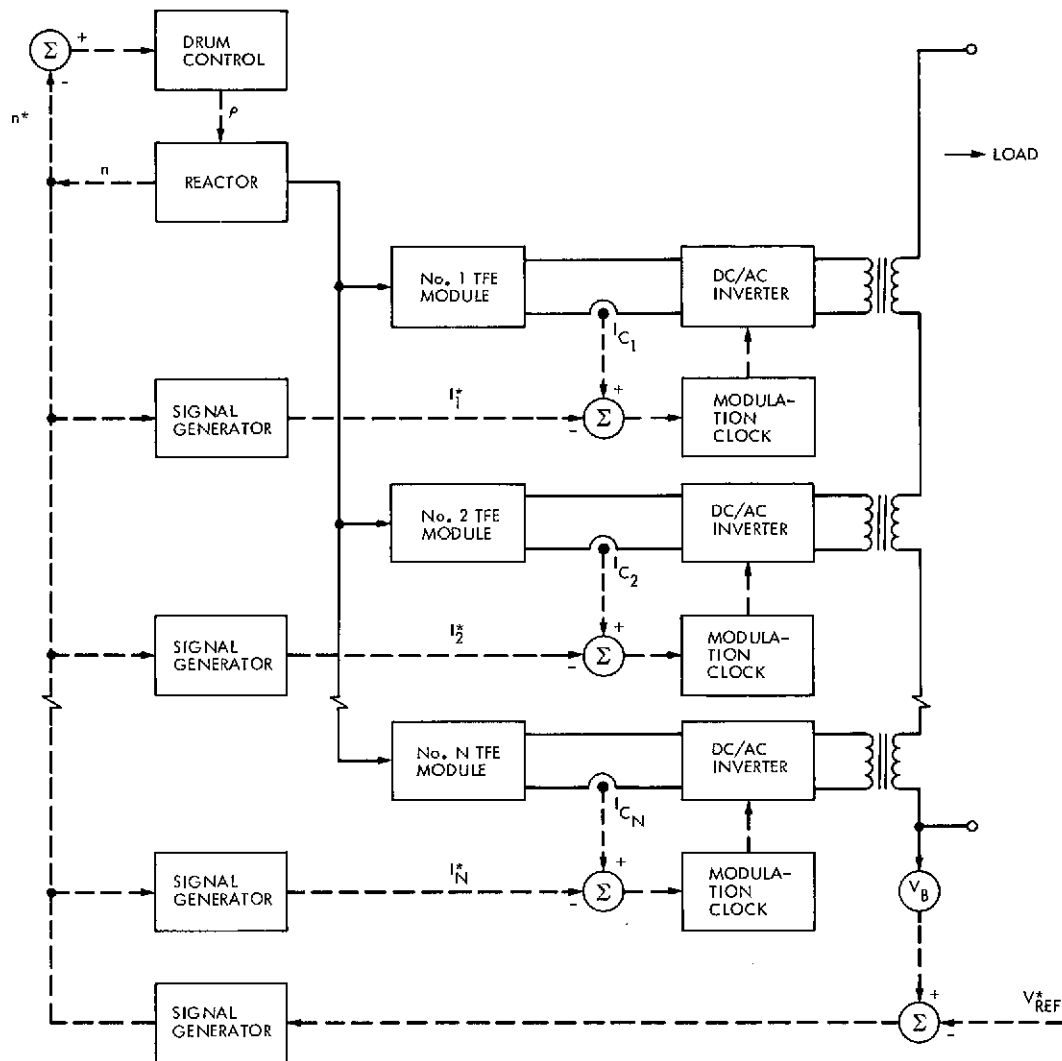
Fig. 14. Block diagram of constant emitter temperature control scheme using a pseudo-neutron power level

characteristics in Fig. 15. The load power drop requires that the neutron power be reduced until the operating point moves from 1 to 2. However, if the signal generator produces a reference value for TFE current which is not equal to I_2 but I'_2, then the final emitter temperature will be T'_E and the system will operate at point 2'. If T'_E is higher than the emitter temperature for thermionic burn-out the converter will be driven to open-circuit voltage.

The control scheme also breaks down when the load power demand exceeds the maximum power output of the reactor for a given set of emitter temperatures. The control system then runs to short-circuit current conditions believing more power means higher converter current density. This could be prevented by limiting the reference

signal I^* at the output of the signal generator. Excessive power demands would then cause a degradation in load voltage and ultimately the neutron power would trip the scram mechanism, causing the reactor to shut down. The onboard computer would either have to adjust the signal generators for higher emitter temperatures or switch out the thruster which is responsible for demanding electrical power before restarting the reactor.

VII. Reactor Current Control

In order to improve the regulation on the bus load voltage and still retain the control capability of restricting TFE emitter temperature fluctuations, an alternate control scheme called constant current control was intro-
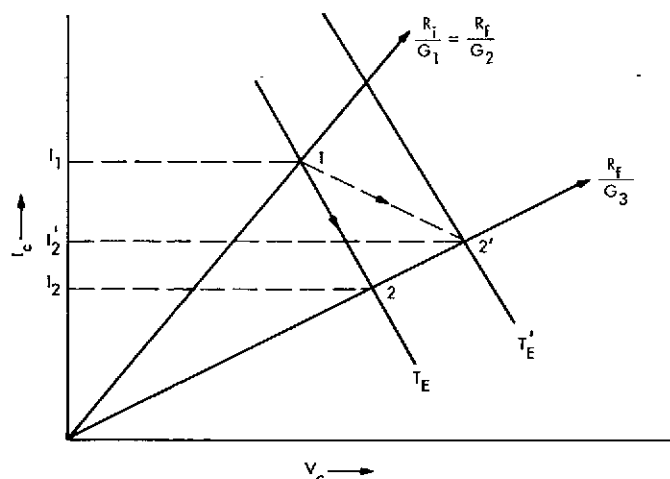
Fig. 15. Converter I-V response characteristics resulting from an untuned signal generator

duced by Sawyer (Ref. 4). The unique feature of this scheme is a constant load voltage profile coupled with a reactor current feedback loop which adjusts the neutron power level for a constant average TFE emitter temperature. The philosophy for the current control system is to use bus voltage feedback to electronically adjust the power conditioner modules for a constant load voltage and use bus-current feedback to match reactor thermal power with electrical load power demands.

Since the electrical power delivered to the load is regulated electronically, the load voltage will remain constant on a millisecond time scale for sudden load power demands or individual TFE module failures. A detailed explanation of the voltage regulation for the power conditioner modules is beyond the intended scope of this report. However, for example, with a push-pull power inverter using time ratio control, it would involve varying the conduction time of the transistor or SCR switches. To ensure that the power conditioner modules do not overheat, the operating point on the converter I–V characteristic curve is located so that a load decrease results in decreased converter current and increased converter voltage (versus increased current and decreased voltage). This means the conduction time of the power inverters must be decreased (reduced inverter voltage gain) for a load power reduction in order to maintain the load voltage constant.

The resultant change in load current is programmed to lower the neutron power to a level where some resultant steady-state average emitter temperature for the reactor core is equal to its equilibrium value before the transient.

The methodology is equivalent to the constant emitter temperature control system, except instead of changing the individual TFE currents using neutron power as a reference, the neutron power is varied using a reference which is equal or proportional to the total reactor current. The relationship between electrical current and neutron thermal power for both control schemes is basically the one of Eq. (2), resulting in a constant static emitter temperature. For the current control scheme, the equation is inverted and solved for a reference neutron power level

$$n^* = aI_T + b \tag{4}$$

where I_T is the total electrical current from the reactor and

$$a = \frac{1}{\sum\limits_{i=1}^{N} B_i f_i} \quad \text{and} \quad b = \frac{\sum\limits_{i=1}^{N} A_i}{\sum\limits_{i=1}^{N} B_i F_i} \tag{5}$$

In this case, the resultant neutron power change for a reactor current change would predict a constant emitter temperature for those converters with a current equal to the average current per converter in the reactor core. Therefore, in contrast to the constant emitter temperature control scheme, the current control scheme trades TFE individuality for a constant load voltage. A schematic diagram of the current control is shown conceptually in Fig. 16.

The ideal characteristics of the current control system for a sudden load power drop are best illustrated by examining the three I–V curves for an average reactor converter in Fig. 17. The load power drop again acts like an increase in load resistance and, therefore, the load line shifts from R_i to R_f in Fig. 17(b). Because the power conditioner module electronically adjusts the voltage gain between the TFE module and the high-voltage bus, the load voltage will remain constant for load power changes occurring as fast as one second. The transition from operating point 1 to 2 in Fig. 17(a) follows a constant emitter temperature because the emitter temperature cannot respond within the time interval assumed for sudden lower power demands. The same argument applies for the neutron power level, and therefore the drop in converter current occurs at constant neutron power as indicated in Fig. 17(c). Because the converter current has suddenly been reduced, the emitter temperature begins to increase, causing the operating point in Fig. 17(a) to finally move to point d. This occurs because the flow of electrons
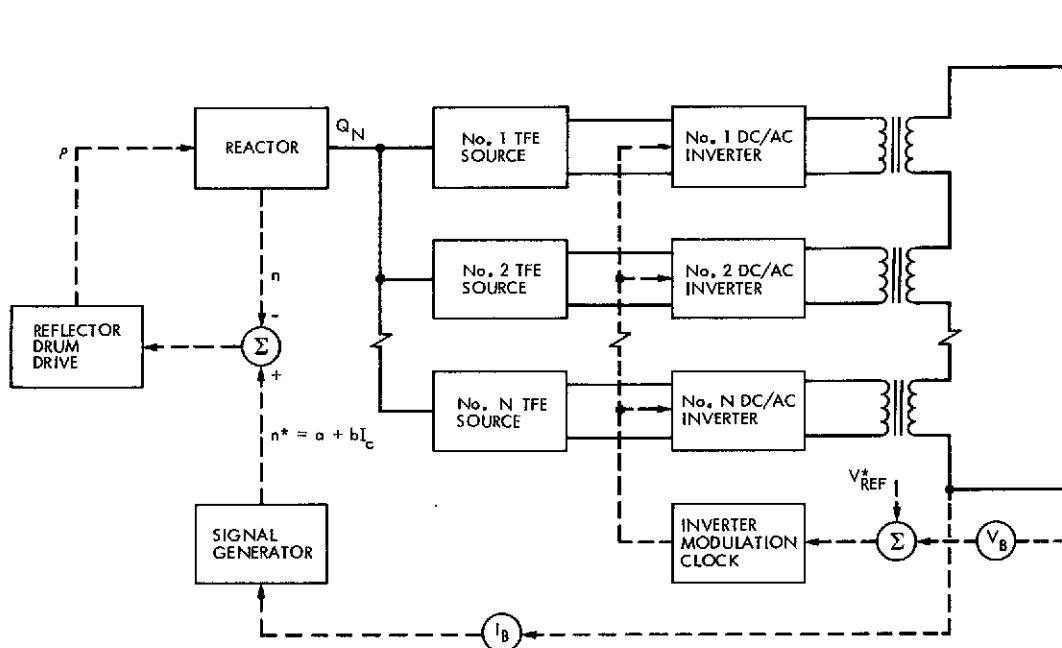
Fig. 16. Block diagram of current control scheme

between the emitter and collector surfaces has been reduced and, consequently, the amount of energy removed from the emitter surface is reduced. The drop in load current in Fig. 17(b) simultaneously generates feedback which reduces the neutron power to the reference level given by Eq. (4). This decreases the heat energy input to the emitter surface until the operating point on the converter I–V curve of Fig. 17(a) returns to the equilibrium emitter temperature at point 2. Since the I–V curves of Fig. 17 are for an average reactor converter, the steady-state temperature will equal the equilibrium emitter temperature before the load power drop and, consequently, operating points 2 and 3 will coincide.

The time responses for a complete load drop are illustrated in Fig. 18. The load voltage remains constant during the transient because of the electronically fast feedback adjustments in the inverter modulation clocks. The average emitter temperature in the jth TFE module does return to the same temperature prior to the transient. The reactivity insertion rate is quite large, but limiting the rate to less than $0.10/s$ does not significantly affect the peak value of the emitter temperature during the fast transients. Consequently, the current control scheme possesses all the characteristics of the unmodified constant emitter temperature control scheme with the additional bonus of a constant load voltage profile.

The current control scheme also suffers from a possible unstable condition if the load demands more than the

maximum power available from the reactor at the emitter temperature associated with Eq. (4). As with the constant emitter temperature control scheme, a limiter has to be set on the reference neutron power level in order to prevent the reactor runaway to short circuit converter current.

The control system has an inherent disadvantage in the fact that the emitter temperature does not remain constant during fast transients. Furthermore, those steady-state emitter temperatures in the core which are not equal to the emitter temperature, T_E, corresponding to the constants in Eq. (4) will not be equivalent to the temperatures before the transient. Previous computer simulation results (Ref. 4) indicate that the discrepancies between the emitter temperatures before the transient and the steady-state valves are not significant for those converters operating at emitter temperatures other than $\bar{T}_E$.

VIII. Multivariable Feedback Control

For completeness, two control system studies using multivariable state-feedback techniques are referenced. The first, by Ferg and Brehm (Ref. 26), concerned a very simplistic mathematical model consisting of five state-variables with three controllable inputs and linearized computer program SIMCON data for the converter electrical characteristics. A feedback control law was computed which resulted in a closed-loop system where pre-
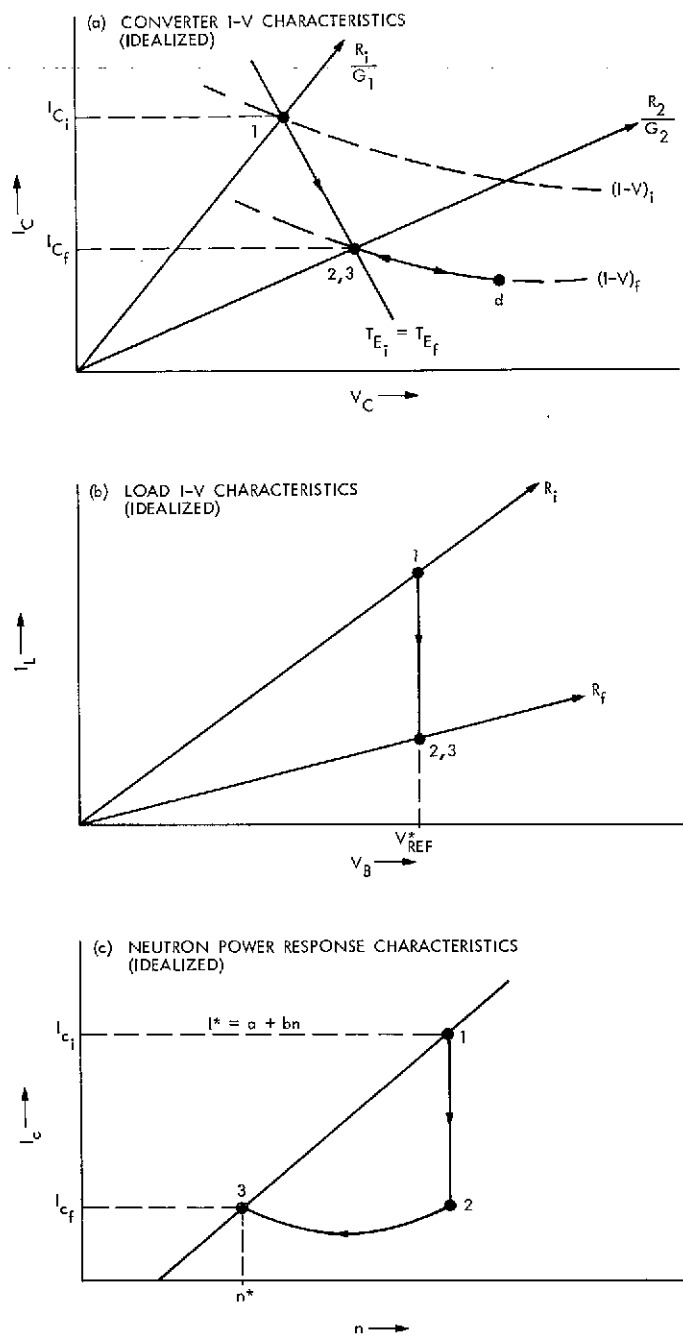
(a) CONVERTER I-V CHARACTERISTICS
(IDEALIZED)

(b) LOAD I-V CHARACTERISTICS
(IDEALIZED)

(c) NEUTRON POWER RESPONSE CHARACTERISTICS
(IDEALIZED)

Fig. 17. Ideal response trajectories for partial load drop with
current control scheme

Fig. 18. Complete load drop and recovery responses with
current control scheme (Ref. 2)

designated transfer functions were synthesized between
the various control inputs and system outputs.

As in the single-input, single-output studies by Weaver,
et al., (Ref. 3) the control system design assumed such
states as average emitter surface temperature and average
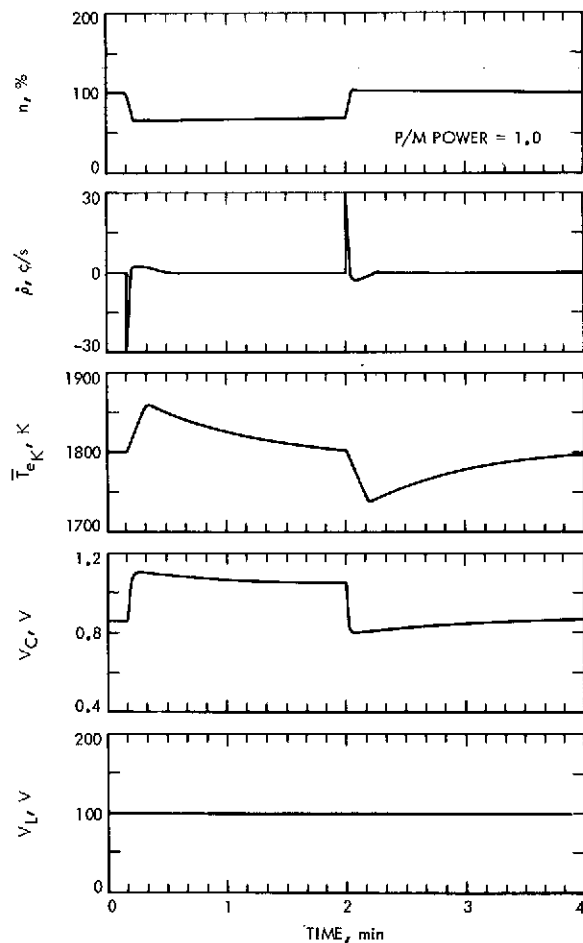collector tri-layer temperature were directly measurable.

Study conclusions with system time responses for
various input perturbations indicate that, theoretically,
diode matrix thermal and electrical coupling can be
eliminated with the proper state-feedback. However, no
effort was made to apply this technique on a reactor
systems level. The study represents, at best, a first attempt
at using multivariable interacting design techniques on a
practical reactor example.

Second, a control system design was made by Ferg and
Dagbjartsson (Ref. 27) for the German in-core thermionic
reactor experiment. This study employed multivariable
decoupling theory on a thirteenth-order mathematical
model having four control inputs. The model consisted
mainly of a lumped-parameter description of the heat
generation and rejection loops, and an actual control loop
design for regulating the converter electrical power was
not considered.

Two separate levels of control were formulated: one designated the braking operational mode for protecting against system perturbations and malfunctions and the other, the driving operational mode, for making programmed changes in the system operating conditions. The driving mode would override the braking mode control loops when an electronic signal appeared at one of the system closed-loop inputs. System time responses showed that the control loops for the braking mode operation were quite satisfactory and that the decoupled nature of the closed-loop system helped localize the effects of internal system perturbations. However, the decoupling feedback for the driving mode controls resulted in a very sensitive closed-loop system (small insertions of reactivity caused large variations in primary coolant mass flowrate).

The design techniques used in the study were again extremely involved and complicated. Until those design procedures and uncertainties are explained and clarified with sound theoretical analyses, the arguments against using multivariable control techniques in present-day engineering problems will remain.

IX. Future Work

The objective of the Thermionic Reactor Systems R&AD Project at the Jet Propulsion Laboratory was to complete the present technology phase and move into the developmental and advanced engineering phase.[1] The reference system design for the developmental phase would be used as a guideline for constructing an engineering model of the NEP propulsion subsystem. The goals of the developmental advanced engineering phase would be to establish and demonstrate useful nuclear thermionic power sources for possible space applications.

Various control system tasks remain, however, before the transition to the developmental and advanced engineering phase could be accomplished with a reasonable assurance that the goals of the engineering model can be achieved. In an approximate chronological order of development, the following items represent suggestions for future or unfinished work.

The next step in evaluating the current control scheme of Sawyer as the reference control system design would be to develop a representative analytical model for the baseline power conditioner designs. Integration of the

model into the present power subsystem description would be useful in evaluating the compatibility and performance of the current control loops with a simulated power conditioner. Another improvement in the present reactor analytical model would be the inclusion of actual converter experimental data to replace the converter characteristics from the SIMCON computer program (Ref. 25). With the power conditioner model, a tradeoff study could be performed to determine if PC power dissipation capabilities during transients might reduce emitter temperature variations. A power dissipation capability could be used to absorb any sudden decrease in load power demand. The actual power dissipation in the PC could then be matched with any subsequent neutron power reduction so that the net effect on the converters would be an almost constant emitter temperature distribution. The present system mathematical model plus an adequate PC analytical description could also be used to obtain and analyze the reactor power subsystem response for reactive load variations where the power factor was not unity. In conjunction with this, the thrust subsystem operating data available from the Solar Electric Propulsion System Tests (SEPST) (Ref. 28) should be examined to determine what load power variations are realistically possible and with what frequency they are expected to occur.

Another important step in qualifying and verifying the analytical results of the TFE module/power conditioner sets would be to breadboard a power conditioner design and laboratory test it with an operating converter. The output converter voltage could be preamplified to simulate a TFE module, and the various load power tests and voltage/current ripple measurements would be available. The test could be conducted with an electrically heated converter in which the emitter temperature and temperature profile were monitored during transients.

The questions associated with the interconnections of the TFEs to form the TFE modules should also be resolved. This would involve a tradeoff study to determine how many TFEs should be connected in series to provide a satisfactory PC input voltage. Possible parallel/series combinations which would provide a minimum or adequate power source reliability and an optimization of the power production should be further investigated.

One area which has not received a great deal of attention is the control loops for cesium reservoir temperature and coolant electromagnetic pump regulation. Initial efforts should center on expanding the system mathematical model to include cesium gap pressure and coolant

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mass flowrate as controllable parameters. A heat rejection description of the power subsystem would provide information on the effect of radiator perturbations and degradations on the thermionic power production and system reliability. The incorporation of coolant mass flowrate as a control parameter may have important consequences in preventing or limiting collector tri-layer thermal shocks. Also, the optimization of reactor power production is certainly dependent upon the cesium reservoir temperature distribution within the reactor core.

Finally, the control system logic required to operate the thermionic reactor power subsystem through a computer interface should be developed. The logic would consist of programs for monitoring subsystem performance, diagnostic and system degradation analyses, setting and varying the reference levels for starting and operating the reactor, and possibly simulated flight power profiles for evaluating the engineering model performance.

X. Conclusions

Early open-loop transient studies (Ref. 1) indicated a need for an active closed-loop control system for the thermionic reactor. Initial design efforts used single converter mathematical models with no power conditioners and TFE interconnections. The control philosophy centered on the formulation of a control law which would constrain the converter output voltage to be constant. Subsequent analyses pointed out, however, that a constant voltage control law could, under certain conditions, lead to thermionic burnout. The use of state-variable feedback and the single converter representation left unresolved problems on how to incorporate the study results into an actual reactor core configuration containing many TFEs. Finally, dynamic responses with the constant converter voltage control laws indicated that the converter voltage did not remain constant for a considerable portion of the transient.

Then, Wilkins and Peck (Ref. 5) proposed an expanded control system design applicable to the entire reactor system and based on a control philosophy of constant emitter temperature for each TFE. The study was the first in which the power conditioner was involved in the power plant control function. The converter description was also improved by using tabular data from the digital computer program SIMCON. The control loops consisted of the following: (1) variations in load voltage were fed back through a reactivity controller which adjusted the neutron power density, and (2) changes in neutron power density drove a parallel string of function generators which

generated a converter current reference for each TFE module. The converter current from each TFE module was then adjusted by the power conditioner to match the corresponding function generator reference signal.

Time responses of the closed-loop control system indicated large load voltage spikes and varying TFE module emitter temperatures during the transient portion of the response. The study was, however, the first detailed systems approach to a thermionic reactor control system synthesis.

The reactor current control scheme of Sawyer (Ref. 2) was an attempt to eliminate the load voltage transients and still preserve the constant emitter temperature characteristics of the emitter temperature control system design. The control philosophy in the current control design consisted of a feedback loop between load voltage variations and the PC voltage regulator. For a given load power change, the PC regulator would maintain a constant load or bus voltage on a millisecond time scale. The resultant reactor current change was then fed to a signal generator which computed a new neutron power reference. The neutron power density was then adjusted to match the reactor thermal power to the electrical load. This match between thermal and electrical power was accomplished with the constraint that the steady-state average reactor emitter temperature before and after the transient be equal.

Transient results with the current control loops indicated that an electronically fast power conditioner with voltage regulation provided a constant average load voltage for varying load power demands. The load drop and recovery perturbations caused variations in the average emitter surface temperature comparable to the emitter temperature transients predicted by Wilkins and Peck. A subsequent analysis by Sawyer (Ref. 4) showed that the temperature transients for those TFE modules with an emitter temperature different from the reactor average were similar in shape and magnitude.

Reviewing the previous thermionic reactor control studies, possible conclusions helpful for the specification of a reference NEP control system are the following. First, the approach used by Sawyer "current control" is the more desirable from a spacecraft user or a thrust subsystem standpoint. Also, for any given set point of operation, the power fluctuations due to thruster arcing, thruster failures, switching scientific experiments on and off, etc., can be handled quite easily by the PC regulation. These power fluctuations are also small enough that

the various converter emitter temperature transients tend to be insignificant.

The constant emitter temperature control scheme has the inherent capability of reducing emitter temperature transients but offers poor constant load voltage profiles with large changes in load power levels. If, however, a programmed change was initiated when the thrust subsystem switched modes of operation (thrust-to-coast, coast-to-thrust, etc.), then a brief degradation in load voltage to spacecraft users would be expected. The importance of emitter surface temperature cycling and its

consequences on TFE lifetime might override planned load voltage variations which would favor the constant emitter temperature control. The power to the on-board experiments and communication equipment could also be adequately filtered to remove the voltage spikes associated with the constant emitter temperature control law.

Therefore, a suggestion for the reference control system might be a design which had the capability of switching from the constant emitter temperature control law to the reactor current control scheme depending on the specific applications for the power subsystem.

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