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SCRAM CONTROLLER
AND
AUTOMATIC CONTROLLER
5-kwe REACTOR THERMOELECTRIC
SYSTEM

AEC Research and Development Report

Atomics International Division
Rockwell International

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R. J. TUTTLE

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ABSTRACT

The design objectives and limitations developed for the scram and automatic controllers are discussed in detail, and to a lesser extent, for the manual and computer control systems and the backup shutdown mechanism. Digital computer simulations used to analyze startup methods are described and the results presented for several candidate methods. The selected startup method uses three reactivity insertion rates to provide a startup satisfying the design objectives and limitations. Improvements in this startup method are recommended. Functional requirements of the automatic and scram controllers are discussed and means of implementing these functions by use of integrated circuits are proposed.

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I. INTRODUCTION

The SNAP 5-kwe thermoelectric reactor system is designed to produce 5 kw of electrical power in space with thermoelectric modules heated by flowing NaK from a beryllium-reflected, U-ZrH-fueled reactor. This report summarizes the operating characteristics of the scram controller and automatic controller as designed for a proposed ground system test which would have been performed if the program had continued. Operating conditions would simulate space as closely as possible; including a vacuum environment with heat rejection from the power system by thermal radiation, automatic startup and control, and minimal changes to the space-flight configuration.

Reactivity control is provided by varying the neutron leakage by means of two sliding reflector segments. The total control requirement is reduced by the use of burnable poison.

The sliding reflector segments are part of the radial reflector which surrounds the reactor core vessel. They change the reactivity by moving parallel to the exterior conical surface, thereby changing the size of the window in the reflector at the axial midplane of the core. This changes neutron leakage from the core and, thus, changes reactivity. The reflector window varies from completely closed to 4 in. open; this provides approximately \$8 of reactivity swing.

A sketch of the flight-configuration reactor (Figure 1) shows the control segments in a partially inserted position. The reactor is shown in the vertical orientation of the proposed ground test system.

The position of each segment is adjusted by means of an electrical actuator driving a screw in a ball nut anchored to the movable segment. The actuator is a reluctance stepping motor with four stator phases; rotation is produced by sequentially flowing current through each phase coil. The direction of rotation is determined by the order in which the coils are supplied power.

The segment is driven in discrete steps corresponding to a single cyclic activation of the four phase coils. This cyclic activation produces a rotation of the actuator rotor of 7.2 degrees, resulting in a segment movement of 0.0054 in. When not being driven in this manner, the actuator is locked against rotation by means of an internal spring-loaded toothed brake. This brake must be released before rotation begins and must be set at the end of the rotary motion.

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Figure 1. Flight-Configuration Reactor

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Two springs, visible in the reflector gap, serve as anti-backlash springs in the flight reactor and as segment support springs (also providing the anti-backlash function) in the ground test reactor. Rotation of the segment in reaction to the ball-screw motion is limited by an axial guide bearing.

The reflector control system performs two functions in the ground test reactor. It provides reactivity control during startup, operation, and normal shutdown. It also provides emergency shutdown, removing reactivity at a sufficiently rapid rate to terminate any postulated power excursions.

A backup shutdown mechanism is provided for use in case of failure of the normal system. This consists of rotating (by 15 degrees) the two radial reflector halves away under the combined force of gravity acting on the offset center of mass and torsion springs mounted on the support pivots. This utilizes the end-of-life shutdown mechanism of the flight system, but unlike the flight system, the ground test reactor has provision to reset the reflector halves into the normal operating position.

The ground test reactor will be controlled by one of three different control systems:

- 1) The manual control system by which a qualified reactor operator adjusts the segment positions to achieve desired operating conditions as indicated by the entire complement of instruments.
- 2) The computer control system in which an on-line computer replaces the qualified operator; only the more important instrumentation read-outs are provided to the computer.
- 3) The automatic controller which simulates the flight controller in the ground test and serves as a demonstration of its performance.

To limit the complexity of the flight system, it is intended to use a minimum of instrumentation to guide the operation of the automatic controller. Thus, no segment position sensors will be provided, nor will monitoring of the reactor power by neutron or gamma-ray detectors. The automatic controller will operate on the basis of a pre-established program with a minimum of information that is easily obtained from existing instrumentation, or simple additions of instrumentation.

Besides these three operating control systems, a scram controller will be used to power the actuators to drive the segments out for a scram. This controller will operate in one direction only and cannot be stopped until the segments are fully withdrawn.

At any time, the manual control system will provide the operator with the means to override the computer control system or the automatic controller. Adjustments in the operating conditions outside the capability of these other two systems can be made by the operator and inappropriate adjustments can be circumvented.

The scram controller will override all other systems when called to do so, to ensure the rapid shutdown of the reactor.

II. DESIGN OBJECTIVES AND LIMITATIONS

A. ORIGINS

The design objectives and limitations arise from a variety of sources. The prime source is the operational requirement to accomplish a postulated mission. This leads to specification of the power level and quality of regulation, the time available for startup, the expected radiation dose, and the desired lifetime.

Attainment of the desired performance objectives is subject to limitations imposed by the capabilities of the system. These are determined by an engineering analysis of the entire system, and in this case result in limits on temperature differentials and rates-of-change, and requirements for flexibility in accommodating uncertainties.

All design approaches must be considered in view of their effect on the safety of the system. The controller designs have been developed to meet IEEE Standard 279-1971, "Criteria for Protection Systems for Nuclear Power Generating Stations." Much of the detailed design principles and philosophy behind this standard, as described by Hanauer and Walker^{*}, has been followed. The control and safety systems, as currently designed, meet the recommendations of USAEC Safety Guide 22, "Periodic Testing of Protection System Actuation Functions."

B. AUTOMATIC CONTROLLER

The automatic controller for the ground test will serve as a prototype for the flight controller. The flight controller is required to start up the reactor after a stable orbit is established and to regulate the reactor power to provide the desired amount of electrical power to the payload. While manual control, with complete operator control over reactivity addition and NaK flow rates, will be used for initial startups of the reactor system, several startups will be accomplished with the automatic controller to demonstrate its feasibility and performance. It is expected that most of the reactor system life test will be conducted under the control of the automatic controller.

^{*}S.H. Hanauer and C.S. Walker, ORNL-NSIC-51, Nuclear Safety Information Center, Oak Ridge, 1968

Design objectives for the automatic controller have been established on the basis of operational requirements, engineering analyses of the system, and safety guides and standards. These objectives are:

- 1) Startup time less than about 5 hr.
- 2) Temperature rise through the core limited to less than 150° F.
- 3) Rate of temperature change in the inlet plenum limited to less than 150° F/min.
- 4) Accommodate uncertainties in reactivity and reactivity coefficients.
- 5) Shutdown margin (cold) in the range of -\$0.50 to -\$3.00.
- 6) Maximum reliability as needed to meet lifetime requirements.
- 7) Minimum number of flight qualified items and minimum number of items to operate near reactor.
- 8) Operating lifetime of 5 years at power, surviving average payload radiation dose.
- 9) Shelf life of 2 years.
- 10) Adjustment of reactor power to produce electrical power within $\pm 2.5\%$ of 5 kw.
- 11) Minimum power overshoot at end of rise to power.
- 12) Ease of modification to meet changes in performance details.

The time available for startup is limited by the battery weight necessary to supply pumping power to the primary and secondary NaK systems. The NaK must be kept flowing to prevent freezing in cold spots prior to startup. Shortening startup time directly reduces the battery weight.

Limiting the temperature rise through the core to less than 150° F prevents generation of excessive thermal stresses in the fuel, cladding, internal reflector, and core vessel. This temperature rise is affected mainly by the reactor power and its rate of increase, and by the primary NaK flow rate.

Limiting the rate of temperature change to 150° F/min avoids severe thermal shock.

The estimated uncertainty in the zero-power critical position of the segments corresponds to $\pm 10\%$. The uncertainty in the fuel temperature coefficient of reactivity prior to determination in the ground test may be $\pm 0.02\%/^{\circ}\text{F}$. Uncertainty in the plenum coefficient may be $\pm 0.05\%/^{\circ}\text{F}$. These uncertainties could combine to produce an error of nearly \$1 at full power.

The orbital shutdown margin may be set between -\$3.00 with no prelaunch insertion to -\$0.50 with the maximum prelaunch insertion.

The reliability of the controller must be judged in terms of performance of the system. For example, failure of the controller to drive one of the segments, near the end of life, will not have a detrimental effect if the other segment has sufficient reactivity control to compensate for the reactivity loss during the balance of the mission.

For simplicity and economy, the controller should require a minimum number of flight-qualified items. The number of items required to operate near the reactor should also be held to a minimum to reduce the hazard of failure resulting from radiation damage.

The required operating life is 5 years at power; in achievement of adequate reliability, as yet undetermined, the expected life may be considerably longer. The average payload radiation dose for 5 years is expected to be 10^{12} nvt (1 Mev equivalent) and 10^6 rad (carbon).

It is expected that a 2-year storage period is adequate and will not affect the operating life of the controller.

Flight regulation of the electrical power produced, by adjustment of the reactor power, conserves reactivity lifetime and reduces the requirements for the power conditioning equipment in the payload.

A small power overshoot at the end of the rise to power is desired to minimize the jolt to components just coming up to operating conditions and near their maximum design conditions.

Changes in the flight conditions and improvement in knowledge of the system operating parameters are expected to occur between design and fabrication of the controller and its use. The operation of the controller should permit modifications to be made to reflect these changes.

In addition to these design objectives, the automatic controller must satisfy the following requirements to permit operation within the ground test control system:

- 1) Regardless of the function being performed by the controller, a scram signal must disable the controller and override its commands.
- 2) Transfer of control from the manual system to the automatic controller must not result in incorrect control signals.
- 3) The manual control system must be able to override the automatic controller.

Basic safety requirements that must be met by the automatic controller are a limit on the reactivity insertion rate and elimination of interferences with the scram controller. The first requirement is met by limiting the stepping rate to 1/sec, with the restriction that only one segment can be moved during a step. The automatic controller must not interfere with proper operation of the scram controller; particularly, failure of the automatic controller in such a manner as to require protective action shall not prevent performance of the protective action.

Permanent, irreversible shutdown in space is planned at the end of 5 years of operation by springing open the radial reflector halves. Prior to this, reversible shutdown can be accomplished by ground control by driving the control segments out. In that circumstance, the reactor can be restarted simply by removing the ground control blocking signal and allowing the normal control circuit to insert reactivity at a very slow rate until the lower current limit is satisfied. The details of such a startup have not been investigated and will depend upon the operating history, and post-shutdown conditions. The fission product decay heat amounts to a few hundred watts for several months after shutdown, fading to about 10 watts at 2 years after shutdown. At some time this power would no longer be sufficient to prevent freezing in cold spots and, thus, could not provide circulation in the primary and secondary systems.

It appears likely that restart might be possible even with a partially frozen system. A restart from 0° F would require approximately 20 hr, at the end of which time the reactor would be at 1200° F and at a power level determined by the heat rejection existing at the time. Heat transfer by conduction and thermal

radiation would probably suffice to melt frozen regions during the restart so that circulation would be normal when operating temperature is reached. Thermal shock and temperature differences may be severe following a melt-through that permits circulation. Clearly, more detailed analysis of this startup is required.

In the ground test program, the automatic controller will be used as a prototype test to demonstrate feasibility and performance. It can serve as the interface for operator control of the reactor by means of the ground control circuit. Use of this feature for most of the normal operations will provide additional information on the performance and reliability of the automatic controller.

The radiation tolerance of the controller can be demonstrated by placing spare controller units on the vacuum vessel containing the ground test system, along with suitable radiation monitors to determine the dose. These spare units will be tested periodically to determine operability.

The present controller design provides flexibility in adapting to different operating modes. The basic reactivity insertion rates can be changed easily by changing the oscillator frequency. Changes in these rates relative to each other can be achieved by modifying the divider circuits. Rate switching points can be changed as required to reflect improved knowledge of the reactor characteristics.

The only instrumentation required for operation of the controller is a current sensor, which can be located in the spacecraft payload, and a temperature sensor, located on the pump as an example. Suitable temperature sensors are already planned as part of the system instrumentation.

C. SCRAM CONTROLLER

The scram controller for use in the ground test system provides the current pulses to the segment actuators to rapidly withdraw the segments for a scram. The requirements that the scram controller must satisfy to perform this function are:

- 1) Unidirectional drive motion
- 2) Uninterruptability

- 3) Stepping rate of 300 (+25, -0) steps per minute
- 4) Self-checking with indication of failure
- 5) Ability to be tested periodically
- 6) High reliability of action.

The requirement of unidirectional drive motion is obviously necessary for a safety mechanism of this sort. This ensures that activation of the scram controller can only result in removal of reactivity. The action of the scram controller shall be uninterruptible to ensure completion of the scram, once initiated. The scram controller is stopped by actuation of an out limit switch operated by the reflector segment. There shall be no other means for stopping the scram controller. In particular, resetting the scram bus or disappearance of the scram signal shall have no effect until the out limit switch has been actuated.

The specified stepping rate is a compromise between the desire to have a high reactivity removal rate and the limitations of the torque/speed performance of the stepping motor. At too high a speed, the inertia of the system, and frictional forces, prevent the actuator rotor from following the rotating magnetic field produced by sequentially supplying current to the phase coils in the stator. At this speed, synchronization is lost and no torque is produced. Therefore, the stepping rate was chosen to provide an excess of torque over the full range of travel even with pessimistic assumptions for friction and the efficiency of the ball screw.

The scram controller shall be self-checking and annunciate any detected failures to alert the operating staff and, thus, prevent operation with a failed unit. In case of an annunciated failure, the faulty unit can be replaced by a spare and repaired. If the detected failure lies outside the scram controller and cannot be repaired (for example, a failure in wiring near the reactor or in the actuator itself) the backup shutdown mechanism will be connected as an instrumented scram. This permits retaining the necessary redundancy in the protective system.

The ability to be tested periodically is necessary to provide more stringent testing than the self-checking feature can provide. Since the complete action of the scram controller cannot be tested in conjunction with the reactor without

excessively interfering with reactor operation, it is necessary to disconnect a scram controller for testing and replace it with a spare. The scram controller will then be tested by connecting it to a simulated reflector drive system and measuring its actual drive rate.

High functional reliability is essential in a safety system. While self-checking and periodic testing greatly reduce the probability of a unit failure affecting the safety performance, a high failure rate would require an extensive repair effort and subject the performance of the scram controllers to suspicion.

D. MANUAL CONTROL

The manual control system provides the reactor operator with direct control over the segment positions. It will provide considerable flexibility, subject mainly to safety restrictions. The following objectives were developed for the manual control system:

- 1) Operator choice of driving either segment, or both, sequentially.
- 2) Operator choice of direction, independently for each segment.
- 3) Operator control of rate.
- 4) Maximum insertion or withdrawal rate of 1 step/sec, with only one segment being moved per step.
- 5) Immediate override of any manual scram control action by the scram controller, when required.
- 6) Automatic override and discontinuance of the automatic controller or computer control system operation, without preventing resumption of the non-manual control.
- 7) Permit switching to the automatic controller or computer control system without causing any incorrect control commands.

E. COMPUTER CONTROL

The computer control system will use a small on-line digital computer to control movement of the segments by comparing instrument values with program values to achieve a desired operating condition. Requirements for this system are:

- 1) Adaptability to a variety of instrumentation signals.
- 2) Full flexibility in segment stepping rates and direction.
- 3) Maximum insertion or withdrawal rate of 1 step/sec, with only one segment being moved per step.
- 4) Capable of being overridden by the manual control system.
- 5) Immediate override of any computer control action by the scram controller when required.

One of the likely uses of the computer control system will be to test variations of the automatic startup plan. Use of the computer will afford greater ease and flexibility in varying the rates and switching points. It will also permit use of automatic limits on the operating conditions to guard against undesirable behavior during startup.

Another possible application will be to demonstrate a minimum time startup. Some rough estimates of the minimum time required may be made. If it were possible to maintain a constant rate of temperature change at the maximum value allowed, $150^{\circ}\text{F}/\text{min}$, the startup could be accomplished in 7.3 min, considering only this limit. The reactivity addition required to go from 50¢ shutdown to full power at the maximum rate of 1 step/sec is somewhat longer, 9.5 min.

These startup times would be accompanied by excessively high temperature differences. Additional time will be required to allow for segment withdrawal to control the rate of power rise subject to the temperature rate and temperature difference limitations. It may be possible to achieve full power operation in as little as 20 to 30 min after beginning startup.

F. BACKUP SHUTDOWN

The backup shutdown mechanism consists of the end-of-life shutdown device modified for ground test use. The radial reflector is divided into two halves that are supported by hinges at the base of the reactor. The pivot points of the hinges are offset from the vertical above the center of mass of the reflector half so that the force of gravity tends to swing the reflectors away from the core. In addition, the hinges are spring-loaded to increase the acceleration at release and to enlarge the final separation angle.

For the ground test reactor, the reflector halves are held in place by magnetic holding coils. Breaking the current to these coils allows the reflector halves to fall away, removing about \$18 in an estimated 0.2 sec.

The backup shutdown mechanism normally will not be part of the automatic protection system. Manual activation will be provided for use in an extreme emergency or if the normal scram system fails to act when required.

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III. DESIGN BASIS

Design of the automatic controller has relied upon digital computer simulation of the reactor system. The simulation program used was written in the IBM CSMP modeling language. A schematic diagram of the system as modeled in the program is shown in Figure 2. Each block represents a lumped temperature node.

Figure 2. System Model Used in Simulations

The reactor kinetic behavior was calculated as the prompt subcritical multiplication of the delayed-neutron source. This approximation is accurate for reactivity up to a few cents less than prompt critical. The maximum reactivity encountered in these simulations was 60¢ , so no error was introduced by this approximation. Reactivity was computed from the specified insertion and withdrawal rates with temperature-dependent reactivity feedback.

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Figure 3. Basic Startup Methods Studied

Heat rejection is by thermal radiation from the radiator to the environment at an ambient temperature of 100°F. This represents the orbital condition with the thermal shroud in place during startup, and also represents the ground test condition.

While reactivity additions and withdrawals by segment motion are actually in discrete steps of $\pm 0.524\beta$, for simplicity, the startup and control phases were converted to equivalent continuous rates. The fuel temperature coefficient was divided among the various fuel nodes in proportion to the square of the relative power.

This simulation model was used to investigate various startup methods. The primary criteria used to select the preferred method were startup time, core temperature difference, and maximum rate of temperature change.

Final consideration of startup methods was restricted to three candidates. These are the single reactivity insertion rate, the single rate with hold above critical, and the multiple insertion rate. These are shown schematically in Figure 3.

The single rate method is simplest, consisting only of a steady insertion until the power control range is reached. The system behavior for a typical insertion rate, as determined by a simulation study, is shown in Figure 4. A

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Figure 4. Startup Transient for Typical Single-Rate Method
(0.01 β /sec 5% Flow)

more complete summary of the results of the simulation studies of single rate startups is listed in Table 1. In each case, at least one parameter exceeded its acceptable value and resulted in rejection of that startup method. These values are indicated in the table by parentheses.

TABLE 1
SUMMARY OF SINGLE-RATE STARTUPS

Reactivity Rate (β /sec)	0.05	0.025	0.01	0.005	0.001*
Time to Full Power (hr)	1.14	2.33	5.9	(12.0)	(60)
Initial Power Transient (kw)	217	112	47	29	8
Reactor Power Overshoot (kw)	25	12	5	3 [†]	3 [†]
Peak Temperature Difference ($^{\circ}$ F)	(560)	(400)	(250)	(182)	82
Peak Rate of Temperature Rise ($^{\circ}$ F/min)	(1440)	(720)	(220)	94	13

*Extrapolated results

[†]Limited by 0.6 β reactivity steps

() Indicates reason for rejection

As shown in the table, the objective that the coolant temperature rise be less than 150 $^{\circ}$ F and the startup time be less than about 12 hr cannot be met by the single rate startup. This is demonstrated graphically in Figure 5, where it is seen that the insertion rates for acceptable temperature rises and acceptable startup times do not overlap. Thus, the single rate startup was determined to be unacceptable under the established objectives.

The single rate with hold above critical is a modification of the single rate startup in which reactivity addition is intentionally halted prior to the initial power transient and then resumed to drive the reactor up to power. The simulation studies for this method are summarized in Table 2.

Taking 10 β reactivity as the most appropriate holdpoint results in meeting the established objectives except for accommodation of the $\pm 10\beta$ reactivity uncertainty. The effect of this uncertainty on the peak coolant temperature rise is shown in Figure 6. Addition of this uncertainty leads to a reactivity, at the hold, of 20 β which results in a peak temperature rise of about 300 $^{\circ}$ F. Subtraction of

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Figure 5. Comparison of Core Temperature Rise (Peak Coolant ΔT) and Time Required for Startup by Single Reactivity Rate Methods

TABLE 2
SUMMARY OF SINGLE RATE WITH HOLD STARTUPS

Reactivity Rate ($\text{¢}/\text{sec}$)	0.025 in all cases			
Reactivity at Hold (¢)	5	10	15	25
Time to Full Power (hr)	3.33	2.84	2.67	2.67
Peak Coolant Temperature Rise ($^{\circ}\text{F}$)	48	130	(215)	(400)
Peak Rate of Temperature Rise ($^{\circ}\text{F}/\text{min}$)	6	34	144	(720)

() Indicates reason for rejection

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Figure 6. Effect of Reactivity Uncertainty on Core Temperature Rise for Single Rate with Hold Above Critical

the uncertainty leaves the reactor critical at very low power during the hold, with the result that the startup transient is produced by reactivity addition during the second ramp. This also causes an unacceptably high coolant temperature rise. Therefore, this startup method was rejected.

The multiple rate startup consists of a rapid rate to bring the reactor near critical, a slow rate through critical to provide a well-behaved initial power rise, and then a moderate rate to drive the reactor to full power.

Simulation studies for several combinations of insertion rates are shown in Table 3.

In the fourth arrangement shown, once the control phase at full power is reached, steps are limited to the slowest rate to provide time for the system to respond. This method appears to satisfy all of the established startup objectives. Details of this startup are shown in Table 4. Results of a simulation are shown

TABLE 3
SUMMARY OF MULTIPLE-RATE STARTUPS

Reactivity Rate (ϕ /sec)				
First	0.05	0.05	0.05	0.25
Second	0.01	0.01	0.005	0.004
Third	0.025	0.05	0.05	0.035
Fourth				0.004
Time to Full Power (hr)	2.57	1.82	2.40	2.89
Peak Coolant Temperature Rise ($^{\circ}$ F)	(250)	(250)	(189)	148
Peak Rate of Temperature Rise ($^{\circ}$ F/min)	(220)	(220)	141	75
Reactor Power Overshoot (kw)	12	25	25	3

() Indicates reason for rejection

TABLE 4
REFERENCE STARTUP

	Switch at	Rate (ϕ /sec)	Time (sec)	Cumulative Insertion (ϕ)
Initial Rate	50 ϕ	0.25	200	50
Second Rate	74.4 ϕ Addition	0.004	6100	74.4
Third Rate	5 kwe	0.035	4100*	182.9
Final Rate		0.004	(Balance of Life)	
Total Startup Time			10,400 sec or 2.89 hr	

*Switching to final rate at attainment of 5 kwe does not change this result for nominal values, but reduces either the actual startup time or the power overshoot for off-nominal cases compared to time-controlled switching.

in Figure 7. (In this simulation, the third insertion rate was used in the control phase, rather than switching to the final rate. With the current design, the power oscillations following the first dip at full power would be somewhat reduced.)

Control of the reactor at full power is based on comparing the current generated by the thermoelectric power modules with reference points set above and

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Figure 7. System Characteristics for Reference Startup

below the current corresponding to the desired power output. If this current is below the lower reference point, reactivity is inserted, at a maximum rate of 1 step in 128 sec, until the current is above this reference. Reactivity is withdrawn, at the same maximum rate, if the current is above the upper reference point.

The initial jump, or drop, in power following a single step is less than 1%. The long-term change is about 0.5%. Depending upon the design of the control

switches, this change may still be within the hysteresis of the actuating switch, resulting in a command for additional control motion. This may be avoided by resetting the control switch after a step has been taken.

All these preliminary simulations had been done assuming a minimum forward flow of 5% in both the primary and secondary coolant systems. However, the pump supply battery would actually provide 5% forward flow in the primary system and 2.5% backward flow in the secondary system. The battery is connected across the primary system pump so that current flows correctly through this pump. Current flows in a backwards direction through the secondary pump and through the pump thermoelectric modules. The battery is connected in this manner because the resistance of the modules is much smaller than that of the pumps at the startup temperature. A connection providing correct current flow in both pumps would require a prohibitively large battery because of the parallel path through the modules.

Performance of the selected multi-rate startup method was retested with these flow conditions by another simulation.

This simulation showed that flow in the secondary system is halted during the first power peak with the result that heat is not removed from the reactor at a significant rate.

The reactor is made subcritical by the ensuing temperature increase and the neutron power decays to a very low level before the continuing insertion of reactivity brings the reactor critical again. In this simulation, the third rate was switched in, on the basis of segment steps, before the power recovered significantly from its decay. As a result, the reactor is over 20% supercritical before any temperature-induced reactivity feedback is produced. The core temperature rise and the maximum rate of temperature change greatly exceed the design objectives.

To avoid this problem, it is recommended that the pump supply battery be disconnected during the first power peak, when the pump temperature increases by 100°F, for example. The heat content of the reactor core would then be sufficient to provide pumping power during the balance of the startup.

It is also recommended that the switching in of the third rate be based on the occurrence of this temperature increase, rather than on the total of segment

Figure 8. Proposed Startup Method Using Pump Temperature Increase for Switching

Figure 9. Generator Power Response to Single Control Step

steps. This would make the startup less sensitive to the reactivity uncertainty and would provide a quicker startup. Otherwise, the startup must be based upon accommodating the extremes of the reactivity uncertainty. An error of -10% , that is, the reactor is initially 60% subcritical rather than 50% subcritical, requires a long period of time at the second insertion rate. This establishes the startup procedure. On the other hand, use of the temperature rise to switch insertion rates eliminates the necessity to design the startup to this worst case. Starting the third rate during the first power peak ensures that sufficient flow exists during the early part of the rise to power. The time from initiation of startup to achievement of 5 kwe ranges from 2.3 to 3.6 hr because of the range in initial subcriticality. The reactivity insertion for the nominal case (-50%) and the two extremes (-40 and -60%) are shown in Figure 8.

This startup has not yet been tested by simulation. The effects of the reactivity uncertainty and the uncertainties in the temperature coefficients have not been tested either.

After the startup has been accomplished, further segment insertion (or withdrawal) is controlled by the condition of the current monitor switches. If the current from the thermoelectric generator is more than 2.5% below the value corresponding to 5 kw (that is, 167 amp at 30 v), the current monitor will signal for insertion of reactivity. Similarly, if the current exceeds the nominal value by more than 2.5% , withdrawal of reactivity will be requested.

The calculated variation of the thermoelectric generator power output for a single step insertion (0.524%) is shown in Figure 9. It can be seen that the increase in power is far less than the width of the control band. (A similar power decrease below the upper current control limit would be observed as a result of a single step withdrawal occasioned by a rise in power to the control limit.) It is likely that the hysteresis of the control switches would exceed the power change, with the result that a single segment step would not move the switch out of its initial condition and so additional steps would be requested. This would introduce a control problem only if the hysteresis were to approach the control band width. In this event, stability can be regained by resetting the current switch after a time interval chosen to allow the power to change sufficiently from the control limit. If there is no stability problem, the effect of a

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Figure 10. Reactor Conditions for Startup Accident with Power Level Scram

significant hysteresis band will be to request several segment steps consecutively and thus place the current closer to the mid-range of the control band after the control action.

While it is expected that only reactivity insertion will be required as a result of long-term reactivity losses, the possibility exists that during significant periods of time the reactivity will increase. One possible cause of this could be an unexpected difference in the burnup rate of the burnable poison and loss of reactivity by the fuel. This would be detected during the course of the ground test and could be adjusted for the flight reactor. The changes in external heat load resulting from varying orbital positions may also induce shorter-term reactivity changes that can be positive. Inclusion of bilateral control, to provide compensation for positive reactivity changes, as well as the expected negative changes, requires only a small increase in the complexity of the automatic controller.

Several postulated accidents were simulated to test the adequacy of the normal scram rate. These simulations are discussed in detail in the summary report on the ground test hazards evaluation and so only some conclusions are presented here.

A series of startup accidents, in which reactivity is added at a constant rate until the power trip level is exceeded, were tested with two scram rates for different reactivity insertion rates. The two scram rates used were $-5.0\text{¢}/\text{sec}$ and $-2.5\text{¢}/\text{sec}$, which are approximately the present nominal scram rate and the scram rate with one segment inoperative. The insertion rates ranged up to $+1.0\text{¢}/\text{sec}$, which is nearly twice the maximum rate allowed by the design objectives.

A power level trip at 125% was used, although a period trip would have started a scram well before this power was reached. Thus, these simulations were conservative and overestimate the severity of the accidents.

The maximum power reached in these cases, and other significant parameters, are shown in Figure 10 as a function of insertion rate. The scram rate provided by both segments is shown to be generally adequate, although the core temperature rise exceeds the design objective for insertion rates greater than about $0.7\text{¢}/\text{sec}$. For insertion rates less than the maximum allowable, all parameters have acceptable values.

The single segment scram, for power level trips, is not completely adequate. For insertion rates above 0.25¢/sec, the core temperature rise exceeds the allowed value. For insertion rates above 0.38¢/sec, the allowed inlet temperature rate-of-change is also exceeded.

While these simulated accidents indicate the potential of damage to the core, in no case is there any hazard to the operating staff or the general public. It should be recognized, moreover, that for the startup accidents used in this study the power level trip serves as a backup to the period trip. Extension of these test cases to the more realistic condition of a period trip, which was planned as part of the ground test hazards evaluation, would show that the period trip would limit the accident results to much less severe values, and that accidents that actually lead to operation of the power level trip also produce much less severe results.

As an example, a startup accident consisting of steady insertion of 0.524¢/sec and terminated by a scram rate of -5.24¢/sec at a period trip of 5 sec, has a maximum power of 2% full scale. All temperature differences and temperature rates in this simulation were negligible.

All other accidents reviewed are less demanding in terms of the scram rate requirement and support the adequacy of the scram controller design.

In flight operation the automatic controller would be located in the instrument payload section of the spacecraft and so must survive the payload radiation dose. The reactor is the major source of radiation to the payload. In the present design the lifetime gamma radiation dose is equivalent to 10^6 rad in carbon. The neutron dose is 10^{12} nvt of 1 Mev equivalent. The automatic control system must operate properly during exposure to the average dose rates and survive the total dose. The average gamma-ray dose rate is 23 rad/hr, while the average neutron flux of 6×10^3 n/cm²/sec corresponds to a dose rate of the order of 0.01 rad/hr for nonhydrogenous materials such as most electronic components.

These dose rates are sufficiently low that damage effects result only from the accumulated dose. The design of the automatic controller is based on the use of bipolar digital integrated circuits as logic units and bipolar power transistors as power switches for the segment actuators. The digital integrated circuits

exhibit moderate degradation at a neutron dose of 10^{13} nvt and a gamma dose of 10^7 rad, both of which are 10 times the expected dose. The power transistors suffer moderate degradation at 10^{12} nvt and 10^7 rad. This degradation is most serious in circuits using low signal levels and operating with fast switching times. In the present application, neither condition exists. Adequate power and power dissipation capability are available and the speed requirement is very slow. This allows considerable derating in the required performance with a resulting increase in the probability of operating properly in spite of the radiation dose.

During its use in the ground test program, the automatic controller will not be subjected to any significant radiation dose. However, additional units will be mounted near the payload position in the ground test system and periodically tested to obtain information on the long-term radiation tolerance of these prototype units.

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IV. DESIGN RESULTS

Functional designs of the automatic controller and scram controller have been developed from the design basis described in the previous section. These functional designs were used to prepare specifications for the two controllers.

A block diagram of the automatic controller is shown in Figure 11. The blocks contained within the dashed line comprise the automatic controller. Telemetry output provides information on the segment position and electrical current. Input is provided to initiate the startup sequence and to permit ground control of the reflector segment positions.

In the automatic controller, a redundant pair of control logic units generate segment step commands based on a preset program during startup and as required to maintain the desired electrical current during power operation. Both control logic units have the same program and are supplied with the same information regarding the segments and the electrical current status.

The control logic units thus act together in sending step commands to the delay unit. This unit passes these commands provided that more than 1 sec has elapsed since the last commands were passed. If a second command occurs less than 1 sec after the previous command, the second command is blocked. This serves to limit the stepping rate and ensures that any previously ordered step has been completed.

Step commands passed by the delay unit are processed by the memory logic unit to insure that the segment positions are balanced. During startup and, it is expected, throughout the operating life of the system, only segment insertion will be required, and the memory logic unit will pass insertion commands alternately to the two segment drive sequences. Should subsequent withdrawal be required, the segment that was last stepped in will be the first to be stepped out; thereafter, stepping will alternate between segments.

The phase sequencer generates a series of pulses that are used to control power switches that pass current to the associated segment actuator. The coils in the actuator are identified as A, B, C, and D for the stator phase coils, and E for the brake release coil. For insertion, the phase coils are energized in

Figure 11. Automatic Controller Block Diagram

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Figure 12. Actuator Current Pulse Forms

the order ABCDA; the E coil is energized midway through the first A pulse, releasing the brake, and is de-energized midway through the final A pulse, setting the brake. For withdrawal, the sequence is ADCBA, with the brake release pulse generated in the same manner as above.

The sequencer should be designed to block additional step commands until the present sequence has been completed.

The pulse forms desired for operating the actuator are shown in Figure 12. An overlap between phase pulses of 10 to 50 msec is provided to ensure that the magnetic field is established in the adjacent pole before termination of the existing field.

Pickoff coils around the brake lead E and the B and D phase coil leads provide signals that indicate a segment step to the position monitor. The brake signal (E') indicates that a step has been started; the order of the B' and D' show the direction. An "in" step adds one count to the segment position monitor while an "out" step subtracts one count. The net number of counts is stored separately for each segment and added together to obtain the total net number of steps in. This quantity is used to control a switching point in the startup program. The individual segment position information is available for telemetry.

The current monitor measures the current produced by the thermoelectric generator and signals to the control logic units if this is below the control band or above. If it is below, insertion is requested; if above, withdrawal. Subsequent demands are blocked for 128 sec to allow the system sufficient time to respond to the reactivity change. If the hysteresis of the current monitor switch is so great as to induce instability, this delay can also be used to reset the switch.

A preliminary design based on integrated circuit logic devices has been developed. This design is shown in Figure 13. A slow oscillator, with a 2-sec period, generates a basic series of pulses that are gated on and off by other parts of the circuit to produce the desired control action. This is determined by signals from the position monitor (identified as P_1), a temperature monitor on the pump (T_1), and the current monitor (I_{LO} , I_{HI}).

The reference startup sequence is shown graphically in Figure 14. The reactor is initially shut down by β_3 relative to the cold critical (zero-power)

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Figure 13. Automatic Controller Control Logic Unit

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Figure 14. Reactor Power and Inserted Reactivity During Preliminary, Startup, and Operation Phases

configuration. During the countdown, the segments are driven part way in, bringing the reactor to 50¢ subcritical, in order to shorten the required startup time and reduce the battery power needed. Further action is delayed until a satisfactory stable orbit has been achieved and verified. At that time, the automatic startup procedure is begun by starting the oscillator.

A rapid insertion rate of 0.26¢/sec (resulting from a stepping rate of 0.5 step/sec) is used to add 45¢. (During this time, the normal control circuit is also requesting reactivity addition, but at so slow a rate that only one or two steps result.) With an estimated uncertainty of $\pm 10\%$, the reactor is between 15¢ subcritical and 5¢ supercritical. This rate is switched off by the position monitor acting on a preset number of segment steps. The normal control circuit continues to add reactivity at a slow rate (128 sec/step) acting in response to the signal from the current monitor that the current is below the lower setpoint.

At the time the reactor is about 9¢ supercritical, a moderately rapid power rise occurs that is terminated by the core temperature coefficient. At this point, the battery supplying pump power is turned off and a third, faster, insertion rate is switched on. Switching of both the battery and the insertion rate is based on a rise in the pump temperature. The normal control circuit is still requesting reactivity insertion also, making the average rate 0.037¢/sec. This insertion rate continues, driving the reactor up to power by overcoming the temperature defect, until the lower current control boundary is reached. The startup circuit is then blocked and all further reactivity adjustment is controlled by the current monitor switches at the maximum rate of one step (0.524¢) per 128 sec. After initial stabilization, it is expected that one step will be required approximately every five days.

The details of operation are as follows: prior to enabling the oscillator with the start signal, no stepping commands are generated. When the oscillator is started, pulses at 2-sec intervals are passed through the first AND gate. These pulses go directly to one AND gate and through an eight-fold divider to another AND gate. The first of these gates passes oscillator pulses, which result in step commands, until the total number of segment steps exceeds a preset number, P_1 . If the pump temperature rises above the setpoint T_1 before

segment position P_1 has been reached, this will also turn off the first rate. This is unlikely to occur but has been included as a precaution. When this gate is turned off, insertion commands continue to be generated by the normal control circuit at a rate of one every 128 sec. This continues until the reactor power generates sufficient heat to raise the pump temperature by approximately 100°F. At that point, the other startup AND gate is enabled and passes the divided-down pulses from the oscillator to increase the reactivity insertion rate to an average of 0.037¢/sec. Simultaneously, the battery supplying pumping power is turned off. This is necessary because the battery-supported flow in the secondary system is backwards and prevents establishment of the necessary temperature differential across the pump thermoelectric modules. With the battery disconnected, the pump power is provided by the thermoelectric modules in rough relation to the reactor power.

This insertion rate drives the reactor up to power, balancing the temperature defect, until heat is generated and transferred at a sufficient rate to produce the desired electrical current. When this condition is achieved, a flip-flop is turned off, blocking passage of oscillator pulses into the startup circuit and also blocking step commands from the startup circuit. Thus, this portion of the controller is eliminated from further operation.

The passage of commands for either insertion or withdrawal generated by the normal control circuit is blocked by a delay circuit for 128 sec following a step. This is done by means of a flip-flop that is turned on by a step signal and enables an AND gate to pass oscillator pulses to a 64-fold divider whose output pulse turns off the flip-flop. The off flip-flop output ($\bar{Q}$) enables insert and withdraw AND gates to pass step commands as determined by the current monitor. The step signal for the delay flip-flop is generated by an EOR gate that also serves to prevent passage of simultaneous insert and withdraw commands in case of a malfunction.

Manual control, or ground station control by means of telemetry, is permitted by use of a pair of signals. One signal (M_C) blocks the other control functions while the second (M_I or M_W) indicates insertion or withdrawal. Discontinuance of the manual control signal returns operation to the automatic controller.

A complete reliability analysis of this preliminary design has not been conducted. Some comments about reliability can be made at this point, however. A large variety of failure modes can be tolerated by the automatic controller without resulting in complete failure. Disabling of one segment drive at any time can be tolerated without immediate severe consequences. If this fault occurs before startup, the startup can still proceed; however, the time to reach power will be doubled. Operation at power will not be affected significantly other than a shortening of the operating life at full power.

Failure of the startup circuit, even if it occurs in both control logic units, will not prevent startup. The normal control circuit will provide the startup reactivity, although considerably more time will be required.

Failure of either control logic unit in a passive mode (no signal out) will not cause any problem. The other unit will provide the necessary control signals. Failure in an active mode, continuously calling for insertion or withdrawal, would cause serious trouble and no protection against this has yet been provided, other than switching over to manual control. A failure in which one control logic unit erroneously calls for insertion or withdrawal at the maximum normal control rate will be compensated by the other control logic unit. Correct control will result for some, but not all, conditions.

Integration of the automatic controller in the ground test operating system has not been developed in much detail, in part because design of the other parts of the operating system have not progressed very far. The automatic controller would interface with the reactor control system by means of a manually operated mode selector switch. This switch places the segment actuator under the control of the automatic controller, the computer, or the reactor operator. Operating information, that is, segment position and thermoelectric current, are supplied constantly to the automatic controller so that it can be switched in at any time without generating inappropriate control commands. Operation under control of the automatic controller would permit manual adjustment by means of the ground control telemetry input.

To provide status information to the operating staff, the automatic controller would have visual annunciators of the current monitor condition and would sound an audible annunciator when a segment step command is generated.

The automatic controller utilizes commercially available integrated circuit digital logic units and analog devices, and power transistors as the active elements. These components and the necessary passive components are suitable for spacecraft applications and, in fact, have a history of such applications. The design of the automatic controller is well within the realm of current practice and can be successfully produced.

The basic scram controller conceptual design consists of a phase sequencer, an actuator power supply, and a set of power switches as shown in Figure 15. This design utilizes much of the circuitry of the automatic controller. The desired form of the current pulses from the scram controller is shown in Figure 16. The order of pulses is always ADCB, to provide withdrawal of the segment. This sequence repeats every 200 msec to yield 5 steps/sec. The leading edge of each current pulse must overlap the trailing edge of the preceding pulse to avoid loss of torque. This overlap is measured at 50% of the pulse height and should be 5 to 10 msec.

The brake release coil is energized midway through the first A-phase pulse following a scram signal, and holds the brake off until the segment is driven against the out limit switch. The coil is de-energized, and the brake set, during the first A-phase pulse after the limit switch is closed. The actuator driving torque is insufficient to overcome the brake holding torque if the brake is not released.

There are two basic requirements that the scram system design must meet. The system shall shut the reactor down when required. The system shall not shut the reactor down when not required. Redundancy and checking are used to insure proper action and protect against incorrect action. At this point it should be noted that redundancy is provided by use of both segments as independent scram mechanisms. Subject to operational limits on segment positions that are discussed in the report on ground test hazards, either segment can provide adequate accident protection. Thus, if common failure modes are excluded in the design and construction of the safety system, no single failure in a scram controller can incapacitate the safety system.

A detailed design has not been prepared for the scram controller. It is intended that this function will be performed by an electronics fabricator who

Figure 15. Scram Controller Block Diagram

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Figure 16. Current Pulses to Actuator for Scram

will build the required units following review and approval of the design. However, to serve as an aid in such a review, a preliminary design has been completed. This is shown, in part, in Figure 17.

The phase sequencer consists of a series of monostable multivibrators (one-shots) and pulse-conditioning flip-flops. Each one-shot is triggered by the previous one-shot turning off after its characteristic on-time of 50 msec. The one-shots are wired so that the sequence ADCBA... is the only possible sequence. The flip-flops stretch the one-shot pulse to provide the desired overlap and eliminate any problems caused by differences in the on-time of the one-shots. Each flip-flop is turned on by its associated one-shot and turned off, with the desired overlap, by the succeeding flip-flop.

A pulse is taken from the A-phase one-shot and used, by means of a one-shot with a 25-msec on-time, to delay release of the brake until midway through the A-phase pulse. The logic units also provide for locking out the brake if a scram signal exists during the second half of the A-phase pulse, and for setting the brake when the out limit is reached.

Self-checking is provided by running the phase sequencer continuously and allowing the generated pulses to partially turn on the phase and brake power switches. This is done by passing the pulses to the power switches through current dividers. The current dividers for the phase power switches are connected to ground, in the non-scram condition, by means of the indicated ground switch. This ground switch is turned off by a flip-flop triggered by the scram signal. Turning off the ground switch eliminates the current division and allows full-current pulses to pass to the power switches. The same flip-flop delivers a signal to the brake logic units, which triggers a flip-flop turning on the brake switch during the second half of an A-phase pulse. This eliminates the current divider for the brake switch.

By partially turning on the power switches, low-current pulses are passed to the phase and brake coils. These current pulses are too low to release the brake or provide any significant stepping torque.

Pulses are sensed at various locations in the circuit and used to check the performance of the scram controller. A conceptual self-checking circuit is shown in Figure 18. This circuit sets an alarm for any one of three failure

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Figure 17. Scram Controller Schematic Diagram

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Figure 18. Self-Checking Circuit for Scram Controller

modes: if a phase sequence pulse has been generated but does not produce a power switch pulse; if a power switch pulse exists without an associated phase sequence pulse; and if the time-averaged current passed by a power switch falls below a reference value. This last fault can result from any of several failures that either cause the current pulses to be too small or at too low a repetition rate.

The alarm would indicate to the operating staff that the unit should be replaced with a spare and repaired.

While the existence of two complete and independent scram systems provides redundancy in favor of ensuring protection when needed, it is desirable to include redundancy in the scram controllers also. Redundancy to guard against generating a scram incorrectly should also be provided. Only a beginning has been made in this direction. A detailed analysis of the controller is required to identify failure modes and the results of those failures.

The most common failure modes of transistor switches are open-circuit failure and short-circuit failure. Either of these modes can incapacitate the scram controller or cause it to malfunction. Open circuits can be guarded against by use of parallel transistors. This is recommended for the power switches in particular; this aids reliability by permitting a greater derating of components. Short-circuit failure of a power switch is detectable by the self-checking circuit.

Short-circuit failure of the ground switch will prevent scram action by that scram controller. Failure by open circuit will erroneously pass full current pulses to the actuator, but this will not result in motion since the brake is not released. To counteract this, the ground switch can be made self-checking against short circuits and also relatively immune to open circuits by using four transistor switches in parallel, each one associated with one of the phase sequencer one-shots and gated off by the firing of the one-shot. Detection of a ground switch transistor conducting while its associated one-shot is on will indicate a short circuit failure and set off an alarm. The four parallel paths reduce the probability of open circuit failures applying full current pulses to the power switches.

Redundancy requirements and self-checking performance for the scram flip-flop and the logic units for the brake have not been developed in such detail.

Because of the system redundancy provided by the two reflector segment drive systems, it is not essential that an individual scram controller function properly in spite of any single failure. However, the failure must be readily detectable. In addition, it is desirable that no failure lead to scram action as a result of the failure.

In addition to the self-checking functions designed into the scram controllers, assurance of proper performance will be provided by periodic testing of each unit. This will be done by having three controllers installed, with two connected to the segment actuators and the third serving as a spare. During each test period, the unit serving as a spare at the time would be tested and then connected to one of the actuators in place of the unit previously connected. The newly designated spare unit would then be tested and any detected discrepancies repaired. This unit would serve as the spare until the next test period, at which

time it would be retested and installed in place of the unit not last tested. Status rotates between in-service and spare among the three units, allowing time between test periods for repairs.

Detailed test procedures have not been prepared. An obvious part of the test would be to determine the speed at which the controller drives out a simulated segment. Other diagnostic tests, such as response time, voltage levels, individual checking of redundant components, and checking of the self-checking circuit would also be required and should be considered in the design. A test fixture is recommended to facilitate the testing and increase accuracy.

The arrangement of the scram controllers in the equipment rack and connection to the actuators is shown schematically in Figure 19. The three controllers are installed in separate bays to provide physical separation. The middle unit is connected to an adapter that permits supplying its output to each of two selectors. The other controllers are each connected to a single selector. Each selector thus has two controllers connected to it. The output of one controller is routed to a segment actuator while the other controller is routed to another adapter for connection to the test actuator. Two controllers provide signals to segment actuators for operation in case of a scram, and the third is available for testing. Mechanical interlocks would be required to prevent connecting one controller to both actuators and to prevent connecting one controller to both the test fixture and an actuator.

Figure 19 also shows details of the wiring connection at the vacuum vessel wall. At this junction, the scram controller wiring and the control system wiring are combined to permit use of only one set of actuator wires within the vessel and on the reactor. Each actuator requires four wires to the phase coils, with two return wires connected to alternate pairs (A, C and B, D phases), and a supply wire and return wire for the brake. Diodes are placed in the incoming lines of the control system to block passage of scram pulses into the control system. A short circuit to ground in the control system could otherwise shunt scram pulses and prevent proper scram action.

The scram and control system cable connectors are different, thus preventing incorrect connection. The scram connector and cable incorporate an additional pair of conductors that are connected together at the vacuum vessel

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Figure 19. Scram Controller Arrangement and Connecting Wiring

adapter. This provides a continuity test circuit to indicate correct connection of all connectors and switches between the controller and the vacuum vessel.

The phase sequencers, power supply, and power switches of the scram controller can be modifications or direct copies of the comparable subsystems of the automatic controller. This commonality of design and components facilitates the design, fabrication, and maintenance of these units.

The manual control system provides the reactor operator with the ability to independently adjust segment position as required to obtain the desired reactor system conditions. In concept, it consists of two manually operated switches, one for each segment, that request drive signals, in or out, depending upon the direction the switch actuator is pressed. A "push-it-in, pull-it-out" analogy would be used for the switches to aid the operator in associating with the segment actuation. The drive signals are generated by a phase sequencer and associated power switches, as used in the automatic and scram controller. Segment steps would be sensed and counted in the same manner as for the automatic controller, but independent of the automatic controller.

Operation of one manual switch would cause the associated segment to be driven in the chosen direction at a rate of 1 step/sec. Operation of both switches, in the same direction or in opposite directions, would cause the two segments to be stepped alternately at a rate of 1 step/sec. Slower rates would be obtained by intermittent operation of the switches. The specified rate is sufficiently slow that the segments may be driven in discrete single steps as required.

No details of the manual control system have been prepared.

Similarly, no details have been developed for the computer control system, beyond possible functional requirements as discussed earlier in this report.

The backup shutdown system, which is an additional safety system intended for use only with the ground test reactor, is based on the end-of-life shutdown device for the flight configuration reactor. Each reflector half would be separately driven into position against the core by means of an air piston. Each reflector half would be held in place by two electromagnets, each capable of holding the segment in place against the gravitational and spring forces. The

driving piston would then be retracted. The redundancy of the electromagnets permits testing of the release circuits and reduces the possibility of false release of a reflector half.

Intentional release of the reflector halves would be caused by interrupting current to the holding coils. This would be done by pressing a "Manual Shutdown" switch or the "Evacuate" switch.

Should the performance capability and redundancy of the normal scram system be reduced, as a result, for instance, of failure of a segment actuator, the backup shutdown could be connected as a fully instrumented automatic scram. This would restore the redundant capability of the protection system and allow continued operation.

V. RECOMMENDATIONS

Clearly, much work is still required on all parts of the control system. Some parts of the conceptual design still require verification, while all of the detailed design work remains to be done. In particular, the proposed startup needs to be tested by simulation, as does the behavior of the system during restart following long-term shutdown. The adequacy of the scram rate should be demonstrated for more realistic accident conditions than has been done so far.

Following fabrication of the controllers, reliability and life testing should be performed. Because of the very low in-service duty cycle, this testing can be accomplished in a relatively short period of time.

During operation of the ground test system, periodic checking of the scram system must be done. The detailed procedures for doing this have not yet been developed.

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VI. CONCLUSIONS

Designs for the automatic and scram controllers have been developed adequately to provide a foundation for the procurement specifications and to form a basis against which final designs may be judged. Redundancy in the scram system and in the scram controller design, self-checking and periodic testing, and proper maintenance are expected to provide a safe and reliable reactor protection system. The automatic controller provides the necessary flexibility, yet is simple enough to have a high reliability.

Some design and functional details still need resolution; however, the basic designs appear to meet all the objectives established to date.