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Highly Efficient Automated Control for an MGR Gas Turbine Power Plant

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Abstract

A control system design for the Modular High Temperature Gas-Cooled Reactor Gas Turbine power plant (MGR-GT) is presented. The control system is designed to provide full-scale automated control functions for power output regulation and plant protection in accordance with utility requirements for modular nuclear power plants. Control of the plant power output is based on a unique integration of inventory control and bypass control, which not only enables required load following capabilities but also offers 45% electric generating efficiency over the power ranges from 100% to 50% of the rated level. The reactor power is controlled based on the strategy of maintaining constant core outlet temperature. This approach minimizes the occurrence of thermal transients and temperature redistribution in the core during reactor power changes. In addition, the control system also provides emergency protective control to protect the plant components and to mitigate the likelihood of bounding safety events in case of severe accidents. The operation of the control system is automated by controllers implemented based on the state-space feedback control methodology. A spectrum of transients in both normal and far-off normal conditions has been simulated to evaluate the operability of the plant. The simulation results for a few selected events will be described. The design demonstrates that the MGR-GT is a highly efficient and robust controllable power plant.

1. Introduction

MGR-GT is a conceptual design for a direct Brayton-cycle nuclear power plant[1]. The plant baseline design configuration is shown in Fig. 1. It consists of a passively-safe 200 MWth high temperature gas-cooled pebble bed reactor (MGR) as energy source, a compact helium-to-helium recuperator, a helium-to-water precooler, and single-shaft turbomachinery directly driving a 2x50 MWe generator at 10,000 rpm. Frequency conversion is accomplished with solid-state electronics. The design is aimed at developing a near-term nuclear energy option that offers both passive safety and economical competitiveness through modular design approach.

This work is intended to develop a control system for the MGR-GT. Unlike conventional nuclear power systems in which problems of control are simultaneously problems of safety, the use of the inherently safe reactor in the MGR-GT has greatly reduced the safety requirements for the control system. As a result, the complexity, and thus the costs, of the control system are reduced. The design of the control system can now focus on achieving the optimum control performance. Although plant protection is still required, such requirements are no longer a safety consideration but merely an issue of investment protection.

The design of the control system is based on the selection and integration of potential control methods suitable to the MGR-GT in accordance with the Utility/User requirements for modular nuclear power plants[2]. The control system is designed to regulate reactor power, to control turbomachinery power and speed, to maintain the turbine inlet temperature, to stabilize the thermal conditions in the plant shutdown. In addition, the control system also provides emergency control to protect plant components and to mitigate the likelihood of bounding safety events in case of severe accidents. The control functions are automated by numerous controllers developed based on the state-space feedback control methodology.

2. Fundamentals of power control

The control modalities applicable to the MGR-GT include helium inventory control, flow bypass control, and reactor reactivity control, as illustrated in Fig. 2.

The most efficient method for power regulation is helium inventory control, which varies the cycle pressure to control the plant power. When the power is to be reduced, helium is withdrawn from the plant circuit via the inventory reduction valve, Vi1, and stored in the inventory control vessel. If the power is to be raised again, the stored helium in the vessel is fed back into the circuit through the inventory increase valve, Vi2. Ideally, the inventory control reduces the system pressure level, but causes virtually no change in the cycle pressure ratio. As a result, if the cycle temperature conditions are kept constant, the flow velocities remain unchanged at reduced power levels and the turbomachinery operates near the design points, maintaining the cycle efficiency near its optimum value.

A few factors govern the applicability of inventory control: First, the range of the power control that an inventory control system can accomplish is determined by the storage volume of the inventory vessel used. The larger the storage volume, the broader the power control range. In the MGR-GT, for example, a 500 m^3 inventory vessel would permit the maximum 25% power changes before a pressure equilibrium is reached[3]. Control for more extended power levels requires using either a larger vessel or a helium transfer pump. The transfer pump can be used to continuously compress the helium into the inventory vessel after the pressure equilibrium. However, the use of the transfer pump

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would undoubtedly make control operations more complicated. Second, the rate of the power control is primarily limited by the size of the inventory control valves. The larger the size of the valves, the more the helium would be allowed to pass through, and thus the faster the power could be altered. In general, large gas turbine systems which possess massive helium inventory would have to rely on both large vessel volume and sizable valves to make the inventory control effective. The inventory control is thus probably not economically justified in the large systems. Finally, inventory control is of limited capabilities in response to rapid power changes[3]. It is also incapable of stabilizing the turbomachinery operation, in particular, the rotor speed, due to the relatively large time constants characterizing helium transfer and storage processes. These drawbacks make inventory control inadequate to satisfy all of the control requirements for the gas turbine operation.

Bypass control varies cycle pressure ratio to control the plant power. For power reduction, part of the helium from the high pressure side of the cycle is bypassed through the bypass valve, Vb, to the low pressure side, as illustrated in Fig. 2. As a result, the turbine pressure head and mass flow rate drop, so that the turbine power decreases. Because of the change in cycle pressure ratio, the cycle thermal efficiency would be reduced at partial power operation. However, the bypass control enables rapid power control to match rapid load changes and to maintain turbomachinery speed. Therefore, it is widely employed in gas turbine power plants, particularly in large systems where inventory control is not feasible.

Reactor reactivity control is used to regulate the reactor power according to the desired thermal power inputs to the gas turbine power conversion system. In addition, it is also required to shutdown the reactor power and secure controlled conditions under any credible operating circumstances, to compensate for the core temperature feedback of reactivity, and to allow for Xenon override and burn-up compensation. Reactor reactivity manipulation is accomplished by introducing an amount of negative reactivity into the core with the insertion of control rods and small absorber spheres.

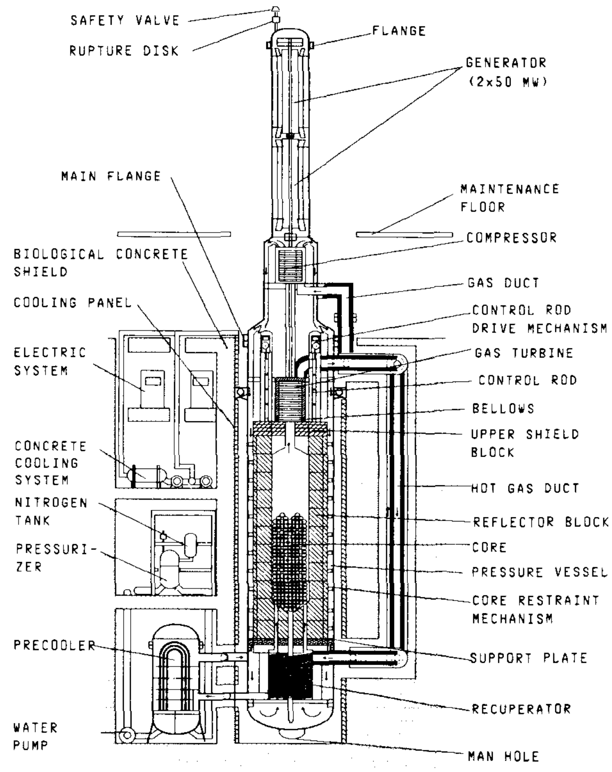


Fig.1: The MGR-GT baseline design configuration

3. Control System Design for the MGR-GT

The foregoing section discussed the control methods on which the design of the MGR-GT control system was based. The MGR-GT control system consists of a Plant Regulation System (PRS) and a Plant Protection System (PPS), the development of which is described in the following.

3.1 Plant Regulation System

The PRS operates the plant using automated control at any electric load within the operating range between 25% and 100% of the nominal level. Specifically, the PRS is required to provide the following load-following capabilities:

1. Normal-rate load changes: up to ±3% of rated load per minute.
2. Maximum-rate load changes: ±5% of rated load per minute.
3. Maximum step load changes: up to ±10 % of rated load.

The major control functions of the PRS include:

1. Control reactor power and maintain the reactor outlet temperature.
2. Control the power and speed of the turbomachinery to match load changes.
3. Provide programmed control for plant startup and shutdown.
4. Control thermal conditions imposed on the components during transients.

3.1.1 Reactor Power and Temperature Control

The MGR-GT reactor core possesses a strong negative temperature coefficient ensuring its inherent shutdown capability. From the control point of view, however, large changes in core temperatures require extended reactivity manipulations with control rod maneuvers in order to compensate for the temperature feedback of reactivity. Furthermore, it is also difficult to make rapid changes in core temperatures because of the large thermal capacity of the core. Therefore, the control for the reactor power should avoid excessive variation of the core temperatures.

A strategy of constant reactor outlet temperature control has been chosen for the reactor power control, *i.e.,* at all operating power levels, the average helium temperature at the reactor outlet is maintained constant at 850°C. The reactor power is adjusted with control rods so as to keep the core outlet temperature unchanged. Constant temperature operation of course has ancillary benefits, the most important of which are that the core thermal transients and temperature redistributions can be minimized during reactor power changes, and that the constant reactor outlet temperature, thus the constant turbine inlet temperature, allows maintaining high system efficiency at reduced power levels.

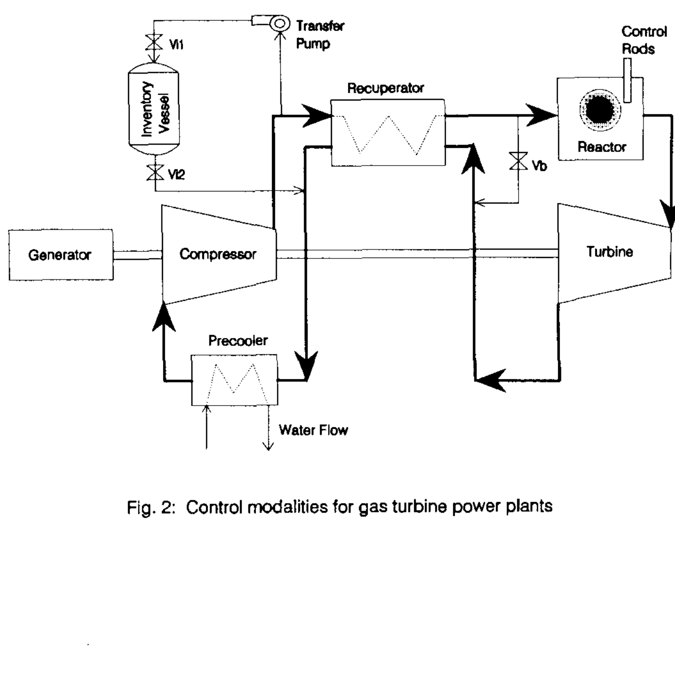


Fig. 2: Control modalities for gas turbine power plants

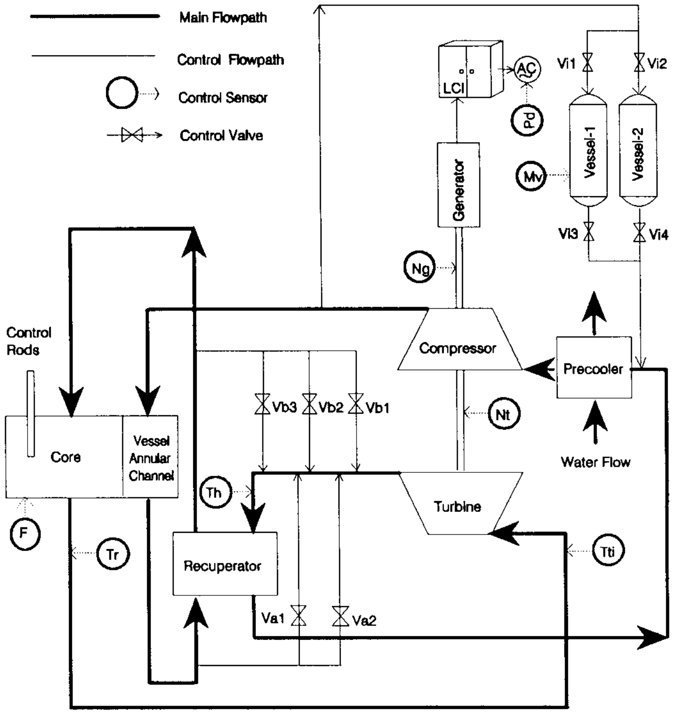


Fig. 3 The MGR-GT control scheme

3.1.2 Load and Speed Control

Inventory control offers the potential for highly efficient power control and is suitable to the control of small power plants. Operation of inventory control may be simple if designed properly. With these advantages, inventory control is selected as a primary means for the power control in the MGR-GT.

The inventory control system developed for the MGR-GT is a two-inventory-vessel system as illustrated in Fig. 3. Two helium inventory reduction valves, Vi1 and Vi2, connect the circuit point downstream of the compressor with the inventory vessels, while two other inventory increase valves, Vi3 and Vi4, connect the vessels with the circuit point upstream of the precooler. On demands for power reduction, a correct amount of helium is withdrawn via the inventory reduction valves into the inventory vessels, which are filled one after another until an equilibrium pressure is reached. If the power is to be raised again, the helium is allowed to leave the vessels in a reverse sequence and return to the circuit through the inventory increase valves.

The use of multiple vessels allows efficient use of vessel storage volume. The two vessels of 500 m^3 each permit a total 40% power change without using transfer pump. The compressor serves as an integral transfer pump with the pressure swing being limited to the compressor ratio. The size of the four inventory control valves is all 10 cm diameter. To obtain the maximum power control capacity, the initial pressures and temperatures in the two vessels are set to be those at the compressor inlet at the time when the individual vessel is put into operation. The number and volume of the vessels as well as the size of the valves are the results of extensive optimization calculations[3].

To overcome the difficulties of inventory control in matching rapid load changes and controlling turbomachinery speed, limited bypass control is integrated into the Plant Regulation System to assist the inventory control system in load and speed control. The resultant integrated load and speed control scheme is as follows. Power control for the load ranges from 100% to 90% is provided by the limited bypass system alone. As a result, potential power necessary to control rapid load changes and speed is reserved in the form of bypass flow, which can be modulated rapidly. Power control between 90% and 68% is accomplished by the inventory control system with the inventory vessel, Vessel-1, while the load between 68% to 50% is controlled by the inventory control system with the second vessel, Vessel-2, after the pressure in the first vessel has reached equilibrium with the circuit pressure. The system efficiency is maintained close to 45% in the load ranges beyond 50%. The bypass control is again used for the load ranges from 50% to 25%. Since long-term operation within the low-load ranges is not expected, the less efficient performance of the bypass control in this low-load region is not a serious concern.

3.1.3 Attemperation control

Attemperation control is only needed to accompany large flow bypass to prevent excessive thermal stressing in the plant components. Since no large bypass control is used during normal power regulation, thermal control is not required for normal operation. However, during plant startup and shutdown, substantial flow bypass is used. As the pressure head of the turbine is significantly reduced due to large flow bypass, the turbine outlet temperature would rise considerably. Consequently, attemperation control must be provided to protect the low-pressure recuperator from thermal overstressing. Through the attemperation bypass valve, Va1, of 10 cm diameter, the cold helium from the downstream of the compressor can be introduced to mix with the hot helium from the turbine exhaust in order to control the thermal conditions at the low-pressure recuperator inlet.

3.1.4 Plant Regulation System controllers

To automate the PRS control functions, a set of controllers as shown in Fig. 4 was developed, including startup/shutdown controller, attemperation bypass valve controller, bypass valve controller, reactor core flux controller, and inventory valve controller[3]. The controllers manipulate several plant operating variables, including turbomachinery speed N_t, helium inventory in the inventory vessels M_v, reactor outlet helium temperature T_r, and low-pressure recuperator inlet temperature T_h. The location of each manipulated variable is shown in Fig. 3.

The interior design of the controllers relies on different feedback control laws depending on the specific control functions that each controller performs. While details of each controller design varies from one another, the design methods can be explained using the bypass valve controller as an example. For the bypass valve controller, the speed of the turbomachinery, N_t, is the manipulated variable which is regulated following the speed regulating signal, N_{tr}. The control loop is composed of proportional, derivative, and integral gains with rate and magnitude limits filtering the amplified control signals. The proportional feedback blended with the derivative signal of speed error ($E_N = N_{tr}-N_t$) provides the capability of stabilizing the rotor speed and shaping the speed behavior with desirable reaction rate and damping. The integral control action, which integrates the speed error over the transient period

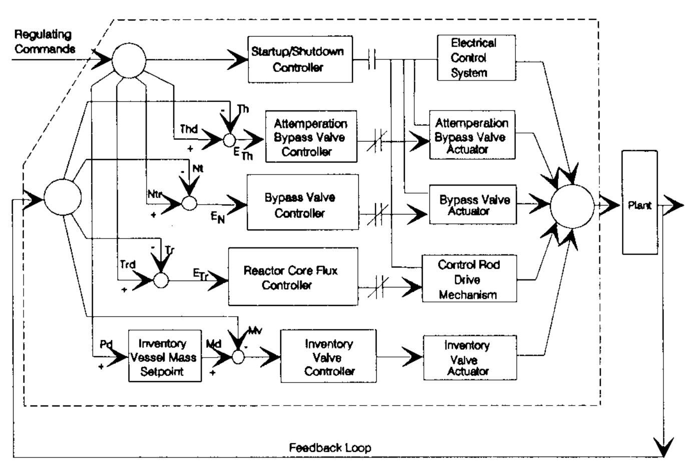


Fig. 4: The Plant Regulation System Controllers

of time, is used to regulate the turbomachinery speed following the speed regulating signal. Filtering of the control signals after amplification is essential to preventing control saturation which could induce system instability. The feedback loops associated with each of the controllers are incorporated into the plant system model based on the state-space implementation methodology[3].

3.2 Plant Protection System

Although the safety protection of the MGR-GT is not required for off-site public protection because of the safety properties of the nuclear core, a protection system is necessary to protect the plant components from damage in case of severe accidents. The PPS is currently designed to handle the following anticipated accidents:

1. Total load rejection from full power,
2. turbomachinery overspeed,
3. turbomachinery rotor or shaft failure,
4. interior pressure surface leaks,
5 system depressurization, and
6. inadvertent withdrawal of control rods or clearup of absorber spheres.

The PPS protective actions include loop and reactor shutdown in the following modes:

1. Idle loop shutdown for decay heat removal, or for subsequent load recovery.
2. Emergency loop shutdown to a stop if a permanent shutdown condition is detected.
3. Reactor scram to set back reactor power in hot temperature conditions.
4. Reactor trip to keep the reactor subcriticality at ambient temperature conditions.

3.2.1 Loop Shutdown

Loop shutdown is accomplished by rapid flow bypass via the shutdown bypass valve, Vb3, which, as shown in Fig. 3, is located between the high pressure recuperator outlet and turbine exhaust. Depending on the specific accident, two modes of loop shutdown may be possible, one to bring the system to an idle state with the turbomachinery continuously running at design speed as, for instance, in case of a load rejection, and the other to shutdown the turbomachinery to a complete stop as required in the event of turbomachinery shaft break. The idle shutdown permits continuous circulation of helium through the core to keep the core temperature low during shutdown period, and also allows a quick, easy recovery to normal operation. On the other hand, the complete loop shutdown must be enforced if an immediate recovery of the normal operation is impossible as results of particular severe accidents. A shutdown bypass valve of 33 cm diameter is sufficient to protect the turbomachinery from reaching destructive speed limits in the worst overspeed accident.

Loop shutdown is always accompanied by thermal protection with the PPS attemperation bypass valve Va2, which is independent of the PRS attemperation bypass valve Va1. This valve, with a size of 10 cm diameter, is located between the high pressure recuperator inlet and turbine outlet as shown in Fig. 3. Through the attemperation valve, cold helium can be introduced to the turbine outlet to suppress any potential thermal shocks imposed on the recuperator. In addition, the generator circuit breaker will be opened ensuing any loop shutdown to protect the electrical system. To avoid functional conflicts between the PPS and PRS, and to protect the PRS control apparatuses, the PRS will be isolated whenever the PPS is in action.

3.2.2 Reactor shutdown

For reactor protection, two protective control modes are provided: active reactor power control and reactor shutdown. Furthermore, the reactor shutdown may be executed with either a reactor scram or a reactor trip.

Active reactor power control is meant to accompany the idle loop shutdown. The reactor power is controlled so as to maintain constant reactor outlet temperature. Since the reactor power is still actively controlled and the core outlet temperature is maintained at the design value, an immediate resumption of the normal reactor operation is easily achievable.

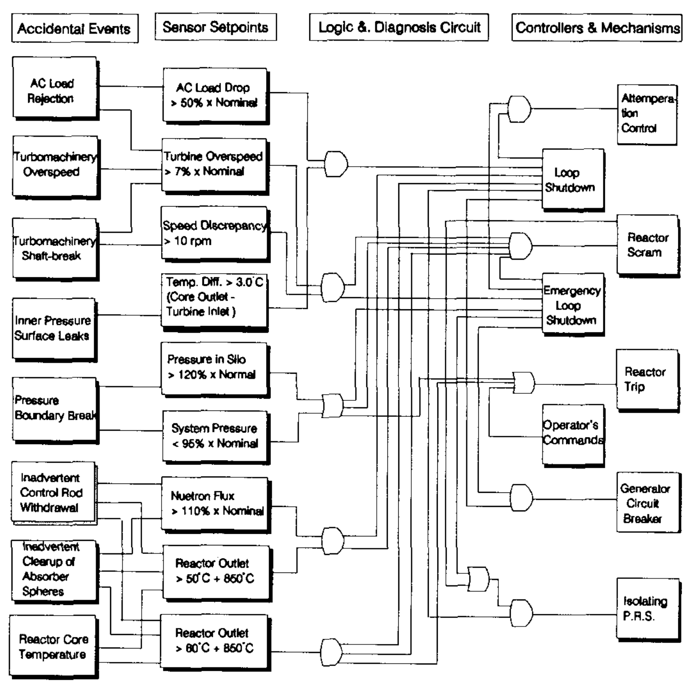
Reactor scram is used to set back reactor power in hot temperature conditions. This is done by dropping the six control rods, by gravity, into the channels located in the side reflector of the reactor. Reactor trip is used to provide long-term reactor shutdown. It is also used as backup to the reactor scram should it fail. To execute the reactor trip, the small absorber spheres are released, by gravity, from the canisters on the top of the core into the columns in the side reflector. Because subsequent removal of the absorber spheres requires a complicated procedure, and because a reactor shutdown is not necessary for the safety of the reactor, the absorber sphere shutdown system is not used unless it is activated by an on-line operator or a permanent shutdown condition is detected.

3.2.3 Protective Logic and Controllers

The Plant Protection System monitors several plant operational parameters, including neutron flux in the core F, reactor outlet temperature T_r and turbine inlet temperature T_{ti}, turbine and generator speeds N_t and N_g, respectively, electric load P_d, and low-pressure recuperator inlet temperature T_h. The location of each parameter is shown in Fig. 3.

Protective logic as shown in Fig. 5 was developed for the PPS operation[3]. In the first column from the left is a list of the anticipated accidents to be dealt with. The PPS sensors detect the occurrence of each accident and send consequential signals to the second column for comparison with sensor setpoints. The sensor setpoints provide gateways from sensor measurements to the logic and diagnosis circuit in the third column. If any setpoint is exceeded, the corresponding signal will be allowed to pass the gateway to enter the circuit. The signal will be analyzed in the circuit and then guided into the appropriate PPS controllers in the far-right column to initiate the designated protective actions. The controllers include two loop shutdown bypass controllers, an attemperation bypass controller, and

Fig. 5: The MGR-GT Plant Protection System



two reactor shutdown controllers. The design of these controllers is similar to the methods used in designing the PRS controllers. The PPS controllers, however, are functionally independent of the PRS controllers.

4. Transient Simulation

A number of transients have been simulated with the GTSim transient simulation code to evaluate the operability of the plant. GTSim is a full-scale MGR-GT system model capable of simulating a broad range of transient events including both normal and far-off-normal behaviors. A full description of the GTSim is given in [3]. The following is a description of the simulation results for four selected transients. The first two events, ±5%/min ramp load changes, and normal plant shutdown and startup, are intended to evaluate the PRS control operation, while the last two, total load rejection from full power, and control rod withdrawal without reactor shutdown, are simulated to assess the PPS protective performance.

4.1 ±5%/min ramp load control

This event is intended to evaluate the automated load following characteristics of the plant over the normal operating load range from 100% to 25% of the rated level. As shown in Fig. 6(a), the steady-state, full power operation is challenged by an electric load reduction starting at t = 0. The electric load is reduced at 5%/min until t = 900 sec when it reaches 25% of the nominal level.

Fig.6(a) shows the transient responses of the turbomachinery parameters along with the control valve maneuvers. For the first 10% load reduction, the turbomachinery power and speed are controlled by the bypass valve Vb1, while the inventory valves remain closed.

As the load drops below 90%, the inventory control system is put into operation. The inventory valve Vi1 is first opened to withdraw helium from the plant circuit into the inventory vessel, Vessel-1. When the load reaches 68%, inventory valve Vi1 is gradually closed as the pressure in Vessel-1 approaches equilibrium with the circuit pressure, while inventory valve Vi2 is opened to allow the helium to flow into the second inventory vessel, Vessel-2. Because of the assistance of bypass control, smooth power reduction and constant speed of the turbomachinery are obtained during the transition between inventory tanks. During the entire period of inventory control, the turbine and compressor powers change at approximately the same rate as that of the load reduction, demonstrating the constant cycle efficiency associated with the inventory control. In fact, the system efficiency stays well beyond 40% over the inventory power control ranges. When the load is reduced below 50%, inventory valve Vi2 is closed, and once again power control is taken over by the bypass control via the valve Vb1.

The recovery of the load from 25% to 100% begins at t = 1000 sec. All the turbomachinery parameters demonstrate behavior nearly

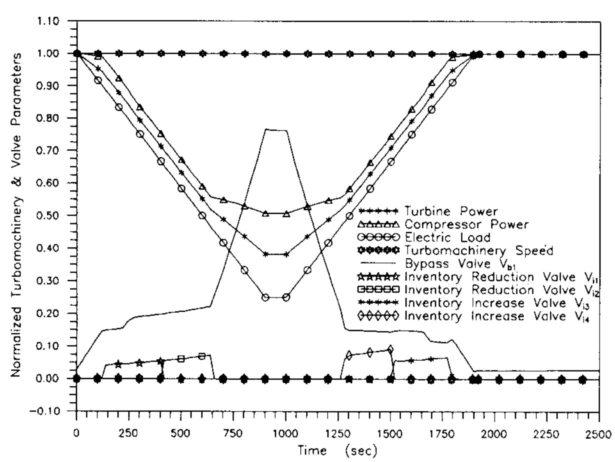


Fig.6(a): Turbomachinery control during ±5%/min AC load changes

symmetrical to those presented during the load reduction, and return to their initial states at full power. It should be pointed out that the bypass valve Vb1 remains slightly open at full power, offering limited reserved power for use in stabilizing the turbomachinery operation against any minor transient disturbances. The bypass flow at full power is about 2 kg/sec.

The simultaneous control of reactor power during the transient is shown in Fig.6(b). The reactor control rods manipulate the core reactivity to control the reactor power, as well as to compensate for the temperature reactivity feedback and for the limited reactivity changes due to altered fission product concentrations associated with reactor power variation. As the load returns to the normal level, the total core reactivity becomes zero, maintaining the reactor critical at full power operation.

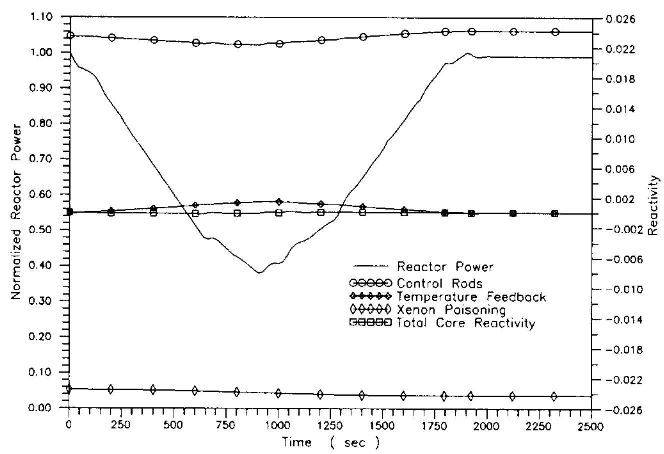


Fig.6(b): Reactor control during ±5%/min AC load changes

4.2 Shutdown and Startup

This simulation is intended to evaluate the programmed procedures proposed for normal plant shutdown and startup, which include the following steps: (1) reduce the electric load at a rate of 10%/min, (2) operate the plant to achieve full speed, idle conditions, (3) reduce the turbomachinery speed from 10,000 rpm to 3,600 rpm, (4) operate the plant at 3,600 rpm to establish low speed, self-sustaining conditions. The plant startup from the self-sustaining state is pursued in a reversed order of the shutdown. The shutdown and startup control is accomplished by the startup and shutdown bypass valve Vb2, as shown in Fig.3, which is 28 cm diameter.

The shutdown begins with the electric load reduction as shown in Fig.7(a). The bypass valve opens to reduce the turbine and compressor powers following the load reduction, while the turbomachinery continues running at the regular speed. After the load is completely disconnected, the plant is further allowed to operate for 5 mins in order to establish new steady-state conditions for the next speed reduction control.

At t = 15 min, the speed reduction command signal is issued. The speed reduction is programmed at 1,000 rpm/min for the rotor speed above 8,000 rpm and 250 rpm/min for the lower rpm. The slower rate of the speed reduction in the low-speed region is necessary to avoid instability of the turbomachinery. Following the speed regulating signal, the bypass controller adjusts the bypass valve so as to reduce the turbine speed accordingly.

The speed reduction ends at t = 35 mins. The plant approaches the steady-state, self-sustaining state with the turbomachinery running at 3,600 rpm. The turbine and compressor powers are approximately 2.5% and 5%, respectively, of the nominal levels. The power consumption by the compressor, which amounts to about 4.5 MW, is also the power that must be supplied by an external power source for use in motoring the turbomachinery from stationary state to such low-speed, self-sustaining conditions in a plant startup from zero rpm.

The simultaneous control of the reactor power is shown in Fig.7(b). As can be seen, the reactor power is reduced almost linearly

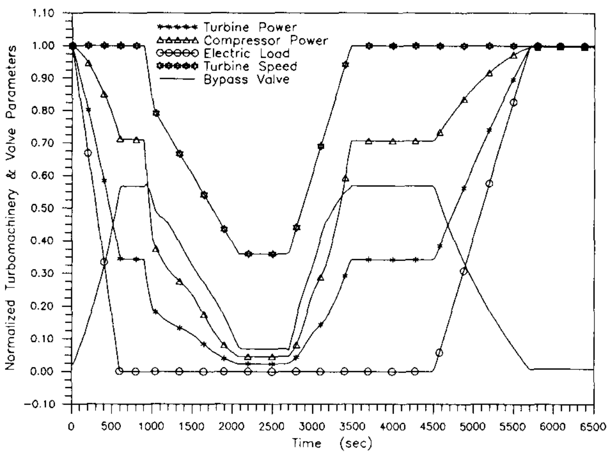


Fig.7(a): Turbomachinery control during plant shutdown and startup

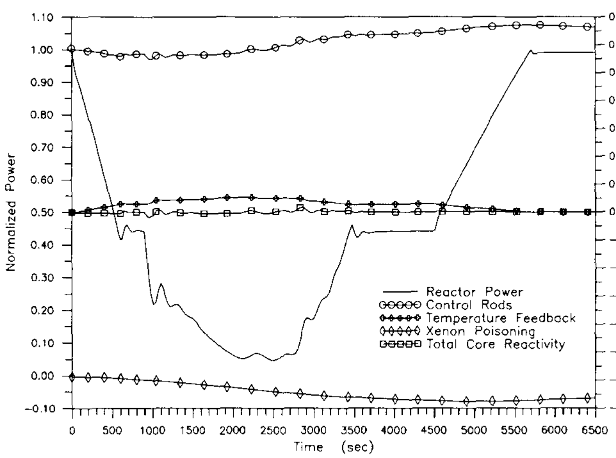


Fig.7(b): Reactor control during plant shutdown and startup

by the reactor control system so as to maintain the constant reactor outlet temperature. In addition to controlling reactor power, the reactor control system also manipulates the core reactivity to compensate for the reactivity effects of fission product poisoning and temperature feedback, as indicated in Fig.7(b). Because of relatively large temperature discrepancy from the design temperature distribution in the core, the temperature feedback of reactivity is significant. Long-term, considerable power changes in the core result in large changes in fission product concentrations which generate a great deal of reactivity fluctuation.

For the subsequent startup, the turbomachinery speed is first controlled to run up at 500 rpm/min to the full speed as shown in Fig.7(a). As the load is gradually connected, the bypass valve is closed to raise the turbomachinery power output. The corresponding reactor power and reactivity transients during this period are depicted in Figs.7(b). It can be seen that the total core reactivity is manipulated by the control rods such that the reactor power is brought up to full power. The total reactivity in the core becomes zero as the reactor criticality is sustained for the full power operation.

Notice that the control rods as shown in Fig.7(b) do not return to the original position even if the reactor power has returned to the full power level. The reason for this is that the residual reactivity of the control rods is used to compensate for reactivity effects of fission product poisoning on a long-term basis.

4.3 Total Load Rejection from Full Power

Simulation of this accident is intended to evaluate the performance of the Plant Protection System. In case of an electric load rejection, loop shutdown is triggered by the PPS sensor signal indicating a sudden loss of load, and is accomplished by the shutdown bypass valve Vb3.

The transient starts at t = 1 sec when the electric load is suddenly dropped to zero, as shown in Fig.8(a). The shutdown bypass valve opens fully in 1 sec to protect the turbomachinery from overspeed. As a result, the maximum overspeed is limited to less than 5%. The overspeed is sensitive to the size and reaction rate of the valve in addition to the rotational inertia available on the rotor. Although only 50% of the bypass valve opening has been utilized in this shutdown control, the rest of the valve capacity is rated for more severe accidents, such as failure of turbomachinery shaft. After a brief speed overshoot, the turbomachinery approaches design speed quickly and aperiodically. The turbine and compressor powers drop to about 33% and 70%, respectively, balancing the power on the shaft.

Substantial bypass flow results in large reduction of the turbine pressure head, which causes the considerable increase of the turbine outlet temperature as shown in Fig.8(b). However, the thermal control

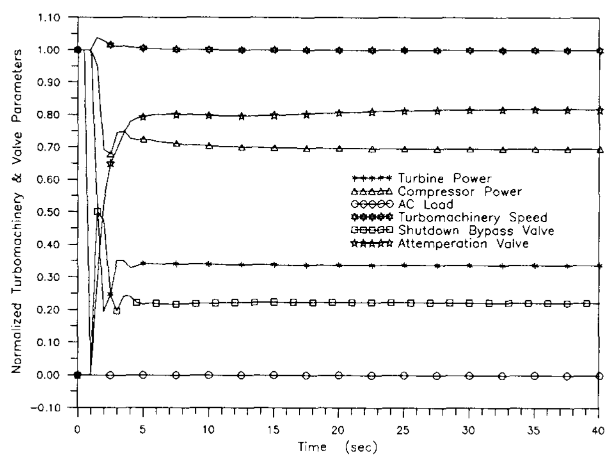


Fig.8(a): Turbomachinery control in case of AC load rejection

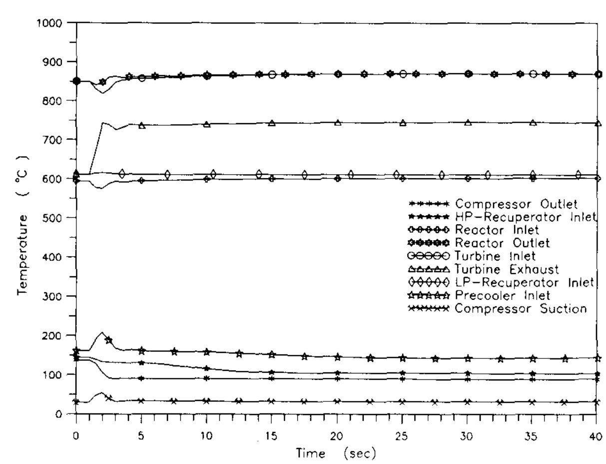


Fig.8(b): Temperature responses in case of AC load rejection by the PPS attemperation bypass valve as shown in Fig.8(a) maintains the temperature at the low-pressure recuperator inlet nearly constant even though the turbine outlet temperature has increased by about 120°C. In addition, the reactor outlet temperature is maintained at 850°C with only minor temperature fluctuation during initial period, which is largely due to the effects of flow compressibility at the beginning of the bypass control. The flow transient responses are shown in Fig.8(c).

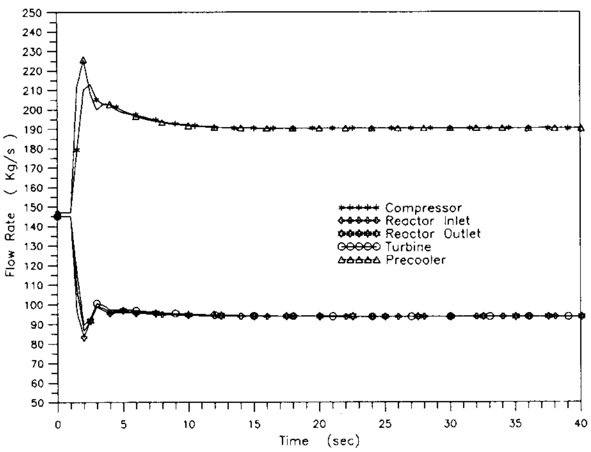


Fig.8(c): Flow transient responses in case of AC load rejection

4.4 Withdrawal of All Control Rods without Reactor Shutdown

Simulation of this design basis accident is intended to analyze the inherent safety and protection capabilities of the plant. The normal protective actions by the Plant Protection System would include reactor shutdown with the re-insertion of the control rods triggered by excess neutron flux or high reactor outlet temperature, followed by an idle loop shutdown for the removal of decay heat with continuous helium circulation through the core.

In case of failure of normal reactor shutdown, however, the core temperature coefficient of reactivity would be the only means for reactor protection. Fig.9(a) clearly demonstrates the shutdown effect by the temperature reactivity feedback. As can be seen, the control rods are initially withdrawn from the core at the maximum control rod drive speed, resulting in a positive reactivity disturbance in the core. The positive reactivity insertion causes the reactor power to increase. As a result, the core temperatures rise, as shown in Fig.9(b), which generates negative

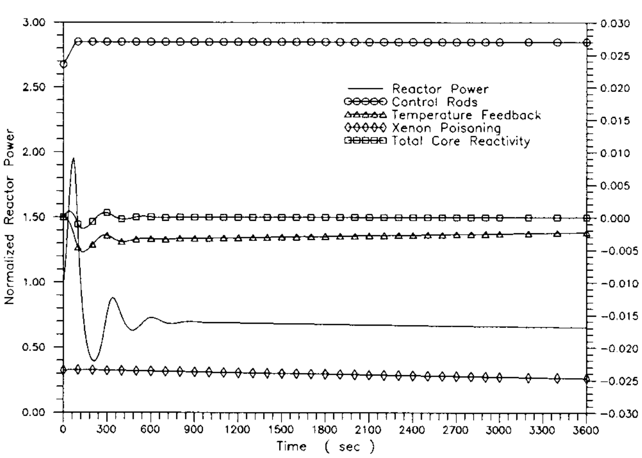


Fig.9(a): Inherent reactor shutdown in case of control rod withdrawal

reactivity by means of the temperature feedback. The temperature feedback reduces the total core reactivity from positive to negative as shown in Fig.9(a). The reactor power is thus inherently set back and stabilized after a short period of oscillation.

Because of the reactor power setback, and because of continuous helium circulation through the core, no fuel temperature is increased by more than 150°C, with the maximum fuel temperature limited to less than 1115°C. After the peak, the fuel temperatures are slowly reduced because of the decay heat removal by helium circulation. The decay heat is transported to the precooler and dissipated to the precooler water flow.

The simultaneous idle loop shutdown is shown in Fig.9(c). The turbomachinery is constantly maintained at the design speed by the shutdown bypass valve. The turbine and compressor powers are reduced to new steady states. The attemperation bypass valve is also manipulated to control the thermal conditions in the plant components.

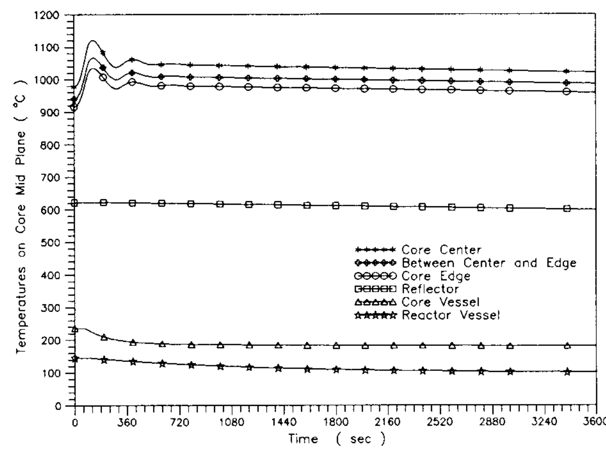


Fig.9(b): Core temperature transients in case of control rod withdrawal

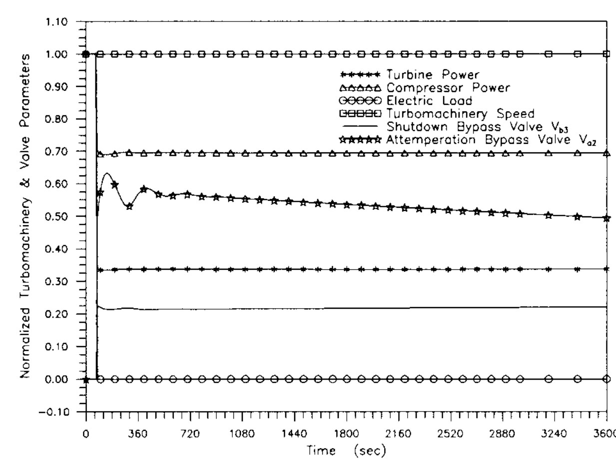


Fig.9(c): Idle loop shutdown in case of control rod withdrawal

5. Summary of Conclusions

The inherent safety of the MGR-GT has greatly reduced the safety requirements for the control system, which has made it possible to emphasize the achievement of high performance in the design of the control system. The selection and integration of potential control methods results in a control system with relatively simple design and operation, which not only enables required load following and plant protection capabilities but also offers high system efficiencies over an extended power ranges. Fig. 10 summarizes the MGR-GT power control approach showing system efficiencies over the entire load range. The study has demonstrated that the MGR-GT is a robust controllable power system.

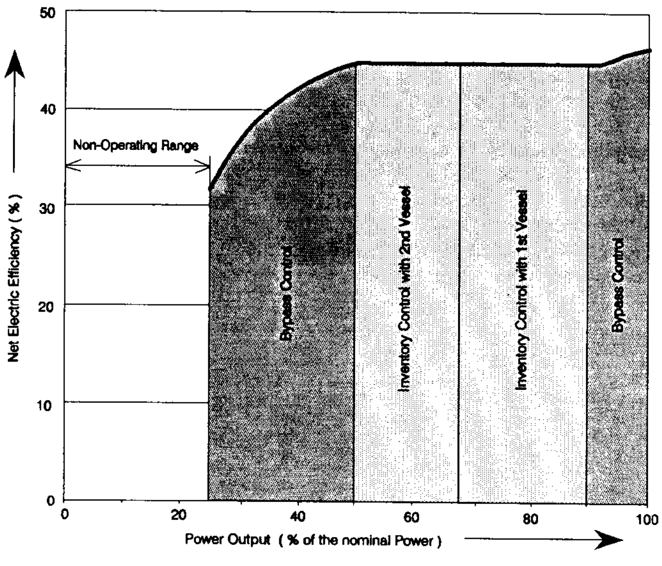


Fig. 10: The MGR-GT power control approach and efficiency

6. Acknowledgements

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7. References

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