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GT-MHR OPERATIONS AND CONTROL

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(Abstract for IAEA meeting on gas reactors, Nov 28-Dec 2, 1994 in the Netherlands)

ABSTRACT

The Gas Turbine Modular Helium Reactor (GT-MHR) combines features that lead to high thermal efficiencies, cycle simplicity, enhanced safety, and improved economics. It uses a high thermal capacity nuclear core that operates at high temperatures, and a Brayton energy conversion cycle. The high temperature helium from the reactor directly drives a gas turbine and electric generator, which is a process that can achieve a net efficiency in the range of 45% to 48%.

Characteristics of the GT-MHR that are particularly important to the development of operation and control schemes for the GT-MHR include the thermal capacity of the core, excess reactivity, negative temperature coefficient of reactivity effects (provided by the fuel and the graphite moderator), Xenon reactivity effects (particularly important for large amplitude power reductions), the inertia of the turbogenerator, the speed of response of the valves that allow helium to be diverted around the core and the turbine for fast power reductions, the rate of helium transfer in and out of the system to accommodate longer term part load operating conditions, and the operating envelopes specified for systems and components. Together, these characteristics and specifications determine time and amplitude response capabilities, and the operating range of the GT-MHR.

GT-MHR operation and control schemes must comply with utility requirements, particularly load following requirements, be compatible with GT-MHR characteristics, and lead to compliance with system and component operating limits. In the power range, the major elements of the control scheme that is being developed to accomplish this may be summarized as follows: (1) Maintain heat sinks operational at high or maximum capacity so that they can accommodate power variations with minimal control action, (2) Use a helium flow bypass around the core and the turbine to accommodate fast reductions in power output demand (this is particularly beneficial in load shedding transients), and (3) Use helium inventory control to follow reactor power variations with corresponding primary coolant inventory changes in order to maintain high operating efficiencies and reduce thermal loads in the operating range.

GT-MHR operation and control schemes under development are being assessed with a first-principles compact simulator that uses touch-sensitive computer driven screens to represent proposed operator interfaces. The simulator runs in real time or faster, and is being used to quantify the transient response of the plant and make preliminary evaluations of proposed operator interfaces. The simulator provides quick visibility of plant behavior to designers.

This paper summarizes the utility requirements and design features that are being addressed, and provides a summary description of the status of the development of operations and control schemes.

1.0 INTRODUCTION

The Gas Turbine-Modular Helium Reactor (GT-MHR) evolved from the steam cycle Modular High Temperature Gas Cooled Reactor (MHTGR) developed over the last decade under the U.S. DOE Advanced Reactor Program.

The GT-MHR combines features that lead to high thermal efficiencies, cycle simplicity, enhanced safety and improved economics (Refs. 1, 2, and 3). It includes key reactor design features (Reference 4) such as the ceramic coated fuel that is able to retain fission products at very high temperatures, a strong negative temperature coefficient of reactivity that gives the reactor the natural tendency to passively shut down with relatively modest temperature increases above operating values, and an annular active core configuration whose low power density and large surface-to-volume ratio facilitates passive heat removal. The Gas Turbine-Modular Helium Reactor (GT-MHR) combines these reactor features with a closed Brayton energy conversion cycle. The high temperature helium from the reactor directly drives a gas turbine and electric generator, which is a process that can achieve a net efficiency in the range of 45% to 48%.

2.0 GT-MHR DESIGN FEATURES

2.1 Configuration

The GT-MHR module arrangement is shown in Figure 1. Each GT-MHR plant is envisioned to consist of four of these modules. Nuclear and power conversion system components are contained within three interconnected vessels: The reactor vessel, the power conversion system vessel, and the interconnecting cross vessel. The three-vessel assembly is installed in an underground concrete silo. The reactor vessel contains the 600 MWt annular core, core supports, control rod drives, and reserve shutdown systems. The control rod drives and reserve shutdown system housings are placed at the top of the vessel, and also serve as access penetrations for refueling. The annular core is formed by hexagonal graphite fuel

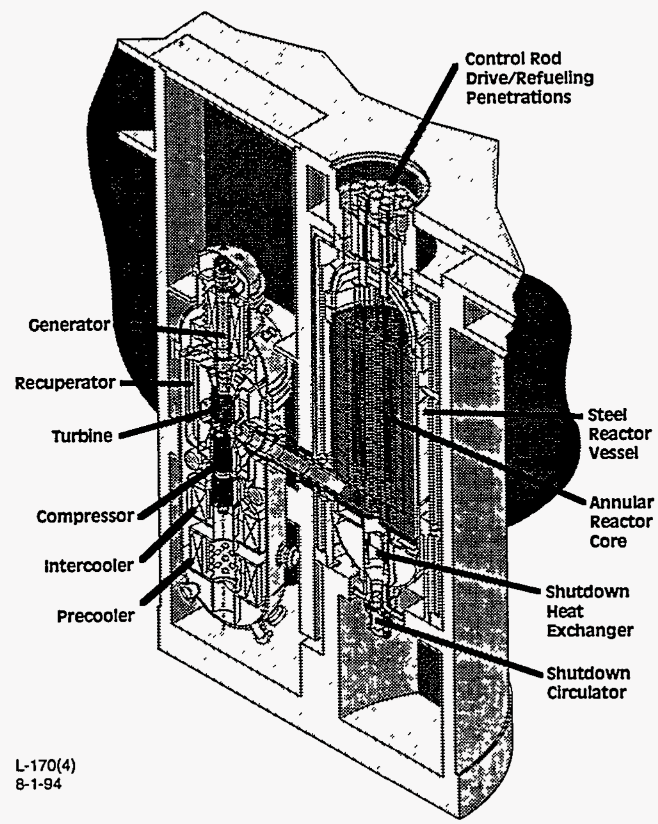

Figure 1. GT-MHR Module Arrangement

columns, which contain a mixture of 20% enriched and natural uranium fuel encapsulated in ceramic coated microspheres with a strong negative temperature coefficient of reactivity. Inside and outside of the core annulus, there are hexagonal graphite nuclear reflector blocks. The annular geometry gives the core a large surface-to-volume ratio. The uninsulated reactor vessel is surrounded by a natural circulation reactor cavity cooling system. A separeate shutdown cooling system provides an alternate forced circulation cooling method to cooldown the reactor in support of refueling and maintenance activities.

The above features give the reactor important operations and control characteristics: The strong negative temperature coefficient of reactivity provides a degree of self control as power levels are increased or decreased. The high thermal capacity of the core tends to minimize temperature transients as a result of power changes. The large core surface-to-volume ratio allows passive heat removal, even if one postulates a loss of primary coolant (in the passive heat removal process, maximum fuel temperatures are below the temperatures that would cause failures in the ceramic coated fuel.) And the helium coolant, which is transparent to neutrons and chemically inert, remains a gas under all reactor conditions. Thus, it does not generate reactivity or thermal interactions with the core.

The same choice of fuel, materials and geometry allow other design selections that promote simplicity and economic benefits. Most importantly, the operation of ceramic coated fuel at high temperatures, which has been successfully demonstrated in commercial reactors in the United States and Europe, leads to high thermal efficiency. This is particularly beneficial when the conversion of thermal to electric power is done directly using a helium driven turbocompressor-generator such as in the GT-MHR. In this manner, the conversion is made without the constant temperature phase change associated with water boiling, which limits achievable thermal cycle efficiency.

The energy conversion system is located in the power conversion system vessel. The system includes the electric generator, the gas turbine, and the two compressor sections mounted on a single shaft supported by magnetic bearings. It also includes three heat exchangers: The compressor precooler and intercooler, which remove low temperature waste heat at the bottom of the thermodynamic cycle, and the recuperator, which is placed between the turbine exhaust and the precooler, ahead of the compressor.

The process flow is shown schematically in Figure 2. Helium exits the reactor core at 850°C (1562°F) and 6.91 MPa (1003 psia), flows through the center hot duct in the cross vessel that connects the reactor and the power conversion system vessels, and is expanded in the turbine. The turbine drives the electric generator and the two compressor sections that are mounted on the same shaft. Helium exits the turbine at 510°C (950°F) and 2.56 MPa (371 psia) and flows through the high efficiency plate fin recuperator. Then, helium flows through the precooler to reject heat to the circulating water system. Cold helium at 26°C (78°F) enters the intercooled compressor where it is compressed to 7.07 MPa (1026 psia) at 107°C (224°F) and passes through the recuperator to recover the heat transferred from the turbine exhaust before it enters the core. Helium flows from the recuperator exit, through the outer annulus within the cross vessel, up to the top of the core through channels in the annular space outside of the core barrel for vessel cooling at 485°C (905°F) and 6.96 MPa (1010 psi), and down through the core to complete the loop.

The direct conversion cycle eliminates the need for steam generators and the rest of the steam and water components associated with steam cycles, thereby simplifying the system. This, along with the high efficiency of the thermal cycle, provide a strong economic basis for the GT-MHR.

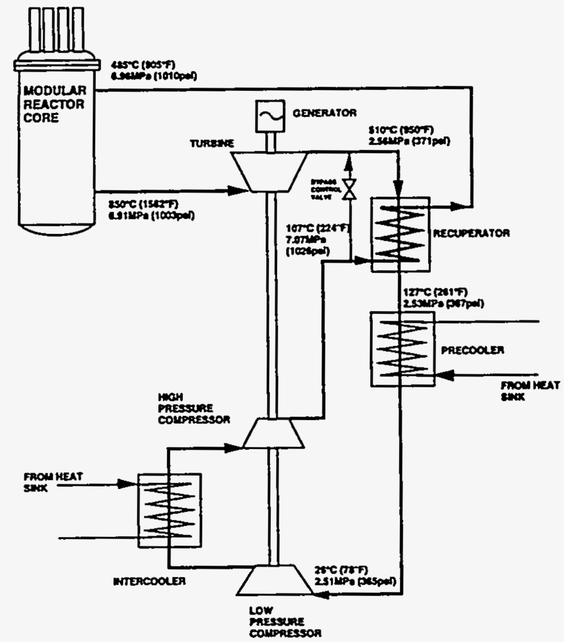

Figure 2. Process Flow Schematic

2.2 Dynamic Features

Controllability and transient performance capabilities are ultimately determined by the dynamic characteristics of the GT-MHR components. Looking at the reactor and the power conversion systems as the two major components, two characteristics are important:

First, reactor thermal response is slow. This is due to the large thermal capacity of the graphite moderated core relative to heat generation (or removal) rates. Furthermore, since the helium coolant remains a gas and does not change phase, temperature changes are smooth and continuous.

Second, turbomachine (turbine, compressor and generator assembly) output and speed response is fast. This is due to the relatively low inertia of the turbomachine relative to operating torque.

The difference in the speed of response of the core and the turbomachine creates both, a demanding coordination requirement between the two systems, and an advantage.

First the demanding requirement: Following a loss of outside electric load and the consequent loss of the retarding torque imposed on the turbomachine through the electric generator, the immediate reaction of the turbomachine is to accelerate. The inertia of the machine and the turning torque delivered by the high temperature helium supplied by the reactor cause an instantaneous acceleration of approximately 440 rpm per second. In order to arrest this acceleration, the accelerating torque must be reduced. This is accomplished by opening a set of redundant valves that allow helium to bypass the core and the turbine. Opening these valves has two effects: It causes the pressure ratio across the turbine to collapse, which reduces the accelerating torque generated by the turbine; and it reduces the resistance to flow offered by the turbine, which increases the flow of helium through the turbocompressor and the retarding torque. The two effects reinforce one another in decelerating the turbomachine. The next logical issue is, how fast do these bypass valves have to open to ensure that turbomachine speed is maintained within design levels? As stated below, the speed of these valves must be on the order of 1 second (which is well within the capabilities of turbine stop valves used in other power plants.)

Now the advantage: The large thermal energy stored in the core and the large thermal capacity of the core allow relatively fast load following in the GT-MHR. In principle, the energy stored in the core can be tapped, or additional energy can be stored, with minimal core temperature changes, essentially as fast as the bypass valves can be actuated. As discussed below in this section, this flexibility is not fully used on load increases. However, it still allows the GT-MHR to meet the specified 5% per minute load following requirement in the 50% to 100% power range with minimal thermal cycling.

Consider now the next level of detail in the set of requirements. Fuel loading is designed to allow excess reactivity for power control during the complete (16 to 18 months) time interval between refueling outages. There is enough excess reactivity so that reactor power can be varied at 5% per minute in the 50% to 100% power range, or even over a wider range (to the 10% house load level) during most of the fuel cycle. However, negative reactivity effects caused by Xenon buildup after large power variations become important in the latter part of the refueling cycle (approximately in the latter 30% of the cycle). This is a relatively slow and long term effect as Xenon peaks in 6 to 8 hours following a drastic power reduction, allowing plenty of time to reduce core temperatures to use the effect of the negative temperature coefficient of reactivity to compensate for Xenon buildup if necessary.

As discussed above, rapid changes in the position of the bypass valves (which allow helium flow to bypass the core and the turbine) allow the GT-MHR to vary output power very rapidly, essentially as fast as these valve can be operated. However, helium flow bypassing the core and the turbine requires pumping power, does not contribute to plant power output, and, therefore, creates inefficiencies. Therefore, for long term operation, it is desirable to operate the plant with no bypass flow. Essentially, bypass flow may be considered as "excess" flow, created by "excess" helium in the reactor and in the power conversion circuit. This "excess" flow can be eliminated by adjusting primary coolant inventory (i.e.: helium mass) so that only the helium flow needed to drive the turbine is present in the helium circuit. In this manner, all the helium circulates through the entire reactor and power conversion circuit, and no helium needs to bypass the core and the turbine ("excess" flow could be controlled by varying turbomachine speed; however, it is simpler to use a constant speed turbomachine synchronized to the grid.) High-efficiency long-term low-load operation then continues at partial inventory. The inventory adjustment process is similar to that used to transfer helium during refueling in prior high temperature gas cooled reactors.

The next logical issue is how fast helium can be transferred in and out of the reactor. On this matter, preliminary analysis indicates that high pressure clean helium in storage bottles can be vented into the reactor is fast enough to meet the 5% per minute load increase requirement. Removing helium for load reductions, on the other hand, is best done through the helium purification system, and so, it can be done only as fast as the helium purification system allows. With the current helium purification system size, helium removal is done more slowly than 5% per minute, probably in the order of 0.75% per minute. However, this is probably acceptable as load reductions can always be accomplished rapidly by opening the bypass valves. Inventory reductions can then follow more slowly as the desired effect from this is simply to restore efficiency.

3.0 OPERATIONS AND CONTROL STRATEGY

Operations and control strategies are designed to comply with utility requirements, particularly load following requirements, be compatible with the GT-MHR design characteristics described in the previous section, and lead to compliance with system and component specifications.

From the operations and control standpoint, the major utility requirements are to be able to follow load demand as fast as 5% per minute in the 50% to 100% power range, and be able to operate in a stable manner, under automatic control, in the 15% to 100% power range. The 50% to 100% is intended to be the load following range, whereas the extended 15% to 100% range is intended to facilitate startup and shutdown, and to sustain stable operations following large load variations that may be needed to accommodate infrequent grid upsets.

Regarding component specifications, those that are most closely linked to the operations and control strategies are thermal loads and temperature boundaries.

The major elements of the operations and control strategies are the following:

1. Maintain the major heat sinks (precooler and intercooler) operational at high or maximum capacity so that they can accommodate power variations with minimal control action. As part of this strategy, heat sinks are the first components to be placed in operation during startup. Correspondingly, latent and decay heat removal is first done through the major heat sinks during the shutdown process by using the turbomachine to circulate helium through the core. The shutdown cooling system mentioned in Section 2.1 may subsequently be used if the turbomachine needs to be stopped for maintenance. Furthermore, helium is first circulated through the core during startup by operating the generator as a motor to rotate the turbocompressor.
2. Use the helium flow bypass around the core and the turbine to accommodate fast reductions in power output demand, which is particularly beneficial in load shedding transients.

3. Make helium inventory follow load in order to maintain high operating efficiencies and reduce thermal loads in the operating range.

3.1 Startup

In the startup process, the major heat sinks, which are the systems that are farther removed from the nuclear systems, especially the power conversion system precooler and intercooler, are placed in service first. These systems are then operated at rated flow so they can accommodate heat load variations with minimum temperature variations and minimum or no operator attention when power is varied. During this operation, the turbogenerator is at rest and primary coolant at atmospheric pressure.

Then, the turbogenerator is synchronized to the electric grid. Synchronization is done with a primary coolant inventory of approximately 7% utilizing a variable frequency power supply to motor the generator and accelerate it to synchronous speed. Since primary coolant density is low under these conditions, the power required to bring the generator (and the rest of the turbomachine) to synchronous speed is low (less than 4 Megawatts.)

The generator is then operated as a motor to circulate helium coolant through the reactor and the power conversion system, also providing heat of compression for limited prewarming of reactor systems. The reactor is then taken critical and power is regulated to slowly raise core outlet temperature to approximately 371°C (700°F). The generator changes from a motoring to a generating mode at approximately 260°C (500°F). Reactor components, including the reactor vessel are warmed up above nil-ductility requirements. Then, reactor power is increased to reach a core outlet temperature of 550°C (1022°F) at a rate of approximately 5.5°C (10°F) per minute. After reaching steady state conditions, helium is added to reach 15% inventory, and reactor power is correspondingly increased to maintain core outlet temperature. At this point, bypass valve position, helium inventory, core outlet temperature, reactor power, and auxiliary systems are all placed in the automatic control mode. Plant output power can then follow load demand as discussed in the next section.

Shutting down the reactor is done in the reverse sequence.

3.2 Load Following

Power output is controlled in the near term (0 to approximately 20 minutes) by varying the position of the bypass valves, and making a simultaneous slower adjustment in reactor helium inventory. Opening the bypass valves diverts helium from reactor core and turbine, which causes an immediate reduction in turbine (and plant) output, an increase in core temperature, and a decrease in reactor power due to the negative temperature coefficient of reactivity. Since thermal effects in the core are slow, control rods are used to achieve a faster core power response.

However, as discussed earlier, helium flow bypassing the core and the turbine creates thermal inefficiencies, which can be avoided by adjusting helium inventory in the reactor so that in the long term, the bypass valve does not have to be open. More specifically, opening the bypass valve to adjust plant output is always followed by a reduction in primary coolant inventory. As inventory decreases, the bypass valves are reclosed to maintain constant mass flow through the core and restore high efficiency. This is a longer term (0 to approximately 60 minutes) process.

Closing the bypass valves causes the reverse: A turbine (and plant) output increase, a core temperature decrease, and a reactor power increase. So, the first action to increase power output is to try to close these valves. However, as stated above, helium inventory is adjusted so that under steady state conditions the bypass valves are closed. Therefore, closing the valves to increase plant output after steady state operation would not normally be an option (they would already be fully closed). In this case, power output is increased by increasing helium inventory.

Preliminary analysis indicates that inventory control can be accomplished by transferring helium between the reactor and the helium storage tanks as follows: Helium is transferred from the high pressure compressor outlet to the tanks via the helium purification system (to remove fission products). In the opposite direction, helium is transferred from the tanks (which contain purified helium) directly into the low pressure compressor inlet. In this manner, the turbocompressor is used to perform the pumping work for the transfer of helium.

Figure 3 shows a full load swing in the entire automatic range (100%-15%-100%), at rates close to 5% per minute. On the downward ramp, the bypass valve is actively open, regulating output power in a linear ramp. As discussed in Section 2.2, this is accompanied by an inventory reduction through the helium purification system at a slower rate. Not shown in the figure is core outlet temperature, which between the 50% and 15% power range is programmed to decrease from the operating value of 850°C (1562°F), to approximately 550°F (1022°F). Although not always necessary, this temperature reduction helps counteract negative reactivity effects caused by Xenon in large power reductions. Notice that on the upward ramp, power output increases fairly rapidly initially. This is made possible by the relatively rapid addition of helium directly from storage into the primary coolant circuit, and the use of stored thermal energy in the core. After helium inventory in the primary circuit reaches 100%, power output increases more slowly as the core temperature is restored to the operating value.

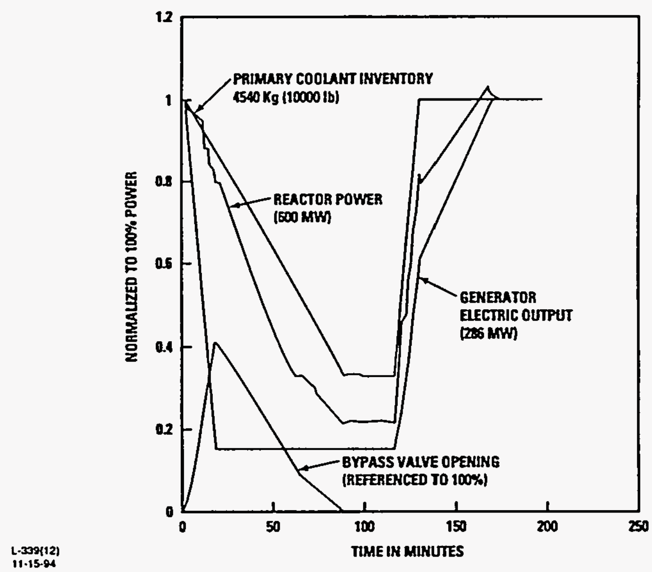

Figure 3. Load Swing: 100%–15%–100%

3.3 Output Reduction to House Load

Three important GT-MHR characteristics contribute to its ability to make rapid output power reductions in a stable manner: The large thermal capacity of the graphite moderated core, the large amount of thermal energy stored in the core during operation, and the fast response of the turbocompressor to reductions in the pressure ratio across the turbine. The first two features produce significant stabilizing effects on core and process temperatures: Temperatures change slowly, even during the most severe changes in reactor power or coolant flows. The third feature allows rapid changes in generator electric output to be made by varying the opening of the bypass valve. This controls the flow that bypasses the core and the turbine, and consequently, the pressure ratio across the turbine.

Thus, it is possible to rapidly reduce generator output from full load to house load by rapidly opening the bypass valve, and be able to accomplish it in a stable manner, with relatively mild thermal variations, and without plant trips. Such capability is of interest because it would mean that the reactor would not have to be shutdown following a loss of outside power. Instead, it would continue to operate supplying its own electric power needs. Then, when grid power is restored, it could be quickly reconnected to the grid and reloaded. The results would be fewer challenges to the shutdown cooling system and to the passive cooldown safety systems, and a higher capacity factor.

Analysis confirms that the GT-MHR can indeed be expected to be able to reduce its power output from full power to house power in a stable manner, without a plant trip. The bypass valves response is fast enough to prevent a turbomachine overspeed condition. Turbomachine speed peaks at 109% (65.4 Hz) at 0.9 s, which exceeds the 60.5 Hz steady state requirement, but returns to the acceptable range in approximately 2.5 s. The impact of these variations on the precooler and intercooler pump motors, which must continue in operation in order to avoid an automatic reactor trip, needs to be evaluated. However, the amplitude of these deviations does not appear to be excessive, particularly in view of their short duration.

As expected, thermal variations in the core and in most of the rest of the plant are of a very benevolent nature. The exception is the precooler, which takes the thermal load rejected by the turbine almost instantaneously after the loss of outside power as illustrated in Figure 4. However, the precooler has a large thermal capacity, and the net effect is a temperature increase

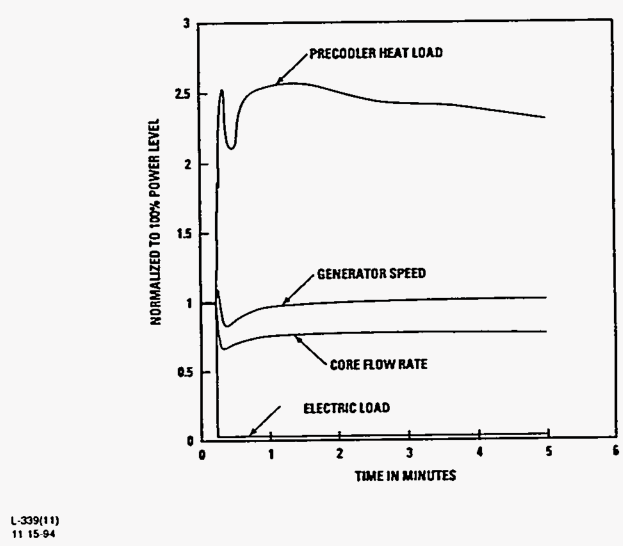

Figure 4. Output Runback to House Load

within design limits. The other consequence is a temporary reduction in plant efficiency. However, given the subsequent reduction in power level, and the temporary nature of this condition, this is not a major consideration.

4.0 USE OF SIMULATOR

One of the best tools to develop and evaluate operations and control strategies is a real time simulator. For the GT-MHR, a first principles compact simulator has been developed, which allows designers to explore design alternatives and obtain instant feedback on the effects of their selections. The simulator is being used to: (1) Demonstrate plant stability and design margins during startup, shutdown, and power maneuvering, (2) Determine the adequacy of operator graphic interfaces, and (3) Demonstrate the feasibility of using commercially available distributed digital control systems for GT-MHR control.

The simulator contains software models of the following processes: Reactor core physics, reactor core thermalhydraulics, fluid and heat flow from the reactor to the power conversion system, gas turbine expansion, recuperating heat removal downstream of the gas turbine, gas precooling, low pressure compression, intercooling, high pressure compression, and recuperating heat addition upstream of the core. These are the sequential processes in the thermodynamic loop. The rest of the simulated processes include core and turbine bypassing, and primary coolant inventory control, which are used to vary electric power output. Also included are ultimate heat sink (cooling tower) processes, separate forced circulation shutdown cooling to allow for short refueling and maintenance outages, and process control and protection algorithms.

The relatively tight coupling of the core (long mean free neutron path), the slow and predictable response of the reactor, the lack of boiling processes, the nuclear transparency and chemical inertness of the helium coolant, and the elimination of the traditional balance of plant systems associated with steam cycles make the simulation relatively simple. As a result, the entire simulation is executed on a platform consisting of a set of 486/66 interconnected personal computers. Four are used to generate interactive touch sensitive operator displays, and two are used to run the nuclear, thermalhydraulic, and rotating machinery simulations.

The core physics process is modeled using six delayed neutron groups. The thermalhydraulic processes are modeled using conservation of mass and energy. The turbine and compressors are modeled using preprogrammed performance maps to calculate shaft power and exhaust gas conditions. Momentum equations are used to calculate shaft acceleration based on net turbine, compressor, and generator torque.

Steps towards software verification and validation are being taken: Model software updates are documented under configuration management control. Also, under a previous MHR development program, preliminary independent reviews of reactor models were conducted, and comparisons of results yielded by other codes over overlapping domains were made. More recently, hand calculations and additional comparisons with other gas turbine codes are being made.

The equations are organized in state variable form. The state vector is integrated in steps of one eighth of a second.

Interaction with the simulator is done through operator displays. Operator displays of fast acting variables are updated once a second. Others are updated at variable, adjusted intervals of time. There is a top level display that provides an overview of GT-MHR conditions (Figure 5). The display shows the major plant performance parameters, and includes a real time graphic heat balance in the form of a bar chart on the left of the central part of the display. The first bar is proportional to reactor power and it is always based at the zero level. Thus, reactor power is always indicated on the left scale by the top of the bar. The second bar is proportional to the power removed from the core. However, the top of this bar is always aligned with the top of the first bar. Thus, the lower end of the second bar indicates core heating if it is above the zero level, core thermal equilibrium if it is exactly at the zero level as shown on the figure, and core cooling if it is below the zero level.

From this top level display, one can adjust the set point for the electric output demand, "zoom" into more detailed displays of processes and instrumentation that allow manual operator actions, or

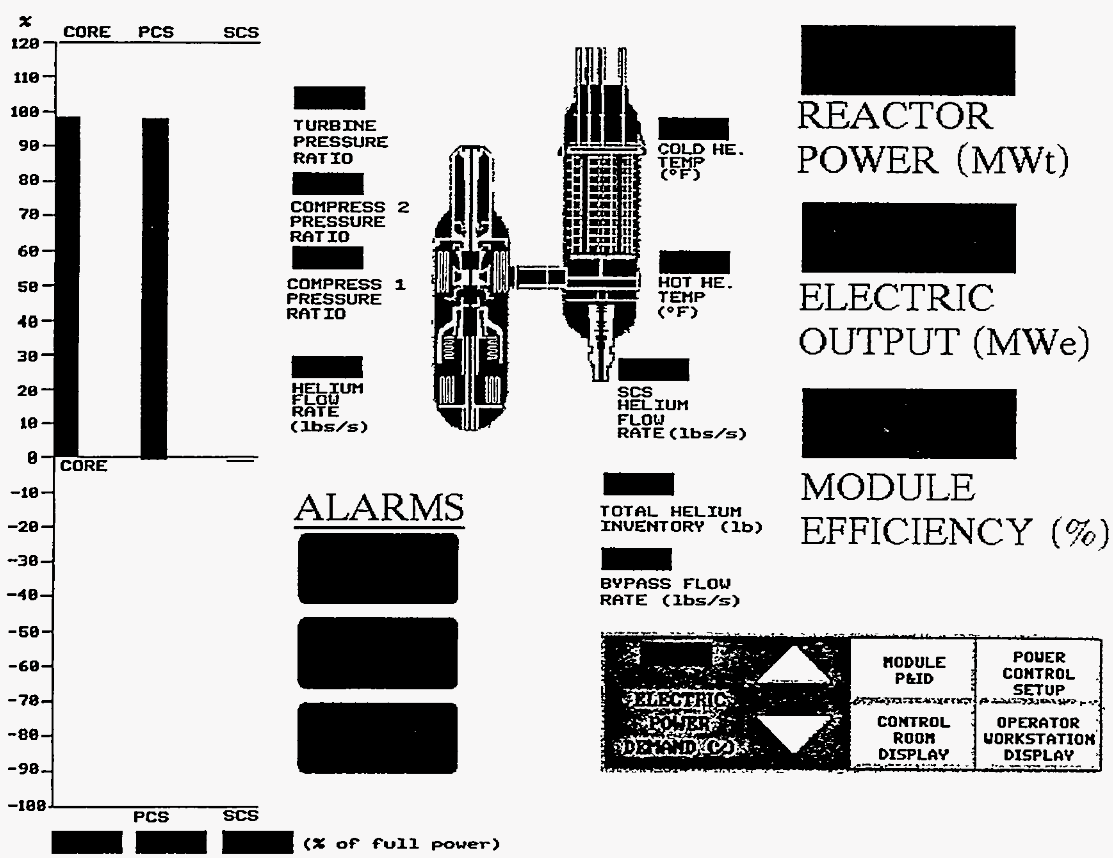

Figure 5. Simulator Top Level Display

call displays of historical performance data that are used for transient response analysis (Figure 6). In these displays, current simulation time conditions are displayed at the right end of the display (at time zero). Past conditions are shown as functions of historical time on a negative scale with respect to current simulation time. These data can be magnified, reformatted, or extracted electronically for additional analysis of stability and design margins, and for preparation of design reports.

The simulator is also used to obtain comments from experienced resident and visiting operations specialists on the effectiveness of proposed operator displays. Integrating these reviews with the design effort from the beginning is expected to produce clearer operator interfaces, simplify operator training, and in general, minimize undesirable surprises during subsequent human factors verification.

Finally, industrial digital distributed control components have been connected to the plant simulation computers to verify the adequacy of the time of response of these systems for GT-MHR control. No surprises are expected about this adequacy as the control requirements in the

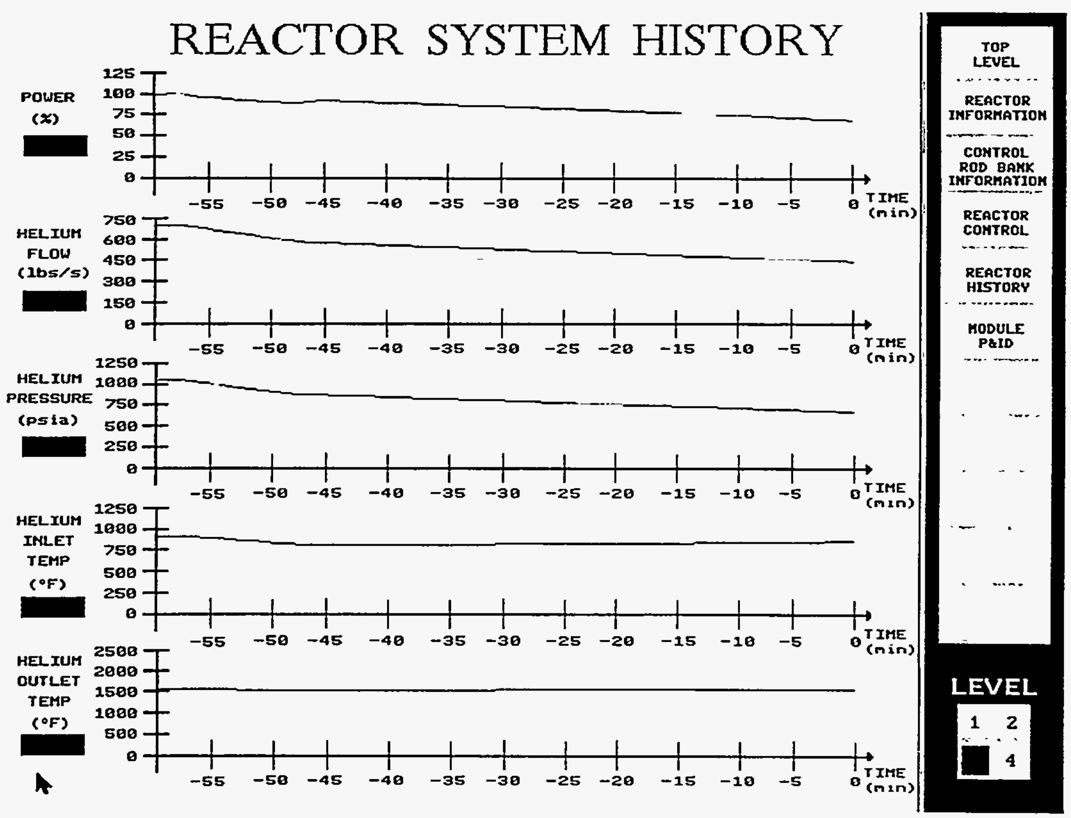

Figure 6. Transient Response Simulator Output

GT-MHR are enveloped by those encountered in fossil fueled power and petrochemical plants where distributed digital controls have been successfully used for many years.

5.0 CONCLUSIONS

GT-MHR operation and control schemes are being developed that are compatible with and take advantage of key dynamic characteristics: Thermal capacity of the core, excess reactivity, negative temperature coefficient of reactivity effects, Xenon reactivity effects, the inertia of the turbogenerator, the speed of response of the valves that allow helium to be diverted around the core and the turbine, and the speed of helium transfer in and out of the reactor. The efforts to date have been focused on startup, load following, and power output reduction to supply house load following a loss of outside power.

The major elements of the operations and control strategies are the following: (1) Maintain heat sinks operational at high or maximum capacity so that they can accommodate power variations with minimal control action, (2) Use a helium flow bypass around the core and the turbine to accommodate fast reductions in power output demand (this is particularly beneficial in load shedding transients), and (3) Use helium inventory control to follow reactor power variations with corresponding primary coolant inventory changes in order to maintain high operating efficiencies and reduce thermal loads in the entire operating range.

GT-MHR operation and control strategies under development are being assessed with a first-principles simulator that uses touch-sensitive computer driven screens to represent proposed operator interfaces. The simulator runs in real time or faster, and is being used to quantify the transient response of the plant, make preliminary evaluations of proposed operator interfaces, and verify the adequacy of using commercially available distributed control systems for GT-MHR control. The simulator provides quick visibility of plant behavior to designers, and has contributed significantly to the design effort. Benefits of a different nature, training, are also expected in the future.

The major conclusions to date are that the GT-MHR is expected to meet time of response utility requirements, that it will be stable in the entire operating range, and that it can be expected to be able to reduce its power output from full power to house power in a stable manner, without a plant trip. During this transient, output power frequency variations go beyond steady state specifications. Therefore, additional work is needed to verify that key components, particularly precooler and intercooler water pump motors, will remain in operation. However, the amplitude of these deviations does not appear to be excessive, especially considering their short duration.

Important future planned work includes: Defining operations and control strategies for reactor trip, shutdown to refueling, refueling cooling, restart from partial cooldown, etc.; defining methods for changing the operation of the main generator between generating and motoring modes; and defining protection schemes.

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