HTGR Technology Course for the Nuclear Regulatory Commission

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Module 12
Instrumentation and Controls (I&C) and Control Room Design

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General Atomics
OUTLINE

• Control and protection systems included in I&C
• Reactor and process control in HTGR plant designs
• Application of digital systems to monitoring, control, and protection equipment
• Reactor protection developed in previous HTGR plants
  – I&C protection system functions and protection hardware interfaces
  – Reliability and interpretation of regulatory criteria
• Control Room and I&C architecture preferred for overall operation of the HTGR and associated heat utilization processes
Three Specific Systems in the HTGR System Structure
Define Instrumentation and Control (I&C)

- **Plant Control, Data, and Instrumentation System (PCDIS)**
  - Provides overall plant control
  - Includes architecture which combines I&C systems and the control room equipment

- **Investment Protection System (IPS)**
  - Initiates back-up cooling to protect reactor equipment in events which could reduce service life or cause a long-term outage

- **Reactor Protection System (RPS)**
  - Initiates reactor trip to protect against nuclear control failure or loss of primary coolant from the primary reactor system
Good Plant Operability Relies Strongly on the Overall PCDIS Design Objectives

- First, the PCDIS provides complete monitoring and control of the reactor and plant processes
  - Includes all phases of plant operation. Startup, power operation, shutdown, etc.
  - Includes all levels of control - automatic, manual, etc.
- Second, the PCDIS provides first-line reactor cooling to minimize standby cooling utilization and enhance operability
- Third, necessary packaging of all I&C functions, as accomplished through the architecture, must compliment development of a human-machine interface suited to plant operability and safety
Assets Required to Develop the I&C Design

• Documentation — overall high level plant design spec, plus specific system documentation within the I&C systems and interfacing systems

• Staffing resources — analytical, instrumentation, administrative, procurement and other disciplines
  – I&C necessarily involves multiple contractors, increasing the documentation, personnel, etc.

• Facilities and I&C development resources
  – computer analysis and real-time simulator development are required
  – component selection and design verification and validation require testing
  – I&C software requires V&V
A Variety of Analysis Efforts are Required to Develop Control and Protection Hardware and Software

- Performance analysis is needed to establish control stability margins, develop algorithms, and establish setpoints for control and protection equipment.
- Real-time simulator analysis is needed to develop operator interface features and assure proper Human-Machine Interface (HMI) design.
- Failure effects and reliability analysis needed to verify reliability.
- Testing/qualification analysis needed to select equipment, verify designs, and assure implementation of design features.
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The Basic HTGR Control Strategy Incorporates Process Measurements with Reactor Power Control

- A process feedback measurement which encompasses reactor heat available to the process, including stored reactor heat, is selected to perform error-based command of reactor power
  - The reactor power control issues on-off, in-out commands to the control rod stepping motors
- Primary flow rate is controlled in proportion to plant output (electric output, etc.)
  - Secondary flow rate (steam generator feedwater flow) control is similar
- Reactor power responds to plant output change through the feedback mechanism
### A Consistent Reactor/Process Control Strategy Has Been Used in HTGR Plant Designs

<table>
<thead>
<tr>
<th>HTGR Plant Type</th>
<th>Feedback Measurement and Command Action</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nuclear Flux</td>
<td>Reactor Exit Temp</td>
</tr>
<tr>
<td>Single reactor/steam-electric</td>
<td>Control Rod Drive command</td>
<td>-</td>
</tr>
<tr>
<td>Multi-reactor/steam-electric</td>
<td>Control Rod Drive command</td>
<td>-</td>
</tr>
<tr>
<td>Gas-Turbine/electric</td>
<td>Control Rod Drive command</td>
<td>Reactor power level command</td>
</tr>
</tbody>
</table>
Reactor Control Capabilities Were Established in
Previous Steam-Electric or Other Plant Designs

- Electric plant load-following — identified by
  requirements such as rapid load change at 5% per
  minute, daily load cycle frequency control, and ±10%
  load step changes — is achievable and can be
  incorporated in the I&C design
  - Steam supply temperature can be held within ±3°C to
    maintain high plant efficiency at lowered power
  - Reactor component and fuel temperatures can be
    maintained well within normal operating levels
  - Transient nuclear power advance is completely
    tolerable

- Reduction of reactor power following electric load
  rejection, as in the GT-MHR electric plant, requires
  even faster power transitions
Several Major Feedback Control Systems are Typical in HTGR Plants Producing Steam Power

- Main steam temperature in command of reactor power
- Reactor power in command of neutron control assembly (NCA) hardware
- Circulator flow rate in command of circulator speed control hardware
- Feedwater flow rate in command of feedwater pump speed control hardware
- Main steam pressure in command of steam throttle-valve hardware
- Main steam de-superheat temperature - startup and shutdown main steam temperature control
- Reactor inlet temperature in command of feedwater holding tank pressure control valve hardware
Typical HTGR Steam-Electric Plant Control

- Nuclear Steam Control
- Steam Temperature Control
- Flux Setpoint Control
- NCA Command
- Circulator Speed Control
- Neutron Detectors
- Reactor Vessel
- Shutdown Circulator
- Feedwater Flow Control
- Steam Generator
- Feedpump Speed Control
- Main Steam Pressure Control
- Main Steam Bypass Control
- Feedwater Train
- Condensate Pump
- Deaerator
- Condenser
- Cooling Water
- Turbine Generator Control
- Turbine Speed
- Stop Valve
- Throttle Valve
- Nuclear Steam Control
- Supervisory Control
• Control and protection systems included in I&C
• Reactor and process control in High Temperature Gas-Cooled Reactor (HTGR) plant designs
• Application of digital systems to monitoring, control, and protection equipment
• Reactor protection developed in previous HTGR plants
  – I&C protection system functions and protection hardware interfaces
  – Reliability and interpretation of regulatory criteria
• Control Room and I&C architecture preferred for overall operation of the HTGR and associated heat utilization processes
Digital-Based I&C Architecture — Advantages Considered in 90’s Era HTGR Designs

• Modern digital displays optimize plant operation and supervision, and improve the human-machine interface
  – Consoles, displays, etc can achieve greater detail, but also provide maximum overview and flexibility, thereby supporting plant operations more effectively.

• Digital communication systems are better suited for multi-level information hierarchies, comprised of separated protection, control, and support networks, and can easily allow plant-wide distribution of instrumentation and command signals
  – Better supports a single Control Room plant design
Digital-Based PCDIS, RPS and IPS Equipment was Selected for Modular HTGR I&C Designs

• Supported single control room visibility and controllability of multiple reactor, multiple process plants
  – Modern graphical operation interface was considered essential

• Commercially proven, microprocessor based, distributed control hardware and operating software were available
  – Reduced I&C development effort

• Improved reliability
  – Reduced wires, connections, and reliance on single points typical of 60s to 70s analog era
Digital Interfaces for Operator Control and Information were Investigated by 90s Era Simulation Techniques
Recent Regulatory Criteria Support Digital I&C

- Regulatory Guide 1.152 offers guidelines that can be applied to the HTGR design
  - Contains criteria for use of computers in safety systems of nuclear power plants
  - Addresses software V&V, security from electronic vulnerabilities, use of commercial pre-developed I&C software and software development phases

- Conversion from analog equipment to digital in existing plants may offer further information on application of the new guidelines
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HTGR Reactor Protection Incorporates a Typical Strategy to Detect, Protect, and Provide Cooling

- **Detect an event which requires a reactor trip**
  - Events fall into various equipment failure categories. Design Basis Events (DBEs) are established for design of the protection system

- **Trip the reactor using safety-related equipment**
  - Gravity insertion of control rods. Backed up by Reserve Shutdown Control Equipment

- **When operable, use the main loop (ML) cooling functions to cool the reactor**
  - Incorporates Defense-in-Depth into the protection design strategy

- **When necessary, use shutdown cooling**
  - Active cooling systems are backed-up by the RCCS
## Non-Safety Cooling Source in Events Requiring Reactor Trip

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Event Description and Reactor Cooling Source (ML=main loop, SCS=Shutdown Cooling System)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Rapid, sustained control rod withdrawal (ML)</td>
</tr>
<tr>
<td>All</td>
<td>Slow, sustained control rod withdrawal (ML)</td>
</tr>
<tr>
<td>All</td>
<td>Operator or process trip (ML)</td>
</tr>
<tr>
<td>All</td>
<td>Loss of primary He flow or pressure (ML or SCS)</td>
</tr>
<tr>
<td>Steam-Electric</td>
<td>Loss of Off-site Power (LOSP) plus turbine protective action (ML) Note: The reactor continues to operate at reduced power, in the Gas Turbine HTGR following LOSP, and this can be designed into steam plants as well.</td>
</tr>
<tr>
<td>Steam-Electric</td>
<td>Steam Generator tube leak, loss of primary or secondary flow, loss of waste heat removal (SCS)</td>
</tr>
</tbody>
</table>
Protective Action Requires Detection, Reactor Trip, and Selection of a Cooling Sequence

- Protective action initiated by comparing measured levels with established levels (Set-Points)
- Additional protection system processing required to confirm and initiate a protective action

Legend:
- Path to Safety-Related Equipment
- Path to Non-Safety Equipment
- Loss Of ML Cooling
- Notify PCDIS
- Stop Main Loop
- Backup SCS Cooling
- Operator or Process Trip
- Reactor Power-to-Flow Error
- Reactor Building Isolation Detected
- SG, FW, CIRC, Condenser Or Other Main Loop Cooling Failure Detected
- Check Primary Flow Rate
- Primary Helium Flow Rate Too Low
- REQUEST CONTROL ROD TRIP IF ANY INPUT IS TRUE
- REQUEST BACKUP COOLING IF NEEDED
- START MAIN LOOP COOLING
- PCDIS Main Loop Cooling
## Typical Steam-Electric Plant Reactor Protection Set-Points and Measurements

<table>
<thead>
<tr>
<th>Protection Set-Point Parameters</th>
<th>Physical Measurements Needed</th>
<th>System Providing Instrumentation (per I&amp;C spec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Power-to-flow ratio</td>
<td>Neutron flux/He flow</td>
<td>Reactor, Reactor building</td>
</tr>
<tr>
<td>Helium Flow Rate</td>
<td>Circulator P, T, Δp and Speed</td>
<td>Circulator</td>
</tr>
<tr>
<td>Reactor Exit/Inlet Helium Temps</td>
<td>He Supply/ Return Temp</td>
<td>Steam Generator/Vessel</td>
</tr>
<tr>
<td>Turbine Status</td>
<td>Trip Signal</td>
<td>Balance of Plant</td>
</tr>
<tr>
<td>SG Boundary</td>
<td>He moisture content, Press</td>
<td>Steam Generator/Vessel</td>
</tr>
<tr>
<td>SG Flow Rate</td>
<td>Feedwater flow</td>
<td>Balance of Plant</td>
</tr>
</tbody>
</table>
### Instrumentation Estimates for a Steam-Electric Plant Provided in Preliminary NP-MHTGR Documentation

<table>
<thead>
<tr>
<th>Significance of Measurements</th>
<th>Distribution of Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Reactor Operation supporting systems such as the Reactor, Shutdown Cooling, Helium Purification, Steam Generator, etc.</td>
<td>2500 measurements, distributed in 22 systems</td>
</tr>
<tr>
<td>Secondary instrumentation supporting plant operation in systems such as plant electrical, He transport &amp; storage, rad monitoring, water treatment, etc</td>
<td>1500 measurements distributed in 19 systems</td>
</tr>
</tbody>
</table>
### Protection System End-Action Method Typical in HTGR Protection Design

<table>
<thead>
<tr>
<th>End-Action</th>
<th>Method Used</th>
<th>System Providing Hardware</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Rod Trip</td>
<td>De-energize CR holding coils</td>
<td>Reactor – Neutron Control Assembly</td>
</tr>
<tr>
<td>Steam Generator Isolation</td>
<td>Activate SG Isolation &amp; Dump</td>
<td>Steam Generator Vessel, BOP</td>
</tr>
<tr>
<td>Start Backup Cooling</td>
<td>Shutdown main circulator and start SCS</td>
<td>Shutdown Cooling System (SCS)</td>
</tr>
<tr>
<td>SCHE Isolation and Drain</td>
<td>Close SCHE Isolation valves. Open SCHE drain</td>
<td>Shutdown Cooling System (SCS)</td>
</tr>
</tbody>
</table>
HTGR Protection Equipment Design Criteria Have Been Established — Fort St. Vrain Experience was Important

- **Protection systems incorporate 2 out of 4 logic to provide redundancy**
  - This strategy reverts to 2 out of 3 logic to support on-line maintenance and testing

- **All protection systems use the same design strategy and use Class 1E equipment**
  - Highest qualification is required for “safety-related” equipment — important criteria determined by specific plant location and design
  - Inherent safety features of the HTGR allow lesser requirements for investment protection equipment not directly associated to public safety
2 out of 4 Logic Provides Redundancy but Prevents Spurious Trips

- Decision logic compares data to set-point
- Coincidence logic confirms that 2 of the same trips — of 4 possible — have been requested, and allows either the A or B trip train to activate the hardware
Basis for 10 CFR 50 Design Criteria Incorporated in HTGR I&C Systems

• 10 CFR 50.55a(h)
  - Addresses the design of I&C systems performing safety functions
  - Incorporates IEEE 603/IEEE 279 describing design bases for reliability, independence, single failures, qualification, HMI considerations, displays, status indication, testing, operating and maintenance bypasses, setpoints, etc

• LWR General Design Criteria (GDC) in Appendix A of the Code of Federal Regulations (CFR), Title 10, Part 50
  - Address design, implementation, construction, testing, and performance requirements
  - Apply to structures, systems, and components important to safety.

• Appendix B of 10 CFR 50 establishes Quality Assurance (QA) requirements
Additional Considerations Affecting Protection and Control Design in HTGR Plants

- Inclusion of Safety-Related electric supply systems
- Specific separation, diversity, and QA requirements for safety Instrumentation, data processing systems, decision logic processors, etc.
- Sharing of safety-related hardware to perform automatic control as well as reactor protection actions
- Provision of dedicated safety consoles, displays and procedures for real-time information, warnings, alarms, and operator initiated protective actions
  - May include remote shutdown.
- Achievement of specific levels of reliability for all instrumentation, control, and supporting equipment affecting overall operability and plant operating goals.
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Conclusions Reached in HTGR Plant Designs
Specifying Operation from a Single Control Room

• Various trade studies conducted by participants in the NP-MHTGR and the MHTGR programs concluded:
  – Supervision and communication aspects are greatly improved
  – Plant operation activities, including maintenance and process observation are better supported
  – Staffing and design costs are lower

• Use of modern computer technology provided an essential space-saving feature, supportive of an advanced operator interface within a single control room
The Four Reactor NP-MHTGR Plant Design Provided

Typical HTGR Control Room Design Strategies

- TECHNICAL SUPPORT CONSOLE
- PAPS TREND A + B COMPUTERS
- MODULE MONITORING AND ACCOUNTABILITY COMPUTERS A + B
- EVENT LOGGING AND ANALYSIS SYSTEM
- PLANT OVERVIEW DISPLAY
- AUXILIARY SYSTEM WORKSTATION
- SUPPORT CONSOLE
- OPERATOR WORKSTATION
- RESERVED FOR FUTURE EXPANSION
- DATA STORAGE
- PRODUCTION SUPERVISORY WORKSTATION
- SHIFT SUPERVISOR OFFICE

INL Idaho National Laboratory

GENERAL ATOMICS
Multiple Levels of Data Transfer Hierarchy in 90’s Era Design Typify the Need for Modern Networking Features

- Plant wide data highways support supervision, maintenance and plant information processing
- Intermediate level data highways exchange instrumentation and control signals
- Lower level data highways exchange information to specific plant areas
Digital Architecture Provides Separation of I&C Systems While Providing Total Information for All Operators
Summary

- I&C provides monitoring and control all plant processes, and incorporates strategies to enhance reactor safety, equipment protection, and plant operability.
- Modern digital equipment is expected to form the basis of the various I&C components, including safety systems.
- The I&C design is aided by past HTGR programs which have developed documentation, inter-system responsibilities, methods, analysis, and testing needs for I&C design.
- The plant architecture provides a multi-level information hierarchy, allowing plant-wide distribution of instrumentation and command signals, and access to all plant functions from a single control room.
Suggested Reading

• DOE-HTGR-86004, Overall Plant Design Specification Modular High Temperature Gas-Cooled Reactor
• DOE-HTGR-86076, Plant Control, Data and Instrumentation System