Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

Nuclear I&C Systems Basics

The role of Instrumentation and Control Systems in Nuclear Power Plants, and their Characteristics

Functions of Nuclear I&C

Functions and significance of the Instrumentation and Control Systems in Nuclear Power Plants

Three primary functions of the I&C system architecture

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

Measurement and sensing

- to provide the sensory (e.g., measurement and surveillance) capabilities to support functions such as monitoring or control, and
- to enable plant personnel to assess status

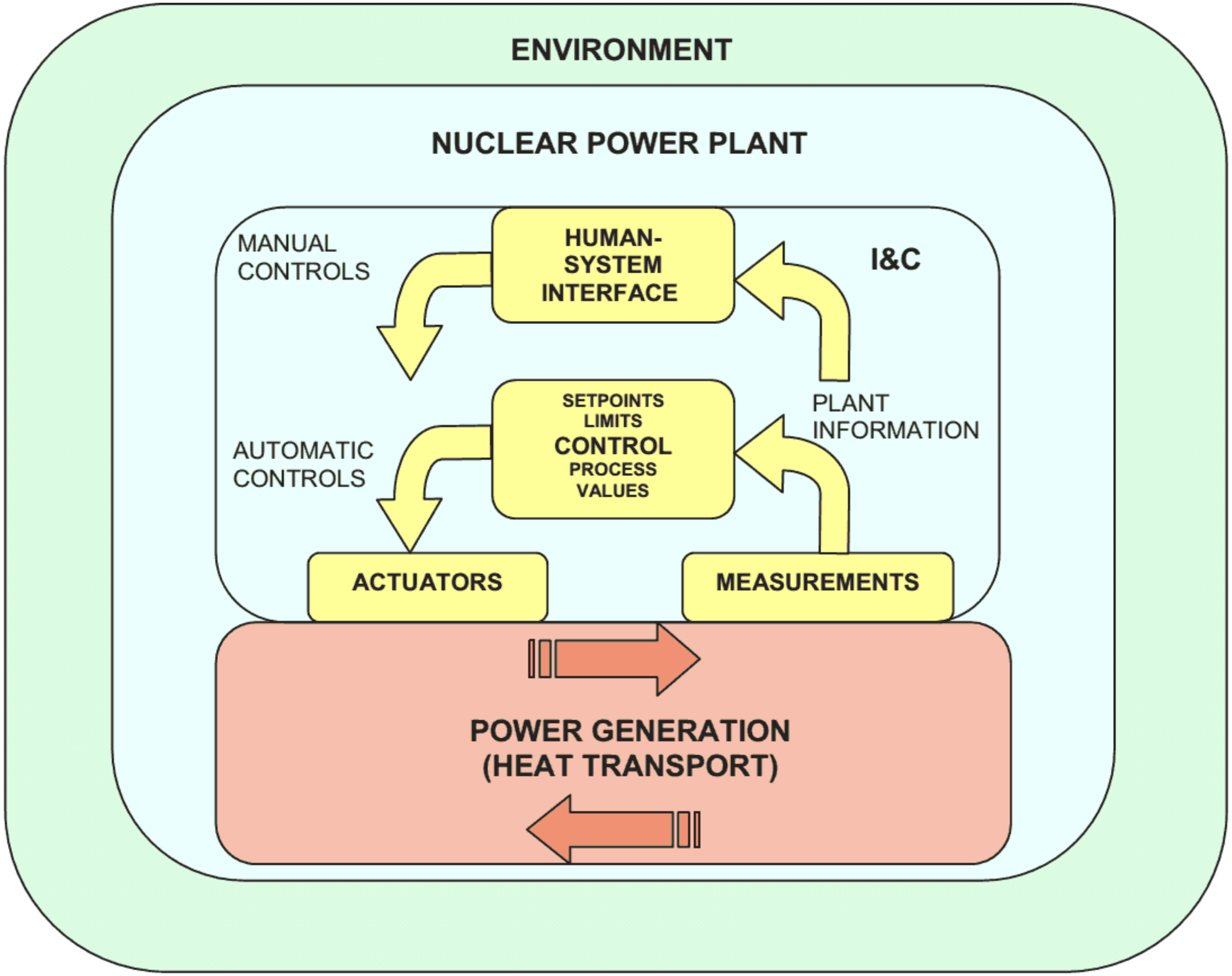
Regulation and control

- to regulate plant processes (i.e. keeping process parameters within acceptable limits), and
- to provide automatic control, both of the main plant and of many ancillary systems → reduces the workload on the operations staff

Protection

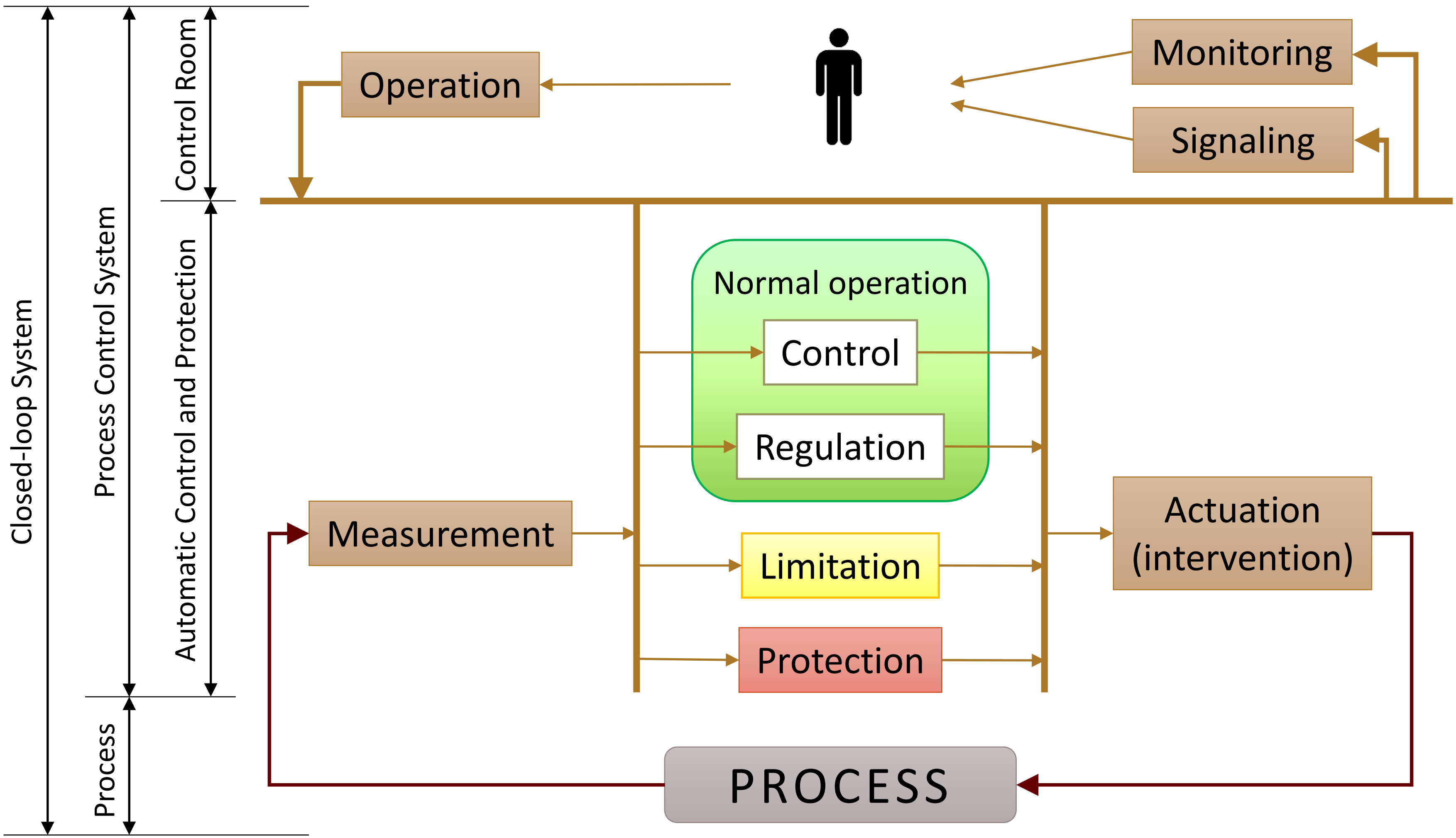
- to protect the plant against abnormal conditions
- to protect from the consequences of any malfunction or deficiency of plant systems or as a result of errors in manual action
- rapid automatic action to protect both the plant and the environment

High-level overview of I&C main functions



Functional view of the Process Control System

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems



I&C Systems by Functional Groups

- Sensors
  - to interface with the physical processes within a plant
  - to continuously take measurements of plant variables such as neutron flux, temperature, pressure, flow, etc.
- Operational control, regulation and monitoring systems
  - to process measurement data, to manage plant operation, and to optimize plant performance
  - surveillance and diagnostic systems that monitor sensor signals for abnormalities are important parts of operational monitoring systems
- Safety systems
  - to keep the plant in a safe operating envelope in case of any postulated initiating event (design basis accident)
- Communication systems
  - to provide data and information transfer through wires, fibre optics, wireless networks or digital data protocols
- Human-system interfaces (HSIs)
  - to provide information to and interaction with plant operating personnel
- Actuators (e.g., valves and motors)
  - to adjust the plant’s physical processes

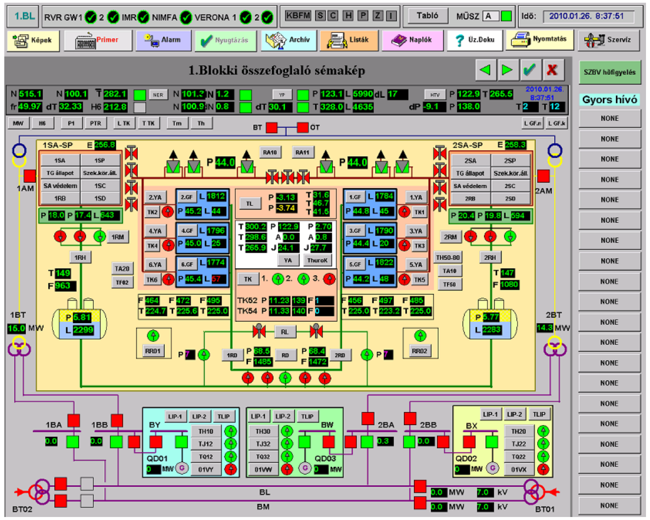
I&C main functions: Measurements

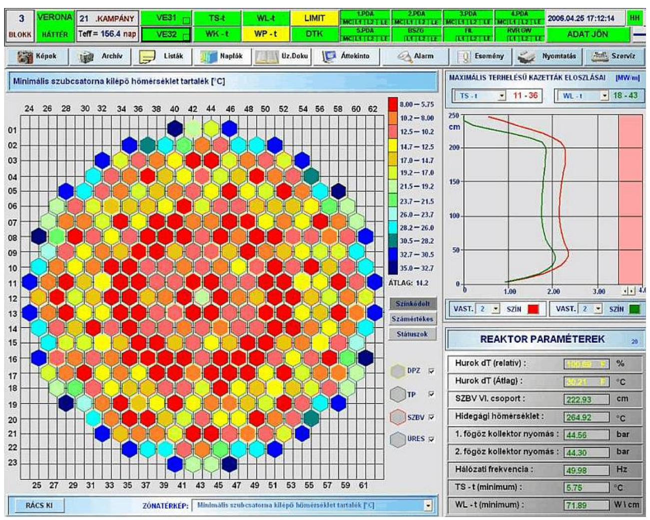
- Information about the state of the process

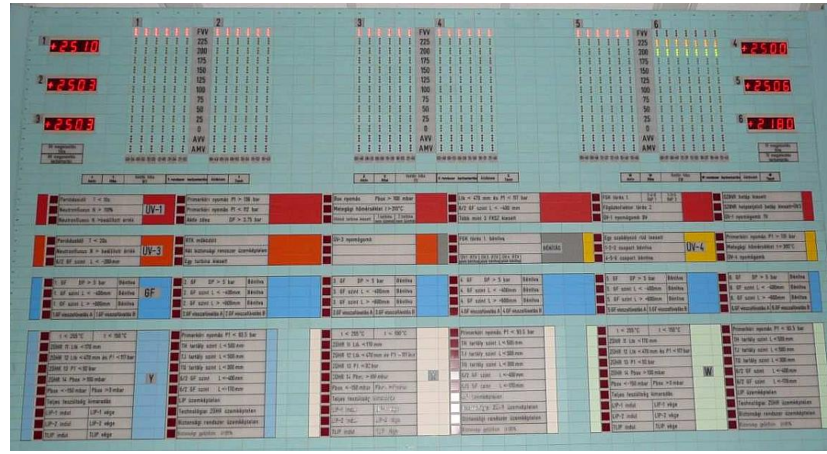
- Nuclear Power Plants:
  - In-core instrumentation
    - Power distribution in the active zone, not used for control
    - SPDN: self-powered neutron detectors
  - Nuclear instrumentation
    - Nuclear power (doubling time) in the active zone
      - from the source range (10^{-12} %) to the overload zone (125%)
        - Paks NPP source range: $10^{-10} – 10^{-4}$ %
        - wide range: 10^{-5} – 10%
        - power range: 1 – 120%
    - Ionization chamber type neutron detectors in the power range

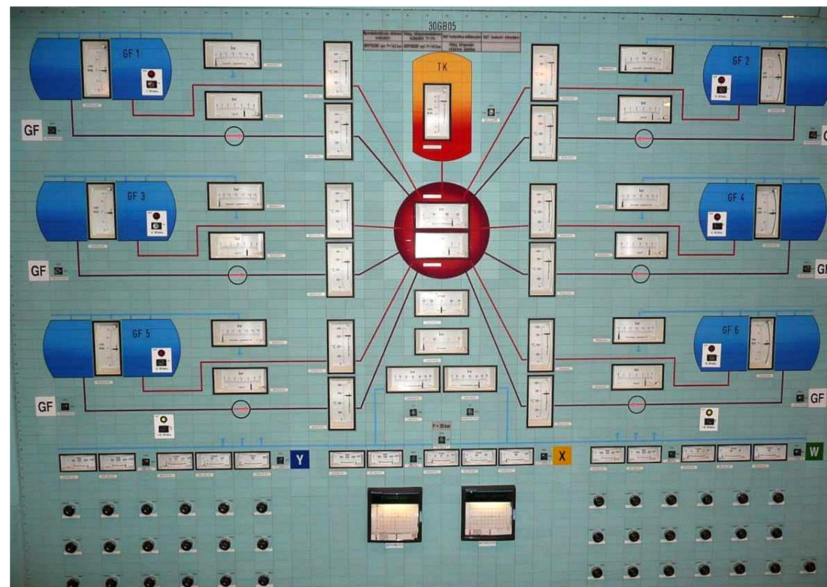
HMI Examples from the Paks NPP

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems









I&C main functions: Visualization

Crystal River Nuclear Plant, Florida, U.S.A.

Paks Nuclear Power Plant, Paks, Hungary

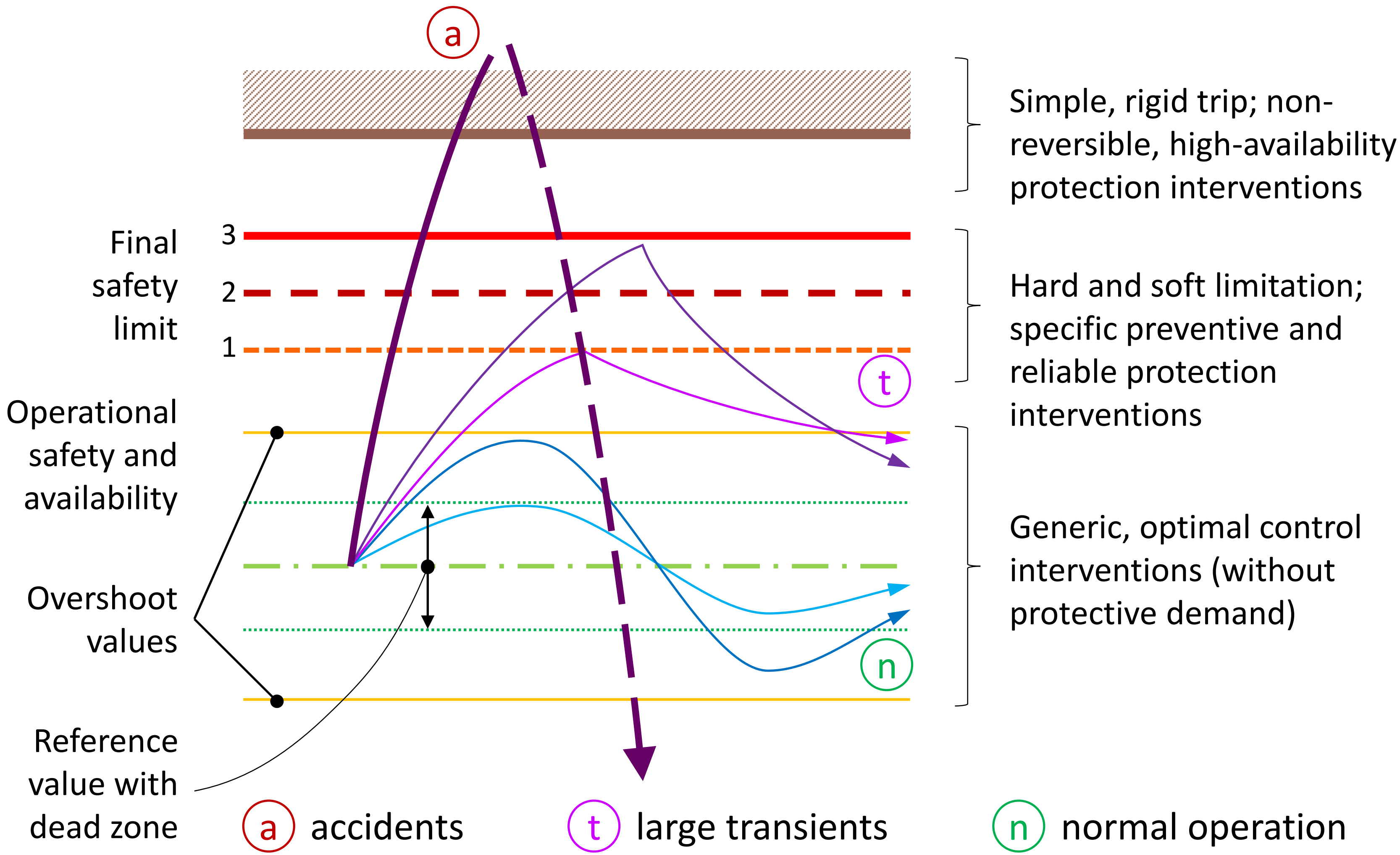
Beznau I Nuclear Plant, Döttingen, Switzerland

Tianwan Nuclear Plant, Lianyungang, China

I&C main functions: Control

- Control
  - in case of disturbances maintains the state variables in nominal conditions,
  - in case of set-point following provides optimal tracking performance.
- The following main control task groups are typical in a PWR NPP:
  - Unit Control
  - Reactor (Power) Control
  - Reactor Coolant Control
  - Steam Generator Control
  - Turbine Control
- Under normal operating conditions, automatically controls the main and auxiliary systems
  - Allows the operator to observe the plant's behavior and displays what is happening in the plant, so that the right corrective intervention can be implemented if necessary.

I&C main functions: Limitation



Interlock Systems

- Interlock systems prevent unsafe conditions or operations, protect personnel and prevent hazards.
- Interlocks prevent actions that could lead to or increase danger or damage to the plant, and do not normally initiate actions to correct conditions.
- Interlock functions may be
  - active functions, which maintain a continuing action to prevent a condition from developing, or
  - passive functions, which prevent an action.
- Interlock functions may be provided by mechanical means or by administrative or electrical methods. Mechanical and administrative interlock functions are not within the scope of I&C systems.

I&C main functions: Protection

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

- Terminology
  - **Reactor Scram** or Reactor Trip refers to the insertion of the control rods.
  - **Turbine Trip** refers to the shutting of the control valves that admit steam to the turbine.
  - **Generator Trip** refers to the opening of the output breakers from the generator.
  - **Engineered Safety Feature Actuation** refers to the actions related to shutting down the reactor, mitigating the effects of a loss of reactor coolant accident, or minimizing offsite release.
  - **ATWS** refers to the extremely low probability postulated event whereby it is assumed all rods do not automatically insert and cannot be manually tripped.
- Functions provided by ESFAS include:
  - **Emergency Core Cooling** (ECCS) start to provide cooling of the reactor core
  - **Emergency Feedwater** start to provide water to the reactor (if a BWR) or steam generator (if a PWR)
  - **Containment Isolation** closure of valves and shutdown of ventilation systems to minimize offsite releases of radioactivity
  - **Containment Ventilation Isolation** closure of dampers in ventilation system exiting the containment to reduce potential for offsite releases
  - **Emergency Ventilation System** start and normal ventilation system shutdown
  - **Emergency Diesel Generator** start to provide a backup power source
  - **Containment Spray** start to reduce the containment pressure

Protection Systems in the Paks NPP

- Reactor (primary circuit) protection
  - Protective actuation is realized by the movement of control rods, and the operation of the technological actuators
    - one-way operation: after it starts it irreversibly operates as long as the initiating parameter(s) (the cause) is not within the limit, or until the reactor shuts down
    - monitored parameters and characteristics are the nuclear and non-nuclear measurements, the state of protection equipment and the operators' activities
  - Protective movement of the control rods (Emergency Protection, EP)
    - EP-1: all the control rods drop into the zone (fast-reactor shutdown: scram)
    - EP-2: consecutive drop of control rod groups (reactor gradual shutdown)
    - EP-3: consecutive lowering of control rod groups at operating speed (slow stop)
    - EP-4: upward movement of the rods (extraction) is prevented (power increase inhibition)
  - In case of EP-2-3-4 the technological actuators do not move
  - In case of EP-1, however, many variations are possible depending on the cause, but there are cause-independent executions as well (e.g. in case EP-1 on both turbines are switched off with 10-second delay)

Protection Systems in the Paks NPP

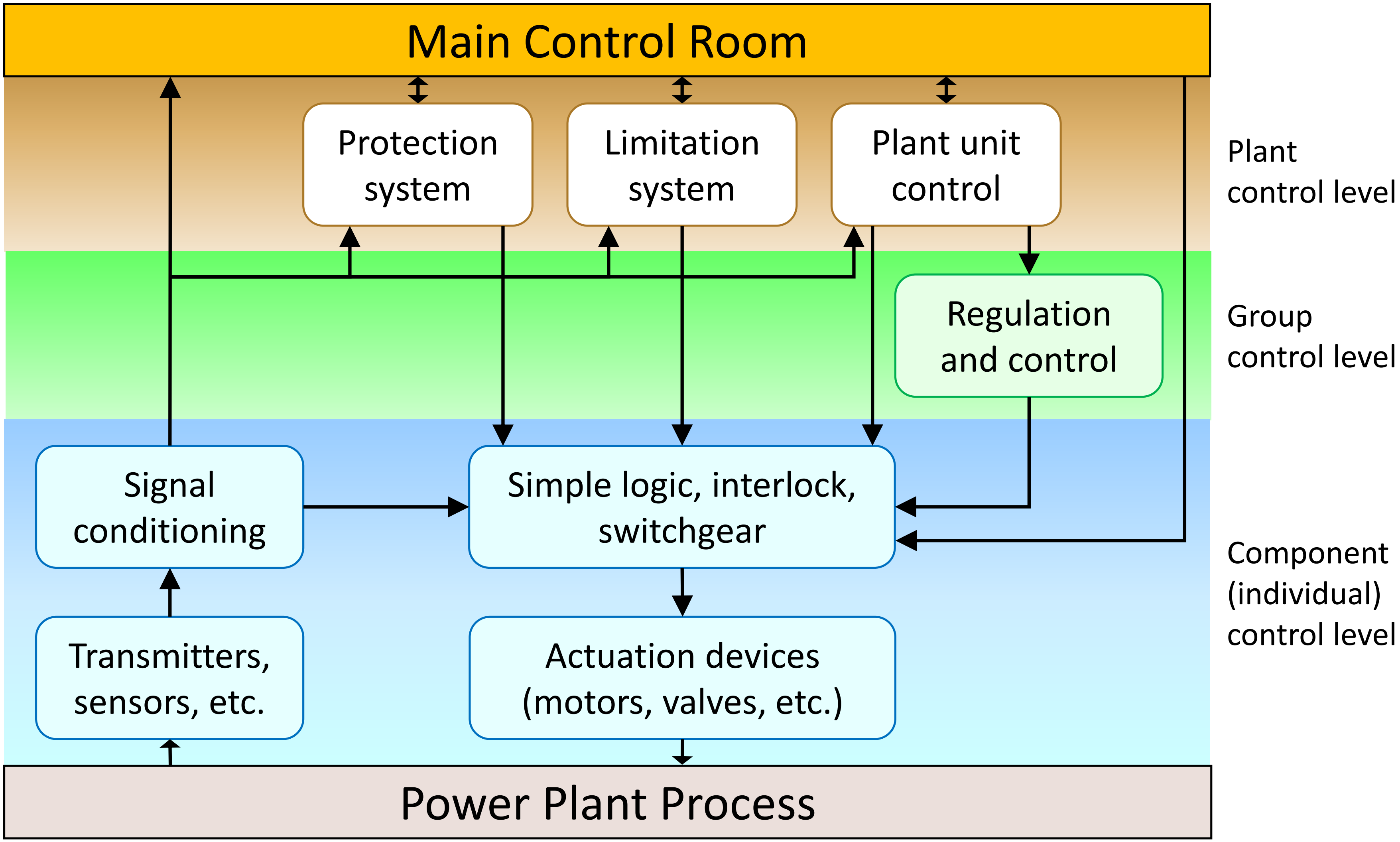
- Secondary circuit protection
  - Protects the main equipment of the secondary circuit from adverse effects
    - as the primary circuit protection, its operation is high-priority, thus if the initiating parameter(s) exceeds the limits, the operator can not affect the operation of the protection
  - Three main groups: reactor unit protection, turbine protection, steam generator protection
- Emergency Core Cooling System (ECCS)
  - In the event of large-scale disturbances (e.g. Large flow of in the primary circuit, steam generator fracture) provides the cooling of (heat transport from) the active zone

Summary of I&C Functions

- Protection functions
  - Protection functions provide a line of defence against failures in other plant systems. They are among the most critical of the safety functions and relate directly to nuclear safety in terms of protecting personnel and the public in the event of a serious failure.
- Control functions
  - Control functions provide assurance that the plant is controlled and kept within its operating envelope under normal and abnormal conditions. Control functions can also mitigate the effects of plant transients or PIEs, thereby contributing to nuclear safety by minimizing the demand on protection functions.
- Monitoring and display functions
  - Monitoring and display functions provide the interface between the plant and the operations and maintenance personnel. These functions are important to safety as they allow the plant personnel to intercept transients and maintain the plant within the envelope for safe operation.
- Testing functions
  - Testing functions provide assurance of the availability and effectiveness of other functions important to safety and confirm that these have not been degraded.

I&C Hierarchical Structure

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

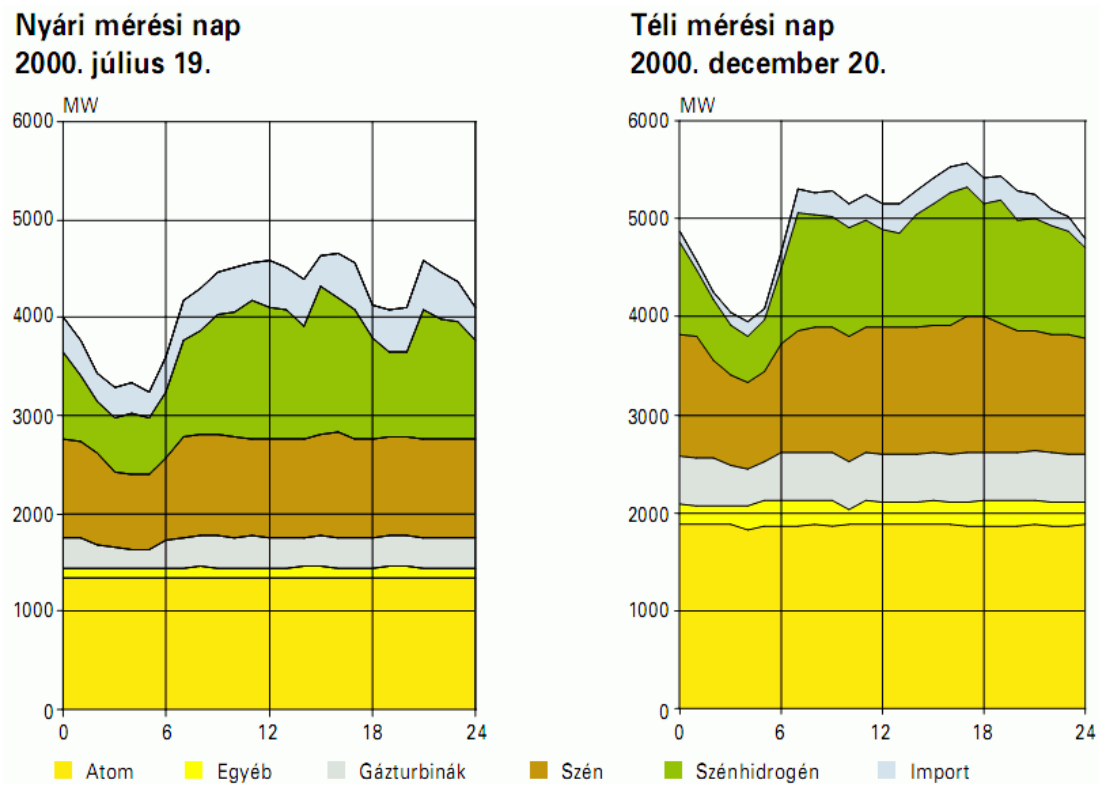


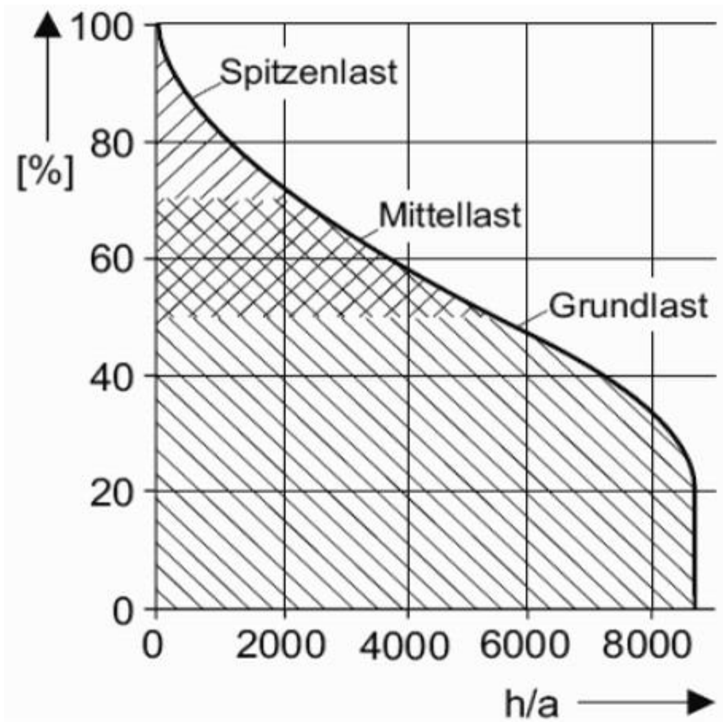
Unit Power Control

Introduction to the basics of Unit Power Control in Nuclear Power Plants

Variation of Consumer Demand

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

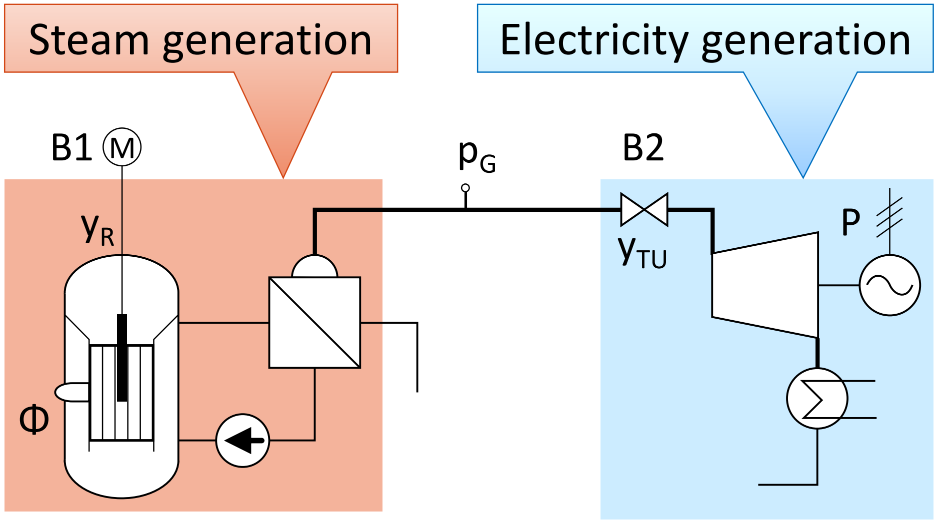




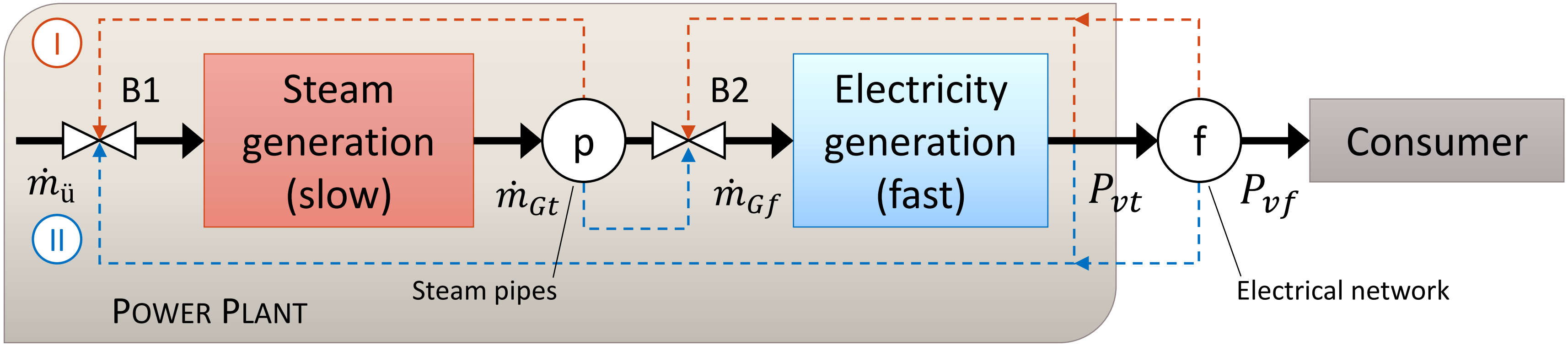
$$\frac{df}{dt} \sim \left(\sum_i P_{vt,i} - \sum_j P_{vf,j} \right)$$

Unit Power Control Strategies

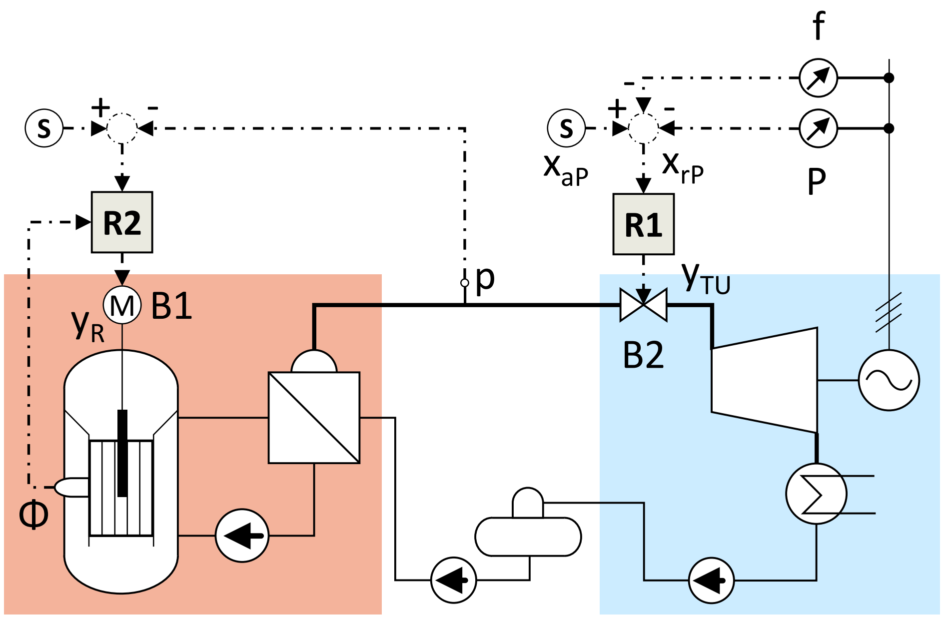
Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems



$$\frac{dp}{dt} \sim (\dot{m}_{Gt} - \dot{m}_{Gf})$$



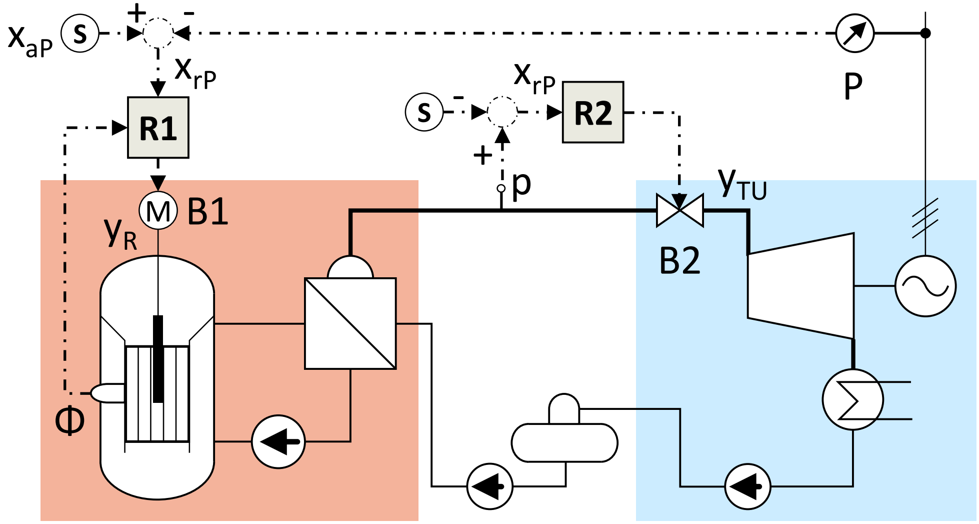
Power Control with Pre-Turbine Intervention



- Intervention is started by frequency and/or MW-controller set point change
  - primary actuation: pressure regulation valve
  - surplus steam demand is supplied by the capacity of the boiler
  - pressure change activates secondary intervention
- Secondary actuation: position of control rods
- Fast power change, flexible power control, pressure control is difficult
- Reactor-following, reactor follows turbine mode

Power Control with Reactor-side Intervention

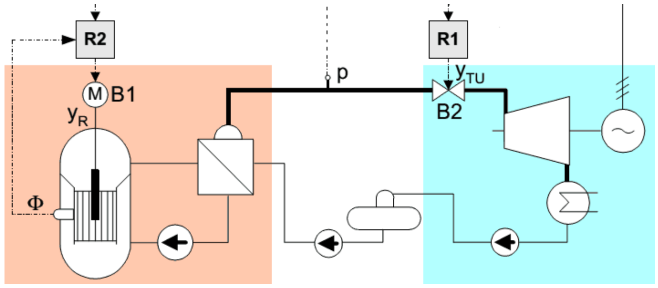
Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems



- Intervention starts on the reactor-side (set point change)
  - primary actuation: position of control rods
  - steam generation and pressure change activates secondary intervention
- Secondary actuation: pressure regulation valve
  - turbine steam consumption and electrical power follows
- Slow power change, inflexible power control, fast pressure control
- Turbine-following, turbine follows reactor mode

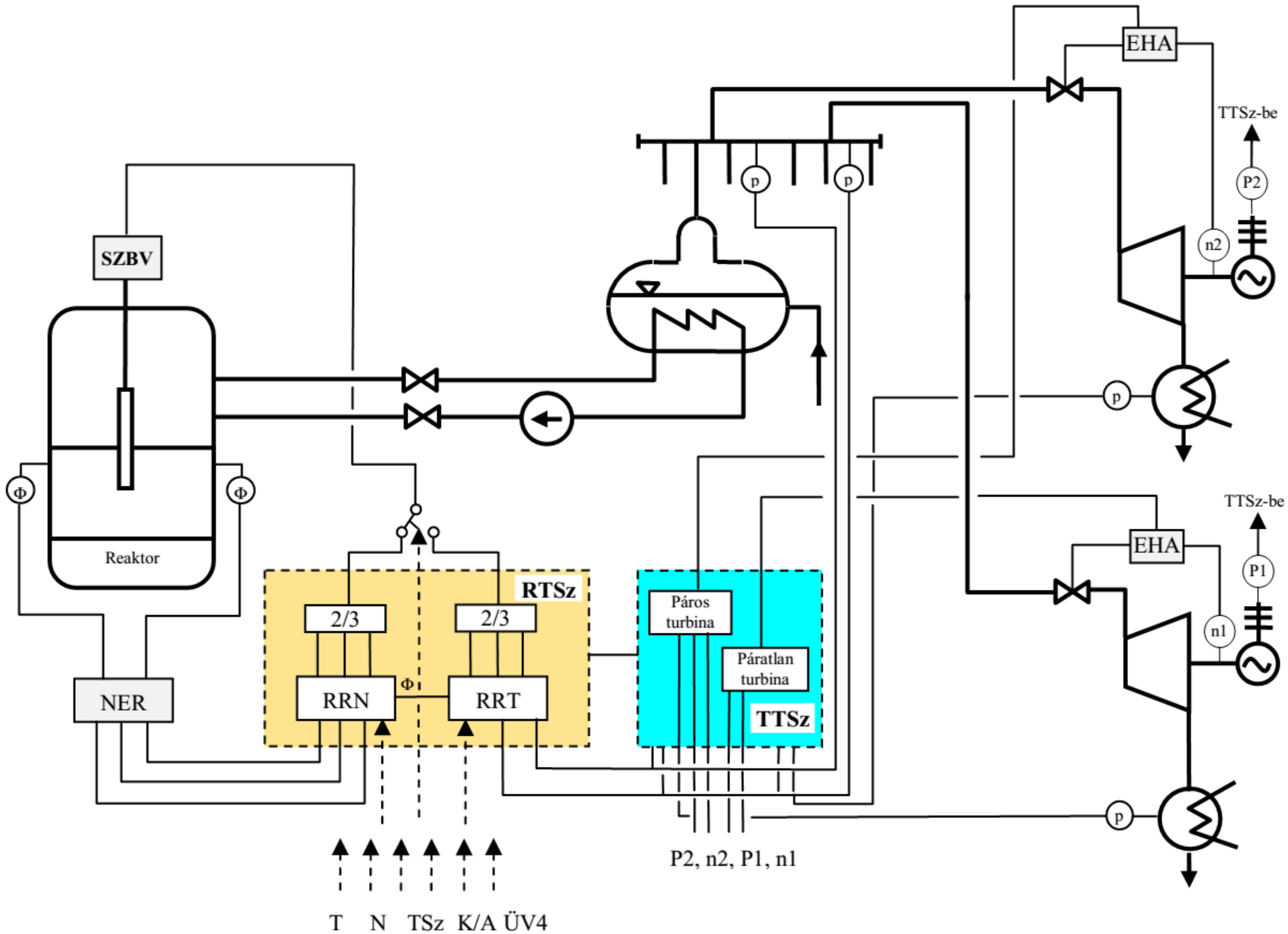
Unit Power Control Strategies and Characteristics

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems



Control objective	Controlled variable	Intervention		
		I.	II.	III.
Electrical Power Control	Electrical Power (P [MW])	Pre-Turbine (B1)	Pre-Reactor (B1)	B1 and B2 coordinated
Pressure Control	Steam Pressure (p [bar])	Pre-Reactor (B2)	Pre-Turbine (B2)	
Unit Control Strategy		**Active Turbine, Reactor Follows**	**Passive Turbine, Turbine Follows**	**Integrated**
Characteristics		Fast power change, significant pressure change, for varying load	Slow power change, sparing operation, for base load	Fast power change, longevity extending operation, for varying load

Unit Power Control in the Paks NPP



I&C Architecture

The Structure and Organization of
Nuclear Instrumentation and Control Systems

Main Safety Functions of I&C

Safety functions for the control of reactivity:

- provide for normal reactivity control within safe limits;
- prevent unacceptable reactivity transients;
- shut down the reactor as necessary to prevent anticipated operational occurrences from leading to design basis accident conditions;
- shut down the reactor to mitigate the consequences of accident conditions;
- maintain the reactor in a safe shutdown condition after all shutdown actions.

Safety functions for the removal of heat from the core:

- remove heat from the core during power operations;
- remove residual heat in appropriate operational states and design basis accident conditions with the reactor coolant boundary intact;
- maintain sufficient coolant inventory for core cooling in normal operational states and following any PIEs;
- remove heat from the core after a failure of the reactor coolant pressure boundary in order to limit fuel damage;
- transfer heat to the ultimate heat sink from intermediate heat sinks used in removing heat from the core.

Safety functions for the confinement of radioactive materials and control of operational discharges as well as limitation of accidental releases:

- maintain the integrity of the cladding for the fuel in the reactor core;
- maintain the integrity of the reactor coolant pressure boundary;
- limit the release of radioactive materials and minimize the exposure of the public and personnel to radiation.

I&C Systems: Reactivity Control

- systems which provide reactor shutdown (trip) initiation;
- systems used to monitor or maintain plant parameters within
  - operational limits important to safety (such as coolant temperature control systems);
  - limits assumed as initial conditions in the safety analysis (such as control systems for reactor power limits);
- systems whose malfunction or failure could place a demand upon systems providing protection functions, such as reactivity control systems;
- systems that perform functions important to maintaining safe shutdown conditions, e.g. provisions for computing the margin to criticality;
- systems that perform functions important to the prevention, termination or mitigation of anticipated operational occurrences or design basis accident conditions, e.g. reactor power setback systems;
- systems provided expressly for diverse backup of the systems providing protection functions, e.g. systems that mitigate anticipated transients without scram or systems that take account of possible design errors.

I&C Systems: Heat Removal from the Core

- systems, such as reactor protection systems and actuation systems for engineered safety features, which automatically initiate the operation of systems
  - to ensure that specified design limits are not exceeded as a result of anticipated operational occurrences,
  - to sense design basis accident conditions and mitigate their consequences, or
  - to override unsafe actions of the control system;
- systems which monitor or control plant environmental conditions that are necessary for the proper functioning of plant equipment important to safety and habitability.

I&C Systems: Confinement of Radioactive Materials

Perform functions of confinement of radioactive materials and control of operational discharges, as well as limitation of accidental releases

- systems whose malfunction or failure could cause a release of radioactive material to the environment and for which no safety system is provided, e.g. those that control waste management and spent fuel cooling;
- systems used to detect and measure leakage from the reactor coolant system;
- systems which monitor or control natural or human made phenomena that could adversely affect safety, e.g. seismic monitors;
- systems used for accident monitoring and assessment, e.g. those that monitor and record, as necessary, containment pressure, containment activity, reactor core cooling, radioactive releases to the environment and meteorological data.

I&C Systems: Support of Safety

- systems that provide a support function to multiple I&C systems important to safety, e.g. digital data communication systems that transmit signals between systems and between components of systems;
- systems used to monitor the status of safety systems, e.g. those that monitor for failure of safety channels and defects in pipes, valves or pumps of safety systems;
- systems that may be utilized in the operation of safety systems, e.g. for testing the protection system; and
- other specific I&C applications important to safety, e.g. for communication, fire detection and suppression, and access control.

I&C Systems by Importance to Safety

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

Plant equipment

Items important to safety

Items not important to safety

Safety systems

Protection system Initiation I&C for:

- Reactor trip
- Emergency core cooling
- Decay heat removal
- Confinement isolation
- Containment spray
- Containment heat removal

Safety actuation system Actuation I&C for:

- Reactor trip
- Emergency core cooling
- Decay heat removal
- Confinement isolation
- Containment spray
- Containment heat removal

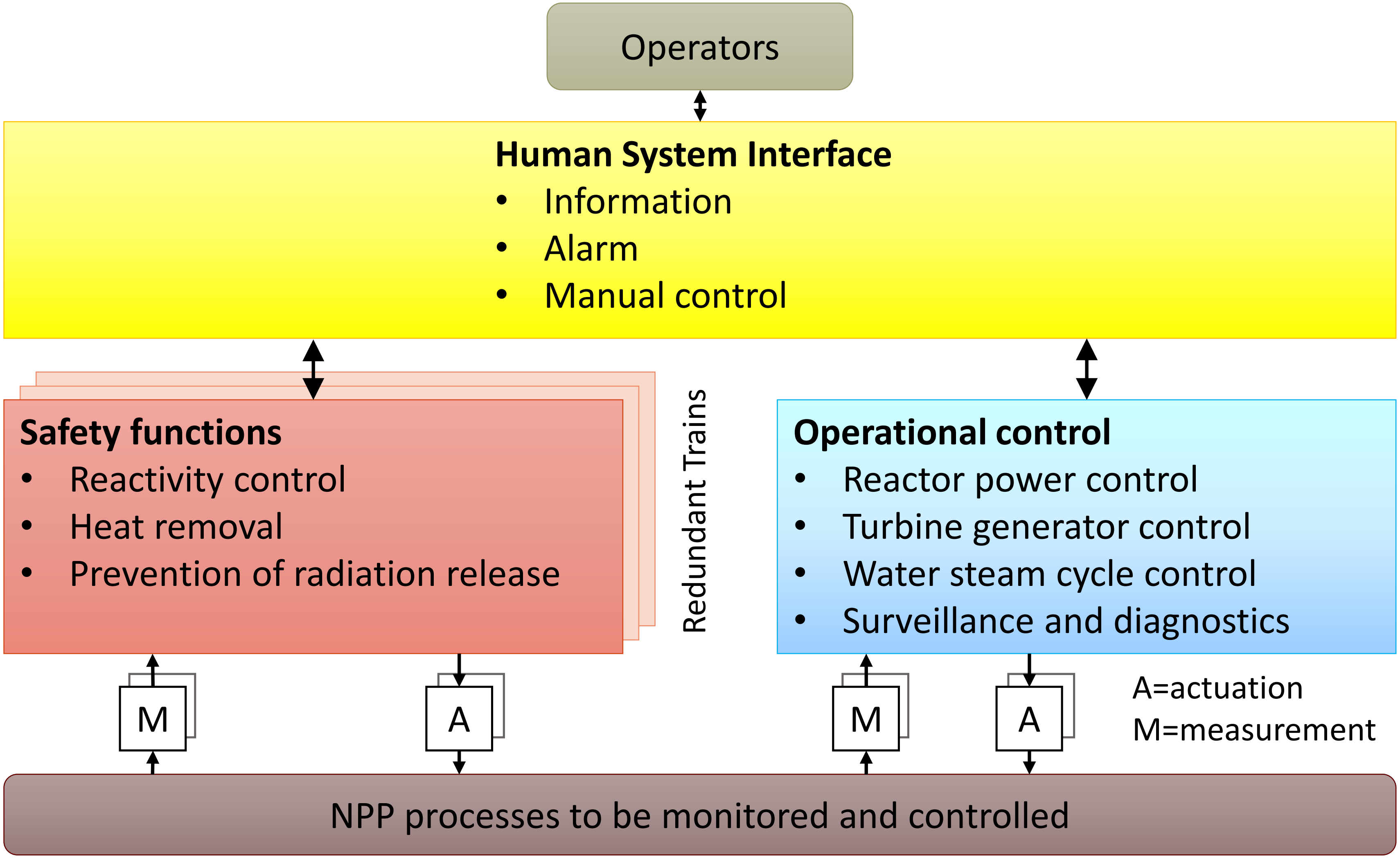
Safety system support features I&C for:

- Reactor control systems
- Plant control systems
- Control room I&C
- Fire detection and extinguishing I&C
- Radiation monitoring
- Communication equipment
- Fuel handling and storage I&C

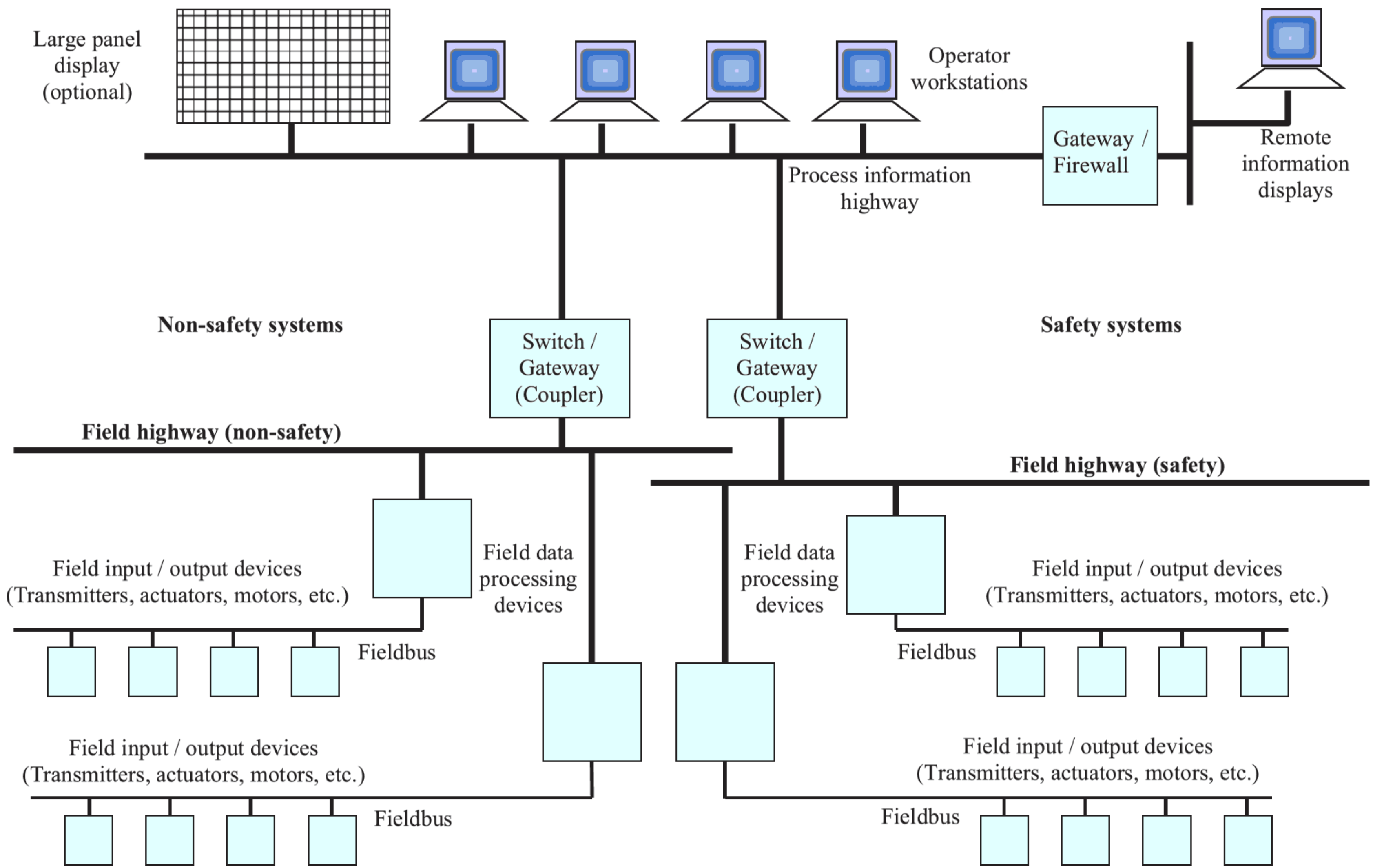
Safety related items or systems

- Limiter systems
- Emergency power supply
- Fire detection and signaling I&C
- Radiation monitoring

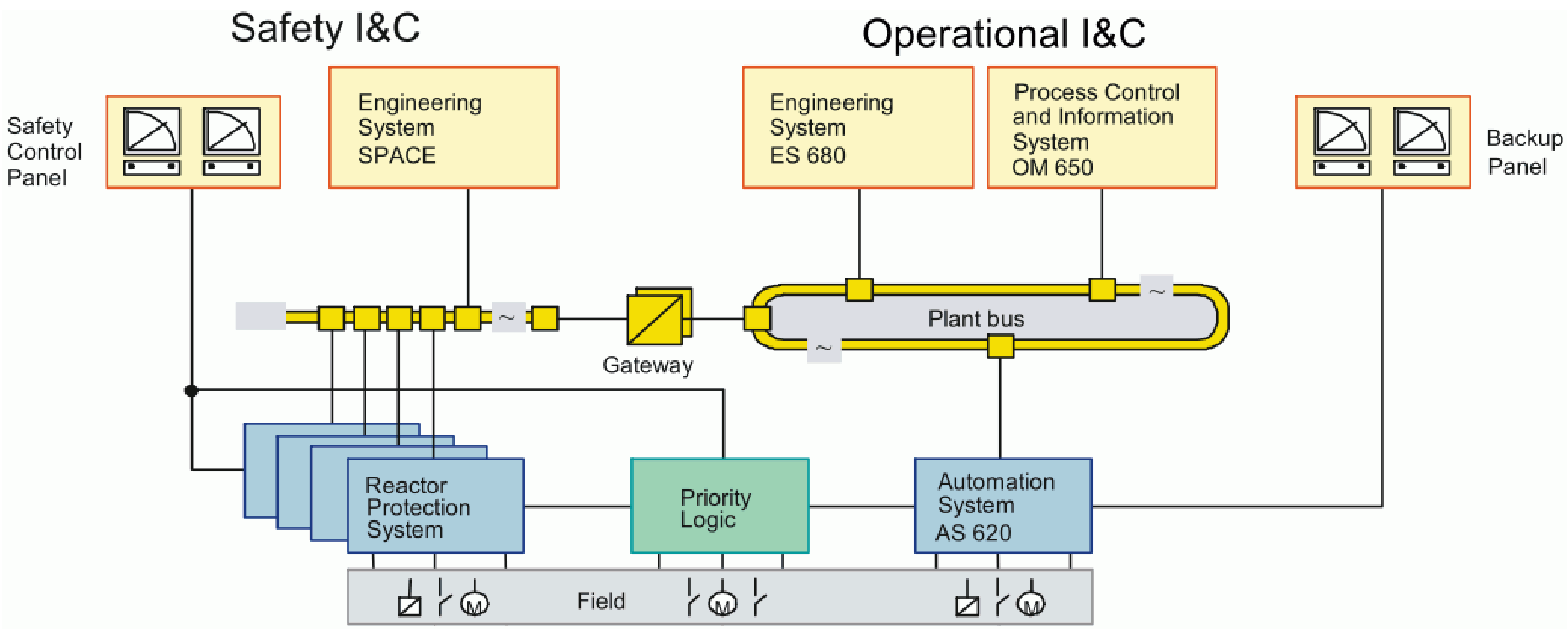
Nuclear I&C Generic Architecture



Distributed Signal Processing and Control



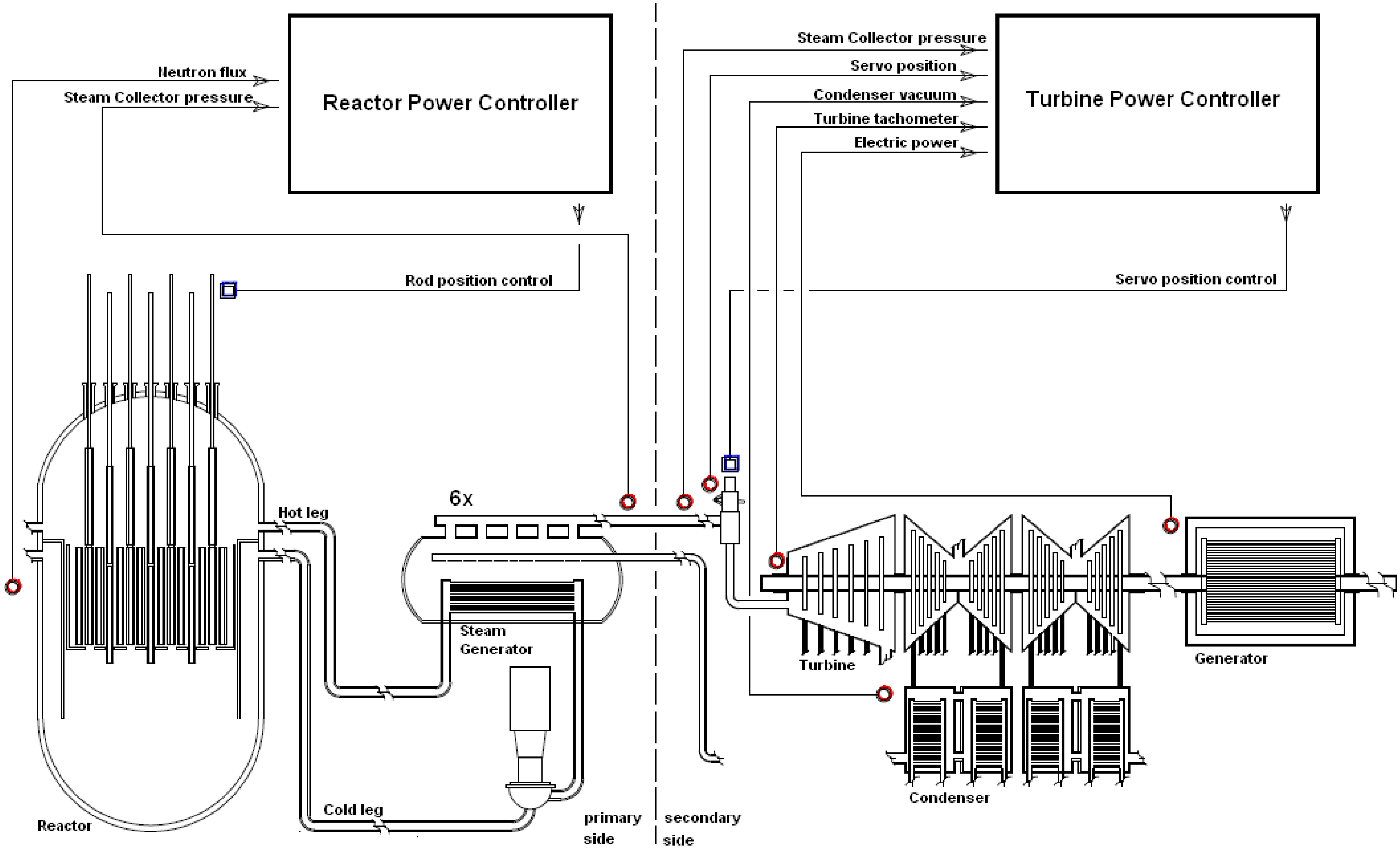
Example: TELEPERM XS and SPPA-T2000



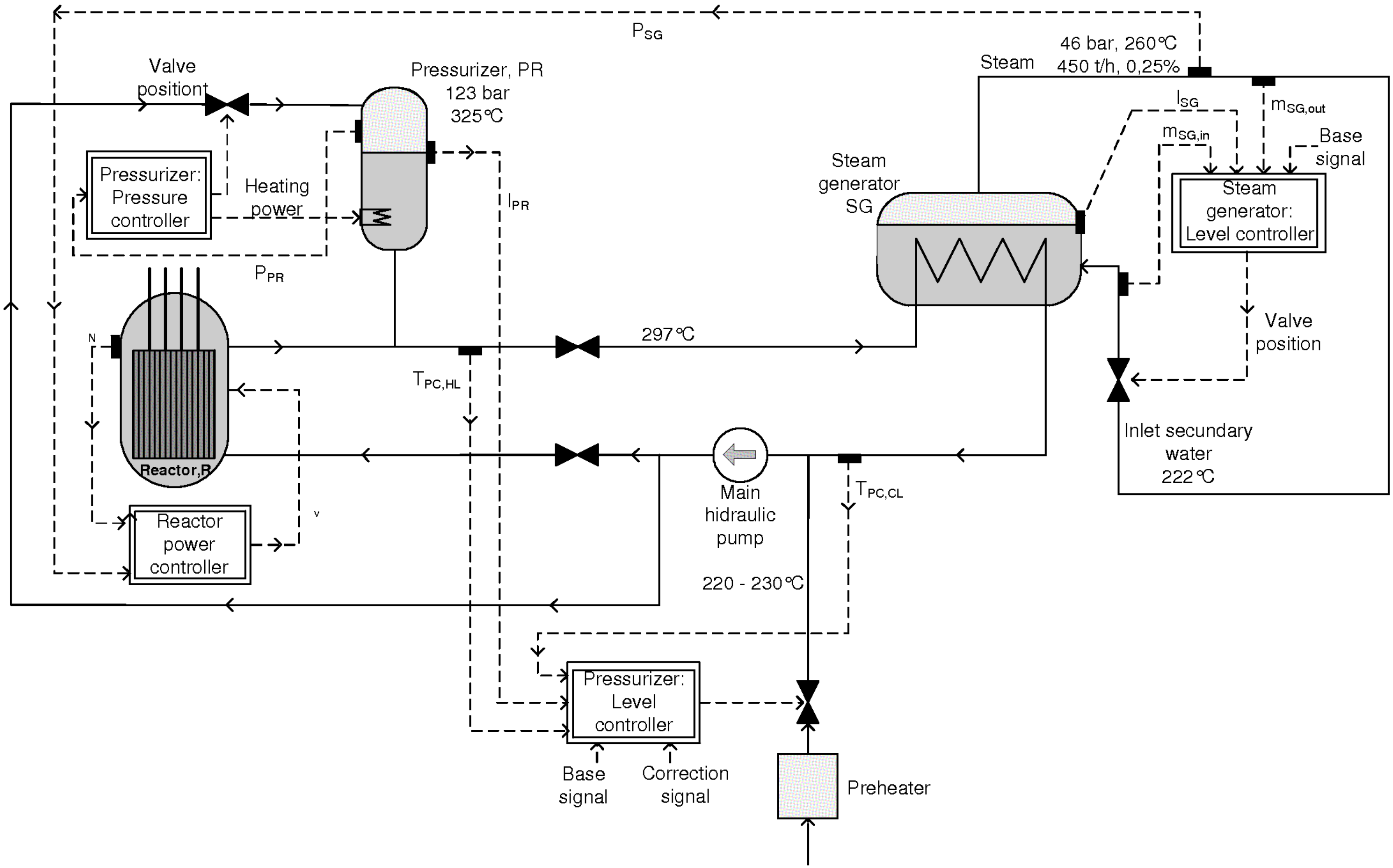
Case Study

The modelling of the Reactor Power Control System of the Paks NPP

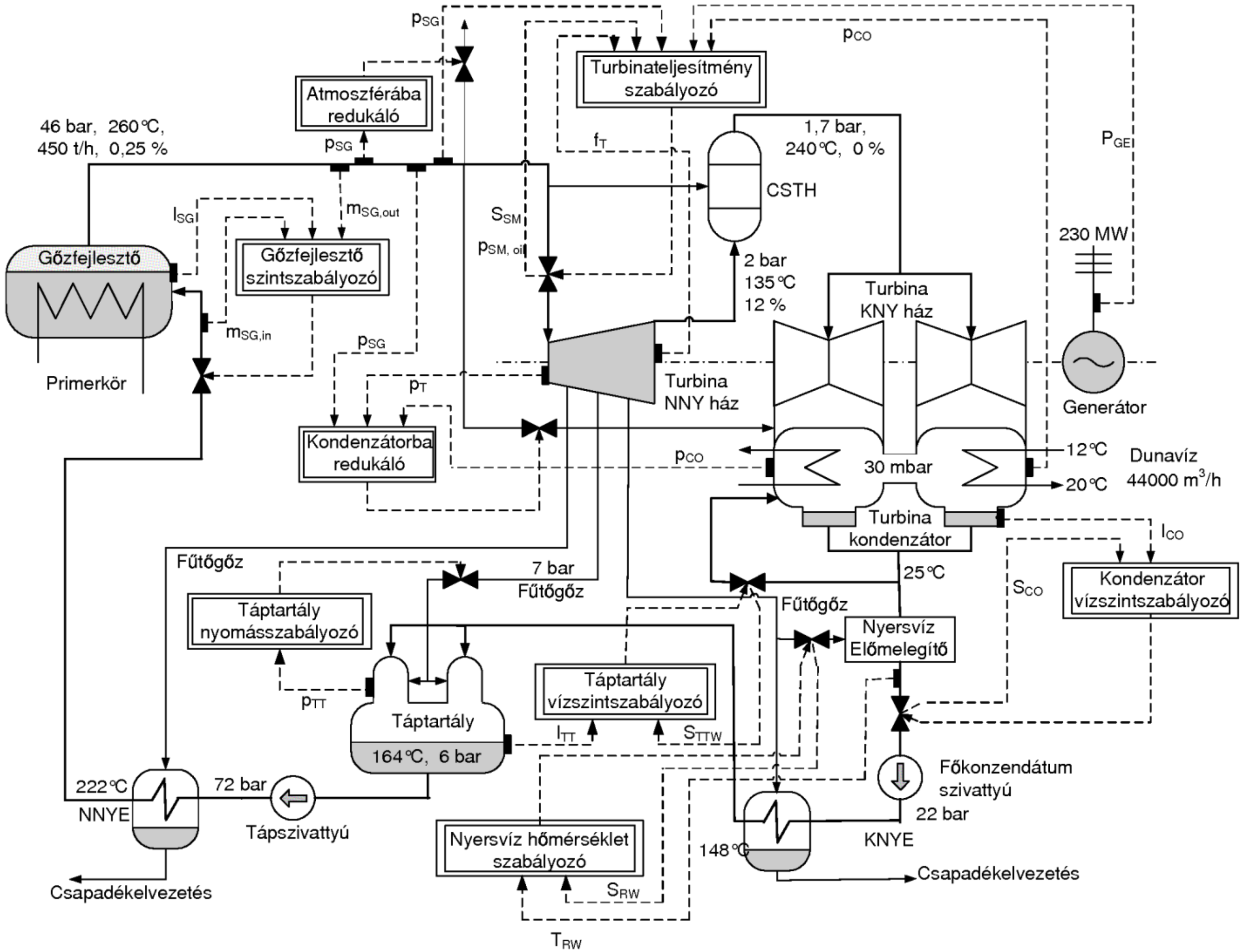
The Scheme of the Unit Power Control System



The Scheme of the Primary Circuit



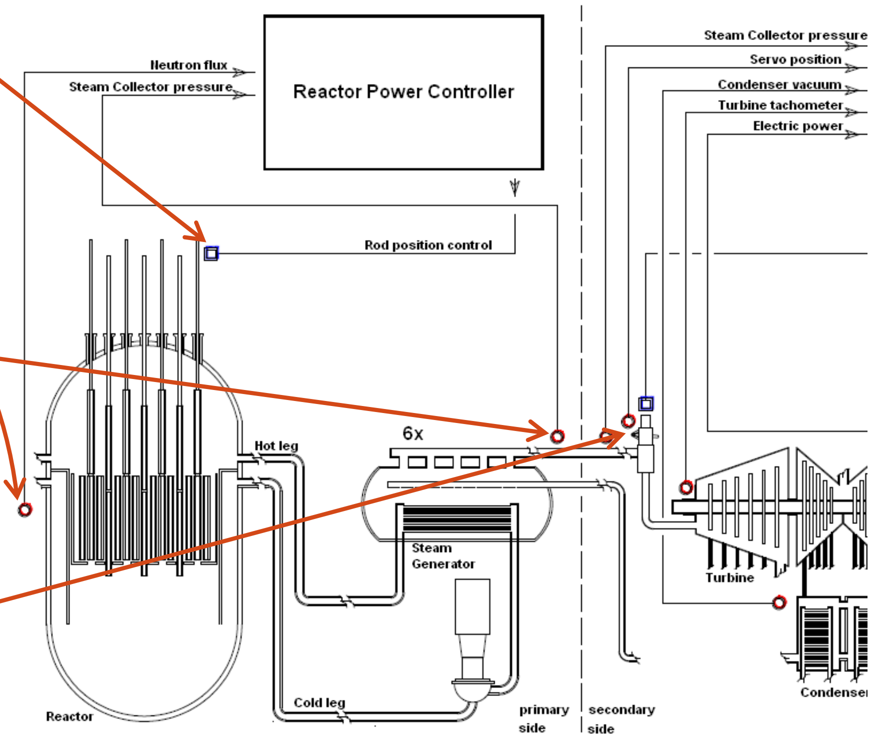
The Scheme of the Secondary circuit



Process from the Control Point of View

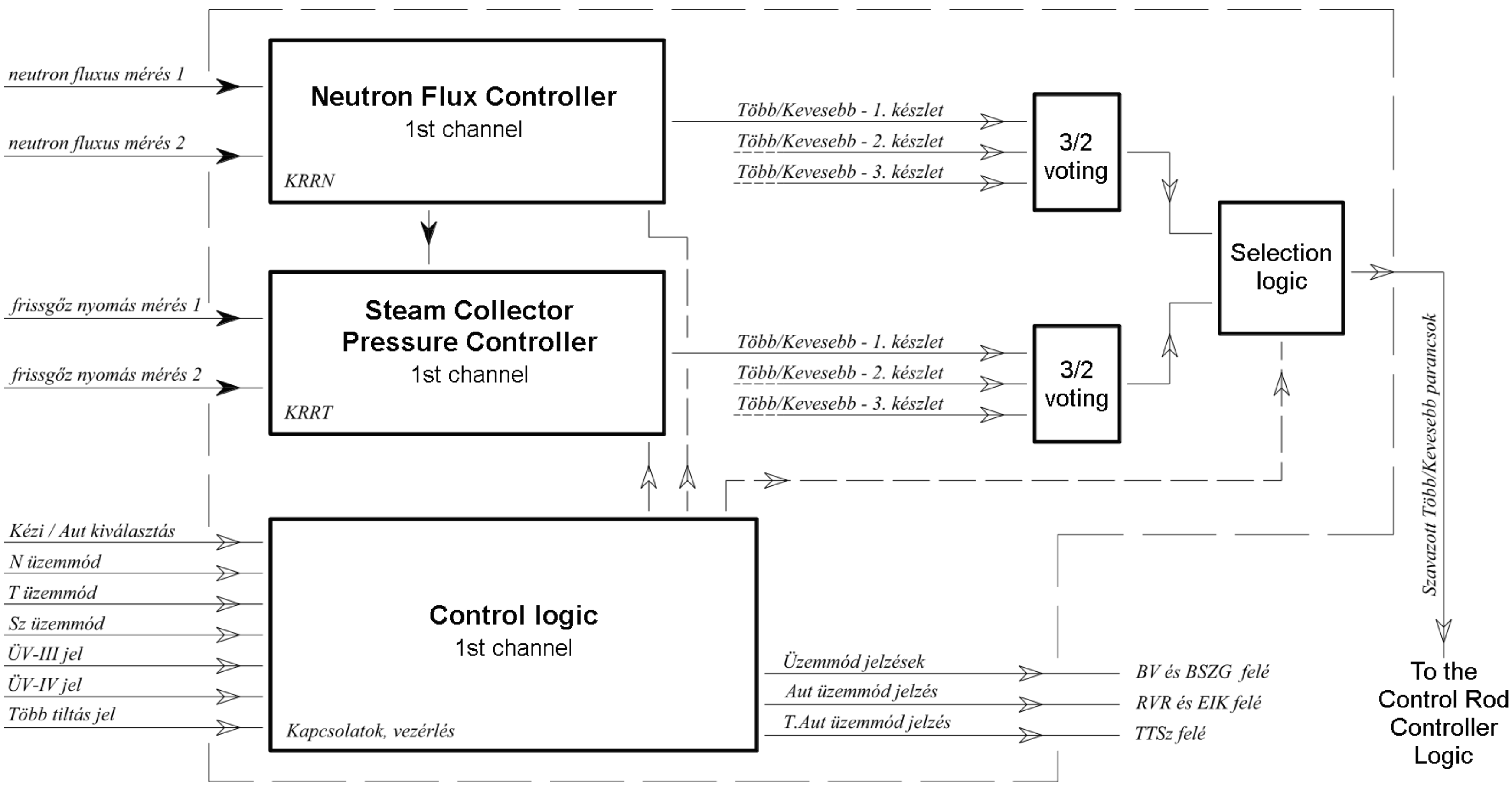
Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

- Actuator, input:
  - Control rod movement direction
  - Discrete valued input
- Controlled variables:
  - N mode: the neutron flux
    - Negative feedback, stability
    - Fast response
  - T mode: steam collector pressure
    - Significant time-delay
    - Neutron flux as auxiliary signal
- Disturbances:
  - Network power need → turbine mass flow, control valve position (fast)
  - Reactor poisoning and fuel depletion (slow)
- Inherent power control ability



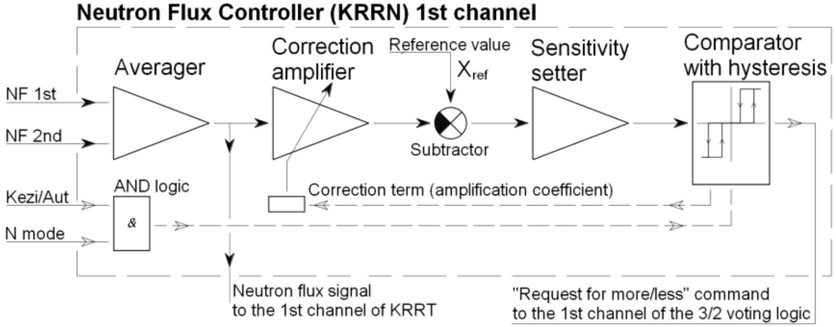
Reactor Power Controller Structure

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems



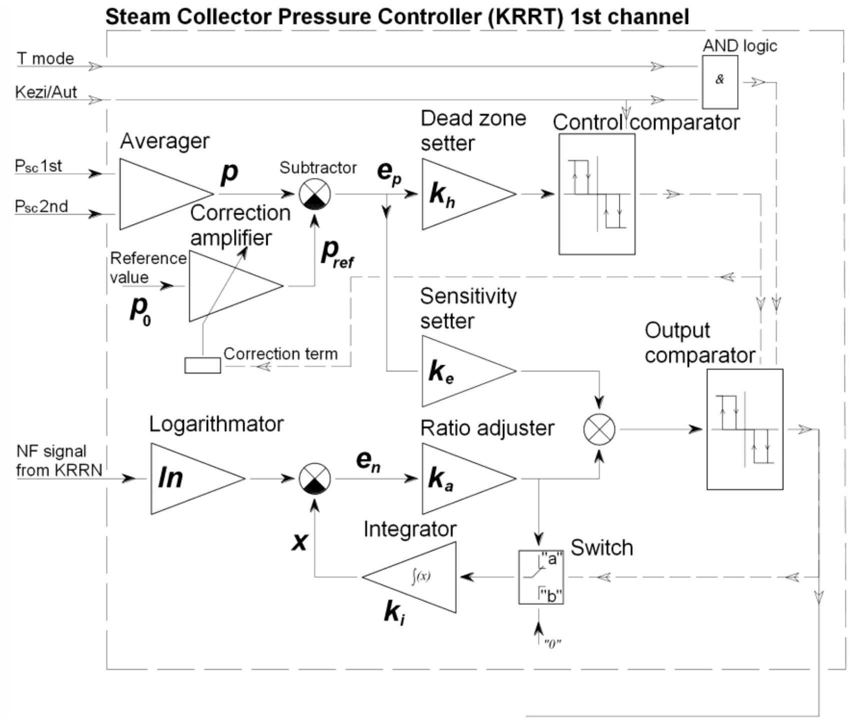
Operation of the KRRN and KRRT modules

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems



- Controlled variable: Neutron flux
- Simple proportional controller with dead zone
- Fixed set-point

- Controlled variable: Steam pressure
- P controller with Integrator type actuator → PI property
- Auxiliary N signal
- Hybrid properties

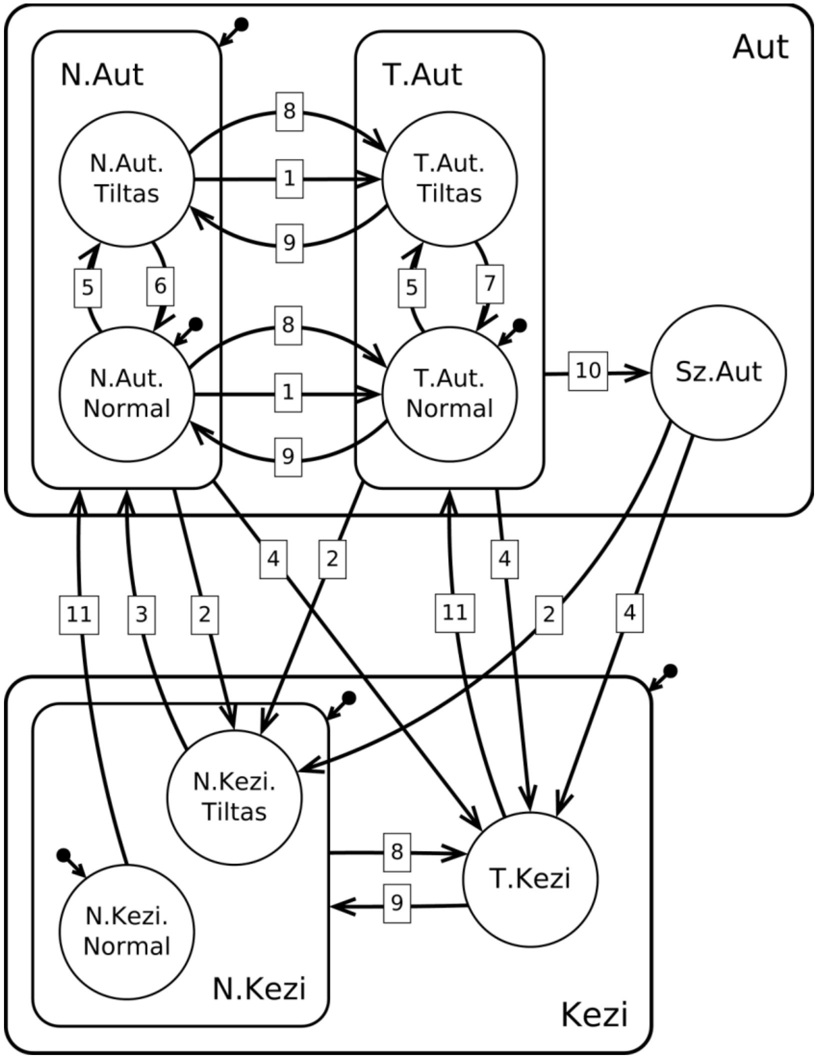


Modelling of the Reactor Power Controller

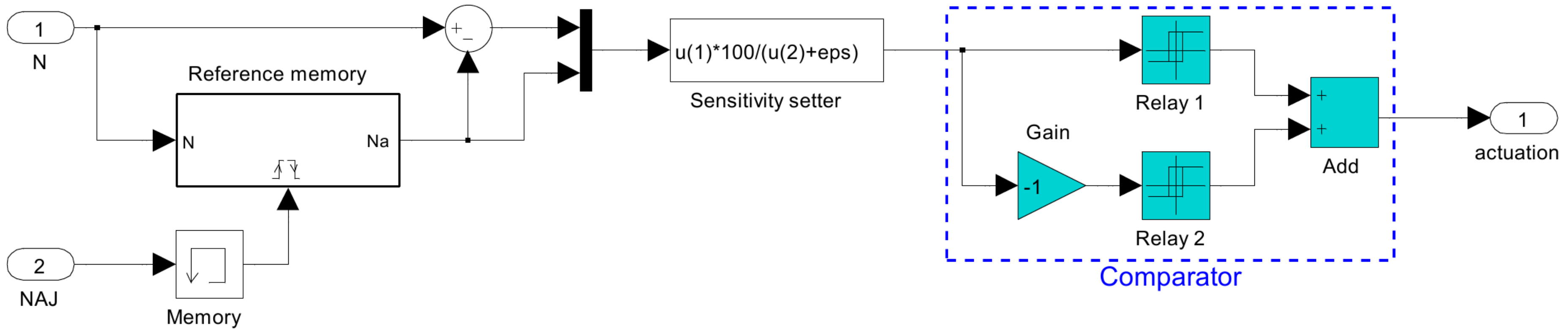
- Main goal
  - To create a formal, mathematically verified specification of the Reactor Power Controller
    - to be used in the specification process
    - to be used for the implementation
- Problems
  - A well-elaborated design basis does not exist
    - Electronic schemes need to be reverse-engineered
  - Requirements are conservative and informal
    - „It should work the same way as the old system, and its performance should be at least as good.”

Reactor Power Controller operating modes

- Automatic and manual operation
- Modelled as a hierarchical state chart
- Switching
  - Automatic
    - Constraints, limits
    - Malfunction protection
  - Operator



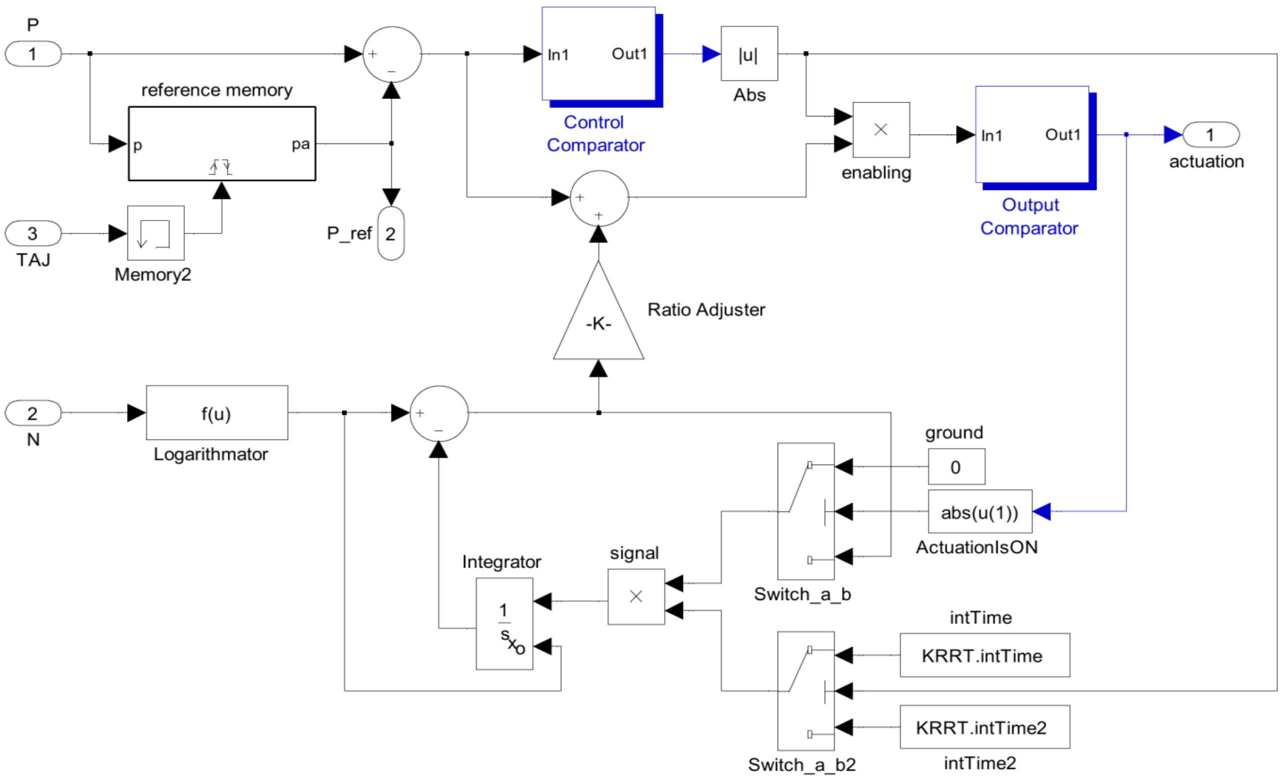
Reactor Power Controller in N mode



- Neutron flux is the controlled variable
- Simple proportional controller with dead zone
- Set-point
  - Last measured value before switching
  - Fix set-point

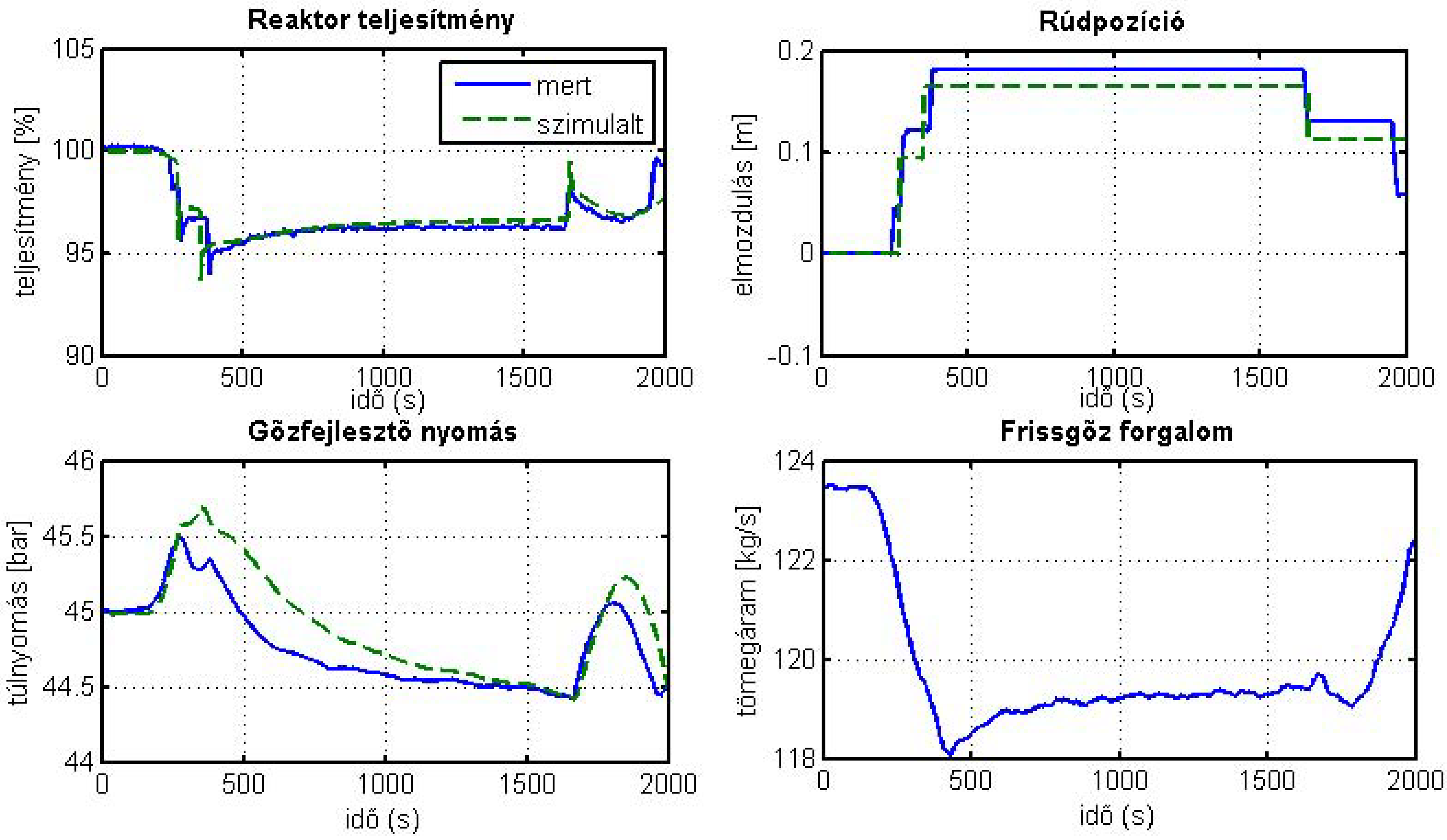
Reactor Power Controller in T mode

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems



- Controlled variable: steam pressure
- Proportional controller
- Significant time delay
  - auxiliary N signal
- Hybrid properties

Verification Results



Case Study

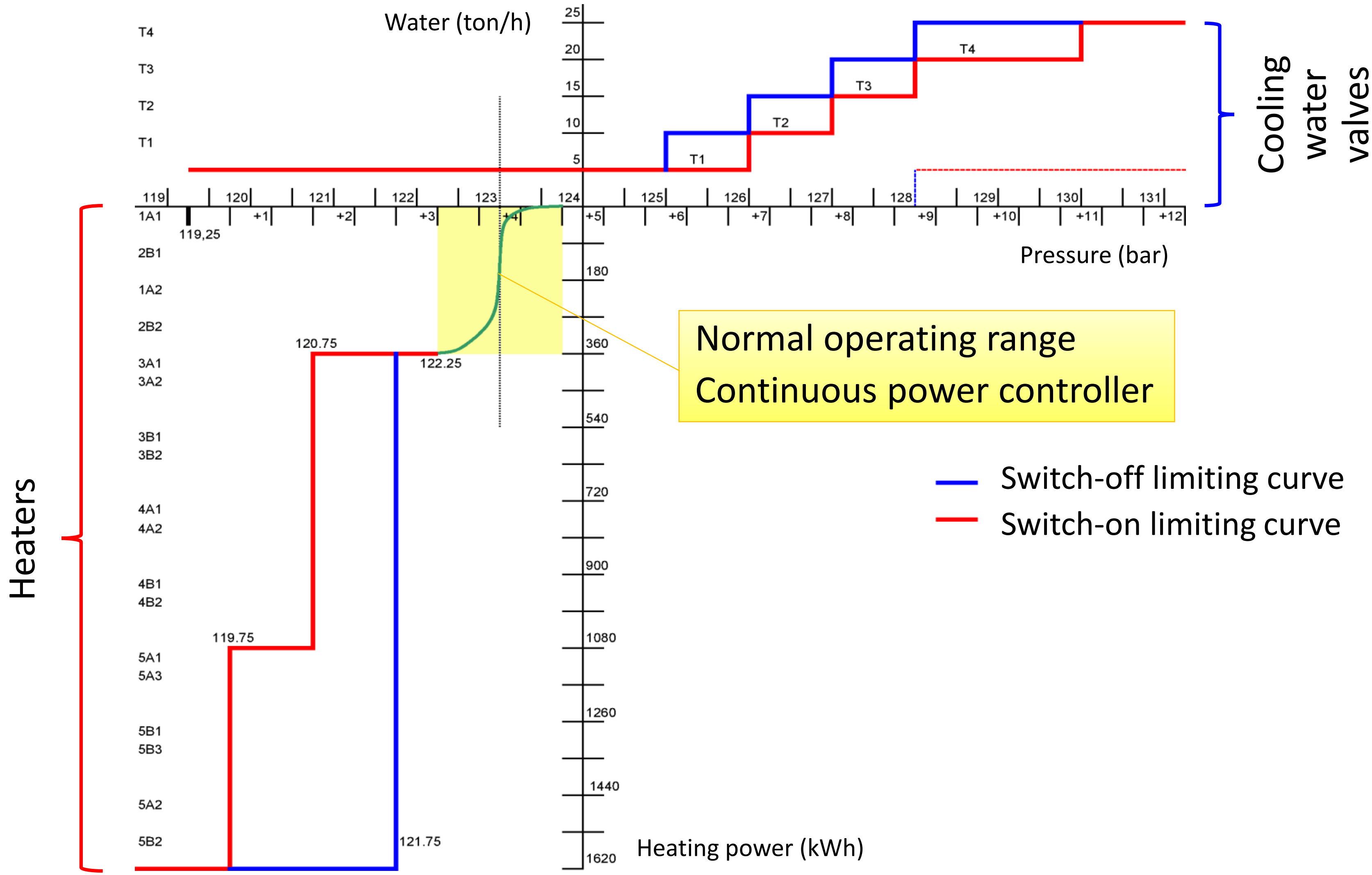
The design of the new Primary Pressure Controller of the Paks NPP

Motivation

- Main goals
  - to make the operation safer and more effective
  - to safely increase the thermal power
- Supporting factors
  - rapidly improving quality of hardware and software
    - measurements, complex computations, redundant structures
  - significant scientific development in process modeling and systems and control theory
- We did not copy the old functions,
  we designed and implemented a new controller

Pressurizer Control Mode Switching Diagram

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

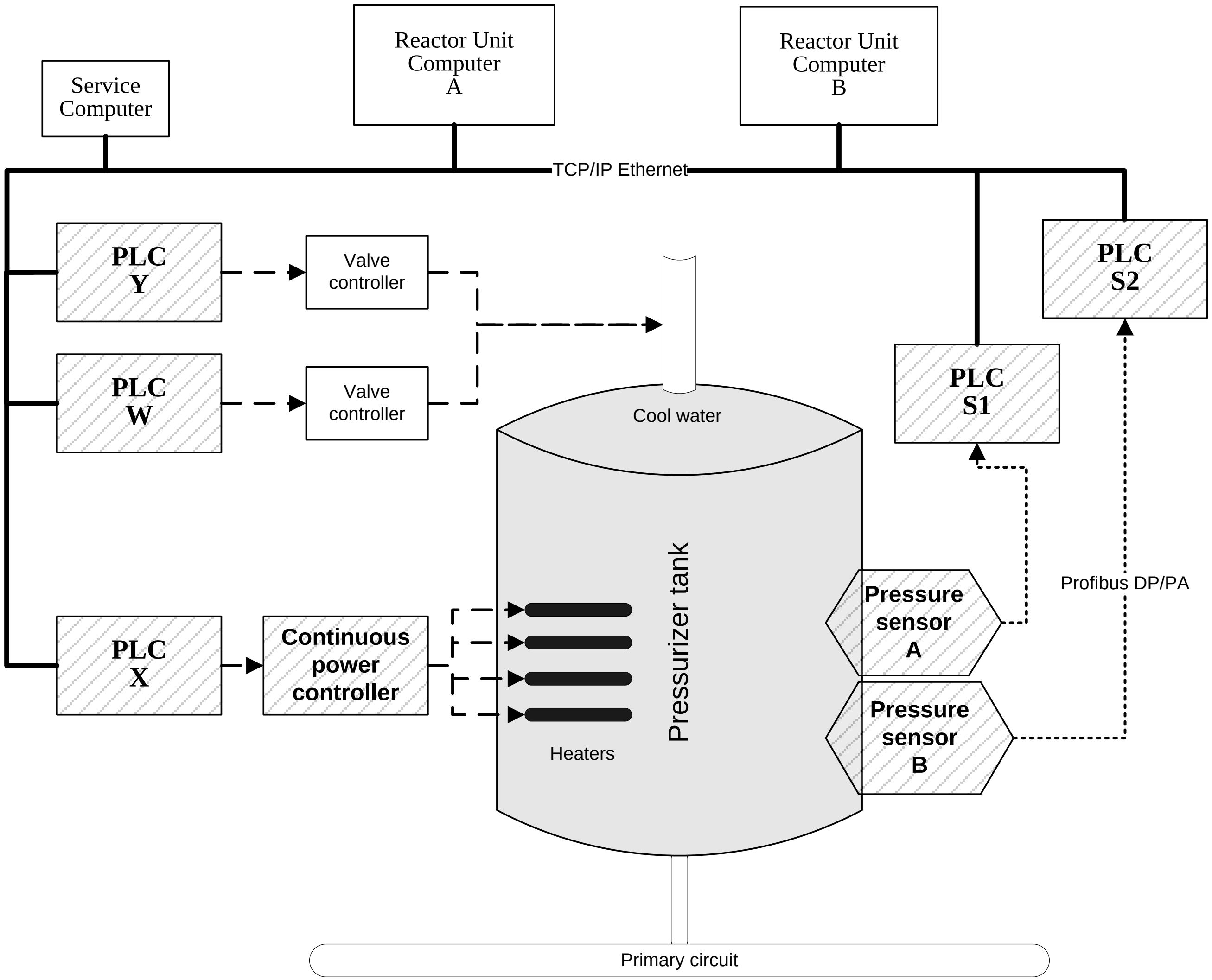


Controller design

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

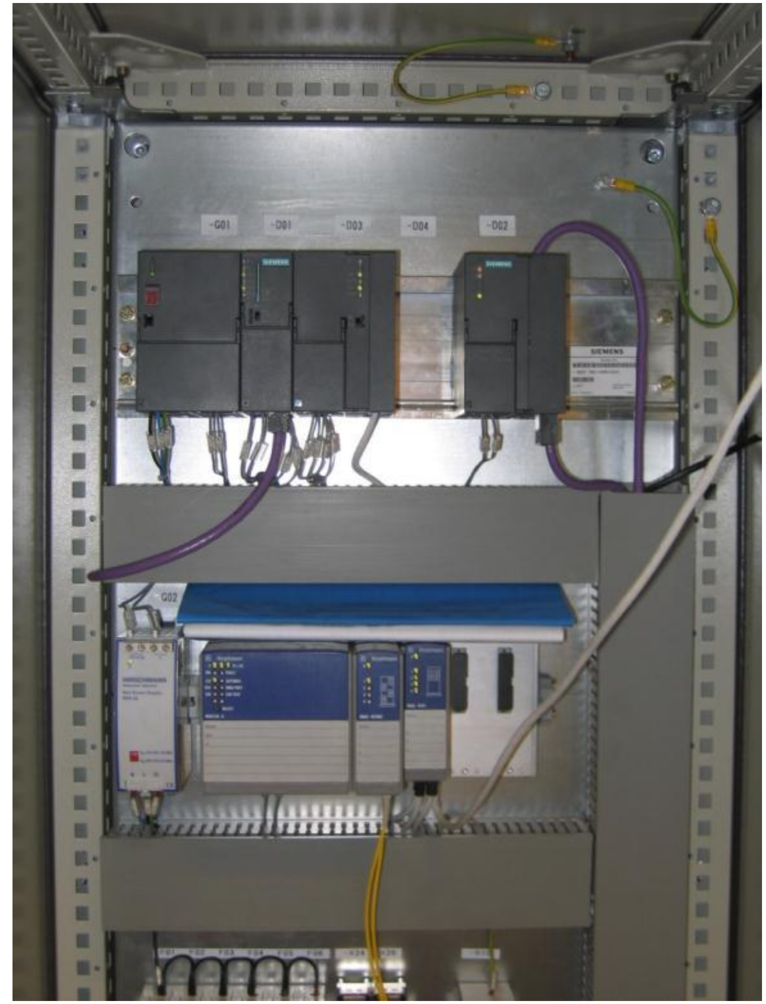
- Control goal
  - to stabilize the pressure at a prescribed reference value — usually 123-124 bars (around 327°C) — under normal operating conditions
- Sampling time: 10s
- Controller design method
  - inner loop: discrete time dynamic inverse based controller
  - outer loop: (H_∞) controller for disturbance rejection and noise suppression

Implementation: Distributed digital system



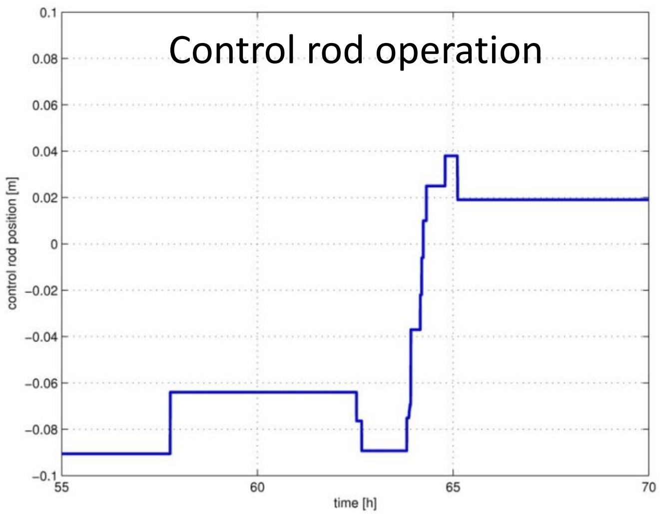
Realization (Pressure Controller)

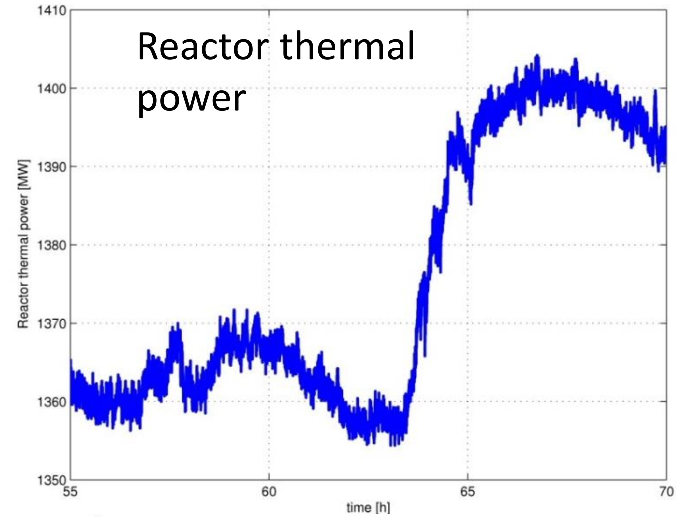
Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

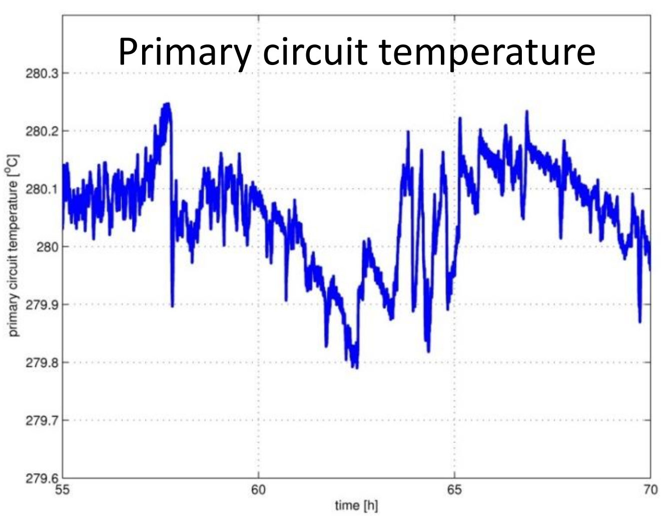


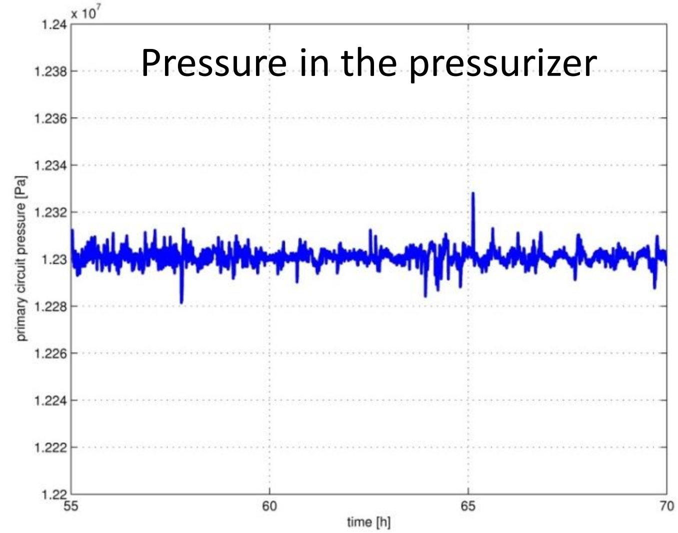
Performance (real measurements)

Budapest University of Technology and Economics
Faculty of Transportation Engineering and Vehicle Engineering
Department of Control for Transportation and Vehicle Systems

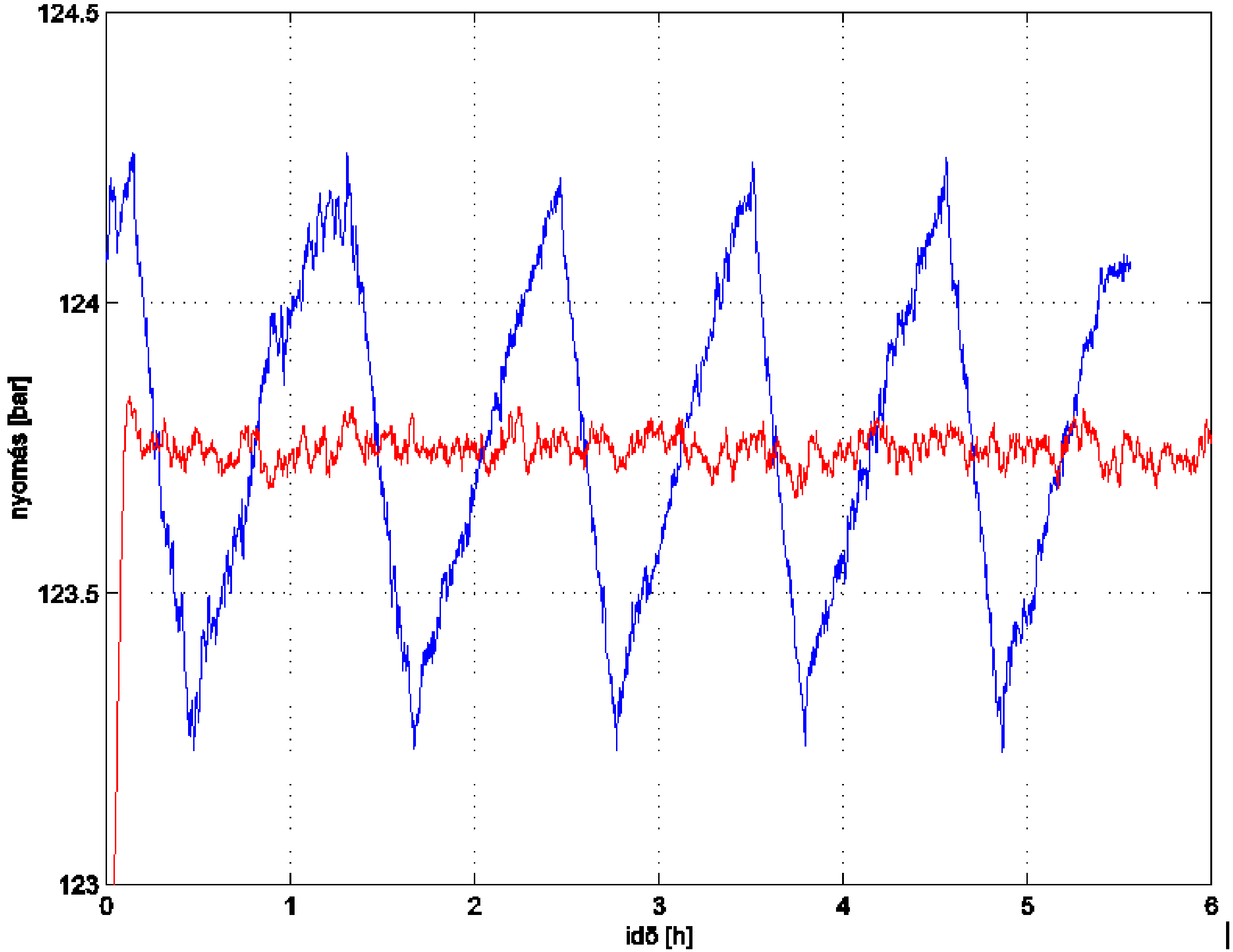








Comparison of the Old and New (real data)



Conclusions

- An advanced pressure controller has been implemented
  - good operational experiences
- Average temperature could be increased by ~1-2°C
  - the thermal power of the units could be increased by ~10%
  - of course this is not solely the result of the new pressure controller, many other modifications were required
- Physical model was important because of the understanding of processes and operational constraints
- The operation became more effective (role of feedback) without significant technical improvement (only replaced sensors and actuators)