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Performance Study of the Control Systems in the presence of Faults and/or Reference Accidents in Pressurized Water Reactors of Evolutive Generation

Stefano Di Gennaro, Bernardino Castillo

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PERFORMANCE STUDY OF THE CONTROL SYSTEMS IN THE PRESENCE OF FAULTS AND/OR REFERENCE ACCIDENTS IN PRESSURIZED WATER REACTORS OF EVOLUTIVE GENERATION

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Titolo

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Argomenti trattati: **Controllo dei reattori nucleari, reattori nucleari ad acqua.**

Sommario

Il presente lavoro, sviluppato dal gruppo del Prof. Stefano Di Gennaro del Centro di Eccellenza DEWS dell'Università degli Studi dell'Aquila, si concentra sui sistemi di controllo per i reattori nucleari ad acqua pressurizzata, e si articola secondo tre deliverables.

I primi due deliverables offrono una presentazione dettagliata dei sistemi di supervisione, controllo e protezione per il circuito primario di reattori ad acqua in pressione di generazione III/III+, e una descrizione della modellizzazione matematica del circuito primario del reattore allo scopo di individuare le proprietà dei controllori impiegati e valutarne le prestazioni, anche in risposta a perturbazioni esterne o interne.

Il terzo documento, di seguito riportato, dal titolo "Studio delle prestazioni dei sistemi di controllo in presenza di guasti e/o incidenti di riferimento in reattori ad acqua pressurizzata di generazione evolutiva", presenta uno studio delle prestazioni dei sistemi di controllo in presenza di guasti e/o incidenti di riferimento nei reattori evolutivi ad acqua in pressione sulla base di un modello più accurato del pressurizzatore.

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DELIVERABLE 3

Performance Study of the Control Systems in the presence of Faults and/or Reference Accidents in Pressurized Water Reactors of Evolutive Generation

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Studio delle prestazioni dei sistemi di controllo in presenza di guasti e/o incidenti di riferimento in reattori ad acqua pressurizzata di generazione evolutiva

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November 30, 2011

Abstract

In this deliverable, a performance study of the control systems, in the presence of faults and/or reference accidents in pressurized water reactors of evolutive generation, is presented. A more accurate model of a PWR pressurizer, for simulation purposes, is determined. Usually a controller is determined on the basis of a model that is easier to handle mathematically. Its simplicity consists of neglecting dynamics which are secondary with respect to the main ones. Hence, a further step to be followed to check the effectiveness of a designed controller is to be tested it on a more complete model that represents, to the best of the possibilities, the "real" behavior of the system. Discarding the implementation with codes like the well–known Relap5, whose interface with the controller implemented in Simulink would have gone far beyond the purpose of this work, it has been chosen to implement the simulation model in Matlab and then to interface it with Simulink. The performance of the pressurizer water level and pressure controllers, proposed in a previous deliverable, has been tested in the case of a turbine trip, which can be due to faulty closure of the turbine stop valve. The resulting prototyping simulation environment has been provided to the ENEA–Casaccia as a benchmark for controller developing and testing.

Riassunto

In questo documento viene presentato uno studio delle prestazioni dei sistemi di controllo in presenza di guasti e/o incidenti di riferimento nei reattori ad acqua pressurizzata di generazione evolutiva. Viene determinato un modello più accurato, ai fini della simulazione, di un pressurizzatore per PWR. Di solito un controllore è determinato sulla base di un modello che è più facile da maneggiare matematicamente. La sua semplicità è consiste nel trascurare le dinamiche che sono secondarie rispetto a quelle principali. Quindi un ulteriore passo da seguire per verificare l'efficacia di un controllore progettato è di testarlo su un modello più completo, che rappresenta, al meglio delle possibilità, il comportamento "reale" del sistema. Scartando l'implementazione mediante codici come il ben noto Relap5, il cui interfacciamento con il controllore implementato in Simulink sarebbe andato ben oltre lo scopo di questo lavoro, è stato scelto di implementare il modello di simulazione in Matlab e poi di interfacciarlo con Simulink. Le prestazioni dei controllori per il livello dell'acqua e della pressione del pressurizzatore, proposti in un precedente lavoro, sono stati testati nel caso di un turbin trip, che può essere causato della chiusura della valvola di arresto della turbina a causa di un guasto. Il risultante ambiente di simulazione di prototipazione è stato fornito alla ENEA–Casaccia come banco di prova per lo sviluppo ed il test di controllori.

1 The simulation mathematical model

This section is devoted to more accurate modeling of the PWR pressurizer for simulation purposes. In fact, a mathematical model describes the dynamic behavior of a system. Its accuracy is strictly connected with the aim of its use. We are here interested to a simulation model, i.e. a model which accurately describes the dynamic behavior of a system. Due to its complexity, very often such a simulation model is not suitable for determining a controller, but it can be used to represent the real system.

This represents the second step to be followed to check the effectiveness of a controller, that has to be tested on a model that represents, to the best of the possibilities, the "real" behavior of the system.

One of the codes more used to simulate the complex dynamics of a nuclear power plant is Relap5$^{©}$. The high fidelity Relap5 model provides accurate simulations of transients. However, its running time may amount to hours or even days and it is thus prohibitive for repetitive simulations of transients needed to optimize control systems and instrumentation designs. Its main purpose instead is for reference and benchmarking analyses.

Since Relap5 code has general and advanced features in thermal–hydraulic computation, it has been widely used in transient and accident safety analysis, experiment planning analysis, and system simulation, etc. Due to the limited functions of simulating control and protection system in Relap5, to design, analyze, verify a new instrumentation and control system of nuclear power plants, and to develop a simulator, it is necessary to expand the its functions for high efficient, accurate, flexible design and simulation. We have already seen that Matlab/Simulink is a powerful tool in research and simulation of plant process control, and it can compensate the limitation [14], [11]. Matlab/Simulink provides a graphical modeling environment that includes expandable libraries of predefined blocks and an interactive graphical editor for assembling and managing intuitive block diagrams. It gives the modeler the ability to manage complex designs by segmenting models into hierarchies of design components. As we see it, the key strength of the Matlab/Simulink environment is the way it allows for rapid model development, while its weakness lies in the difficulty of modeling extremely complex systems while maintaining precise control over all components, particularly with respect to how and in what order Matlab/Simulink solves equations.

There are two key techniques to be solved when coupling Matlab/Simulink and Relap5. One is the dynamic data exchange, by which Matlab/Simulink receives plant parameters and returns control results. A database can be used to let the two codes communicate. Accordingly, a Dynamic Link Library (DLL) is applied to link database in Relap5, while DLL and S–Function is applied in Matlab/Simulink.

The other problem is the synchronization between the two codes for ensuring consistency in global simulation time. Because Matlab/Simulink always computes faster than Relap5, the simulation time is sent by Relap5 and received by Matlab/Simulink. A time control subroutine is added into the simulation procedure of Matlab/Simulink to control its simulation advancement. Through these ways, Matlab/Simulink is dynamically coupled with Relap5.

Thus, in Matlab/Simulink, one can design control and protection logic of nuclear power plants, and test it with best–estimated plant model feedback. In practice, the PWR can be modeled by Relap5 code, and its main control and protection system can be implemented in Matlab/Simulink.

The development of a reliable interface between Simulink and Relap5 goes far beyond the purpose of this work. For this reason, the position here considered is a good tradeoff consisting in a more accurate modeling of at least one of the main components of the primary circuit, the pressurizer. The reason of this choice is well understandable, given its important role and the peculiarity of its dynamics.

1.1 Mathematical modeling for simulation of a pressurizer

In this section we present the bases for setting up a thermal–hydraulic model of a generic PWR pressurizer, including controls. In [19], [16] the basic equations for setting up a thermal hydraulic (TH) model of a Pressurizer of a PWR are presented. Moreover, the control logics for a pressurizer are described, assuming that a three tier approach (protection system, limitation system, control system) is adopted.

1.1.1 Geometry and description

The pressurizer is a component of a PWR with the function to control the pressure. It is a vertical, cylindrical vessel closed at the ends by hemispherical heads. The pressurizer is connected to the reactor coolant system (RCS) by the surge line, coming from one of the hot legs of RCS, and leading to the bottom head. During normal operation the pressurizer is filled with a saturated mixture of water and steam. Since the temperature of the hot leg is lower than saturation temperature, some designs include a thermal sleeve in the surge line to protect the pressurizer against thermal shock. The spray line, coming from one or more of the cold legs of the RCS, is connected at the upper head. Electrical heaters are located inside the bottom in vertical position. There are about 250 heater elements, divided into groups which could be controlled with a proportional or on–off logic.

Spray valves and heaters work in conjunction to maintain pressure in a desired control band. If primary system (PS) pressure increases (e.g. due to an in–surge of water from the loop), the sprays acts to mitigate this event by condensing steam and limiting the pressure increase. If pressure decreases, heaters are actuated to maintain the pressure at the set point. To operate the system in defined condition the pressurizer should be always in saturation – therefore during normal operation, a continuous spray flow, which effects are compensated by a minimal value of heater power is maintained. Heaters compensate also thermal losses.

The upper head hosts also safety and relief valves. Other systems could be connected to the pressurizer, e.g.: degasification system, vacuum vent system, nitrogen injection system. Various nozzles to host controls, monitoring and sampling systems are also present. In the case of a loss connection to the grid spray and heaters can operated by emergency power from diesel generators.

Typical design parameters	**Typical values**
Design pressure	17.48 MPa
Design temperature	362 °C
Nominal operating pressure	15.14 MPa
Nominal operating temperature	345°C
Minimum internal volume	75.01 m^3
Steam volume during nominal operation	25.00 m^3
Maximum spray flow	59.97 kg/s
Continuous spray flow	0.35 kg/s
Maximum heaters power	2500 kW
Continuous heaters power to compensate spray	150 kW
Vessel nominal inside diameter	2.83 m
Pressurizer total height	14.4 m
Pressurizer nominal water level	9.6 m
Spray lines pipe diameter	0.1 m
Surge line inside diameter	0.32 m
Pressurizer safety/relief valves	3
Safety valve relief capacity (at opening pressure set point)	80 kg/s
Base materials for the pressurizer	ferritic steel, cladded with stainless steel
Surge line material	stainless steel
Thickness of the surgeline piping	typically around 4 cm, with 30 cm diameter
Thickness of the pressurizer walls	typically around 15 cm
Total mass of the pressurizer structures	150000 kg

Table 1: Typical design values of a generic pressurizer

1.1.2 Mathematical modeling

The following section gives an overview on common used equations and correlations to model a pressurizer and surgeline. The equations are subdivided in three groups

1. Balance equations: Differential equations modeling the system. Three balance equations are commonly used – mass balance, momentum balance and energy balance. For special components, or in special situations, balance equations can be joined or additional balance equations can be considered.

2. State relationships: Relationships between physical properties. For example, the density of a fluid can be provided as a function of its pressure and temperature. Often state relationships are not available in analytical form, and have to be modeled by interpolation of tables.

3. Constitutive equations: Correlations that describe special processes in special situations. Often correlations, that have been derived from experiments and that are valid only for a narrow range

of parameters are used. Examples are correlations for heat transfer between wall and fluid, or heat transfer between liquid and gaseous phase of water.

This section presents two separate formulations of these basic set of equations: a first for the surgeline, and a second for the pressurizer itself. At the end of the section the possibility to model main components of the whole plant with lumped parameters will be mentioned [12].

In 1–Dimentional representation, a possible set of independent variables is given by the time t and the elevation z, while a possible set of dependent variables includes the temperature $T(t,z)$ or the energy $U(t,z)$, the pressure $p(t,z)$, and the velocity $v(t,z)$. Finally, the boundary conditions are on the inflow/outflow from RCS, the heat losses from pressurizer wall, the inflow from spray line, and the power supplied by heaters.

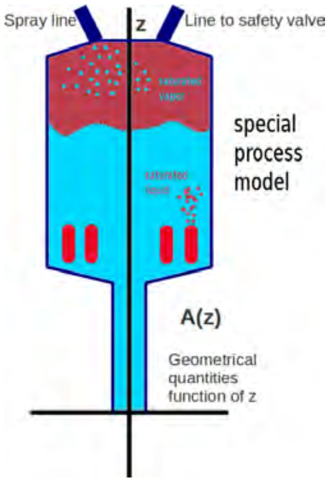


Figure 2: Possible elements and set of coordinates for pressurizer model

1.1.2.1 Surgeline

In view of the purpose of this work, it is possible to consider a 1–D approach to model the surge line. It is further proposed to use the homogeneous equilibrium model, that assumes phases are in thermal equilibrium, and move at the same speed. The model performs well if only one phase is present, and may provide sufficiently realistic results even in two–phase situations. One of the limitation of the model is that in a situation where a water volume is located on top of a steam volume, and the pressure in the steam volume compensates the pressure head from the water volume, the (single) momentum equation will predict a steady state – which means that the water volume will stay on top of the steam volume.

Water is injected in the steam volume if the pressurizer spray is actuated. There are ways to "save" the HEM model also in this situation, however, it is easier to adopt a different approach, which assumes a separate steam and liquid volume. Instead of conservation of the momentum, the total volume is conserved. Details are provided in Section 1.1.3.

2.2 Mathematical modeling

The following section gives an overview on common used equations and correlations to model a PR surgeline. The equations are subdivided in three groups:

Balance equations: they are the basic differential equations to model the system. Three balance equ are commonly used – mass balance, momentum balance and energy balance. For special components special situations, balance equations can be joined or additional balance equations can be considered.

State relationships: state relationships are known relationships between physical properties. For exa the density of a fluid can be provided as a function of its pressure and temperature. Often relationships are not available in analytical form, and have to be modeled by interpolation of tables.

Constitutive Equations: constitutive equations are relationships that describe special processes in s situations. Often correlations, that have been derived from experiments and that are valid only narrow range of parameters are used. Examples are correlations for heat transfer between wall and or heat transfer between liquid and gaseous phase of water.

The section presents two separate formulations of these basic set of equations: a first for the surgelin a second for the pressurizer itself (See Fig. 2 and Ref. [1-4]).

At the end of the section the possibility to model main components of the whole plant with lu parameters will be mentioned (Ref. [6]).

Possible set of independent variables in 1D representation:
Time (t) and elevation (z)

Possible set of dependent variables in 1D representation:
Temperature T(t,z) or Energy U(t,z)
Pressure P(t,z)
Velocity v(t,z)

Boundary conditions:
Inflow/outflow from RCS
Heat losses from PRZ wall
Inflow from spray line
Power supplied by heaters

Fig 2: Possible elements and set of coordinates for PRZ model.

2.2.1 Surgeline

For the scope of the present application it is proposed to model the surge line using a 1-D approac further proposed to use the homogeneous equilibrium model, that assumes phases are in th equilibrium, and move at the same speed. The model performes well if only one phase is present, an provide sufficently realistic results even in two-phase situations. One of the limitation of the model i in a situation where water a water volume is located on top of a steam volume, and the pressure

1.1.2.2 Basic balance equations

To keep the mathematical model simple, but provide nevertheless a realistic description of the behavior the surge line, the following assumptions are made

1. The fluid properties are assumed to be homogenous in the radial plane of the surge line – only variations in time and the axial directions are modeled (1–DDrepresentation);

2. For parts where fluids move in pipes (surgeline, if of interest spray line) the two phases are assumed to be always in mechanical and thermal equilibrium (non equilibrium situations, like coexistence of two phases in conditions other than saturation, are not modeled).

In specific cases also equilibrium between two phases permits to achieve a reasonable accuracy. In the followings the HEM 1–D basic equation are described.

1.1.2.3 Mass balance

The mass conservation differential equation is given by

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial (A\rho v_z)}{\partial z} = S$$

where t is the time (s), z is the elevation (m), S is a source or sink of mass (to describe in– or out–flow at the boundaries) (kg/(s m3)), ρ is the density of the fluid (kg/m^3), A is the area (m^2), v_z velocity in z–direction (m/s).

1.1.2.4 Momentum balance

The momentum equation expresses the fact that the rate of change of momentum in control volume equals the momentum flow rate into the control volume minus the momentum flow rate out of the control volume plus the net external force such as gravitational, friction, pressure and inertial forces. The 1–D equation is given in the form

$$\frac{\partial \rho v_z}{\partial t} + \frac{1}{A}\frac{\partial (A\rho v_z^2)}{\partial z} = -\frac{\partial p}{\partial z} - \rho g \sin\vartheta + \tau_w \frac{P_f}{A} + \rho f_z$$

where p is the pressure (Pa), g is the acceleration due to gravitation (m/s^2), ϑ is the angle in case the surge line is not vertical (for vertical problems $\sin\vartheta = 1$), τ_w is a coefficient for wall friction (kg/m^2), P_f is the wetted perimeter (m), f_z is a acceleration due to external forces (to model boundary conditions) (m/s^2).

1.1.2.5 Energy balance

The energy equation expresses the fact that the rate of change of total energy in control volume must be equal to the rate at which internal energy is brought into the volume by the mass flow, minus that removed by the mass outflow, plus the heat transported by diffusively or generated, minus the work performed by the medium in the volume and the work needed to put the flow through the volume. The 1–D equation is given in the form

$$\frac{\partial \rho u^\circ}{\partial t} + \frac{1}{A}\frac{\partial (A\rho u^\circ v_z)}{\partial z} = q''' + \frac{P_h}{A}q'' - \rho g v_z \sin\vartheta + \tau_w \frac{P_f}{A} v_z + \rho f_z v_z$$

where u° is the stagnation internal energy per unit mass

$$u^\circ = u + \frac{1}{2}v_z^2$$

u is the internal energy per unit mass (J/kg), q''' is a volumetric heat source (J/(m^3 s)), q'' is the wall heat source (or heat sink) (J/(m^2 s)), P_h is the heated perimeter (m).

1.1.2.6 Structure of the problem, constitutive equations and state relationships

The equations contain in total 14 unknown variables. However, not all of them are independent variables which should be solved. The major part, nine variables, describes geometry or boundary conditions. Of the remaining five variables, three are connected by a state relationship, and one can be derived from a constitutive correlation. Table 34 provides an overview.

$S(t, z)$	Volumetric mass source, boundary condition; in the case of the surge line in–surge and out–surge it can be described here)
$A(z)$	Area of the surge line, description of geometry
g	Gravitational acceleration, constant
$\vartheta(z)$	Angle of pipe segment, description of geometry
$P_h(z)$	Heated Perimeter, description of geometry (heaters); in the case of surge line terms containing P_h disappears
$P_f(z)$	Wetted Perimeter, description of geometry; in the case of the surge line equal to the perimeter of the pipe
$f_z(t, z)$	External acceleration, boundary condition; in the case of the surge line, it can be used to describe insurge/outsurge
$q'''(t, z)$	Volumetric heat source (or sink), can be used to describe pressurizer heaters; in the case of surge line terms containing q''' it disappears. A direct, immediate transfer of heat to the fluid is valid as a first approximation.
$q''(t, z)$	Surface heat source (or sink), can be used to describe pressurizer heaters; in the case of surge line terms containing q''' it disappears. It could be used to model the metal piping of the surge line. Imposing a heat flux from or to the wall could be a first approximation. For a more detailed model the metal structures of the wall or the heaters should be modeled, heat conduction in the walls, and heat transfer from the fluid to the wall. Additional basic balance equations as well as constitutive correlations are necessary in this case, refer to [13] for more details. q'' can be either a pure boundary condition, or a boundary condition combined with a constitutive correlation, depending on the level of detail of the model.

Table 2: Variables which describe the geometry or boundary conditions

The friction term is dependent on the materials of the wall, the fluid (density and viscosity) and the fluid velocity

$$\tau_w = \tau_w(\rho, v_z, \mu, \cdots).$$

The friction could be neglected in a first approximation. For a more precise simulation, a constitutive model should be chosen for the specific fluid, wall material and flow conditions [19], [20], [21], [13].

steam volume compesates the pressure head from the water volume, the (single) momentum equation will predict a steady state – which means that the water volume will stay on top of the steam volume.

Water is injected in the steam volume if the PRZ spray is actuated. There are ways to “save” the HEM model also in this situation, however, it is easier to adopt a different approach, which assumes a seperate steam and liquid volume. Instead of conservation of the momentum, the total volume is conserved. Details are provided in section 2.2.2. PRZ.

Basic balance equations

To keep the mathematical model simple, but provide nevertheless a realistic description of the behavior the surge line, the following assumptions are made:

(1) The fluid properties are assumed to be homogenous in the radial plane of the surge line – only variations in time and the axial directions are modeled (1-Dimensional representation)

(2) For parts where fluids move in pipes (surgeline, if of interest spray line) the two phases are assumed to be always in mechanical and thermal equilibrium (non equilibrium situations, like coexistence of two phases in conditions other than saturation, are not modeled => HEM EVET)

In specific cases also equilibrium between two phases permits to achieve a reasonable accuracy.

In the followings HEM one-dimensional basic equation are described.

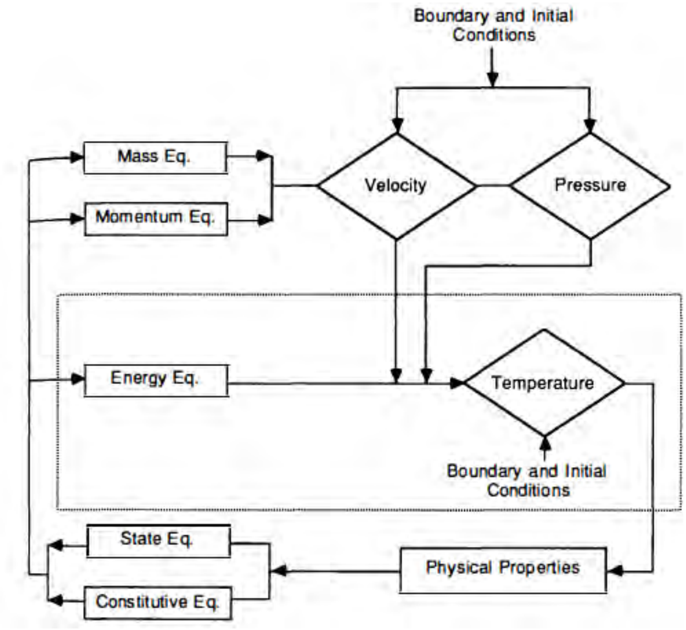


Fig 3: Flow chart for solving hydraulic system using HEM [1].

Mass balance

The mass conservation differential equation is given by:

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial}{\partial z}(\rho v_1 A) = S$$

Remain the variables which describe the process, and which should be a result of the calculation: the fluid pressure $p(t, z)$, the fluid density $\rho(t, z)$, the fluid velocity in direction of the pipe $v_z(t, z)$ and the internal stagnation energy per unit mass $u°(t, z)$.

In addition to the three balance equations, a fourth relationship between the variables allows solving the set of equations. The density of the fluid is related to the pressure and the internal energy

$$\rho = \rho(p, u)$$

where this relationship is usually provided in tables (Mollier diagram). Software libraries which contain the tables and interpolate are commercially available. Other quantities of interest, which are not presented here (most important to mention the temperature of the fluid, but also enthalpy) can be derived from state relationships for the fluid as well.

Figure 3: Flow chart for solving hydraulic system using HEM [19]

1.1.3 A simulation model for a pressurizer

Although the HEM model described in the following for the surge line may be used as first approximation for the pressurizer as well, with special care to avoid formation of a liquid pool on top of the steam volume in case of spray, and with the limitation that an insurge of subcooled fluid leads to unphysical condensation, it is advisable to adopt a slightly different set of equations for the pressurizer.

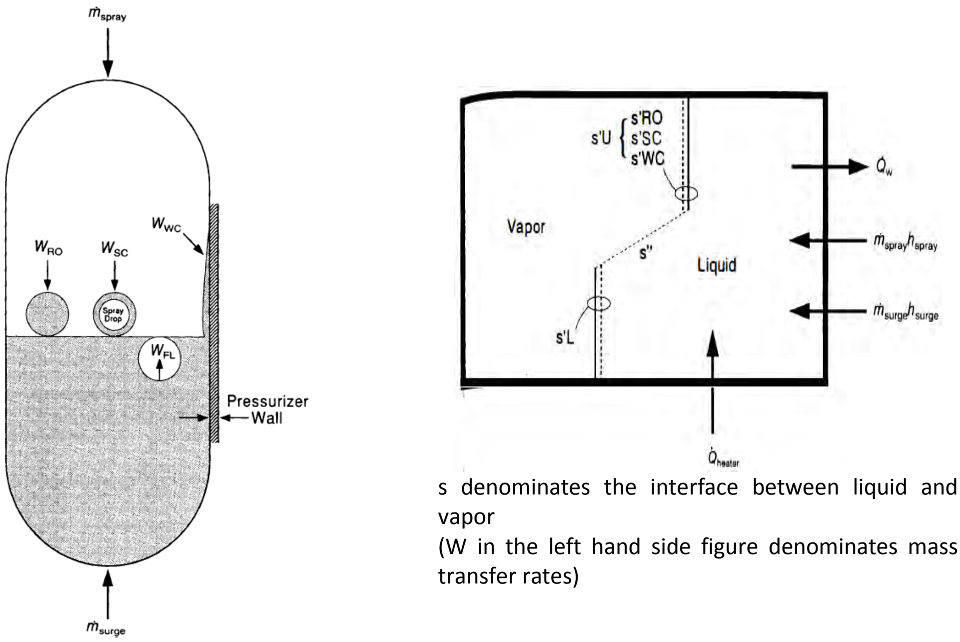
The reason is that movement of fluid within the pressurizer is not of main interest. Furthermore, a model considering the separation of the steam and liquid is quite feasible. On the other hand, such an approach would greatly improve the mathematical model without increasing its complexity.

In fact, various models can be derived for the pressurizer, with different complexity. Three of them (one zone, two zones, and four zones) are described in [19], while a fourth model can be found in [21].

Hereinafter, the two–zone model is described [19], [16]. The general properties for the two zone formulation are (see Fig. 4)

1. The pressurizer is divided in two volumes, the lower one filled with liquid, the upper with vapor;
2. The spray reaches instantly the lower region, together with the steam, that condenses;
3. Phase changes due to pressure changes (flashing of liquid, rain out of vapor) are possible and are assumed to happen instantaneous;
4. Condensation or evaporation by heat transfer from the pressurizer wall to liquid and fluid volume is considered;
5. Instantaneous evaporation by pressurizer heaters is considered.

- Condensation or evaporation by heat transfer from the PRZ wall to liquid and fluid volume is considered
- Instantaneous evaporation by PRZ heaters is considered



s denominates the interface between liquid and vapor
(W in the left hand side figure denominates mass transfer rates)

Fig. 4 – a PRZ component following a two zone approach [1]

Figure 4: The two zone approach [19]

Equations for the two-zone PRZ model:

The equations for the two zone pressurizer model are the following. The vapor mass balance is

$$\dot m_v = \dot m_{vs}$$

Mass balance

Vapor

where m_v is the vapor mass (kg), and $\dot m_{vs}$ is the vapor mass transfer across the interface vapor–liquid (kg/s).

$$\frac{d}{dt} m_v = \dot m_{vs}$$

m_v vapor mass (kg)

m'_{vs} vapor mass transfer across the interface vapor liquid (kg/s)

Liquid

The liquid mass balance is

$$\dot{m}_l = \dot{m}_{ls} + \dot{m}_{spray} + \dot{m}_{surge}$$

where m_l is the liquid mass (kg), and $\dot{m}_{ls}$ is the liquid mass transfer rate across the interface vapor–liquid (kg/s), $\dot{m}_{spray}$, $\dot{m}_{surge}$ are the liquid spray and surge rate masses (kg/s).

Furthermore, the vapor energy balance can be written as

$$\frac{d}{dt}(mu)_v = \dot{m}_{vs}h_{vs} + \dot{Q}_{vs} - \dot{W}_{vs}$$

where u is the specific internal energy (J/kg), h_{vs} is the specific vapor enthalpy (J/kg), $\dot{Q}_{vs}$ is the energy flow between phases (heat) (W), $\dot{W}_{vs}$ is the mechanical work to expand/compress volume when moving mass between the phases (W).

Analogously, the liquid energy balance is

$$\frac{d}{dt}(mu)_l = \dot{m}_{ls}h_{ls} + \dot{Q}_{ls} - \dot{W}_{ls} + (\dot{m}h)_{spray} + (\dot{m}h)_{surge} + \dot{Q}_h + \dot{Q}_w$$

where h_{ls} is the specific liquid enthalpy (J/kg), $\dot{Q}_{ls}$ is the energy flow between phases (heat) (W), $\dot{W}_{ls}$ is the mechanical work to expand/compress volume when moving mass between the phases (W), $\dot{Q}_h$ is the heat transfer between pressurizer heaters and liquid (W), and $\dot{Q}_w$ is the heat transfer between pressurizer wall and liquid (W).

Moreover, jump conditions describe mass and energy transfer between the phases, and are given by

$$\dot{m}_{vs} = -\dot{m}_{ls}$$

$$\dot{m}_{vs}h_{vs} + \dot{Q}_{vs} - \dot{W}_{vs} = -\dot{m}_{ls}h_{ls} - \dot{Q}_{ls} + \dot{W}_{ls}$$

while a volume conservation equation describes that in the specific volume v of the respective phase (liquid/vapor) (m^3/kg)

$$\frac{d}{dt}\Big((mv)_v + (mv)_l\Big) = 0.$$

Finally, relationships for water are available from tables (programming libraries providing state equations exist)

$$v_v = v_v(p, u_v)$$

$$v_l = v_l(p, u_l)$$

$$h_{vs} = h_{vs}(p, u_v)$$

$$h_{ls} = h_{ls}(p, u_l).$$

Since one has 16 variables and 13 equations, three constitutive equations are needed describing mass and energy transfer between the phases.

In a first approximation the pressurizer can be assumed to be adiabatic – in this case the heat transfer from and to the pressurizer wall can be neglected. The remaining two equations can be determined by disallowing non equilibrium states within the vapor and the liquid region, i.e. it is assumed that vapor can be either saturated or superheated, and liquid can be either subcooled or saturated. With this assumption one can determine for pressure increases and decreases the amount of transfer of energy and mass between the phases.

In this model the pressurizer relief and safety valves are not modeled. One could take them in consideration by imposing an outflow from the steam volume, adopting a simple correlation for critical flow, e.g. that taken from [17].

The state variable that have been chosen in this deliverable are those indicated in Section 2.2, where the two zone pressurizer model is explicitly determined.

1.2 Pressurizer control and instrumentation

This section describes, with slight simplifications, the instrumentation and control systems needed for controlling a pressurizer, together with indication on how to model the pressurizer. The pressurizer has the two main functions of pressure and mass control. The controls for the pressurizer can be divided in three levels

1. *Protection system.* The protection system constitutes the highest level of control. In the case a signal from the protection system is triggered, it has precedence over signals from the control or the limitation system. In some nuclear power plants the components used to build the protection system are analog, which makes the system highly reliable. The functions are kept simple.

2. *Limitation system.* The limitation system does not exist in all nuclear power plant designs. Typically german nuclear power plants use this level, as well as the EPR. The limitation system is a layer between the control system and the protection system. It uses more complex functions than the protection system, and its set points are such that it interventions come before the protection system. The limitation system has precedence over the control, but not over the protection system. Often an intervention of the protection system can be avoided by the limitation system.

3. *Control system.* The control system has the lowest priority, but the most complex functions. It is responsible of the control of the unit during normal operations. Functions, which lead the reactor from safe to operating conditions, are fulfilled exclusively by the control system (e.g. the control is the only system that increases the reactor power).

1.2.1 Pressurizer instrumentation

To determine the actual pressure and pressure set points, the actual pressurizer level, and the pressurizer level set point, the mean primary system temperature and the pressure of various parts of the system have to be measured.

The pressurizer actual level is based on pressure difference between top and bottom of the pressurizer, which is then transformed to a level, assuming that the pressure difference stems from the hydrostatic pressure of a water column.

As a general rule, more than one pressure/temperature measurement device is used to register pressure and temperature in one location. For example, in a typical example of derermination if a pressure limit has been overpassed, four pressure gauges are placed at the location of interest. The signal is generated if two out of the four pressure gauges show a pressure above the set point.

Measurement devices do not follow instantaneously changes of the physical properties they are measuring. In addition, measurement devices usually work in a specific range. Limiting the range is an easy task, when measurement devices are simulated in advanced programming languages, like Fortran and C.

The following equation could be used to model the delay of the measurement

$$T_m(t + \mathit{\Delta} t) = T_p(t + \mathit{\Delta} t) + \Big(T_p(t + \mathit{\Delta} t) - T_m(t)\Big)e^{-\mathit{\Delta} t/\tau}$$

where T_m is the measured temperature, T_p is the physical temperature, and τ is the delay constant, that should be declared by the supplier of the measurement device. A typical value for a temperature measurement device could be 3 s.

1.2.2 Pressure control

The pressure control system maintains pressure within design limits trough spray, heaters safety and relief valves.

1.2.2.1 Pressurizer spray (from logic level of controls)

The regulation logic of spray of a typical PWR is summarized in Fig. 5, where the left hand side shows the stepwise opening of up to four spray valves (increasing the spray flow). The normal operation spray, from controls, takes fluid from the primary system loops via the spray lines. The normal operation spray is only available if the main coolant pumps are running. The right hand side shows the stepwise closing of the spray valves. The values are given in bar, and refer to pressure above the nominal pressure in the pressurizer of 150 bar. If the average primary system temperature is below 150°C, the nominal pressure of the system is 35 bar.

When pressure increases over each set point a valve is opened to increase mass flow rate through the spray nozzle. The valves are closed when pressure decrease below the closure set point. Regulation set point is 35 bar when coolant temperature is below 150°C and is set to 150 bar when coolant temperature increases over 150 °C.

1.2.2.2 Pressurizer heaters (from logic level of controls)

Fig. 6 shows the regulation logic of pressurizer heaters. When pressure decrease under nominal set point heaters act to recover pressure inside nominal range. Set points to switch off every stage consider the inertia of heat transfer, so the signal to switch of heaters stage is imposed significantly before the set

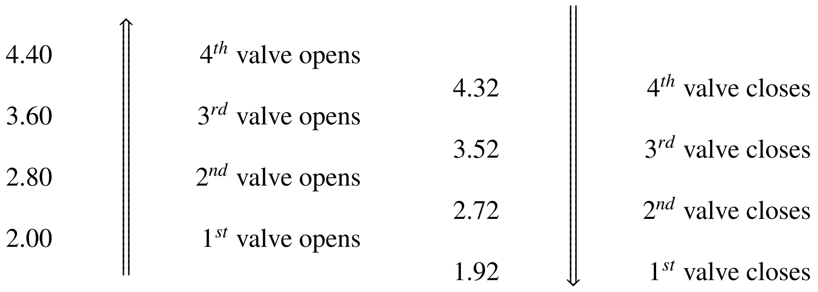


Figure 5: Set point for spray regulation

point pressure value. The heaters from control system are only operational if the reactor is operating, or the connection to the grid is stable. In addition, the pressurizer level has to be above a certain value (to protect the heaters).

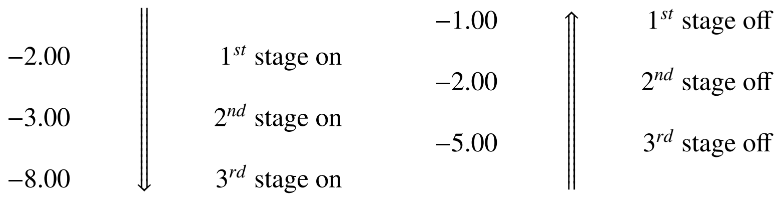


Figure 6: Set point for heaters regulation

1.2.2.3 Pressurizer spray (from logic level of limitations)

The pressure limitation system contributes to prevent the protection system and consequent shut down of the reactor. If loop spray cannot mitigate pressure increase, additional valves can be opened and make–up spray system can be used. Auxiliary spray (spray from the loop, but operated from the limitation system) is also used in case of steam generator tube rupture to decrease primary pressure in order to limit mass flow from primary to secondary side. Fig. 7 and Fig. 8 regard auxiliary and make up system spray control. As one can see, limitation system is designed to maintain a steam region in the pressurizer, stopping his action when water level increases over fixed maximum set points.Spray from loop is available only if main coolant pumps are operating, while spray from make–up is independent from this system and emergency power supplied. Some design considers another make–up spray system which starts with a delay respect the principal and stops at the same set point of the principal one.

1.2.2.4 Pressurizer heaters (from logic level limitation system)

In case of pressure decreasing that pressure control system cannot mitigate, heaters from limitation are used to prevent reactor trip for low pressure. Regulation logic of this function is shown in the diagram of Fig. 9.

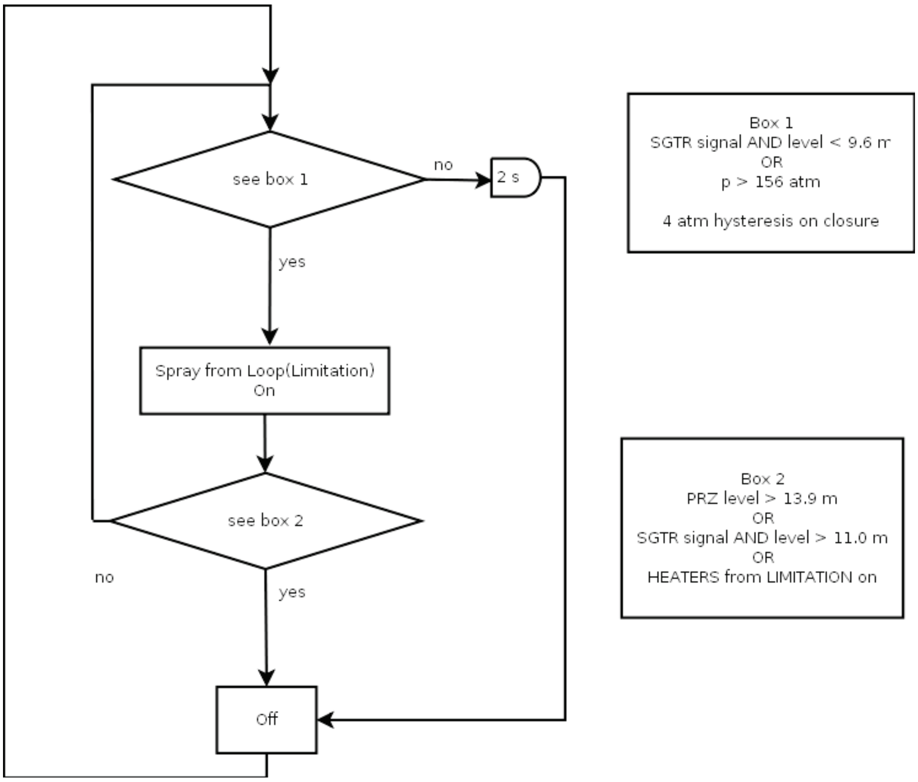


Figure 7: Control logic for spray from loop, controlled by the limitation system

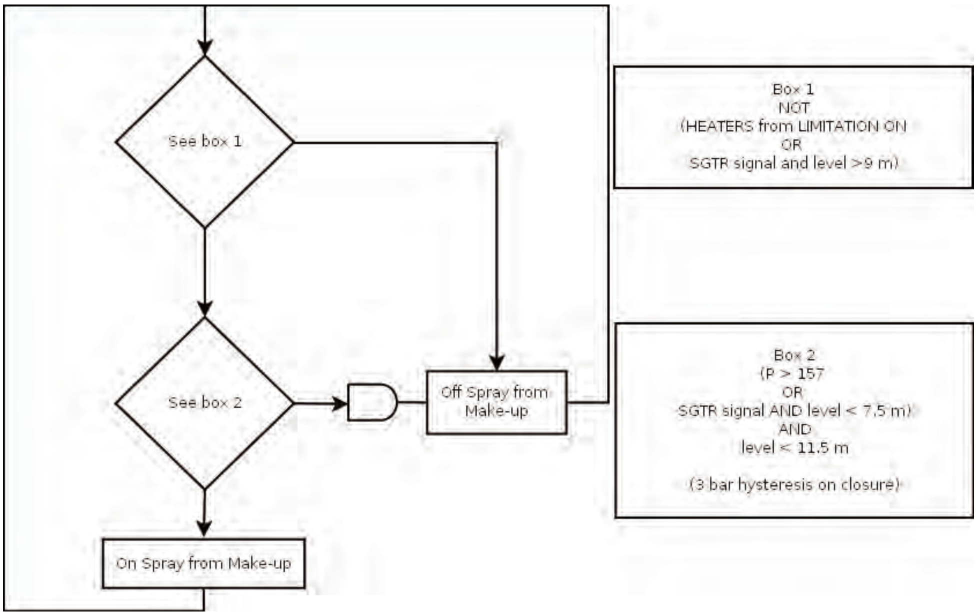


Figure 8: Control logic of spray from make–up system, controlled by the limitation system

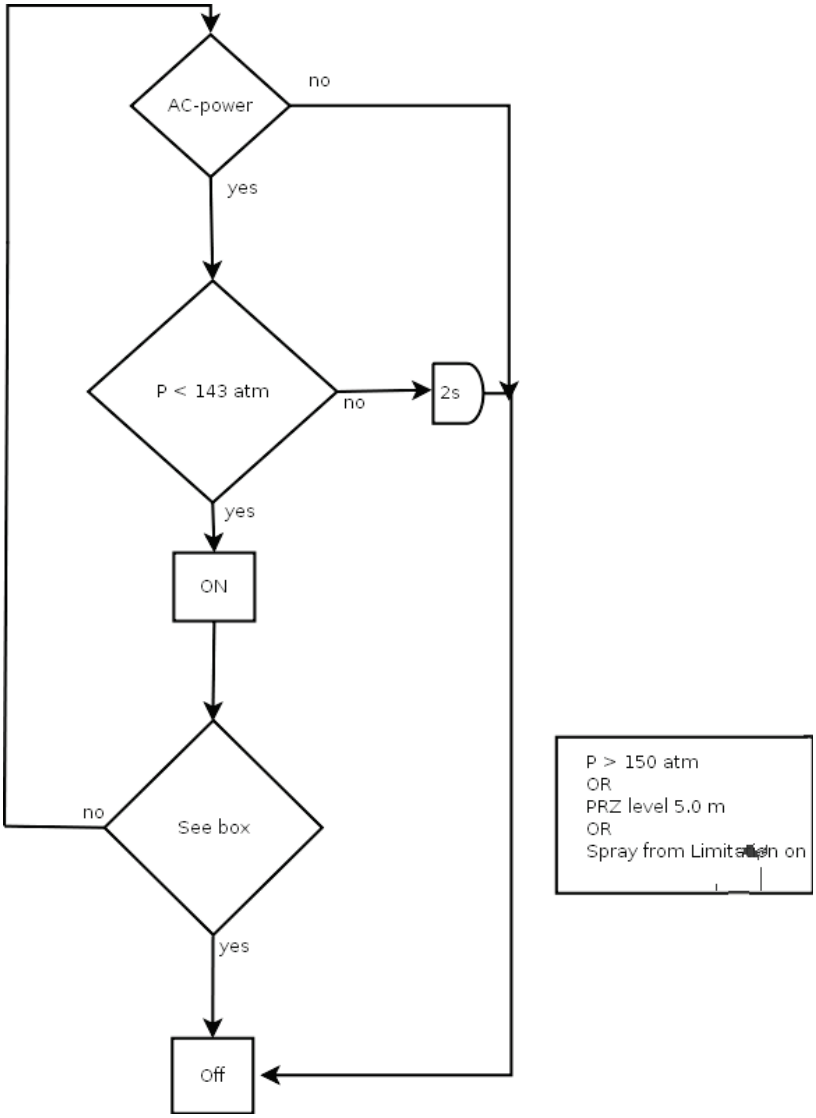


Figure 9: Control logic of auxiliary heaters

1.2.2.5 Protection against rapid pressure in – or decrease – logic level protection system

The protection system reacts to pressure increase by first tripping the reactor, then by opening primary system relief and safety valves. In case of pressure decrease, which cannot be limited by control or limitation system, the protection system, again, shuts down the reactor. Pressurizer related set point signal for reactor trip are indicated in Fig. 10. If pressure increasing continue also after reactor trip a set of safety valves are available to handle this condition. Safety valves are not regulated and act with an OPEN–CLOSE logic.

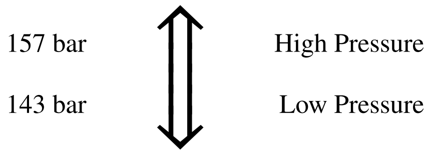


Figure 10: Reactor trip signal for high or low pressurizer pressure

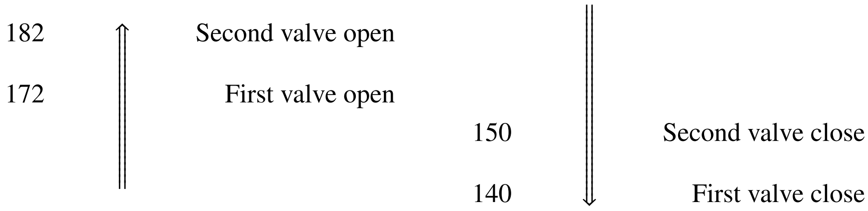


Figure 11: Safety valve set point for opening and closure

1.2.3 Mass control

1.2.3.1 Level regulation

The pressurizer is involved in the primary mass control since the regulation of this parameter is derived controlling the water level in the pressurizer itself.

The set point value for the pressurizer level is fixed in dependence of the average temperature in the reactor given by the measurement in selected points. the pressurizer set point can vary in a range of 2.5 around design value of 9.4 m. When temperature increases, the set point value is increased to balance the density increase, in order to maintain water mass to the same value, while when temperature decreases the set point is decreased, to obtain the same result. In the case of SGTR its value is set to a constant value, about 10.5 m.

The pressurizer level set point as function of temperature is given by

$$l_{pr,\mathrm{ref}} = c_{r,1}(T_{pc,cl} + T_{pc,hl}) - c_{r,2}.$$

where $T_{pr,cl}$, $T_{pr,hl}$ are both expressed in °C. Possible values of the constants are $c_{r,1} = 0.093$ m/°C, $c_{r,2} = 47.63$ m.

1.2.3.2 Injection and extraction mass flow rate value

The make–up system has two pumps, one of which operates continuously to ensure make–up system alimentation. Maximum injection mass flow rate depends on the number of available pumps.

Number of operating pump	**Maximum mass flow rate (kg/s)**
1 pump	12.5
2 pump	22.2

The extraction mass flow rate is regulated by two valves, one of which is opened in case of excessive pressurizer level by limitation system. A minimum extraction mass flow rate is ensured to feed the make–up system.

Parameter	**Value**
Maximum mass flow rate	15 kg/s
Minimum mass flow rate	3 kg/s

The control system regulate valve one of the two valves with a PI controller, while the second valve is controlled by the limitation system with an open–close logic. The extraction point is located after the main coolant pump (MCP) while injection point is located before MCP.

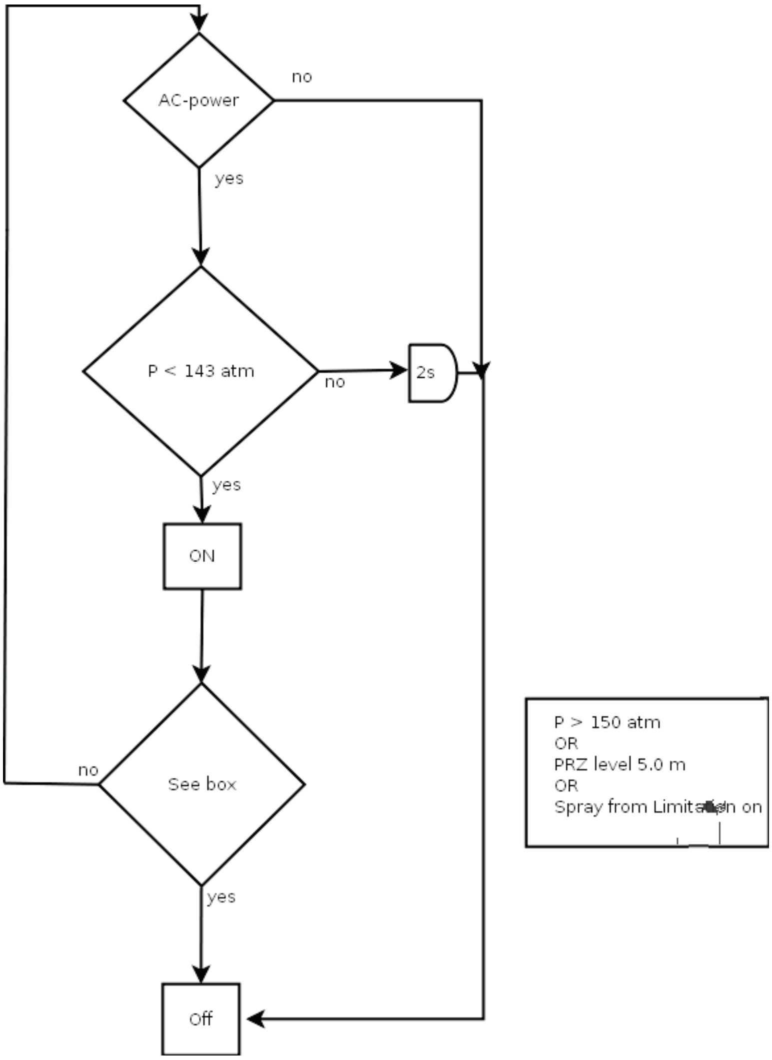


Figure 12: Injection and extraction points for the make–up and let down system

1.2.3.3 Level regulation by control

To regulate the water mass inside primary system, the balance between extraction and injection mass flow rate is controlled. The variable which is controlled is the difference between the actual level, and the set point for the level. The control system hysteresis is 0.2 m around set point value.

1.2.3.4 Level regulation by Limitation

If the difference between level and its set point is more than 0.5 m another pump is switched on or an extraction valve is closed, ensuring the minimum extraction needed by the make–up system.

If pressurizer level exceeded minimum or maximum value of set point limitation system act with the same logic in order to tempt to avoid the reactor trip. The hysteresis to reset the signal witch control this function is 0.05 m. When the auxiliary spray from make–up system is operating, the injection mass flow needed to by the level control system is delivered by the spray which has the priority over normal injection system.

1.2.3.5 Level control by protection system

The protection system responds to high and low level of the pressurizer with reactor trip. In addition to monitoring fixed limits (e.g. level above or below a certain value) the protection observes the derivative of the level increase or decrease. This is done by calculation of so called “sliding limits”. A sliding limit follows a measured value with a certain distance. However, the maximum change, with which the sliding limit may follow the measured value, is limited (the sliding limits may not change by more than 3.5 cm/s). This means, that if the increase (or decrease) in level is more rapid, the distance between sliding limit and actual value will decrease. If the actual, measured value crosses the sliding limit, the “sliding limit” signal is generated. Fig. 13 shows the fixed reactor protection system values, Fig. 14 the sliding ones.

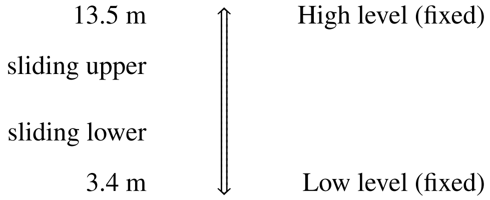


Figure 13: Reactor trip signal for high or low pressurizer water level

Sliding limits for water level in the pressurizer are imposed to limit the level rate of change. The logic to set these limit is shown in the diagram of Fig. 14.

1.3 Conclusive remarks

We have shown how to model a pressurizer, including logics. Anyway, other parts of the nuclear power plants, which can influence the pressurizer dynamics, are not modeled. There are two possible approaches to overcome this problem. The first would be to assume all feedback from systems other than the pressurizer as boundary conditions, in which case the present document should suffice for developing a model. Should, however, be needed, in [12] it is shown a more realistic representation for other components of the plant, by means of simplified models.

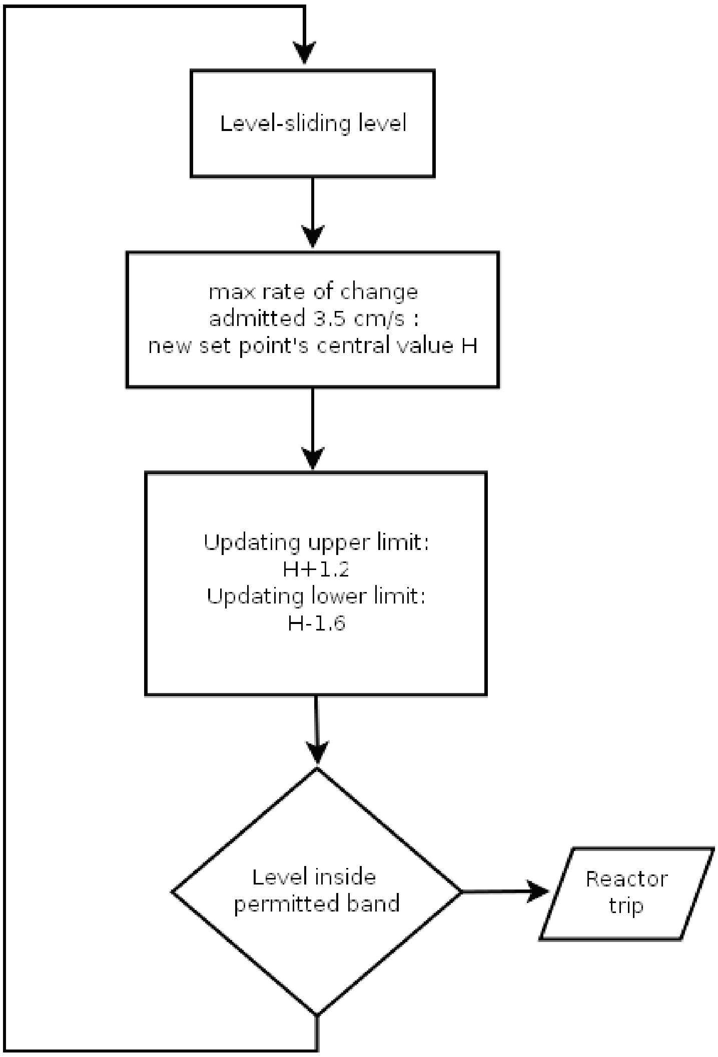


Figure 14: Generation of sliding limits logic

2 Analysis of the pressurizer dynamic behavior in the case of turbine trip

This section describes the behavior of a typical PWR during a turbine trip, with the response of the control system. First, the turbine trip is described as event–possible cause, and typical countermeasures taken by the control system of a PWR. Then, the model that has been adopted only for the pressurizer, for the controls related to the pressurizer, and the interfaces to the other parts of the NPP are described. Finally, the results of the turbine trip event, simulated with a more accurate pressurizer model, and defining appropriately the boundary conditions, are described.

2.1 Turbine Trip–Event

2.1.1 Turbine trip due to faulty closure of the turbine stop valve – General transient description

During normal operation, the main steam flows from the steam generators through parallel pipes to a header, from where the steam is led to main steam stop and control valves by individual pipes of the high pressure turbine. Branch lines provide the possibility to bypass the turbine during transient operations. In normal conditions, the bypass station remains closed and the steam passes through the main stop and control valves and expands in the high pressure turbine.

The main steam stop valves have dual function. They isolate the turbine from the main steam line or from the steam generator. They rapidly interrupt the supply of steam to the turbine after being triggered by monitors if a dangerous condition arises. Therefore they have been designed for quick closing and maximum reliability.

The control valves, on the other hand, regulate the flow of steam to the turbine according to the prevailing and provide a second means of isolation for the turbine in case of emergency.

The control valve is operated by the piston of the servo–motor which is subjected to the spring force in the closing direction and the pressure of the control fluid in the opening direction. The position of the valve is determined by the secondary fluid pressure which is controlled by the governor.

In case of undue operating conditions within the turbine–generator plant the turbine trip system is released by means of protective devices for turbine and generator (turbine protection system). Hereby the main steam stop and control valves are closed. The steam produced in the steam generators is bypassed via bypass stop and control valves and dumped into the condenser.

When turbine trip is initiated, the pressure drop in the trip oil circuit also causes the secondary fluid pressure to collapse because it is fed from it. The result is that both stop valve and the control valve close rapidly. The time for closing the stop valve is about 150 ms and for the control valve about 200 ms.

In events like excessive load reductions, load rejection or turbine trip, the main steam maximum pressure limitation opens valves in the main steam bypass station and the main steam is passed into the condenser. The main steam pressure in the header is used as actual value for the control. The set–point is a few bars above the main steam operating pressure. Main steam relief station may also be used for controlling the main steam pressure.

2.1.2 Possible Causes for a Turbine Trip

Besides manual trip or spurious actuation, turbine trip initiation may be caused by steam turbine protection system components, like

1. Overspeed protection;
2. Overspeed trip selection;
3. High condenser pressure protection;
4. Thrust bearing trip;
5. Low lube oil pressure trip;
6. Fire protection;
7. Main steam minimum pressure signaling;
8. Electrical or mechanical generator protection.

2.1.3 General remarks on development and safety countermeasures

After the turbine stop valves have closed, main steam pressure increases challenging the steam generator secondary side heat removal capability. Coolant temperature and pressure will increase and, unless adequate countermeasures are timely provided, heat removal from the core may be challenged too.

Turbine trip events can be dealt with only through measures and design features (provisions) of the Level 2 of the defense in depth. The Level 1 has the design capabilities of operational systems to deal with expected changes in load demands. The objective for the Level 2 is the detection of failures and the control of abnormal operations. Essential means for achieving such objective are control, limitation and protection systems and other surveillance features.

For the scenario of turbine trip (stop valve closure), the following systems may start to operate

1. Actuation signals for reactor trip are:

   i. Main steam pressure in 1st steam generator > maximum or
   ii. Main steam pressure in 2nd steam generator > maximum or
   iii. Pressurizer level > sliding limit value

2. Effective controls
   i. Reactor power control
   ii. Generator power control
   iii. Coolant pressure control
   iv. Pressurizer water level control
   v. Main steam generator maximum pressure control
   vi. Steam generator water level control
   vii. Moderator temperature control

3. Effective limitations
   i. Reactor power limitation
   ii. Near–simultaneous rod drop actuation
   iii. Coolant pressure, inventory and temperature gradient limitation

2.1.4 Event Development

On turbine trip, after the turbine stop valves have closed, secondary side heat removal is abruptly interrupted leading to a sudden increase in the main steam pressure. However, the pressure excursion is rather limited by the prompt response of the turbine bypass station.

The main steam bypass valves open immediately because the MS pressure goes above the maximum pressure set–point, which is reduced on turbine trip and then raised to a maximum at which it is held.

In the first 10 s after the turbine trip, degraded heat removal conditions in the secondary side of the steam generators cause an increase in the coolant average temperature and a consequent expansion of coolant volume.

Because of the high reactor minimum load, the overall temperature changes in coolant and moderator are rather small. Consequently, the volumetric changes are also limited, as can be seen in the behavior of the pressurizer water level.

Closed–loop control and limitation systems are called upon to deal with the effects of power mismatch between reactor and the electric generator, keeping process variables within acceptable limits. Partial rod dropping is initiated by comparing reactor and generator power and, after 1.1 s delay time, the reactor is run back to a minimum load of approximately 80%, as a consequence of the % inserted reactivity by rod movement.

A minor transient is observed in the coolant pressure which demands the intervention of pressurizer heating power.

With the available main steam bypass system, the secondary relief station stays closed. Due to the main steam pressure rise, the steam generator water level initially slightly decreases and it is brought back to normal by the main feed–water control.

Due to the effective response of control and limitation systems, promptly reducing the reactor power and early opening of the main steam bypass station, the process variables differ only insignificantly from their set–points, keeping reasonable margins to the limits of the reactor protection system, which are not reached.

2.2 Turbine Trip – Pressurizer Model

A model for the pressurizer has been developed, as well as a model for the control systems which intervene in a Turbine Trip under best estimate assumptions, as described above. The present section describes the development of the thermal hydraulic model, the control systems and their models, the MatLab Scripts that have been developed for the simulation, and, finally, boundary conditions and results.

2.2.1 Pressurizer Thermal Hydraulic Model

Following the model developed in Section 1.1.3, the two zone (one zone for liquid, one for the steam) pressurizer model is explicitly determined. The chosen five state variables are

1. Pressure;
2. Vapor internal energy;
3. Liquid internal energy;
4. Total vapor mass;
5. Total liquid mass.

The differential equations have been developed using

1. Conservation of total mass;
2. Conservation of total energy;
3. Conservation of the volume.

Moreover, mass and energy transfer to the other parts of the nuclear plant have to be imposed on the model as boundary conditions

1. Spray flow and temperature;
2. Surge flow and temperature.

A simple assumption has been used to complete the system of equations: the vapor formed in the liquid part, due to pressure changes (flashing), or the liquid formed in the vapor part, due to pressure changes (rain out), is assumed to be instantaneously removed to the respective volume. See Figures 15 and 16 for the definition of the variables, and for the mass and energy transfers across the interfaces.

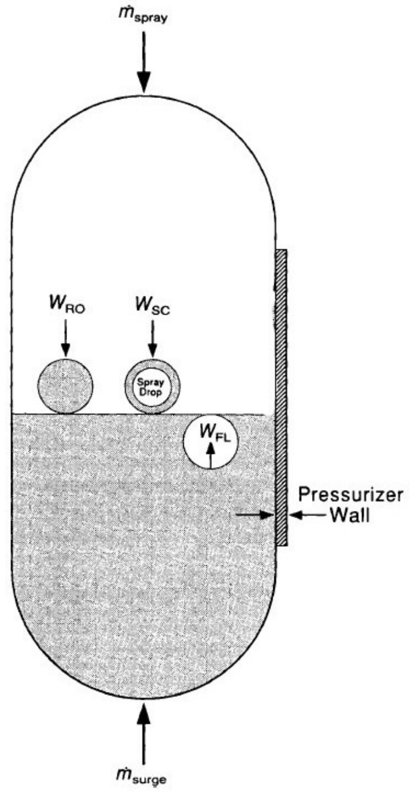


Figure 15: Pressurizer mass flows across the interfaces

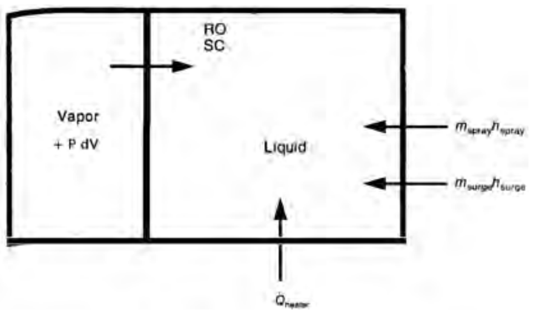


Figure 16: Pressurizer energy transfer across the interfaces

The power $W_{heat,pr}$ transferred from the pressurizer heaters is determined on the basis of the controller

2.2.2 Conservation equations

Liquid Mass Conservation. Let k_m (kg/s) describe the mass exchange rate between the two phases, which can occur by

- Rainout W_{ro} (kg/s), i.e. steam condensed due to pressure changes;
- Flashing W_{fl} (kg/s), i.e. liquid evaporated due to pressure changes;
- Steam condensed by spray W_{sc} (kg/s).

Note that W_{sc} just denominates the flow of condensed steam, and does not include the water from the spray.

The mass exchange between the two phases is therefore

$$k_m = -W_{fl} + W_{ro} + W_{sc}$$

where

$$W_{sc} = \dot{m}_{spray} \frac{(h_f - h_{sp})}{h_{fg}}$$

with h_f (h_g) the specific enthalpy of the saturated liquid (vapor) (J/kg), h_{sp} the specific enthalpy of the spray, and $h_{fg} = h_g - h_f$ the difference of the specific enthalpies at a certain value of the pressure.

A positive sign of k_m means flow from the steam to the liquid volume. It is assumed that the spray water is brought to saturation, and that the energy needed for this increase in enthalpy is taken by condensing steam.

Furthermore, the spray and surge water (both add to the liquid volume only) ratio S_m (kg/s) is simply the sum

$$S_m = \dot{m}_{spray} + \dot{m}_{surge}$$

with $\dot{m}_{spray}$, $\dot{m}_{surge}$ are the liquid spray and surge ratio masses (kg/s)

Liquid mass conservation. Denoting by M_l the pressurizer liquid mass (kg), the balance is

$$\dot{M}_l = k_m + S_m.$$

Steam mass conservation. Denoting by M_v the pressurizer vapor mass (kg), the balance is

$$\dot{M}_v = -k_m.$$

Liquid internal energy conservation. A portion of the energy k_e (J/s) may come from or go to the vapor part, together with the transfer of mass. This part is expressed as a function of W_{fl}, W_{sc} and W_{ro}, and the respective enthalpies

$$k_e = h_f W_{ro} + h_g (W_{sc} - W_{fl}).$$

Positive k_e means energy from vapor to liquid. A second part S_e (J/s) may come from external energy sources (spray, surgeline, heaters)

$$S_e = \dot{m}_{spray} h_{spray} + \dot{m}_{surge} h_{surge} + W_{heat,pr}.$$

All contributions are only added to the liquid part. A third contribution comes from the mechanical work when expanding or contracting. Positive volume change requires work, and the energy is taken from the respective volume.

Liquid Internal Energy Conservation. The balance for the pressurizer liquid internal energy U_l (J) is given by

$$\dot{U}_l = k_e + S_e - p_{pr}\dot{V}_l$$

where p_{pr} is the pressurizer pressure (Pa), and V_l is the liquid volume (m^3).

Steam Internal Energy Conservation. The balance for the pressurizer steam internal energy U_v (J) is given by

$$\dot{U}_v = -k_e - p_{pr}\dot{V}_v$$

where V_v is the steam volume (m^3).

Conservation of volume. Obviously,

$$V_l + V_v = V$$

with V (m^3) the total pressurizer volume. Clearly, $\dot{V}_l = -\dot{V}_v$.

Change from total values to specific values. Considering the specific values u (J/kg) and v (m^3/kg) for the energy and mass

$$U_l = M_l u_l$$

$$U_v = M_v u_v$$

$$V_l = M_l v_l$$

$$V_v = M_v v_v$$

substituting and solving for the derivatives of M_l, M_v, u_l, u_v, one gets

$$\begin{aligned}
\dot{M}_l &= k_m + S_m \\
\dot{M}_v &= -k_m \\
M_l \dot{u}_l &= k_e + S_e - (k_m + S_m)(u_l + p_{pr} v_l) - p_{pr} M_l \dot{v}_l \\
M_v \dot{u}_v &= -k_e - p_{pr} M_v \dot{v}_v + p_{pr} k_m v_v + k_m u_v.
\end{aligned}$$

As state variables, the pressure p_{pr}, the liquid and vapor masses M_l, M_v, and the liquid and vapor internal energies u_l, u_v are chosen. In order to determine a differential equation for p_{pr}, let us consider two additional equations, used to eliminate the specific volume derivatives

$$v_l = F(p_{pr}, u_l)$$

$$v_v = F(p_{pr}, u_v)$$

with F an experimental function, usually given by tables. Denoting

$$\mathcal{P}_1 = \frac{\partial F(p_{pr}, u_l)}{\partial p_{pr}} \qquad \mathcal{P}_3 = \frac{\partial F(p_{pr}, u_v)}{\partial p_{pr}}$$

$$\mathcal{P}_2 = \frac{\partial F(p_{pr}, u_l)}{\partial u_l} \qquad \mathcal{P}_4 = \frac{\partial F(p_{pr}, u_v)}{\partial u_v}$$

one can write

$$\dot{v}_l = \mathcal{P}_1 \dot{p}_{pr} + \mathcal{P}_2 \dot{u}_l$$

$$\dot{v}_v = \mathcal{P}_3 \dot{p}_{pr} + \mathcal{P}_4 \dot{u}_v$$

Moreover, using the conservation of volume and considering the specific volumes

$$\dot{M}_l v_l + M_l \dot{v}_l = -\dot{M}_v v_v - M_v \dot{v}_v$$

i.e.

$$(k_m + S_m) v_l + M_l(\mathcal{P}_1 \dot{p}_{pr} + \mathcal{P}_2 \dot{u}_l) = k_m v_v - M_v(\mathcal{P}_3 \dot{p}_{pr} + \mathcal{P}_4 \dot{u}_v)$$

from which one obtains a fifth differential equation

$$(\mathcal{P}_1 M_l + \mathcal{P}_3 M_v)\dot{p}_{pr} = -(k_m + S_m) v_l + k_m v_v - (\mathcal{P}_2 M_l \dot{u}_l + \mathcal{P}_4 M_v \dot{u}_v).$$

Therefore, from the equations for u_l, u_v, p_{pr} one works out

$$\begin{pmatrix} \dot{u}_l \\ \dot{u}_v \\ \dot{p}_{pr} \end{pmatrix} = \begin{pmatrix} (1 + p_{pr}\mathcal{P}_2)M_l & 0 & p_{pr}\mathcal{P}_1 M_l \\ 0 & (1 + p_{pr}\mathcal{P}_4)M_v & p_{pr}\mathcal{P}_3 M_v \\ \mathcal{P}_2 M_l & \mathcal{P}_4 M_v & \mathcal{P}_1 M_l + \mathcal{P}_3 M_v \end{pmatrix}^{-1} \times$$

$$\times \begin{pmatrix} k_e + S_e - (k_m + S_m)u_l - (k_m + S_m)p_{pr}F(p_{pr}, u_l) \\ -k_e + p_{pr}k_m F(p_{pr}, u_v) + k_m u_v \\ -(k_m + S_m)F(p_{pr}, u_l) + k_m F(p_{pr}, u_v) \end{pmatrix}.$$

Finally, the pressurizer mathematical model is

$$\begin{aligned} \dot{M}_l &= k_m + S_m \\ \dot{M}_v &= -k_m \\ \dot{u}_l &= \frac{C_{11}\mathcal{F}_1 + C_{12}\mathcal{F}_2 + C_{13}\mathcal{F}_3}{\varDelta} \\ \dot{u}_v &= \frac{C_{21}\mathcal{F}_1 + C_{22}\mathcal{F}_2 + C_{23}\mathcal{F}_3}{\varDelta} \\ \dot{p}_{pr} &= \frac{C_{31}\mathcal{F}_1 + C_{32}\mathcal{F}_2 + C_{33}\mathcal{F}_3}{\varDelta} \end{aligned} \tag{1}$$

where we have defined

$$\begin{aligned}
\varDelta &= \mathcal{P}_1 M_l(1 + p_{pr}\mathcal{P}_4) + \mathcal{P}_3 M_v(1 + p_{pr}\mathcal{P}_2)\\
C_{11} &= \frac{\mathcal{P}_1 M_l(1 + p_{pr}\mathcal{P}_4) + \mathcal{P}_3 M_v}{M_l}\\
C_{12} &= p_{pr}\mathcal{P}_1\mathcal{P}_4\\
C_{13} &= -p_{pr}\mathcal{P}_1(1 + p_{pr}\mathcal{P}_4)\\
C_{21} &= p_{pr}\mathcal{P}_2\mathcal{P}_3\\
C_{22} &= \frac{\mathcal{P}_1 M_l + \mathcal{P}_3 M_v(1 + p_{pr}\mathcal{P}_2)}{M_v}\\
C_{23} &= -p_{pr}\mathcal{P}_3(1 + p_{pr}\mathcal{P}_2)\\
C_{31} &= -\mathcal{P}_2(1 + p_{pr}\mathcal{P}_4)\\
C_{32} &= -\mathcal{P}_4(1 + p_{pr}\mathcal{P}_2)\\
C_{33} &= (1 + p_{pr}\mathcal{P}_2)(1 + p_{pr}\mathcal{P}_4)\\
\mathcal{F}_1 &= k_e + S_e - (k_m + S_m)u_l - (k_m + S_m)p_{pr}F(p_{pr}, u_l)\\
\mathcal{F}_2 &= -k_e + p_{pr}k_m F(p_{pr}, u_v) + k_m u_v\\
\mathcal{F}_3 &= -(k_m + S_m)F(p_{pr}, u_l) + k_m F(p_{pr}, u_v)\\
k_m &= -W_{fl} + W_{ro} + \frac{(h_f - h_{sp})}{h_{fg}}\dot{m}_{spray}\\
k_e &= h_f W_{ro} + \frac{(h_f - h_{sp})h_g}{h_{fg}}\dot{m}_{spray} - h_g W_{fl}\\
S_m &= \dot{m}_{spray} + \dot{m}_{surge}\\
S_e &= h_{spray}\dot{m}_{spray} + h_{surge}\dot{m}_{surge} + W_{heat,pr}.
\end{aligned}$$

Additional information for evaluation of k_m, k_e, S_m, S_e are needed. Partially, these information have to be imposed as boundary condition (surgeline and spray related parameters), partially the information can be resolved by evaluation of the state equation (e.g. the needed partial derivatives). The remaining variables W_{ro}, W_{fl}, which describe the flow between the vapor–liquid interface, can be derived by excluding unstable conditions (i.e. subcooled vapor or superheated liquid).

2.2.3 Control system simulation

In this section we want to test the capabilities of the pressurizer water level and pressure controllers proposed in the [3], [4], [5], [9] in the case of turbine trip. For the sake of completeness we recall that the controllers considered in [9] were

$$
\begin{aligned}
\dot{I}_{e_{l_{pr}}} &= l_{pr} - l_{pr,\mathrm{ref}} \\
\dot{\hat{T}}_{pr} &= -\frac{k_{wall}}{c_{p,pr}M_{pr}}(\hat{T}_{pr} - T_{pr,wall}) + \frac{1}{c_{p,pr}M_{pr}}W_{heat,pr} + \delta_{pr}\Big(\frac{c_{p,pc}m^{\circ}_{pr}}{c_{p,pr}M_{pr}}(T_{pc} + \mathit{\Delta}^{\circ}) - \frac{m^{\circ}_{pr}}{M_{pr}}\hat{T}_{pr}\Big) \\
\dot{T}_{pr,wall,\mathrm{ref}} &= \frac{k_{wall}}{c_{p,wall}}(T_{pr,\mathrm{ref}} - T_{pr,wall,\mathrm{ref}}) - \frac{1}{c_{p,wall}}W^{\circ}_{loss,pr} \\
m_{in} &= \frac{A_{pr}}{\psi(M_{pc},T_{pc})}\Big[-\Big(k_p(l_{pr} - l_{pr,\mathrm{ref}}) + k_i I_{e_{l_{pr}}}\Big)\varphi^2(T_{pc}) + m^{\circ}_{out}\varphi(T_{pc}) \\
&\quad + \frac{1}{c_{p,pc}}\Big(\frac{2c_{r,1}}{M_{pc}}\varphi^2(T_{pc}) + \frac{\partial\varphi(T_{pc})}{\partial T_{pc}}\Big)\Big(c_{p,pc}m^{\circ}_{out}\mathit{\Delta}^{\circ} + c_{\psi}N - n_{sg}k_{t,sg}(T_{pc} - T_{sg}) - W^{\circ}_{loss,pc}\Big)\Big] \\
W_{heat,pr} &= -\Big(k_{wall} + c_{p,pr}M_{pr}\frac{k_{wall}}{c_{p,wall}}\Big)(T_{pr,wall} - T_{pr,wall,\mathrm{ref}}) + c_{p,pr}M_{pr}\Big[\dot{T}_{pr,\mathrm{ref}} \\
&\quad + \frac{k_{wall}}{c_{p,pr}M_{pr}}(T_{pr,\mathrm{ref}} - T_{pr,wall,\mathrm{ref}}) - \delta_{pr}\Big(\frac{c_{p,pc}m^{\circ}_{pr}}{c_{p,pr}M_{pr}}(T_{pc} + \mathit{\Delta}^{\circ}) - \frac{m^{\circ}_{pr}}{M_{pr}}T_{pr,\mathrm{ref}}\Big)\Big]
\end{aligned}
\tag{2}
$$

and

$$
\begin{aligned}
\dot{I}_{e_{l_{pr}}} &= l_{pr} - l_{pr,\mathrm{ref}} \\
\dot{I}_{e_{p_{pr}}} &= c_0 - c_1\hat{T}_{pr} + c_2\hat{T}^2_{pr} - p_{pr,\mathrm{ref}} \\
\dot{\xi} &= \hat{T}_{pr} - T_{pr,wall} - \frac{1}{k_{wall}}W^{\circ}_{loss,pr} - \frac{1}{k}\frac{1}{c_{p,pr}M_{pr}}C_{pr} \\
\hat{T}_{pr} &= k\Big(\frac{c_{p,wall}}{k_{wall}}T_{pr,wall} - \xi\Big) \\
C_{pr} &= \frac{c_{p,pr}M_{pr}}{-c_1 + 2c_2\hat{T}_{pr}}\Big(\dot{p}_{pr,\mathrm{ref}} - K_p\Big(c_0 - c_1\hat{T}_{pr} + c_2\hat{T}^2_{pr} - p_{pr,\mathrm{ref}}\Big) - K_i I_{e_{p_{pr}}}\Big) \\
m_{in} &= \frac{A_{pr}}{\psi(M_{pc},T_{pc})}\Big[-\Big(k_p(l_{pr} - l_{pr,\mathrm{ref}}) + k_i I_{e_{l_{pr}}}\Big)\varphi^2(T_{pc}) + m^{\circ}_{out}\varphi(T_{pc}) \\
&\quad + \frac{1}{c_{p,pc}}\Big(\frac{2c_{r,1}}{M_{pc}}\varphi^2(T_{pc}) + \frac{\partial\varphi(T_{pc})}{\partial T_{pc}}\Big)\Big(c_{p,pc}m^{\circ}_{out}\mathit{\Delta}^{\circ} + c_{\psi}N - n_{sg}k_{t,sg}(T_{pc} - T_{sg}) - W^{\circ}_{loss,pc}\Big)\Big] \\
W_{heat,pr} &= k_{wall}(\hat{T}_{pr} - T_{pr,wall}) + C_{pr} + \delta_{pr}\Big(c_{p,pr}m^{\circ}_{pr}\hat{T}_{pr} - c_{p,pc}m^{\circ}_{pr}(T_{pc} + \mathit{\Delta}^{\circ})\Big).
\end{aligned}
\tag{3}
$$

The reader is referred to [9] for further details. In the following we will refer to the controller (3), since the system responses are very similar and because it is a simpler controller. We have also implemented all the further control actions expected to intervene in a turbine trip transient. These are

Pressure control. A turbine trip transient can be dominated by the control system alone. Four successive spray valves have been modeled, each one opening at a higher pressure than its predecessor. The spray valves are closed at opening pressure minus a hysteresis value.
Spray valve opening

- Valve 1: $p_{pr} > p_{\max 1}$;

- Valve 2: $p_{pr} > p_{\max 2}$;
- Valve 3: $p_{pr} > p_{\max 3}$;
- Valve 4: $p_{pr} > p_{\max 4}$.

Spray valve closure

- Valve 1: $p_{pr} < p_{\max 1} - \epsilon_{\text{hyst}}$;
- Valve 2: $p_{pr} < p_{\max 2} - \epsilon_{\text{hyst}}$;
- Valve 3: $p_{pr} < p_{\max 3} - \epsilon_{\text{hyst}}$;
- Valve 4: $p_{pr} < p_{\max 4} - \epsilon_{\text{hyst}}$.

with ϵ_{hyst} an hysteresis value.

The pressurizer heater power is controlled in a analogous way. Three banks of heaters are successively switched on and off

Pressurizer heaters bank switch on

- Bank 1: $p_{pr} < p_{\min 1}$;
- Bank 2: $p_{pr} < p_{\min 2}$;
- Bank 3: $p_{pr} < p_{\min 3}$.

Pressurizer heaters bank switch off

- Bank 1: $p_{pr} > p_{\min 1} + \epsilon_{\text{hyst}}$
- Bank 2: $p_{pr} > p_{\min 2} + \epsilon_{\text{hyst}}$
- Bank 3: $p_{pr} > p_{\min 3} + \epsilon_{\text{hyst}}$

Level control. A set–point for the pressurizer level is calculated, depending on the average RCS temperature. This last has to be provided as boundary condition. If the difference between actual level and set point exceeds a value $l_{pr,\max}$ or $l_{pr,\min}$, a net in– or outflow is added to the surge line flow. The set point for the level is calculated to

$$l_{pr,\text{ref}} = c_{r,1}(T_{pc,cl} + T_{pc,hl}) - c_{r,2} = \bar{c}_{r,1} T_{pc,average} - c_{r,2}.$$

Switch on makeup system: $l_{pr,\text{ref}} - l_{pr} > l_{pr,\min}$;
Switch off makeup system: $l_{pr,\text{ref}} - l_{pr} < l_{pr,\min} - \varepsilon_{\text{hyst}}$;
Switch on letdown system: $l_{pr} - l_{pr,\text{ref}} > l_{pr,\max}$;
Switch off makeup system: $l_{pr} - l_{pr,\text{ref}} < l_{pr,\max} - \varepsilon_{\text{hyst}}$.

2.2.4 Implementation in Matlab

The system has been implemented in Matlab scripting language. Please refer to Fig. 17 for the logic structure of the program.

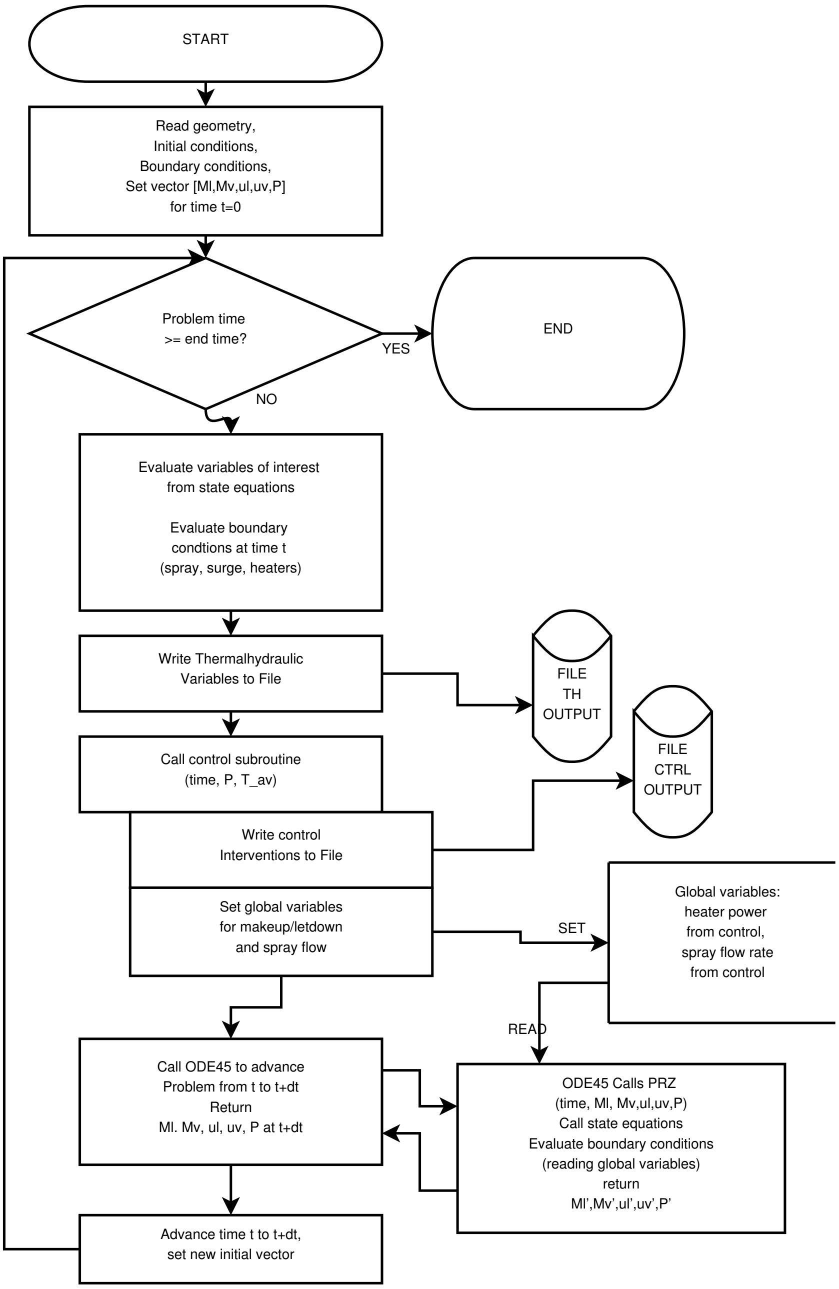


Figure 17: Program Matlab Flow Diagram

In the following each file is listed and described.

main_program.m is the main program script to be launched. All other routines are called from here. The initial conditions (temperature, level, initial pressure), as well as the names of the output files are set in this script. It reads also the file “data”, which contains the boundary conditions from the remaining part of the NPP, and stores it in a global variable.

control_system.m Control system is called by main_program.m as indicated in the flow diagram. The function calculates the control (3), and determines all the further control action previously described. The control system interacts with the pressurizer by actuation of the spray, which is done by changing the value of the global variable SPRAYFLOW, by actuation of the pressurizer heaters (global variable HEATERSPOW) and by extraction or injection into the primary system. It is assumed that no voids are present in the primary system, such that injection or extraction will result in a change of the surge line flow. The contribution of makeup/letdown system to the surge line flow is stored in the global variable LVLFLOW.

prz.m prz takes the main variables of the system, $M_l, M_v, u_l, u_v, p_{pr}$ and the time t as input, and returns their derivatives. prz.m contains the system of explicit ODEs $\dot{x} = f(t, x)$.

boundary_conditions.m The function boundary_conditions.m provides the surge and spray line flows, for a given moment in time. The surge flow is the sum of the flow imposed as external boundary condition in the file data, and the surge flow resulting from the interactions of the control system.

XSteam.m XSteam.m is a free MatLab script for calculation of water properties.

h_pu.m XSteam does not calculate the specific enthalpy as function of pressure and specific internal energy. A MatLab subroutine has been written for that purpose.

data The program expects to find a file “data” in ascii format t–x1–x2, three space separated columns of numbers, where where t indicates the problem time, x1 the surge line flow one wishes to impose on the system, and x2 the average system temperature.

output two output files are produced: “th.out”, which contains all relevant thermohydraulic quanitities, and “ctrl.out”, which lists main interventions of the control system. In addition, at each advancement in time a status message is written to the matlab output screen.

2.3 Turbine trip – Example results

The feed back of the overall system on the pressurizer during a turbine trip is governed by the reactor power and the secondary system pressure. The secondary system pressure increases shortly, until the bypass opens. As an result, the primary system coolant temperature rises for the time of about five seconds, see Fig. 18. However, the power mismatch is detected almost instantaneously, and the reactor power (and with the power also the average primary system temperature) is decreased, see Figs. 19 and 18).

The average temperature is proportional to the surge line flow. This means during the secondary pressure increase and average temperature increase a insurge can be assumed, followed by an outsurge during the power reduction, see Fig. 24.

From now on, results from the presented model are given. The surge flow is governing the pressure. The primary pressure increases during the insurge, see Fig. 22, and causes the spray valve one to open, see Fig. 23. The spray together with the outsurge results in a rapid decrease of pressure, and pressurizer heaters bank one is switched on, see Fig. 25.

After roughly 400–500s the nominal pressure is reached, the level is stabilized at the new set point, see Fig. 20, and the transient reached a new stable steady–state.

One remark on the intervention of the let–down system due to difference between actual pressurizer level and set–point is greater than $l_{pr,\mathrm{max}}$, see list below and Fig. 20. This appears the result of the limitations of the model, and may not be justified by physics. A finer modeling of flashing might improve the situation. Following the feedback of the controls is listed

- Control: $t = 2.00$ s Opening spray valve 1;
- Control: $t = 11.50$ s Closing spray valve 1;
- Control: $t = 14.00$ s Turning on heaters group 1;
- Control: $t = 15.50$ s $l_{pr} - l_{pr,\mathrm{ref}} > l_{pr,\mathrm{max}}$ – turning on letdown–system;
- Control: $t = 46.50$ s $l_{pr} - l_{pr,\mathrm{ref}} < l_{pr,\mathrm{max}} - \varepsilon_{\mathrm{hyst}}$ – turning off letdown–system;
- Control: $t = 410.50$ s Turning off heaters group 1.

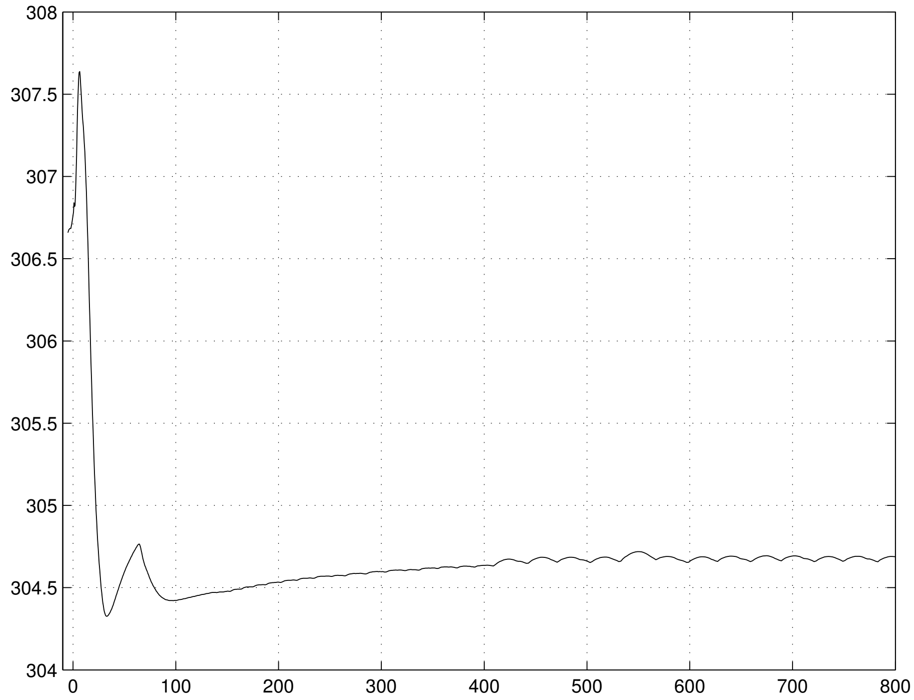


Figure 18: Boundary condition – Average fluid temperature between hot and cold leg temperatures [°C]

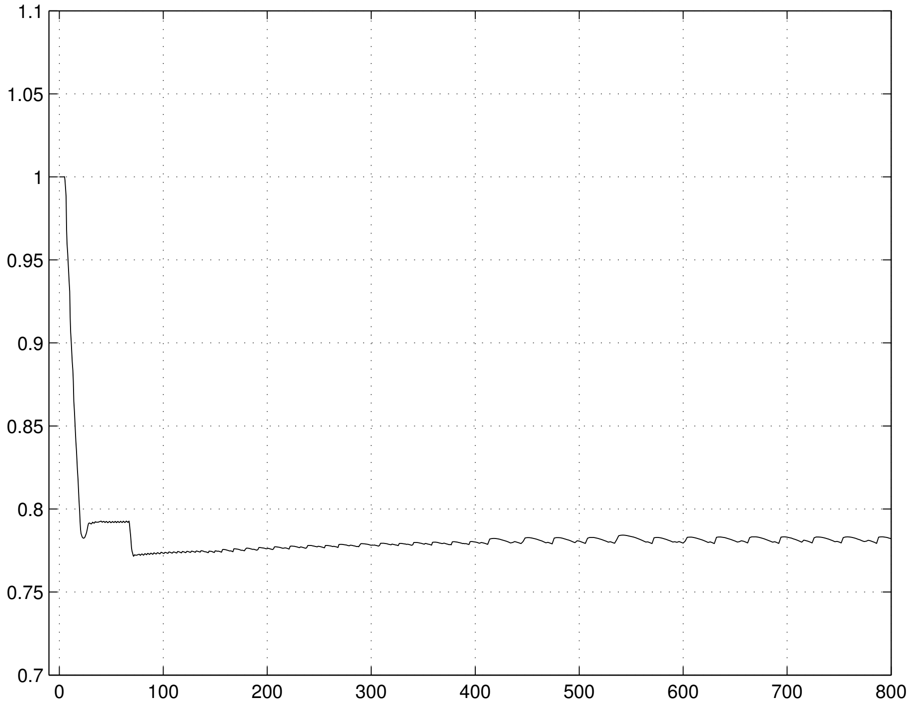


Figure 19: Boundary condition – Relative reactor power [–]

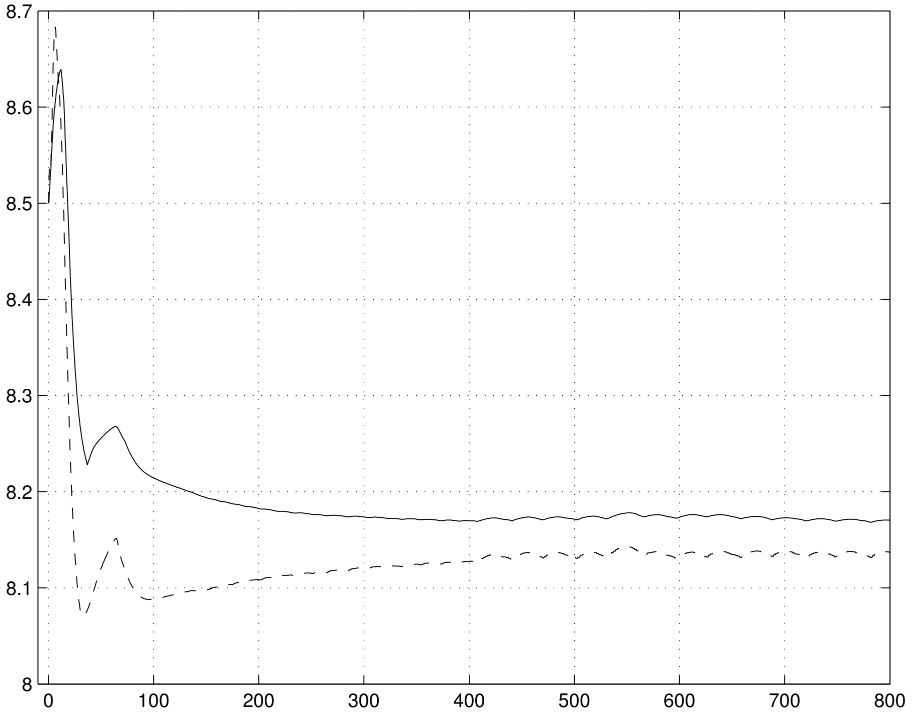


Figure 20: Pressurizer level – Actual (solid) and set point (dashed) mass flow [kg/s]

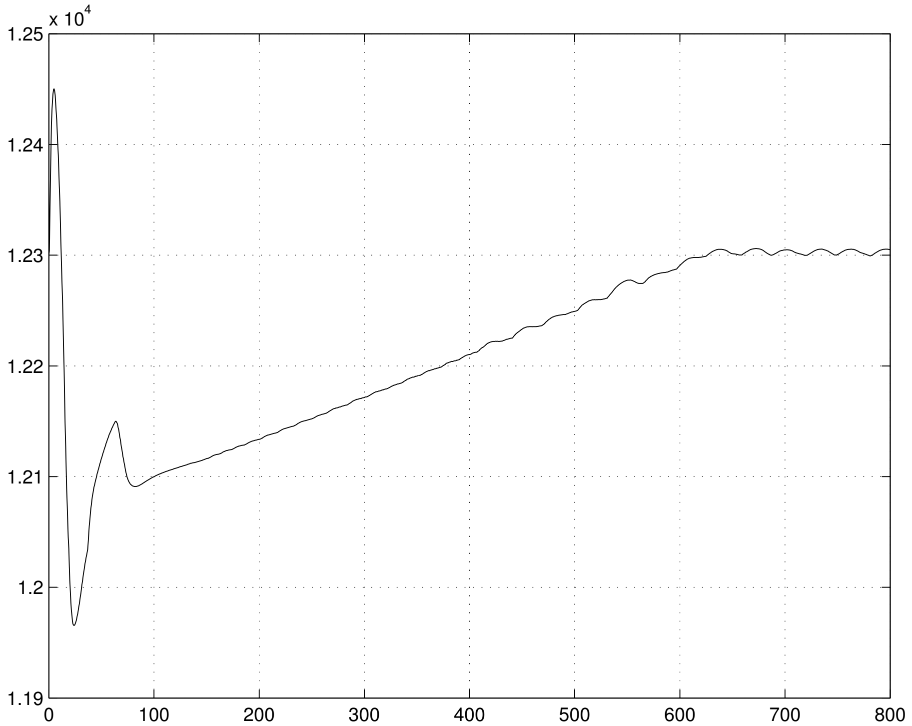


Figure 21: Pressurizer pressure [kPa]

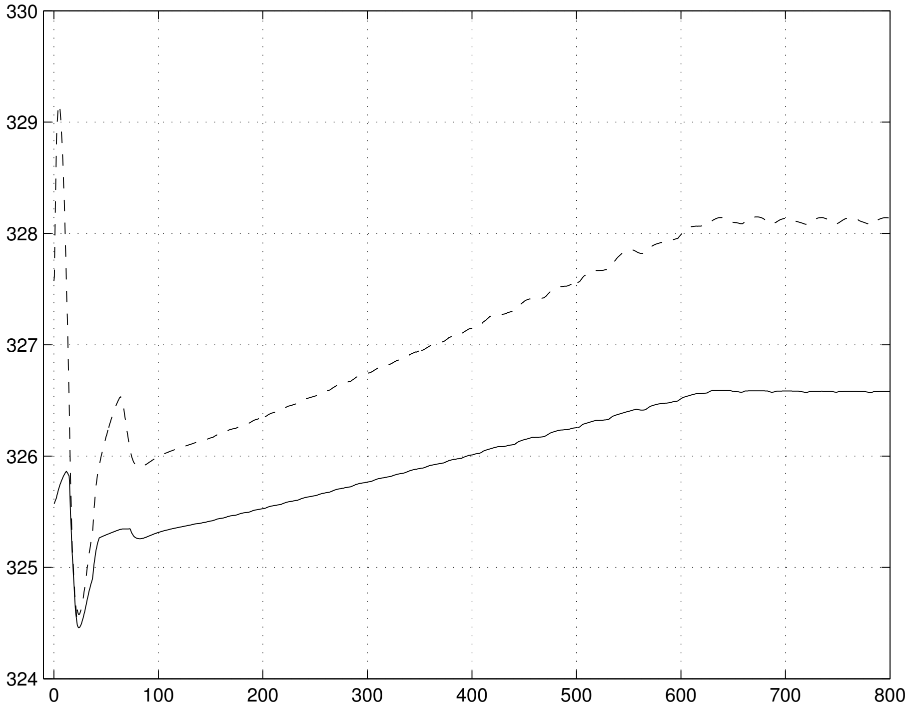


Figure 22: Pressurizer temperature, liquid (solid) and vapor (dashed) volume [°C]

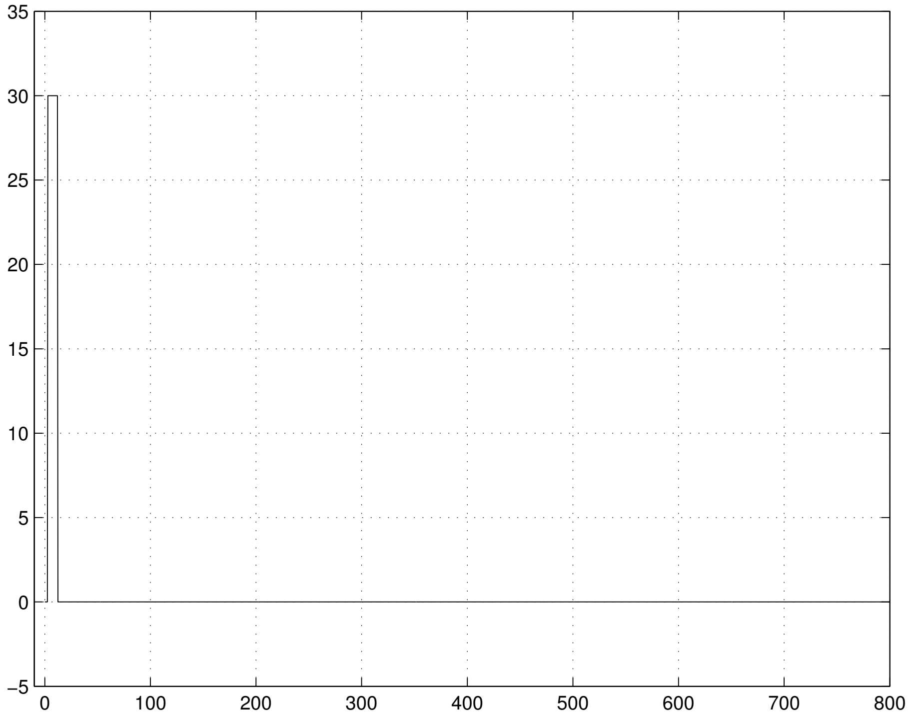


Figure 23: Pressurizer spray mass flow [kg/s]

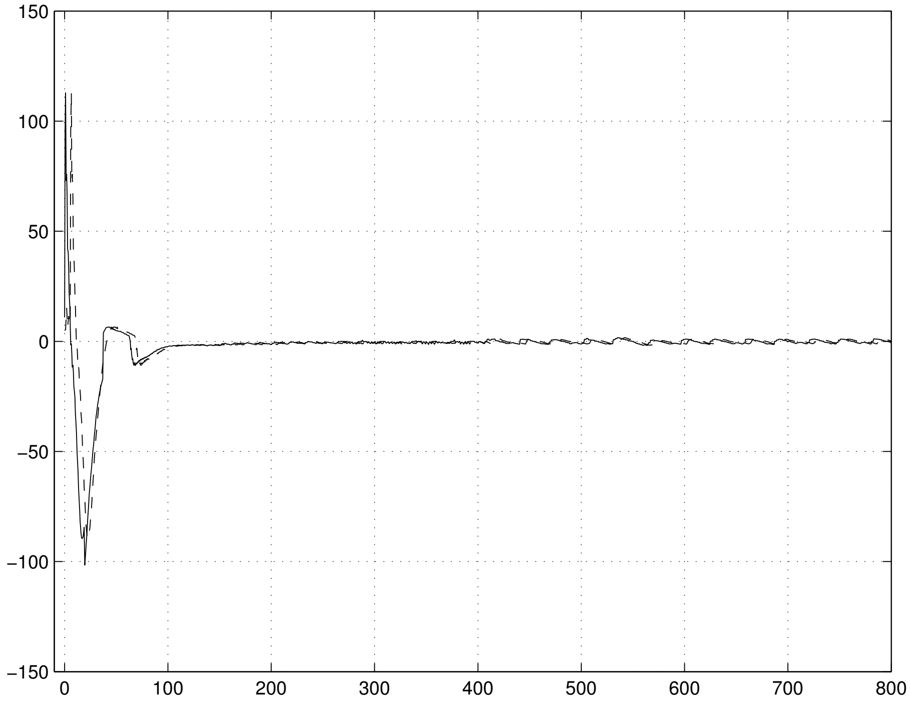


Figure 24: Boundary condition and result – Actual (solid) and imposed (dashed) pressurizer surge mass flow [kg/s]

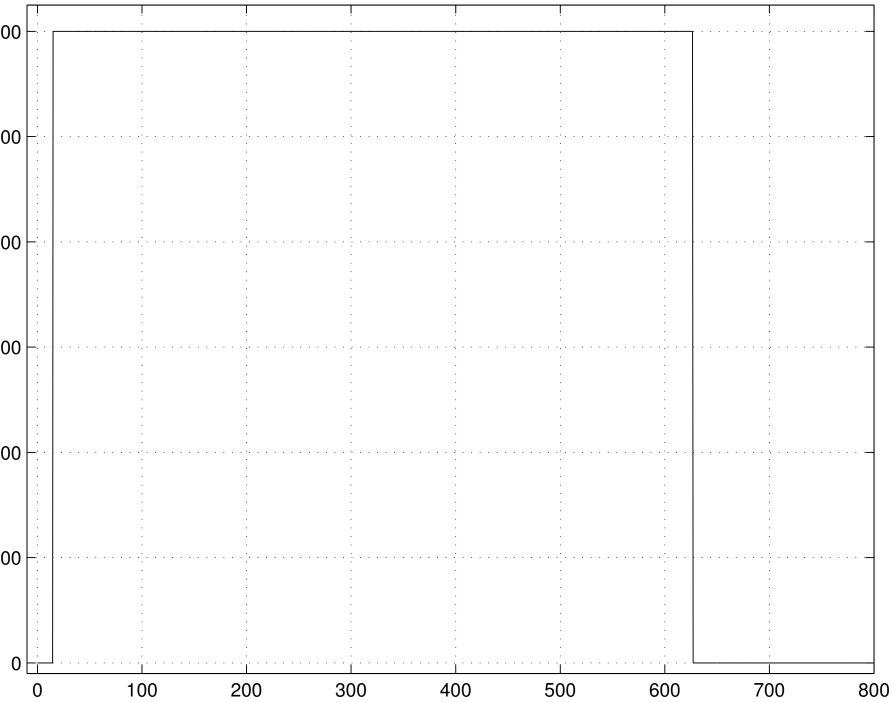


Figure 25: Pressurizer heater power [kW]

Conclusions

In this deliverable a more detailed two–zone model for the pressurizer has been derived and used to check the performance of the inventory controller and pressure controller for the pressurizer of a PWR. These controllers ensure a good performance, also in the presence of uncertainties and disturbances.

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