Multimodeling Representation for Physical Systems Application to PWR Primary Coolant Loop

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Abstract

This paper deals with the *multimodeling* principle to represent physical systems. It shows that when we apply this approach to a *Pressurized Water Reactor (PWR)* nuclear power plant, we face some difficulties especially in representing behavioral model. In order to solve this problem we propose a solution consisting in introducing bond graph concept at the behavioral level.

1 Introduction

Model-based reasoning is currently a very active area of A.I. research. Most of the developement in this field is based on the qualitative reasoning concept which exploits only structural and behavioral knowledge in order to support a variety of tasks, such as design and diagnosis [MQ&D, 1995]. Recently, a new concept of model-based reasoning called "*multimodeling*" has been proposed. Its main contribution is characterized by the representation of many diverse, explicit models of a physical system which are used in a cooperative way in specific problem solving tasks. The purpose of this multiple model cooperation is to improve the efficiency of reasoning about physical systems. Several research efforts have been devoted to the issue of multimodeling representation for physical systems. As a related work in this field, we refered mainly to the function-based research which introduces structural, behavioral and functional knowledge in its reasoning tasks [Sticklen and Bond, 1991], [Franke, 1991], [Everett, 1995], [Vescovi et al., 1993], [Abu-Hanna et al., 1991], [Sasajima et al., 1995], [Keuneke, 1991], and [Chittaro et al., 1993].

In this paper, we focus on the multimodeling representation proposed in [Chittaro et al., 1993] which is considered as an appropriate method to represent physical systems. It consists in representing physical systems with two categories of knowledge: *fundamental* and *interpretative* knowledge. The fundamental knowledge is devoted to describe the various components which constitute the system and their potential behaviors. The interpretative knowledge consists in deriving subjective interpretation of fundamental knowledge in terms of system functions and goals. The models generated by this approach can be reused unaltered for several applications including design and diagnosis. These models are described briefly in section 2. When we apply this multimodeling approach to complex physical systems such as a PWR nuclear power plant, we face some difficulties especially in representing behavioral models. Our aim in this paper is to adapt this approach in order to apply the multimodeling representation for complex physical systems. Thus, we propose, in section 3, a method to represent in a clear and precise way complex physical system behavioral models. In section 4, we explain how to derive functional knowledge according to these behavioral models. And the last section concludes this paper.

2 Multimodeling representation

As illustrated in [Chittaro et al., 1993], the multimodeling approach provides four model types depicted in Figure 1:

1. The *structural* model is based chiefly on the topology of a physical system. It represents the various components which constitute the system and their interconnections.

2. The *behavioral* model is dedicated to represent the potential behavior of system components using physical quantities and physical equations.

3. The *functional* model describes how system component behaviors contribute to the achievement of the goal assigned to the system by its designer.

4. The *teleological* model specifies the physical goals assigned to the system by its designer.

Problematic: in the multimodeling representation described above, the behavioral model of a physical system is made up of a collection of component physical equations holding among physical quantities. However, in complex physical system cases, the derivation of such set of physical equations is an intricate task due to the complexity and the great number of system physical laws. In order to remedy this problem, we propose to introduce the *bond graph* concept at the behavioral level. The bond graph model represents complex physical system behaviors in a clear and precise way and provides easily their formal equations. Moreover, it can be used to derive both qualitative *causal graph* and functional knowledge.

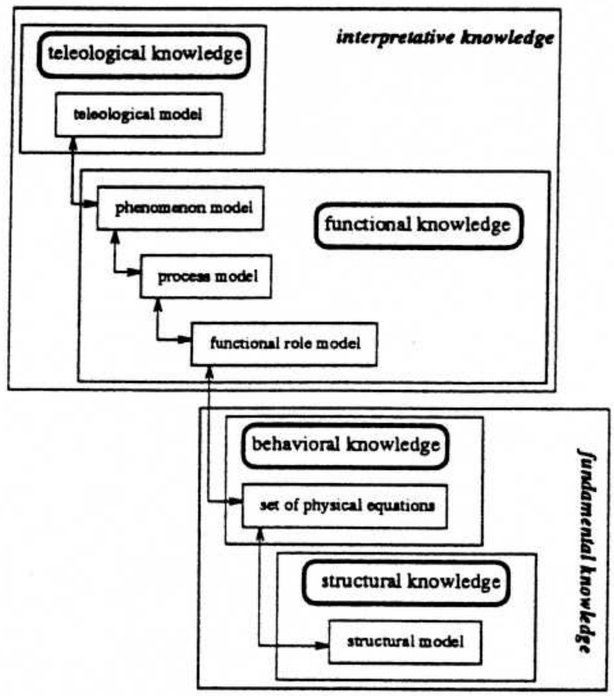


FIG. 1 – *The organization of the multimodeling approach.*

In order to apply the multimodeling representation, let us introduce the PWR primary coolant loop system. Its structure shown in Figure 2 includes four principal components: the *reactor* which represents the primary heat source of the system, the *pressurizer* controling the primary "hot" leg pressure, the *steam generator* which provides steam using the reactor's heat and the feedwater, and finally the pump controling the primary "cold" leg pressure. The steam generated by this system will be used in the secondary coolant loop to supply electricity.

3 The behavioral knowledge

The behavioral knowledge is dedicated to represent how components operate and interact with each other. The multimodeling approach proposed in [Chittaro et al., 1993] consists in representing behavioral model using physical equations holding among physical quantities. However, it don't precise how to specify these physical equations. In this section we define a method enabling this approach to indicate physical equations. This method consists in introducing *bond graph* concept at the behavioral level.

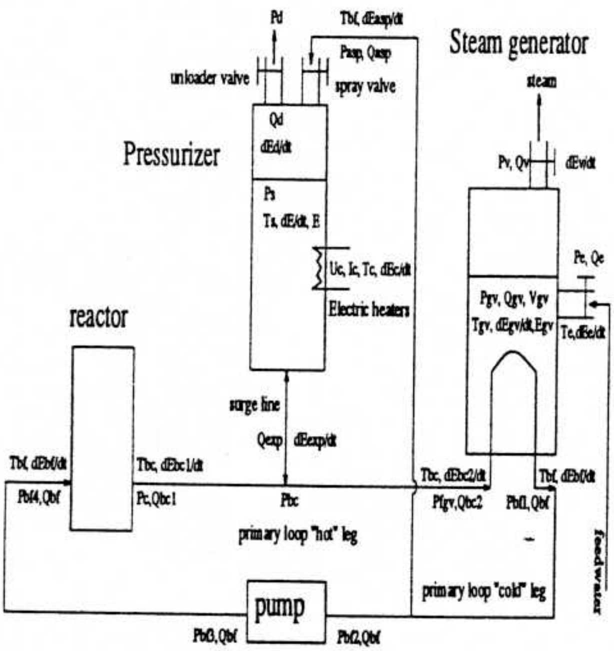


FIG. 2 – *The Pressurized Water Reactor (PWR) primary coolant loop system.*

The bond graph theory is based essentially on power exchanges (effort and flow) through the structure of physical systems [Rosenberg and Karnopp, 1986]. In a bond graph, the physical system is split into several basic elements linked by branches called bonds through which power is transferred. The power flow is the product of effort and flow and it is represented in a bond graph by a half arrow. The bond graph model is represented using the following elements: the resistance elements R, the capacitance elements C, the inductance elements I, the transformer elements TF, the gyrator elements GY, the effort sources SE and the flow sources SF. There are also junction structure elements: 0-junction and 1-junction. The 0-junction is represented by a single effort on all its bonds and the algebraic sum of the flows is null. The 1-junction has a single flow on all its bonds and the algebraic sum of the efforts is null.

The other property of the bond graph theory is the possibility of obtaining information about system causality. This decision is based on the impossibility of imposing or controling both effort and flow simultaneously. Each arrow of the bond graph holds a little stroke to show the direction where the effort is applied. This representation method imposes imperative and preferential rules to assign causality. For some junctions between components, the causality is imposed by the physical behavior which we want to represent in the model. The remaining ambiguity cases (for example the resistance causality) can be solved in an arbitrarily way.

Since bond graph incorporates physical assumptions of a system in a clear and precise way and takes causality into account, we can derive easily all its physical equations. The bond graph provides two types of physical equations: *constitutive equations* which involve the bond graph's elements (R, C, I, TF, GY, SE and SF) and *structural equations* involving balance equations.

The bond graph model is based on the object centered ontology and needs a bond graph for each system component. Global bond graph can be obtained by connecting component bond graphs using 0-junction, 1-junction or information arrow. The information arrow is a particular bond transferring information about effort or flow instead of transferring power. It is represented in a bond graph by a complete arrow. This kind of bond can be used to create internal energy sources or to define resistance, capacitance, inductance, transformer and gyrator coefficients (Figure 3).

In this paper, all thermal bond graphs are based on the pseudo bond graph in which the product of effort and flow variables do not represent a mesure of power. It substitutes the entropy flow of the true thermal bond graph by the heat (energy) flow rate.

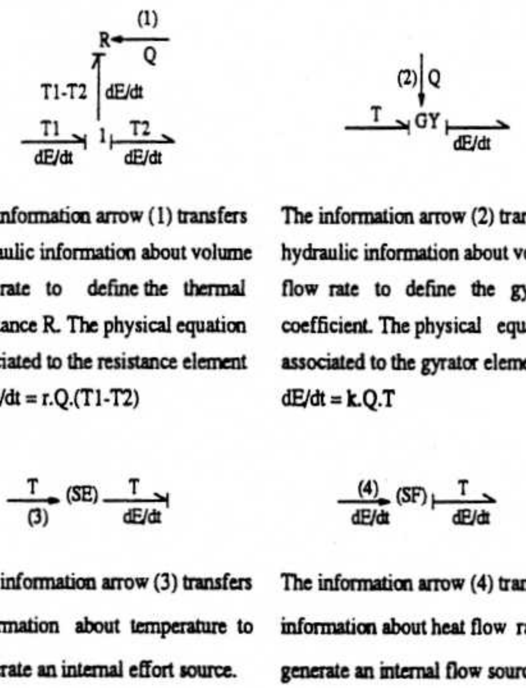


FIG. 3 – *Example of information arrows.*

As an example of bond graph, we illustrate the spray valve model shown in Figure 4. Its thermal and hydraulic bond graphs are related by an information arrow tranferring information about volume flow rate (Q_{asp}) in order to define the thermal gyrator coefficient.

Figure 5 describes the global bond graph of the PWR primary coolant loop system. In the reactor component, "cold" fluid (at pressure P_{bf4}, volume flow rate Q_{bf}, temperature T_{bf} and heat flow rate $\frac{dE_{bf}}{dt}$) is heated by the heat flow rate ($\frac{dE_{k}}{dt}$) in order to provide "hot" fluid (at pressure P_c, volume flow rate Q_{bc1}, temperature T_{bc} and heat flow rate $\frac{dE_{bc1}}{dt}$) to the primary "hot" leg. The pressurizer bond graph assumes to obtain pressure (P_s) by transformation of its temperature (T_s) which depends on the surge, spray, electric and unloader heat flow rate ($\frac{dE_{esp}}{dt}$, $\frac{dE_{asp}}{dt}$, $\frac{dE_c}{dt}$ and $\frac{dE_d}{dt}$). In the steam generator, the "hot" primary fluid (at pressure P_{fgv}, volume flow rate Q_{bc2}, temperature T_{bc} and heat flow rate dE_{bc2}/dt) leaves the steam generator tubes at "cold" state (with pressure P_{bf1}, volume flow rate Q_{bf}, temperature T_{bf} and heat flow rate $\frac{dE_{bf}}{dt}$). In the steam generator tubes, the difference in heat between hot and cold primary fluid ($\frac{dE_p}{dt}$) is absorbed by the secondary fluid in order to generate steam.

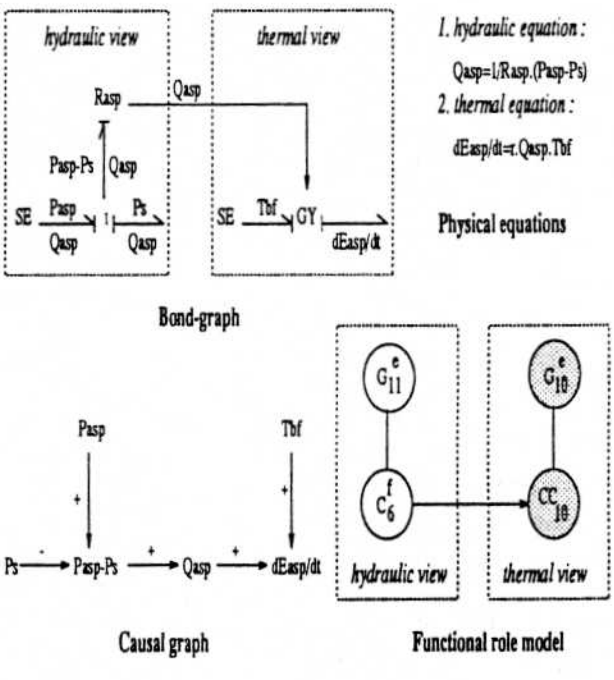


FIG. 4 – *spray valve bond graph, physical equations, causal graph and functional roles.*

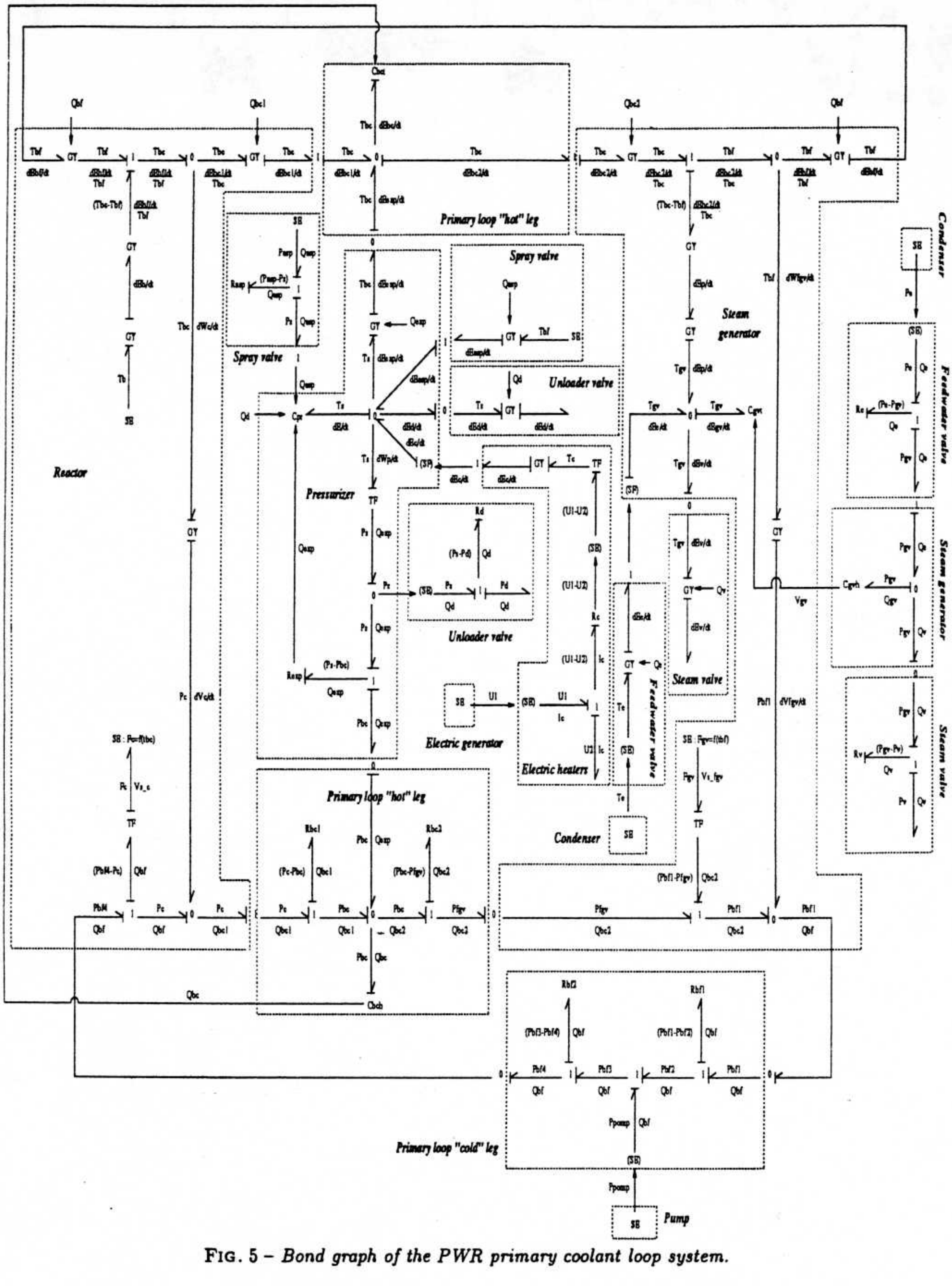


FIG. 5 – *Bond graph of the PWR primary coolant loop system.*

Since bond graph takes causality into account, we can derive the cause-and-effect relations between physical variables to represent the system causal graph. The qualitative causal graph model uses arrows to represent the direction of causal influences, and associated signs (+/−) represent the relative direction of movement of the cause and effect variables [Oyeleye et al., 1990]. Figure 4 shows the spray valve causal graph and physical equations derived from the bond-graph model.

The qualitative causal graph is mainly motived by the lack of precise numerical values for system quantitative data such as resistance (R) and capacitance (C) parameters which may be difficult to estimate. It will be used to predict and simulate the system behavior for a given deviation of system variables. In order to make easier the prediction and simulation tasks, this causal graph can be simplified taking into account only the most significance causal influences.

Considering again the PWR primary coolant loop system. From its bond graph described above, and using its causality, we represent the causal graph shown in Figure 6.

The behavioral representation approach proposed in this paper faces surely the bond graph limitations. However, it is assumed to be sufficient for representing complex physical systems by considering simple physical approximations.

4 The functional knowledge

As illustrated in [Chittaro et al., 1993], functional knowledge can be represented through three types of models: *functional role* model based on object centered ontology, *process* model based on hybrid ontology and *phenomenon* model based on system centered ontology. In this section, we explain how to define this functional knowledge according to the behavioral model based on bond graph.

1. The functional role model is defined as an interpretation of behavioral model of system components. Since our behavioral model is based on the bond graph concept, functional role represents an interpretation of a bond graph's element (R, C, I, TF, GY, SE and SF) in terms of conduit (of effort or flow), reservoir (of displacement or impulse) or generator (of effort or flow). In the following Table 1 we identify seven functional roles which are assumed to be sufficient for interpreting the behavior of a large set of physical systems. The functional roles can be connected with two relation types:

- mutual dependency: functional roles FR_i and FR_j are mutually dependent if they share a physical variable, or if there exists a structural equation that links a physical variable of FR_i with a physical variable of FR_j.
- influence: a functional role FR_i influences a functional role FR_j if a physical variable of FR_i is a parameter of FR_j.

Figure 4 describes the spray valve functional role model generated according to the bond-graph description. In this figure, the functional role C_6^f (conduit of volume flow rate with dissipation of pressure) influences the functional role CC_{10} (purely conductive conduit of thermal energy) because the volume flow rate Q_{asp} of the C_6^f equation ($Q_{asp} = \frac{1}{R_{asp}}(P_{asp} - P_s)$) is a parameter in the thermal CC_{10} equation ($\frac{dE_{asp}}{dt} = r.Q_{asp}T_{bf}$).

Let us consider again the PWR system. The following Figure 7 represents the functional role model derived from the bond graph given above.

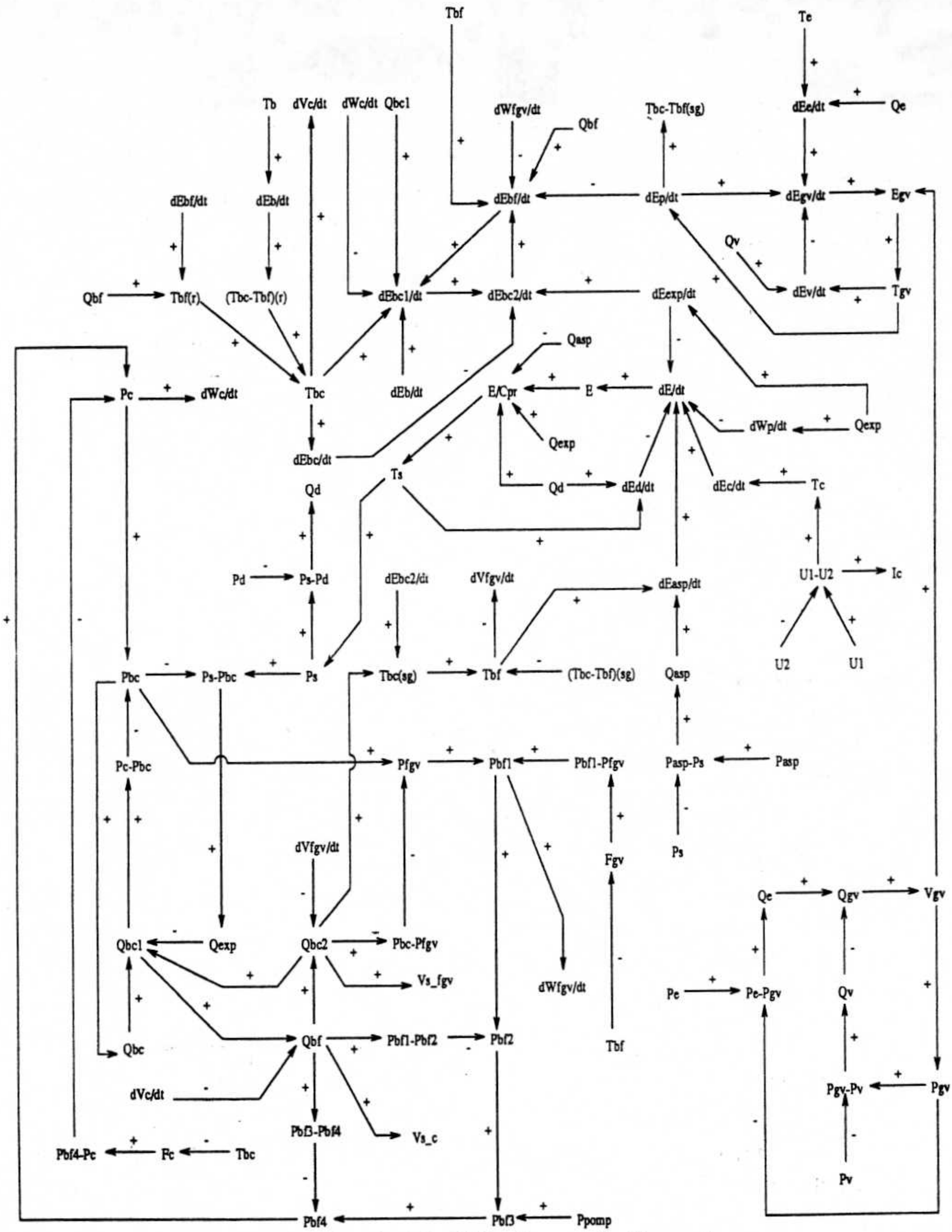


FIG. 6 – *Causal graph of the PWR primary coolant loop system.*

Bond-Graph	Functional roles
resistance R	C_e : conduit of effort from one point to another in the structure of a system with dissipation of flow. C_f : conduit of flow from one point to another in the structure of a system with dissipation of effort.
capacity C	R_q : accumulation of displacement.
inductance I	R_p : accumulation of impulse.
transformer TF	generator of effort (G_e) or flow (G_f).
gyrator GY	If the input and output physical view of the gyrator are the same: purely conductive conduit of power (CC). Else: generator of effort (G_e) or flow (G_f).
SE	G_e: generator of effort.
SF	G_f : generator of flow.

TAB. 1 – *Bond graph's elements and associated functional roles.*

The figure 7 involves mutually dependency link between roles C_1^f (conduit of volume flow rate with dissipation of pressure in the primary "hot" leg) and C_5^f (conduit of volume flow rate with dissipation of pressure between the pressurizer and the primary "hot" leg) because there exists a structural equation ($Q_{bc1} = Q_{bc2} + Q_{bc} - Q_{exp}$) that links one physical variable of the C_1^f equation ($P_c - P_{bc} = R_{bc1}Q_{bc1}$) with one physical variable of the C_5^f equation ($Q_{exp} = \frac{1}{R_{exp}}(P_s - P_{bc})$). Pressurizer roles R_1^q (reservoir of heat) and G_3^e (generator of pressure) are related by an influence link, because the temperature T_s of the R_1^q equation ($T_s = \frac{1}{C_{pr}}E$) represents a parameter in the hydraulic G_3^e equation ($P_s = F(T_s)$). In the steam generator, the influence link between R_2^q (reservoir of heat) and R_3^q (reservoir of water) means that the capacity of accumulation of heat is influenced by the volume of water.

2. The process model describes the possible physical processes that may occur in the system and their relationships. Each process is defined by a functional role network introducing which roles are necessary and how they must be related together, a condition enabling the occurrence of this process, an effect characterizing the situation during the process and a posteffect characterizing the situation after the end of the process. The main processes that we can identify in physical systems are: transporting current (effort or flow) from one point to an other ((G[e,f]-C[f,e]) or (G[e,f]-C[f,e]-G[e,f])), charging substance (displacement or impulse) in a storage element (G[e,f]-C[f,e]-R[q,p]) and discharging substance from a storage element ((R[q,p]-C[f,e]) or (R[q,p]-C[f,e]-G[e,f])) [Chittaro et al., 1993]. These processes are noted respectively TRANS, CHARG and DCHARG. Processes can be connected using three types of relations:

- causality: a process P_i causes a process P_j if the effect or the posteffect of P_i entails the condition of P_j.
- regulation: a process P_i regulates a process P_j if there exists a variable in the equations associated to the P_i functional roles which can be considered as a resistance parameter in the equations associated to the P_j functional roles.
- support: a process P_i supports a process P_j if there exists a variable in the equations associated to the P_i functional roles which can be considered as a capacitance or inductance parameter in the equations associated to the P_j functional roles.

Processes have two possible functional states: active or not active. A process is active if its functional roles are present and its condition is satisfied.

In the multimodeling approach proposed in [Chittaro et al., 1993], the condition enabling the charging process to occur is always "the generator (G) effort > the reservoir (R) effort".

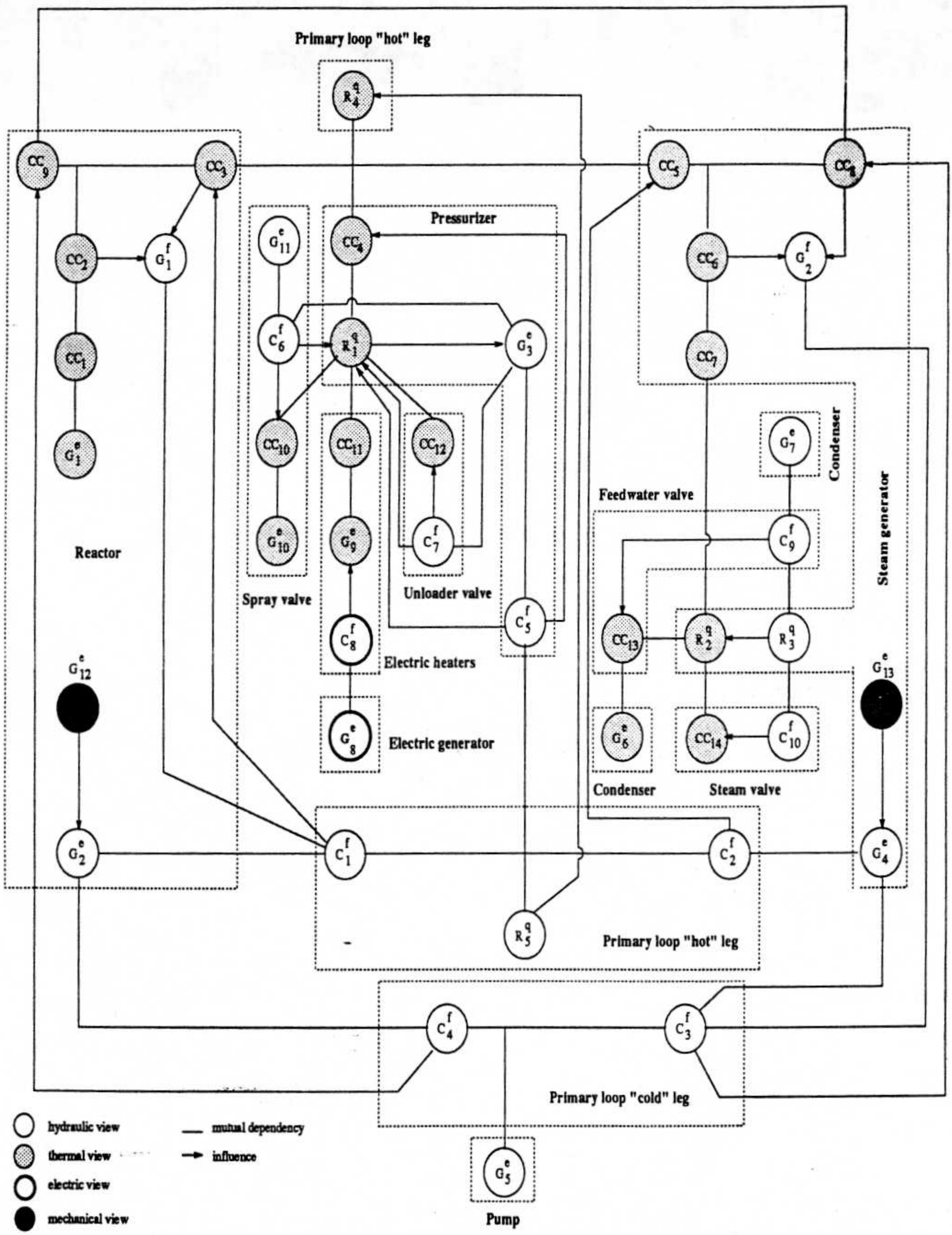


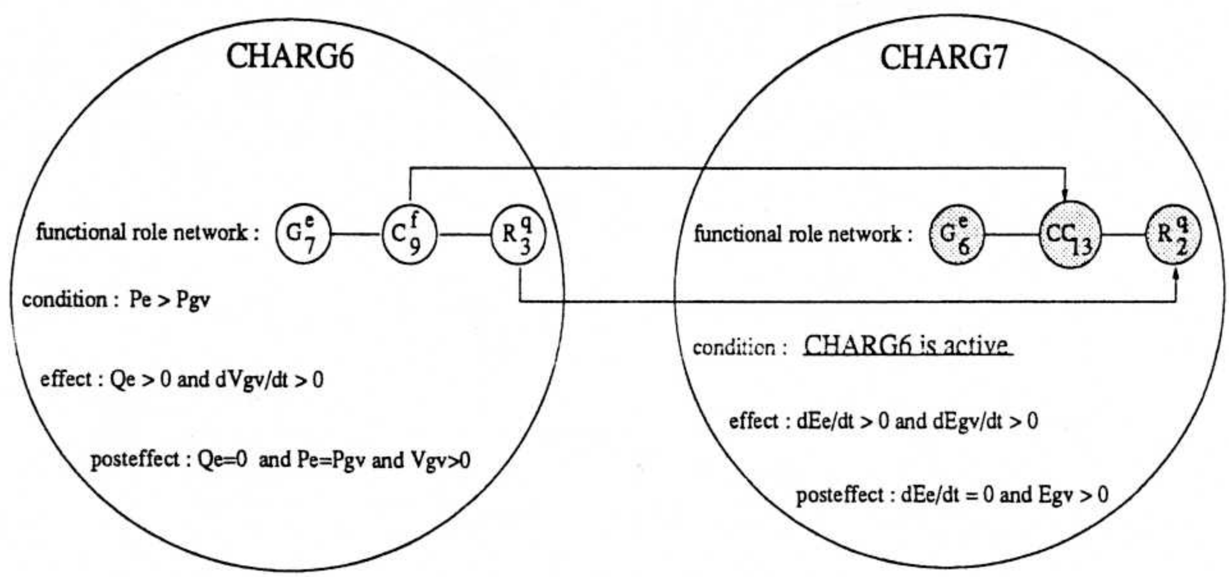
FIG. 7 – *Functional role model of the PWR primary coolant loop system.*

However, in some cases such as the heat charging process of the steam generator from the condenser $CHARG_7$ ($G^e_6 - CC_{13} - R^q_2$), the amount of the reservoir energy (steam generator heat E_{gv}) can increases even if the generator effort (condenser temperature T_e) is less than the reservoir effort (steam generator temperature T_{gv}).

In order to solve this problem, we propose to introduce in the condition, instead of the difference in temperature, the active state of the water charging process $CHARG_6$ ($G^e_7 - C^f_9 - R^q_3$) which enables $CHARG_7$ to occur.

feedwater valve ($Q_e > 0$) and an increasing amount of volume in the steam generator ($\frac{dV_{gv}}{dt} > 0$). The posteffect is that the volume flowing through the feedwater valve and the difference between the condenser pressure and the steam generator pressure become zero, and the amount of volume in the steam generator is greater than zero.

The functional role C^f_9 influences the thermal feedwater valve functional role CC_{13} (purely conductive conduit of thermal energy), because the volume flow rate Q_e of the C^f_9 equation is considered as a coefficient in the CC_{13} equation.



The steam generator water charging process from the condenser

The steam generator heat charging process from the condenser

The functional role network of the steam generator water charging process from the condenser ($CHARG_6$) comprises three functional roles: G^e_7 (generator of pressure), C^f_9 (conduit of volume flow rate with dissipation of pressure) and R^q_3 (reservoir of heat). The functional roles are related by mutually dependency link. The condition of this process is that there must be a difference between the condenser pressure and the steam generator pressure. Its effect is a volume flowing through the

Thus, we can deduce that process $CHARG_6$ regulates $CHARG_7$. The influence relation between R^q_2 and R^q_3 (meaning that the capacity of accumulation of heat is influenced by the volume of water) introduces a support relation between $CHARG_6$ and $CHARG_7$. After defining regulate and support relation between these processes, we can say that the only condition enabling the $CHARG_7$ process to occur is the active state of $CHARG_6$.

So, when we can't introduce in the charging process condition the difference between the generator effort and the reservoir effort, we can specify the active state of the process enabling the charging process to occur. Figure 8 shows an example of a PWR process model derived from the functional role model described in Figure 7.

charging $CHARG_{10}$ (R_4^q - CC_4 - R_1^q) of the pressurizer from the primary hot leg. The condition of this process is $DCHARG_1$ is active and $E_{bc} > 0$. $DCHARG_1$ represents the water discharging of the primary hot leg to the pressurizer and E_{bc} represents the amount of energy in the primary hot leg.

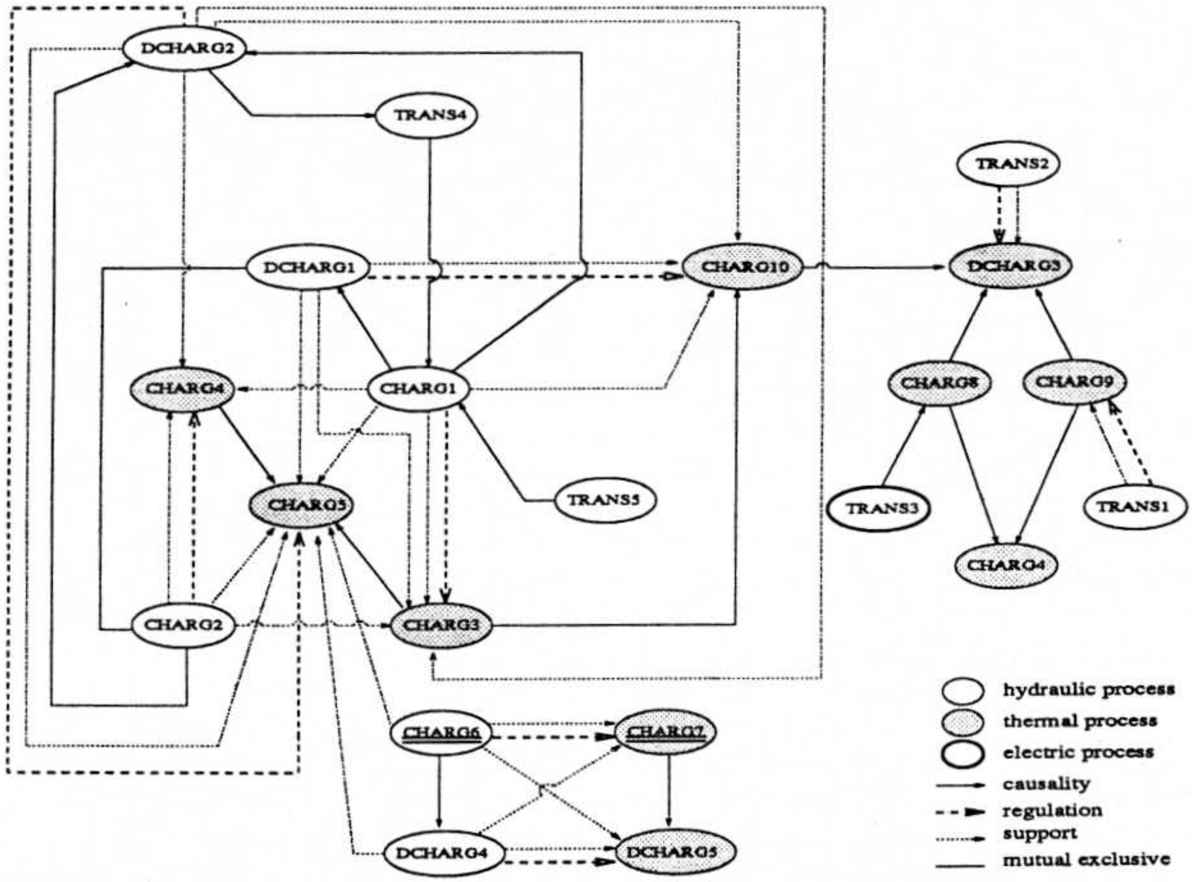


FIG. 8 - *Process model of the PWR primary coolant loop system.*

In this process model, we introduce a second type of charging process defined by the following functional role network: R1[q,p],C[f,e],R2[q,p]. This process represents the R2 reservoir charging and the R1 reservoir discharging. The condition which enables this process to occur is "R1 effort > R2 effort and R1 energy > 0" or "*Process$_i$* is active (the process enabling the charging process to occur) and R1 energy > 0".

As an example of this process we define the heat

Processes can be used to represent phenomenon and teleological model. The phenomenon model denotes a subjective interpretation of the process model. It describes how system goals can be realized in terms of process network.

5 Conclusion

This paper has presented a multimodeling concept of model-based reasoning focused on the approach proposed in [Chittaro et al., 1993]. This representation introduces a clear separation between structural, behavioral, functional and teleological knowledge to improve the efficiency of reasoning about physical systems. Our contribution in this multimodeling representation consists to consider the bond graph concept as the source of the behavioral knowledge. The benefit of using the bond graph model which is based on the object centered ontology is to generate the physical equations and the causal graph at the behavioral level and the functional role model at the functional level. Using this functional role model based on the object centered ontology and taking some domain knowledge into account we can derive the process model.

Our futur activity will consist first in exploiting this multimodeling representation for interpretation tasks, and second in developing a PWR diagnosis algorithm based on multiple models.

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References

[Abu-Hanna et al., 1991] Ameen Abu-Hanna, Richard Benjamins, and Wouter Jansweijer. *Device understanding and modeling for diagnosis. IEEE expert, vol. 6, n°2, 1991.*

[Chittaro et al., 1993] Luca Chittaro, Giovanni Guida, Carlo Tasso, and Elio Toppano. *Functional and teleological knowledge in the multimodeling approach for reasoning about physical systems: a case study in diagnosis. IEEE transactions on systems, 1993.*

[Everett, 1995] John O. Everett. *A Theory of mapping from structure to function applied to engineering thermodynamics. IJCAI, 1995.*

[Franke, 1991] David W. Franke. *Deriving and using descriptions of purpose. IEEE expert, vol. 6, n°2, 1991.*

[Keuneke, 1991] Anne M. Keuneke. *Device representation. The significance of functional knowledge. IEEE expert, vol.6, n°2, 1991.*

[MQ&D, 1995] the French "Modélisation Qualitative et Décision" group, coordinated by Philippe Dague. *Qualitative reasoning: a survey of techniques and applications. AICOM Vol.8, 1995.*

[Oyeleye et al., 1990] O.O. Oyeleye, F.E. Finch, and M.A. Kramer. *Qualitative modeling and fault diagnosis of dynamic processes by MIDAS. Chem. Eng. Comm 1990.*

[Rosenberg and Karnopp, 1986] Ronald C. Rosenberg and Dean C. Karnopp. *Introduction to physical system dynamics. Book 1986.*

[Sasajima et al., 1995] Munehiko Sasajima, Yoshinobu Kitamura, Mitsuru Ikeda, and Riichiro Mizoguchi. *FBRL: A Function and behavior Representation Language. IJCAI, 1995.*

[Sticklen and Bond, 1991] Jon Sticklen and William E. Bond. *Functional reasonning and functional modeling. IEEE expert, vol.6, n°2, 1991.*

[Vescovi et al., 1993] Marcos Vescovi, Yumi Iwasaki, Richard Fikes, and B. Chandrasekaran. *CFRL: A language for specifying the causal functionality of engineered devices. AAAI, 1993.*