251

Qualitative Reasoning about a Large System Using Dimensional Analysis

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Abstract

We present a simple qualitative model of a large system, viz. a nuclear power plant using a pressurized water reactor. We use the technique of dimensional reasoning, which has recently been shown to be useful in the traditional small-scale problems of qualitative physics, such as springs, boilers, etc. Here we extend the technique so that it can be applied to large systems. Our model is devoted to one aspect of the system, its *thermal hydraulics*. Using this model we are able to capture the effects of a sudden loss of water on the secondary side of the plant and reach conclusions similar to those reached by a conventional numerical simulation. The dimensional approach, although restricted, has a wide range of applicability, and appears useful because it uses the symbolic content of physics.

1 Introduction

In recent work we have been able to use dimensional analysis to provide descriptions of some of the devices current in QP, such as springs, heat exchangers, projectiles, pressure regulators and so on[1]. In this paper, we are concerned with qualitative models of large systems. We will build a simple qualitative model of the *thermal hydraulics* of a nuclear power plant similar to the one at Three-Mile Island (TMI). The TMI accident has spawned a great deal of work in applying AI techniques in the nuclear power plant industry[6]. From the point of view of qualitative physics, the primary reason for choosing TMI as an example lies in the compelling evidence of qualitative physics at work as human operators decided to take specific actions on the day of the accident. Further, TMI provides a realistic example of a large multi-component coupled system.

In the rest of this paper, we will first briefly describe the technique of dimensional analysis (Section 1.1). We will then provide an abbreviated description, in ordinary language, of how a nuclear reactor works, and then provide dimensional models of two of the plant's main components: the nuclear reactor and the steam generator. We will use the dimensional characterization of these two components to describe the consequences of a single event during the accident, a drop in the flow of feedwater to the steam generator. These consequences are presented in terms of physical events such as increases and decreases of physical variables, rather than in numerical terms as a conventional simulation might.

Before we proceed, a caveat is in order. Although we provide a description of the events surrounding the accident, what we present is not in any sense an accident analysis. Such an analysis requires independent sources of evidence, and a numerical precision in the answers, which we are neither able to nor intend to provide. Our intention is simply to examine whether a particular method for qualitative reasoning, dimensional analysis, is robust enough to describe the general functioning and specific events relating to a large system such as a nuclear power plant.

1.1 Dimensional Reasoning

Physical variables have a symbolic content, their dimensional representation. For example, the dimensional representation of force is $[MLT^{-2}]$ and that of specific heat $[L^2T^2\theta^{-1}]$. This dimensional representation can be used to reason about the direction of relative change of input and output variables.[1]

If a physical system can be characterized by a set of inputs (x_j) and a set of outputs (y_i) then it is possible, under certain conditions to decompose the system into a series of dimensionless products of the form

$$\pi_i = y_i \prod x_j^{\alpha_{ij}} \tag{1}$$

where the π_i are dimensionless. We can rewrite (1)[2] as

$$y_i = k_i \prod_j x_j^{\beta_{ij}} \tag{2}$$

The qualitative abstraction, direction of change in y_i with respect to a change in x_j is then given by the sign of $\left(\frac{\partial y_i}{\partial x_j}\right)$, which in turn is simply the sign of β_{ij}. Using this dimensional approach it is possible to characterize a variety of physical systems. Figures 1 and 2 briefly illustrate the technique. In modelling large systems however, it is usually the case that unlike the spring example there may be (1) more than one regime, and (2) more than one ensemble. Inter-regime partials are defined in Figure 2, while inter-ensemble reasoning is discussed later in the context of a specific example.[3]

1.2 A Pressurized Water Reactor Plant

We now present an overview of the thermal hydraulics of the TMI-II plant. The objective of this section is to give the reader a sense of the complexity of the modeling task. The detailed dimensional modeling is presented elsewhere [7] and more detailed descriptions of such a reactor can be found in an introductory text such as [2]; here we will outline the components each of which is described via an ensemble. Figure 3 presents a schematic diagram of the plant.

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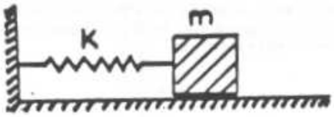
[1] Although this paper uses the dimensional method, presenting or discussing the method and its application is outside the scope of this paper. Such a discussion of dimensional analysis and its application to qualitative physics is available in [1]. Here we simply outline the method.

[2] π_i of Equation (1) is rewritten as k_i in Equation (2). Of course $\beta_{ij} = -\alpha_{ij}$.

[3] For a complete discussion of the limits of qualitative reasoning with signs, see Samuelson[8, pp. 23-29].

PROBLEM: Consider a horizontal spring attached to a mass (see figure below); how does the time-period of oscillation vary with the mass and the stiffness of the spring?



1. Make a list of all the variables relevant to the problem and their dimensional representation.

t	$\equiv$ *time period of oscillation*	$[T]$
m	$\equiv$ *mass of object attached to the spring*	$[M]$
K	$\equiv$ *stiffness of spring*	$[MT^{-2}]$

2. Partition the n variables into two sets: basis or independent set with r variables, and the performance or dependent set with $n - r$ variables; r is the number of independent dimensions that occur in the dimensional representation of the variables. The partitioning is based on dimensional representation as well as some heuristic information. We shall refer to the independent variables as x_j and to the dependent variables as y_i. The goal is to evaluate the signs of the partials of performance variables with respect to the basis variables i.e. sign of $\left(\frac{\partial y_i}{\partial x_j}\right)$.

   In this example, the time period of oscillation, t, is the performance variable and the mass m and the stiffness K are the basis variables. In this case $r = 2$ and $n = 3$. The object is to find the signs of the partials $\left(\frac{\partial t}{\partial m}\right)$ and $\left(\frac{\partial t}{\partial K}\right)$.

3. Buckingham's Π – theorem, provides a method for characterizing a system in terms of $n - r$ dimensionless products or Πs. In our terminology, for each y_i we can construct a dimensionless product, as follows: $\Pi_i = y_i x_1^{\alpha_{i1}} x_2^{\alpha_{i2}} \ldots x_r^{\alpha_{ir}}$. For each Π_i the values of the exponents α_{ij}, $1 \le j \le r$, can be obtained by solving r equations, of the form sum of exponents of a dimension equals zero, in r unknowns.

   In our example, $n - r = 1$ so we have a single dimensionless product Π_t. As $\Pi_t = t m^{\alpha_1} K^{\alpha_2}$ is dimensionless, the exponents of the M dimension and the T dimension will each add up to zero. Thus for the M and T dimensions respectively we have

$$\alpha_1 + \alpha_2 = 0$$

$$1 - 2\alpha_2 = 0$$

   Solving we get, $\alpha_2 = \frac{1}{2}$ and $\alpha_1 = -\frac{1}{2}$. Thus $\Pi_t = \left(\frac{tK^{1/2}}{m^{1/2}}\right)$

4. If Π_i is assumed constant, it is possible to determine the sign of the partial $\left(\frac{\partial y_i}{\partial x_j}\right)$ from the sign of the exponent α_{ij}. If α_{ij} is positive, the partial is negative, and vice versa.

   In our example, $\left(\frac{\partial t}{\partial K}\right)$ is negative, and $\left(\frac{\partial t}{\partial m}\right)$ is positive.

These signs of partials, i.e. qualitative abstractions, have been obtained without any explicit reference to the laws of physics.

Figure 1: How to do dimensional reasoning

PROBLEM: Given two non-basis variables y_a and y_b we might need to determine the effect of changing y_b on y_a. Such reasoning is needed when y_b is an exogenous variable that could not be accommodated in the basis. Since y_a and y_b have corresponding regimes Π_a and Π_b, an inter-regime reasoning mechanism is needed; inter-regime partials provide such a mechanism as shown below.

Suppose x_k is a basis variable that occurs in Π_a and Π_b; thus a change in x_k will affect changes in both y_a and y_b. Intuitively this can be understood as indirect causation i.e. the change in y_a is being caused by the non-basis exogenous variable y_b. An inter-regime partial is written as $\left[\frac{\partial y_a}{\partial y_b}\right]^{x_k}$. Since the inter-regime partial is in the context of x_k, we assume that other basis variables do not change. Under these assumptions it can be established that:

$$\left[\frac{\partial y_a}{\partial y_b}\right]^{x_k} = \frac{\left(\frac{\partial y_a}{\partial x_k}\right)}{\left(\frac{\partial y_b}{\partial x_k}\right)}$$

Note that the inter-regime partial is not a partial derivative in the strict sense; it is instead the ratio of two partial derivatives. We use it to reason about the sign of $\left(\frac{\Delta y_a}{\Delta y_b}\right)$.

The above equation can be derived as follows:

1. Since only y_a and y_b change there exists a function of the form $F(y_a, y_b) = 0$
2. Both dy_a and dy_b can be written in the form $dy_i = \sum_{j=1}^{j=r} \left(\frac{\partial y_i}{\partial x_j}\right) dx_j$
3. Also $dF = \left(\frac{\partial F}{\partial y_a}\right) dy_a + \left(\frac{\partial F}{\partial y_b}\right) dy_b = 0$
4. Assuming $dx_j = 0$ for $j \neq k$, we can obtain the expression for $\left(\frac{dy_a}{dy_b}\right)$ which corresponds to our inter-regime partial shown above

Figure 2: An inter-regime partial

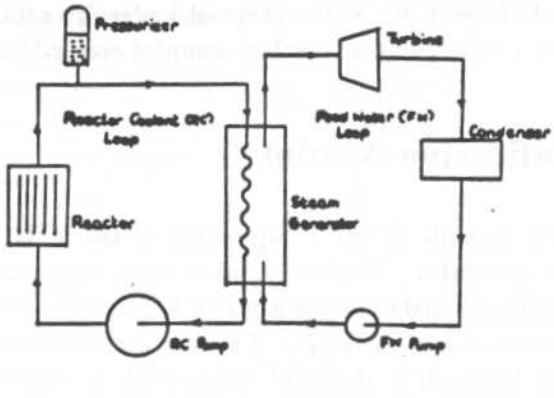


Figure 3: TMI Schematic

The plant can be viewed as consisting of two basic loops — the reactor coolant (RC) and the feedwater (FW) loops. The RC side is the radioactive side where the nuclear reaction takes place. It carries cooling water that passes through the reactor, transfers the energy thus gained to the hot side of the heat exchanger called the steam generator, and carries the cooled water from the steam generator back to the reactor through a coolant pump. This water is at a pressure of 150 atmospheres; as a result it will not boil even at the operating temperature of 580° F. The FW loop delivers cold feedwater to the cold leg of the steam generator which transfers heat from the hot leg of the RC side to the cold leg, the feedwater is then converted to steam and is fed to the turbine. The outlet of the turbine goes through a condenser to the feedwater pump and back to the steam generator. Actually, there is a third loop that carries the hot water from the condenser to the cooling towers and back; we do not model or concern ourselves with this loop.

The components along the RC loop are the reactor, the pressurizer, the steam generator and the reactor coolant pump. The FW loop contains the steam generator, turbine, condenser and the feedwater pump. The most interesting components are the pressurizer on the RC side, and the steam generator, which is common to both loops. The pressurizer is a pressure regulator that maintains the reactor pressure within an operating range; it relieves excess pressure by opening a pressurizer overhead relief valve or PORV. In addition to the basic components there are two main emergency subsystems that provide water to each of the two loops. These subsystems are modelled in terms of the variable they manipulate i.e. the mass flowrate.

Using this level of description, the thermal hydraulic aspects of TMI-II will be modelled as a collection of so-called *coupled ensembles*.

2 A Qualitative Model

We now present models of two components of the TMI plant, the reactor and the steam generator. We have chosen these components because they illustrate important aspects of our approach, in particular the role of inter-regime and inter-ensemble analysis. These two components are also central to the thermal hydraulics of TMI.[4] With each model we will present an analysis local to the component. We will then use these models to generate a qualitative account of the effects of one of the several component failures that actually occurred at TMI on the day of the accident, the failure of the feedwater pump that supplies water to the steam generator on the cold, or secondary side. Finally, we provide a summary of the entire analysis that we have made of TMI.

2.1 Reactor

The reactor is a pressure vessel that contains fuel assemblies; some assemblies contain fuel rods while others contain control rods and instruments. Reactor coolant, pressurized water, is pumped through the reactor to remove the heat generated by the nuclear reaction. The water in the reactor is maintained at a very high pressure; this prevents the water from boiling even though its temperature is far in excess of $212°F$. Formation of steam in the reactor jeopardizes the cooling provided and can also lead to adverse, because exothermic, chemical reaction with the cladding of the fuel rods. Based on this account we choose the following variables to provide a simple model of the reactor:

[4] Models of other components are available in a detailed technical report[7].

Reactor coolant Temperature	T_r	$[\theta]$
Reactor coolant pressure	p_r	$[ML^{-1}T^{-2}]$
Reactor heat generation rate	$\dot{Q}_r$	$[ML^2T^{-3}]$
Mass Flowrate of coolant	$\dot{m}$	$[MT^{-1}]$
Specific heat of Coolant	s	$[L^2T^{-2}\theta^{-1}]$
Reactor Diameter	D	$[L]$

Using $(\dot{Q}_r, \dot{m}, s, D)$ as the basis we obtain the following Πs:

$$\Pi_{p_r} = \frac{p_r D^2}{\dot{m}^{1/2} \dot{Q}_r^{1/2}}$$

$$\Pi_{T_r} = \frac{T_r \dot{m} s}{\dot{Q}_r}$$

Now we can reason about the behavior of the reactor in terms of these regimes. For instance, as the heat generation rate increases, the temperature and the pressure increase, assuming the mass flowrate remains constant. This follows from the fact that both $\partial T_r / \partial \dot{Q}_r$ and $\partial p_r / \partial \dot{Q}_r$ are positive. Hence the qualitative behavior may be summarized as:

$$(\Delta \dot{Q}_r > 0) \rightsquigarrow (\Delta T_r > 0) \ and \ (\Delta p_r > 0)$$

It is also possible to reason about the qualitative relationship of pressure and temperature (p_r and T_r). Thus, assuming Π_{p_r} and Π_{T_r} constant, we may write

$$dp_r = \left(\frac{\partial p_r}{\partial \dot{Q}_r}\right) d\dot{Q}_r + \left(\frac{\partial p_r}{\partial m}\right) dm + \left(\frac{\partial p_r}{\partial D}\right) dD$$

$$dT_r = \left(\frac{\partial T_r}{\partial \dot{Q}_r}\right) d\dot{Q}_r + \left(\frac{\partial T_r}{\partial m}\right) dm + \left(\frac{\partial T_r}{\partial s}\right) ds$$

Thus,

$$\left[\frac{dp_r}{dT_r}\right]^{\dot{Q}_r} = \left(\frac{\left(\frac{\partial p_r}{\partial \dot{Q}_r}\right)}{\left(\frac{\partial T_r}{\partial \dot{Q}_r}\right)}\right)$$

Recall (from Figure 2) that the sign of $\left[\frac{dp_r}{dT_r}\right]^{\dot{Q}_r}$ informs about the relative direction of change of $P-r$ and T_r when $\dot{Q}_r$ is the only variable that changes. In this case it can be seen to be positive. That is, when $\dot{Q}_r$, the heat generation rate, increases, P_r increases with respect to T_r. Similarly $\left[\frac{dP_r}{dT_r}\right]^{\dot{m}}$ can be seen to be negative.

Clearly this is a very simple model for a nuclear reactor; however we have been able to reach a number of conclusions about the reactor. All of these phenomena have to do with the thermal hydraulics of the reactor. Important aspects of the reactor can be abstracted away. For example, we do not model the nuclear reaction but instead represent it simply by the heat generation rate, $\dot{Q}_r$. Similarly, we leave out material reactions as well as apparatus for raising or lowering the fuel rods. More sophisticated models can be constructed by hierarchical refinement; for example the basis variable $\dot{Q}_r$ can become the performance variable at the next lower level and its basis can be constructed from variables that characterize nuclear reactions.

2.2 Steam Generator

2.2.1 Reactor Coolant Side

In the case of the TMI-II steam generator, the reactor coolant side ("hot" leg of the exchanger) consists of tubes through, which the pressurized water flows. The following quantities are used to obtain the RC ensemble:

Coolant Temperature Drop	$(T_{in} - T_{out})$	$[\theta]$
Coolant Mass Flowrate	$\dot{m}$	$[MT^{-1}]$
Coolant Pressure	p_c	$[ML^{-1}T^{-2}]$
Heat Rejection Rate	$\dot{Q}_{rej}$	$[ML^2T^{-3}]$
Thermal Conductivity of Pipe	k	$[MLT^{-3}\theta^{-1}]$
Coolant Specific Heat	s	$[L^2T^{-2}\theta^{-1}]$
Heat Transfer Area	A	$[L^2]$

Using $(\dot{m}, A, s, \dot{Q}_{rej})$ as the basis we obtain the following Πs:

$$\frac{(T_{in} - T_{out})\dot{m}s}{\dot{Q}_{rej}}, \quad \frac{kA^{1/2}}{\dot{m}s}, \quad \frac{p_c A}{\dot{Q}_{rej}^{1/2}\dot{m}^{1/2}}$$

Many detailed aspects of the device have been omitted to keep the analysis simple e.g. we do not model the effects of natural convection heat transfer. The geometrical parameters have been kept at a minimum; only a single area parameter is used.

2.2.2 Feedwater Side

This component constitutes the "cold" leg of the steam generator. Heat absorbed from the reactor coolant, in the "hot" leg, is primarily used to convert feedwater into steam — therefore, in this case, we model heat transfer using latent heat rather than specific heat. The following quantities are used to construct the FW ensemble:

Feedwater Mass Flowrate	$\dot{m}_{fw}$	$[MT^{-1}]$
Feedwater Side Steam Pressure	p_{fw}	$[ML^{-1}T^{-2}]$
Heat Gain Rate	$\dot{Q}_{gain}$	$[ML^2T^{-3}]$
Latent Heat	l_h	$[L^2T^{-2}]$
Heat Transfer Area	A	$[L^2]$

Using $(\dot{m}_{fw}, A, l_h)$ as the basis we obtain the following Πs:

$$\frac{\dot{Q}_{gain}}{\dot{m}_{fw} l_h}, \frac{p_{fw} A}{\dot{m}_{fw} l_h^{1/2}}.$$

A more elaborate analysis of this component could take into account variables such as amounts of water and steam in the steam generator as well as the water level.

2.2.3 Coupling Regimes

The objective of *coupling* is to relate variables from topologically neighboring ensembles. We connect ensembles using *coupling regimes* that are simple[5] dimensionless ratios involving one variable from each ensemble. Examining the steam generator ensembles, the pairs of variables that are candidates for coupling regimes are — (p_c, p_{fw}), $(\dot{m}, \dot{m}_{fw})$ and $\dot{Q}_{rej}, \dot{Q}_{gain})$. Couplings

[5] A simple dimensionless ratio consists of only two variables — the variables have dimensional representations that are either identical or linearly dependent.

can be unidirectional or bidirectional, in terms of how changes are to be propagated across the connection between components. A unidirectional coupling is obtained by relating a performance variable in one ensemble to an exogenous basis variable in the other ensemble; of course the dimensional representation of the variables should be compatible as mentioned earlier. A bidirectional coupling connects pairs of performance variables or pairs of exogenous variables; such regimes capture the equilibrium behavior of the system and also allow us to reason about departures from equilibrium.

The coupling regime for the steam generator is $(\dot{Q}_{rej}/\dot{Q}_{gain})$. From this regime we infer that the partial $\left(\frac{\partial \dot{Q}_{rej}}{\partial \dot{Q}_{gain}}\right)$ is positive. Hence an increase in $\dot{Q}_{gain}$ causes an increase in $\dot{Q}_{rej}$ and vice versa. We will use this information in the next section to demonstrate the role of coupling regimes in inter-ensemble analysis.

2.3 Qualitative Analysis Across Ensembles

Analyzing the behavior of the steam generator requires reasoning across the Reactor Coolant (RC) and Feedwater (FW) ensembles, using a coupling regime. Similar mechanisms are needed to reason about changes in the reactor caused by changes in the steam generator. We will now provide a qualitative account of the consequences of a single event.

Consider the situation that the feedwater pumps have failed. amounts to a drop in the feedwater mass flowrate i.e. for the exogenous variable $\dot{m}_{fw}$, $\Delta\dot{m}_{fw} < 0$. We can now construct a qualitative account of how this change is propagated from the FW ensemble to the RC ensemble. The account consists of:

- $(\Delta\dot{m}_{fw} < 0) \leadsto (\Delta\dot{Q}_{gain} < 0)$ [From $\Pi_{\dot{Q}_{gain}}$ in the FW ensemble]
- $(\Delta\dot{Q}_{gain} < 0) \leadsto (\Delta\dot{Q}_{rej} < 0)$ [From the coupling regime]
- Since $\dot{Q}_{rej}$ is decreasing we can reason from the RC ensemble as follows:
  - Assuming $\dot{m}$ to be constant, it must have been the case that $(\Delta T_{drop} < 0) \leadsto (\Delta\dot{Q}_{rej} < 0)$ [From $\Pi_{\dot{Q}_{rej}}$]
  - Further $(\Delta T_{drop} < 0) \leadsto (\Delta p_c < 0)$ [From Π_{p_c}]

– Note that this conclusion could also have been reached using the inter-regime partial $\left[\frac{\partial p_c}{\partial Q_{rej}}\right]^{T_{drop}}$

In order to propagate changes from the RC ensemble to the Reactor ensemble we need further couplings. To simplify the arguments we will ignore the effects of the coolant pump that completes the loop by connecting the RC side to the reactor. Here again the coupling regime is (p_c/p_r). Using this coupling we conclude that $(\Delta p_c < 0) \leadsto (\Delta p_r < 0)$ or that the reactor starts depressurizing. Moreover, using the inter-regime partial $\left[\frac{\partial T_r}{\partial p_r}\right]^{\dot{m}}$, we infer that the reactor tempreature will rise. Similar qualitative accounts have been produced for events that occurred during the TMI accident.

2.4 Summary of Accomplishments

In this section we will summarize our work on the TMI-II plant and the accident; for details the interested reader is referred to [7]. A dimensional characterization of the thermal hydraulics of the TMI-II plant was obtained. The mechanics of the modeling was demonstrated in the previous sections using the reactor and the steam generator as examples. The components modelled as ensembles were the basic components in the central hydraulic circuit: the reactor, pressurizer, steam generator and the reactor coolant pumps. The emergency core cooling and feedwater systems were modelled implicitly by the change they affect on the appropriate mass flowrates. Other components such as turbines, condenser and feedwater pumps were not modelled for this study.

From this dimensional model we constructed a qualitative account of the accident at TMI-II; the account focuses on the first eight minutes of the accident. The account is much like the example presented earlier for the steam generator's response to a shutdown of the feedwater pumps. An interesting conclusion from the task is that relatively simple models, obtained using dimensional representations, proved adequate for providing a qualitative acconut of the accident.

We put the dimensional model of TMI-II to another test of producing qualitative accounts. As part of their investigation of the accident, the Presidential Commission posed six hypothetical questions about how the accident might have proceeded e.g. *what would have been the effect if the* *auxiliary feedwater system had been avaiable as designed?* In order to answer these hypothetical questions detailed numerical simulations were done at the Los Alamos Scientific Laboratory, the results were analyzed by experts and short answers were provided for the Commission. The answer to the question mentioned earlier, published in the report was as follows — ... *the system would have started depressurizing earlier than occurred, but after 30 minutes there would have been little difference between the two cases.* We answer the question by providing a causal chain that starts $\Delta \dot{m}_{fw} > 0$ (i.e. feedwater flow is reduced) and ends with $\Delta p_r < 0$ (thereby signalling the depressurization of the reactor). However, since our analysis is qualitative, we cannot produce the time-interval 30 minutes, as part of our explanation.

In the next section we discuss the practical implications of the approach to qualitative physics presented in this section.

3 Possible Applications

The technique of dimensional modeling, discussed in the previous section, can be incorporated in a variety of systems for monitoring the plant as well as supporting the operator. We will concern ourselves with two broad issues — the utility of direction of change information and the use of such information in conjunction with other established tools.

In a complex system, such as a nuclear plant, situations often arise that call for operator intervention. Let us consider a scenario from the TMI accident to illustrate the point. The emergency core cooling system has been automatically activated and is delivering 2000 gallons of water per minute to the reactor. The pressurizer level seems to be rising rapidly, and soon the pressurizer may go "solid" i.e. beyond some established level. Should the operator throttle or shut off the emergency core cooling system? What will be the effect on the pressurizer level? Crudely, the decision to be made can be characterized qualitatively as follows: what is the sign of the partial $\partial L/\partial \dot{m}$ where L and $\dot{m}$ are the pressurizer level and reactor coolant mass flowrates respectively? If this sign can be determined unambiguously then it provides a justification for the action. However, if it is ambiguous (e.g. depends on whether PORV is open or not) then further analysis is needed to support the action. In general when an operator takes an action that manipulates the value of a variable x_j in order to affect a change in some other variable y_i, information needed to support the action includes:

- Sign of $\partial y_i/\partial x_j$ and the *assumptions* used in deriving the sign (e.g. the variables that are assumed to be constant)
- Other effects of changing x_j also in terms of signs of partials

The direction of change information is useful in capturing the intuitive result of an action but it is often not enough to support the action. In the previous case the operator might wish to know the amount by which the emergency core cooling system must be throttled so that the pressurizer level falls by 50 *cm* in the next 10 *minutes*. Such an answer cannot be obtained from a qualitative model alone; this calls for numerical simulation. Here we see an opportunity to connect a qualitative model to a numerical model. It is our conjecture that such a connection can be obtained using the numerical values of the relevant Πs calculated from the values of the variables. The direction of change information as well as the dimensional model can be used to focus the amount of numerical simulation needed. The objective is to produce reasonable estimates of numerical values, with a minimal amount of computation.

3.1 Conclusions

In this paper we have demonstrated the use of dimensional modeling to reason about the qualitative behavior of a large multi-component system. The example used was a nuclear power plant, similar to the one at Three-Mile Island, using a pressurized water reactor. The model presented can be refined, using two approaches. Hierarchical refinement can be accomplished by taking an exogenous variable at one level (e.g. heat generation rate $\dot{Q}_r$ in the Reactor) and modeling it as a performance variable at the next lower level (e.g. using nuclear reaction parameters as the exogenous variables). Another kind of refinement consists of decomposing a component into multiple subcomponents with appropriate couplings (or connections), as in the case of the steam generator.

The dimensional approach appears applicable to a wide class of physical phenomena and we are currently exploring its utility in several different semantically rich physical domains.

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