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[54] SYSTEM DIAGNOSTICS USING QUALITATIVE ANALYSIS AND COMPONENT FUNCTIONAL CLASSIFICATION

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[52] U.S. Cl. 364/551.01; 364/495; 376/245; 395/915

[58] Field of Search 364/550, 551.01, 138, 364/492, 495; 376/245, 246, 247, 258; 395/912, 914, 915

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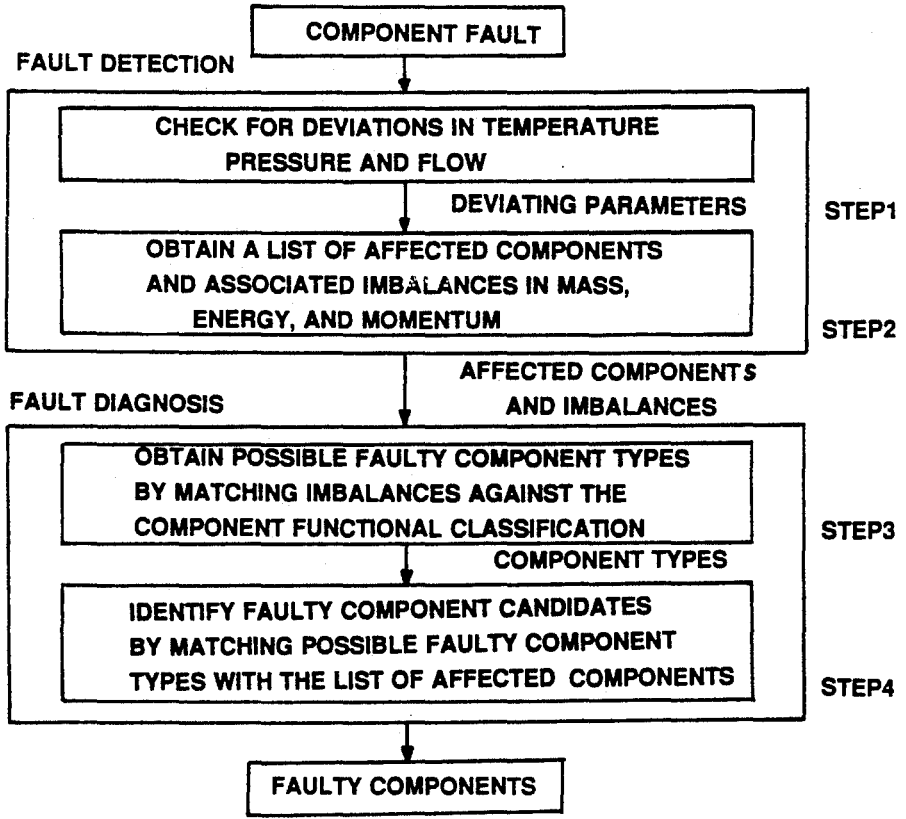
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[57] ABSTRACT

A method for detecting and identifying faulty component candidates during off-normal operations of nuclear power plants involves the qualitative analysis of macroscopic imbalances in the conservation equations of mass, energy and momentum in thermal-hydraulic control volumes associated with one or more plant components and the functional classification of components. The qualitative analysis of mass and energy is performed through the associated equations of state, while imbalances in momentum are obtained by tracking mass flow rates which are incorporated into a first knowledge base. The plant components are functionally classified, according to their type, as sources or sinks of mass, energy and momentum, depending upon which of the three balance equations is most strongly affected by a faulty component which is incorporated into a second knowledge base. Information describing the connections among the components of the system forms a third knowledge base. The method is particularly adapted for use in a diagnostic expert system to detect and identify faulty component candidates in the presence of component failures and is not limited to use in a nuclear power plant, but may be used with virtually any type of thermal-hydraulic operating system.

15 Claims, 3 Drawing Sheets



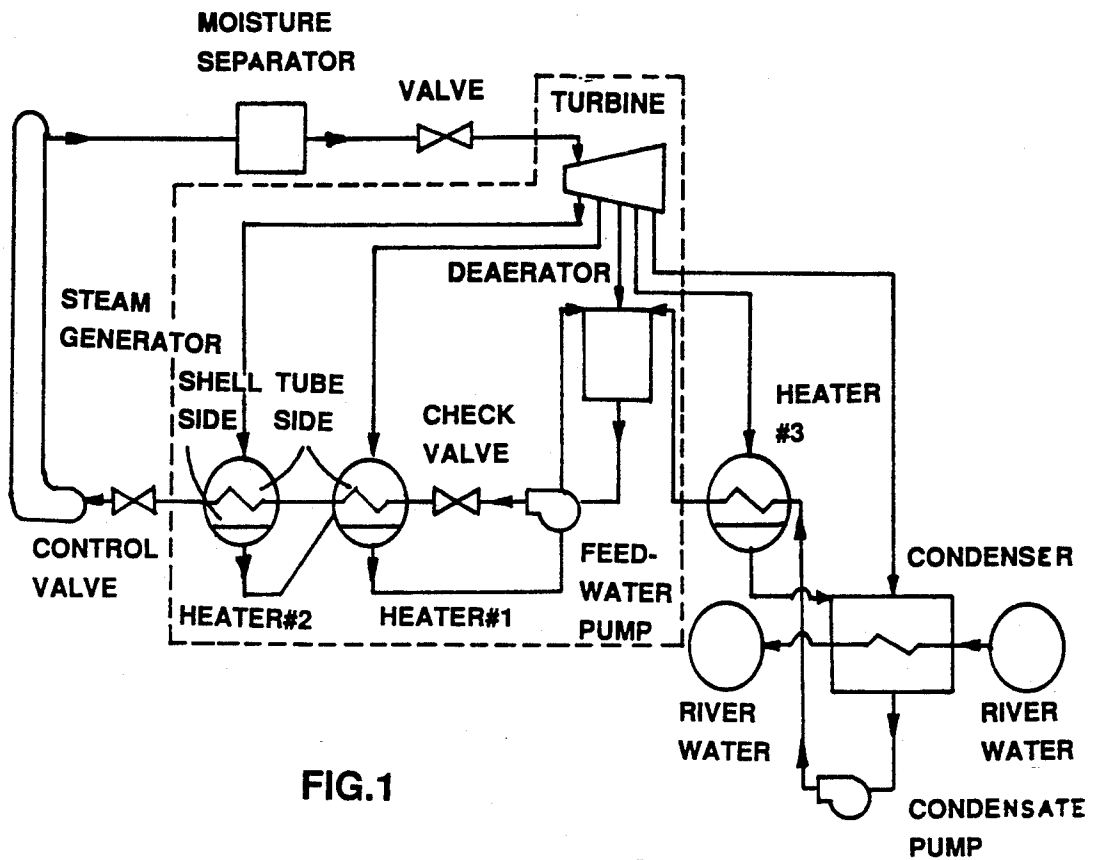


FIG.1

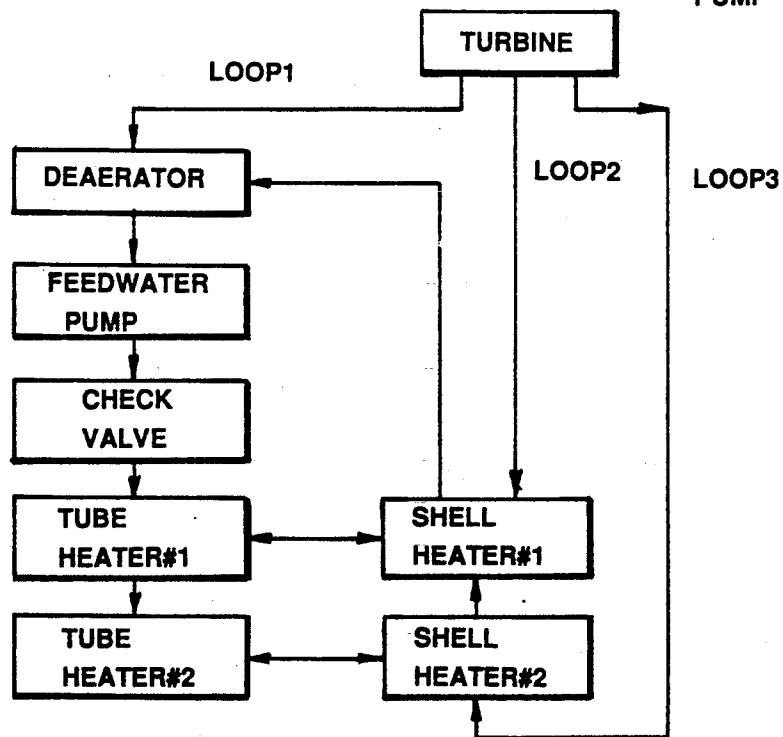


FIG.2

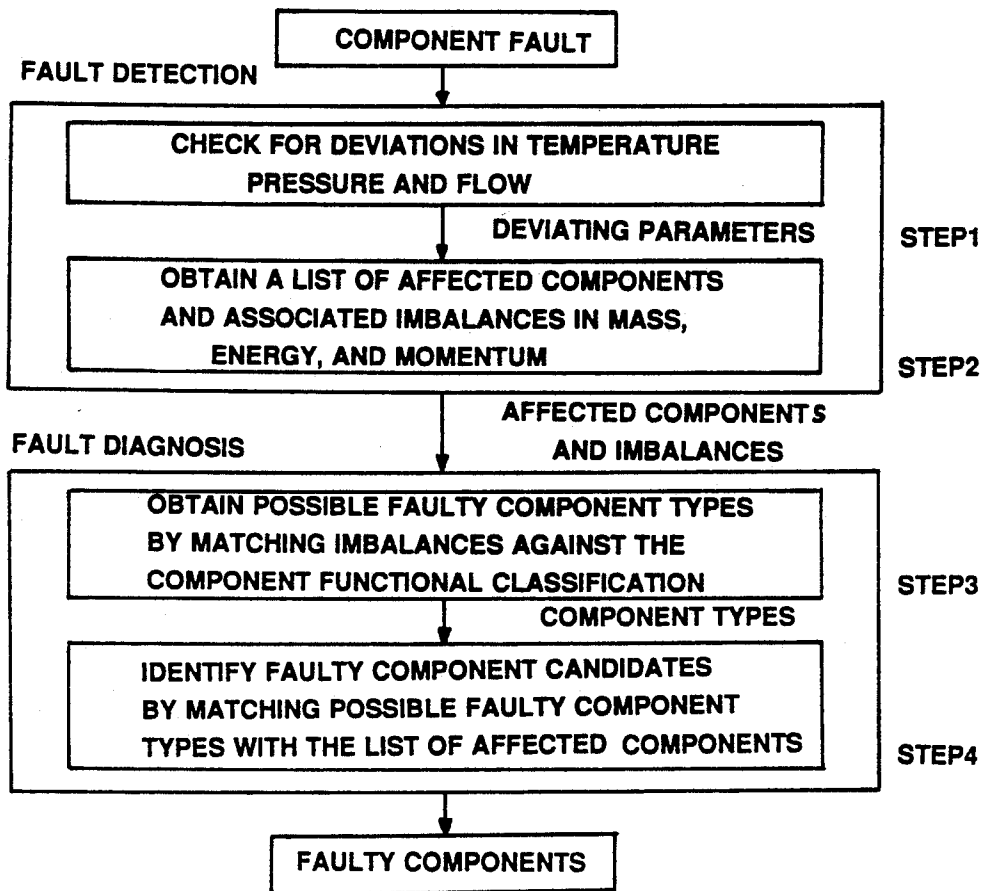


FIG.3

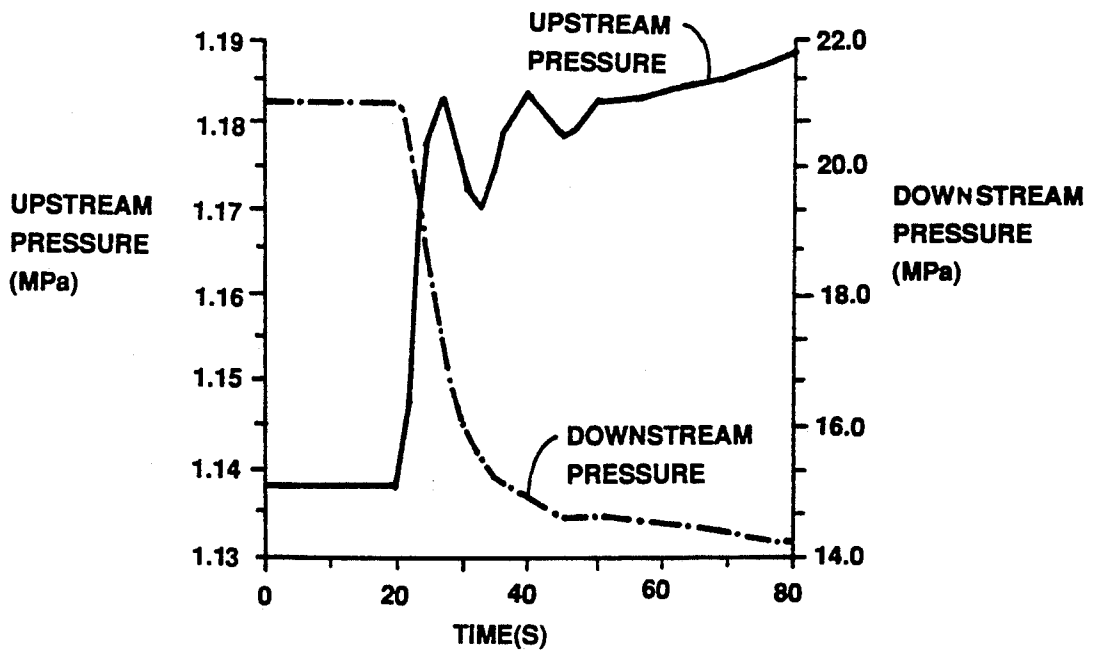


FIG.4

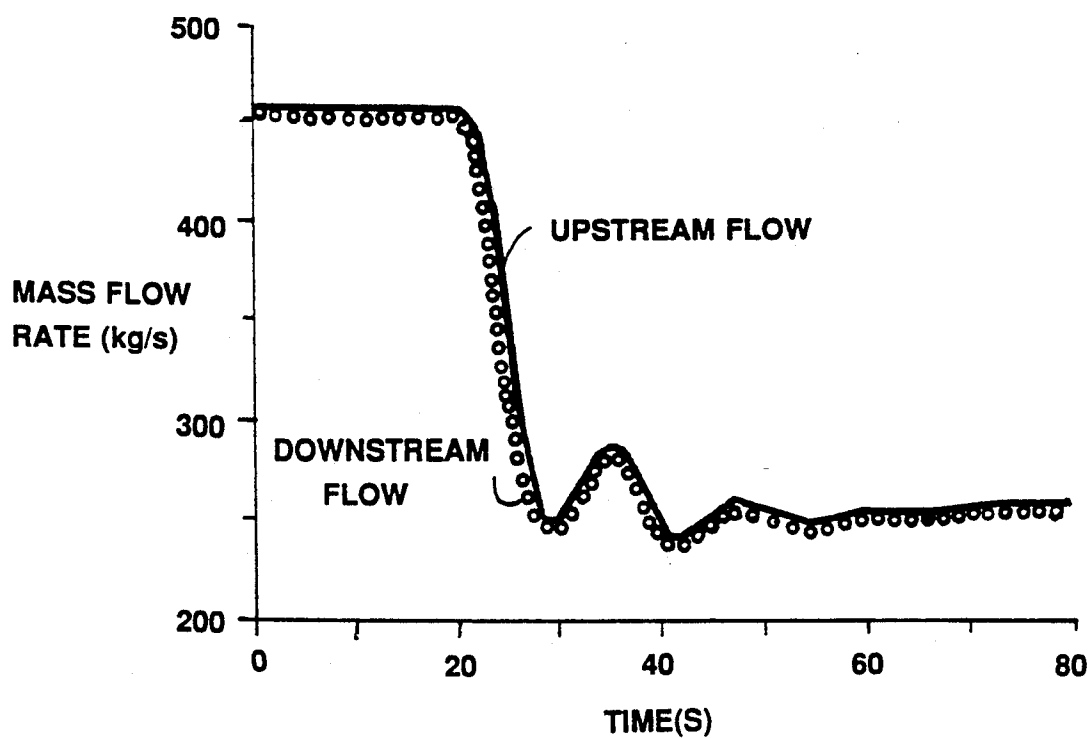


FIG.5

SYSTEM DIAGNOSTICS USING QUALITATIVE ANALYSIS AND COMPONENT FUNCTIONAL CLASSIFICATION

CONTRACTUAL ORIGIN OF THE INVENTION

The United States Government has rights in this invention pursuant to Contract No. W-31-109-ENG-38 between the U.S. Department of Energy and The University of Chicago representing Argonne National Laboratory.

FIELD OF THE INVENTION

This invention relates generally to the analysis and diagnosis of an operating system and is particularly directed to a method for detecting and identifying faulty components in an operating system such as a nuclear power plant.

BACKGROUND OF THE INVENTION

Knowledge representation for process diagnosis expert systems has evolved from simple rule-based systems, known as shallow knowledge, to more complex model-based systems, or deep knowledge. Shallow knowledge represents the domain information through a set of "if . . . then" rules. These rules are generally acquired from a domain expert based on experience and judgmental knowledge with no functional representation of the underlying phenomena. The weakness of rule-based systems is one of verification and validation. Procedures cannot be developed to test heuristically generated rules for correctness and completeness. Even if the diagnostic rules are generated in a systematic fashion, diagnostic event-based rules cannot guarantee functional completeness. It is simply not possible to anticipate and formulate rules to cover every conceivable system situation. Deep knowledge represents the domain information through mathematical models of the process under consideration. This model-based system in the form of quantitative and qualitative simulation algorithms describes the underlying phenomena of the physical system.

To alleviate the limitations of rule-based systems, attempts have been made to combine both shallow and deep knowledge as the knowledge structure of a process diagnostic expert system. One approach is to use shallow rules to hypothesize about the possible failures first, then follow with deep knowledge reasoning to test each one of the hypotheses. The success of this approach is highly dependent on the ability of the shallow rules, which cannot in general be verified and validated, to hypothesize correct faulty candidates.

The present invention addresses and overcomes the aforementioned limitations of the prior art by providing a method of diagnosing failures in the operation of a process by identifying faulty component candidates of process malfunctions through basic physical principles of conservation, functional classification of components and information from the process schematics. Except for the information from the process schematics, the method is completely general and independent of the process under consideration.

OBJECTS AND SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide a method for diagnosing failures in the oper-

ation of a process carried out by a number of components.

It is another object of the present invention to provide a method for the diagnosis of faulty components in an operating system carrying out a process through the macroscopic balance equations of mass, momentum and energy with the equation of state in thermal hydraulic control volumes associated with each process component.

Yet another object of the present invention is to provide for process diagnosis through the generation of a database for the functional classification of each component type as a source or sink of mass, momentum and energy and also through the information of the physical location of the various components carrying out the process as another independent database.

A further object of the present invention is to provide for the verification and validation of the rules for diagnosing a process in terms of the various components carrying out the process which is not dependent upon a multiplicity of rules where the accuracy and completeness are generally uncertain.

A still further object of the present invention is to provide a diagnostic method particularly adapted for use with nuclear power plants, but which may also be applied to virtually any other type of thermal-hydraulic process carried out by a plurality of components.

Another object of the present invention is to provide a diagnosis method for an operating thermal-hydraulic system comprised of various components which provides an analysis based on basic physical principles that reduces the number of possible rules to a small and verifiable knowledge base and which does not rely on an extensive set of an unverifiable set of rules.

It is yet another object of the present invention to provide for the analysis of the operation of a thermal-hydraulic system by identifying a component malfunction with respect to violations in the conservation of mass, momentum and energy and which relates unusual changes in these factors with appropriate component functionality.

The present invention contemplates a methodology for identifying faulty component candidates of process malfunctions through basic physical principles of conservation, functional classification of components and information from the process schematics. The basic principles of macroscopic balance of mass, momentum and energy in thermal-hydraulic control volumes are applied in the inventive approach to incorporate deep knowledge into the knowledge base. Additional deep knowledge is incorporated through the functional classification of process components according to their influence in disturbing the macroscopic balance equations. Information from the process schematics is applied to identify the faulty component candidates after the type of imbalance in the control volumes is matched against the functional classification of the components. Except for the information from the process schematics, this approach is completely general and independent of the process under consideration. The use of basic first-principles, which are physically correct, and the process-independent architecture of the diagnosis procedure allow for the verification and validation of the system.

BRIEF DESCRIPTION OF THE DRAWINGS

The appended claims set forth those novel features which characterize the invention. However, the invention itself, as well as further objects and advantages

thereof, will best be understood by reference to the following detailed description of a preferred embodiment taken in conjunction with the accompanying drawings, where like reference characters identify like elements throughout the various figures, in which:

FIG. 1 is a simplified schematic diagram of a balance of plant (BOP) for a liquid metal nuclear reactor (LMR) plant which is typical of an operating system with which the diagnostics method of the present invention is intended for use;

FIG. 2 is a simplified graph structure illustrating a plurality of interconnected nodes, where each node corresponds to a respective component or component part surrounded by the dashed lines in FIG. 1, while the physical connections between components, i.e., the pipings, are represented by the directed edges or arcs of the graph structure in the figure;

FIG. 3 is a simplified flowchart of a fault detection and diagnosis method in accordance with the present invention;

FIG. 4 is a graphic representation of the variation in pressure just upstream of a pump and downstream in the tube side of heater #1 in FIG. 1; and

FIG. 5 is a graphic representation of the variation in flow in the piping connecting the deaerator to the pump and in the piping connecting the tube sides of heaters #1 and #2 in FIG. 1.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The inventive diagnostic methodology described herein utilizes basic physical principles and process-based knowledge. Basic physical principles are used both for analysis of macroscopic mass, energy and momentum balances in thermal-hydraulic control volumes and for the physical functional classification of the process components. Process-based knowledge is used to represent the structural arrangement of the various components and systems of the process and corresponding connectivity relations. Described herein is the framework for development of the balance equations, the functional classification of components and the process structural information that form a first-principles knowledge base.

The Macroscopic Balance Method

In this method, the analysis of macroscopic mass, energy and momentum imbalances in thermal-hydraulic control volumes is characterized by the effect of the variations of thermal-hydraulic and thermodynamic macroscopic properties in the equations of state. The equations of state, which describe the relations among macroscopic properties, can be used to relate the variations of properties such as fluid velocity v , pressure P and temperature T to the total mass M , energy U and momentum \underline{M} inventories for a given control volume V

$$M = \rho(P, T)V, \quad (1)$$

$$U = M h(P, T) - P V, \quad (2)$$

$$\underline{M} = M v, \quad (3)$$

where $\rho(P, T)$ is the fluid density and $h(P, T)$ is the fluid specific enthalpy. Imbalances in the mass, energy and momentum inventories are characterized by analyzing the changes in fluid velocity, pressure and temperature in Eqs. (1) through (3). The process of evaluating these imbalances is divided into three categories: (A) Single-

phase mass and energy balances, (B) Two-phase mass and energy balances, and (C) Momentum balance.

A. Single-Phase Treatment of Mass and Energy Balances

For control volumes containing single-phase fluid, pressure and temperature are two independent thermodynamic properties which are readily available and can be used to specify the state of a substance in both sub-cooled liquid and superheated steam conditions. Changes in pressure P and/or temperature T of a single-phase fluid would cause changes in the fluid density $\rho(P, T)$ and specify enthalpy $h(P, T)$, which in turn would cause variations in mass M and energy U inventories of Eqs. (1) and (2), respectively. Analysis of the variations of M and U as a function of changes in P and T can be obtained through the analysis of the differentials dM and dU of Eqs. (1) and (2), for a fixed volume V

$$dM = V \left(\frac{\partial \rho}{\partial T} \cdot dT + \frac{\partial \rho}{\partial P} \cdot dP \right), \text{ and} \quad (4)$$

$$dU = V h \rho \left\{ \frac{1}{\rho} \left[\frac{\partial \rho}{\partial T} \cdot dT + \frac{\partial \rho}{\partial P} \cdot dP \right] + \frac{1}{h} \left[\frac{\partial h}{\partial T} \cdot dT + \frac{\partial h}{\partial P} \cdot dP \right] \right\}, \quad (5)$$

where the term $P V$ in Eq. (2) has been neglected.

With the use of tables that represent the equations of state, e.g., steam tables for water, the variations of ρ and h as a function of P and T can be directly obtained and used to analyze dM and dU . The analysis can be quantitative or qualitative. Quantitative analysis consists of a table lookup, where values for ρ and h are obtained from measurements of P and T and are then compared with the expected values of ρ_0 and h_0 to determine dM and dU as

$$dM = M(\rho) - M(\rho_0), \text{ and}$$

$$dU = U(\rho, h) - U(\rho_0, h_0).$$

Quantitative analysis requires the storage of the equation-of-state tables in a program routine and is performed on-line for each diagnosis operation. On the other hand, qualitative analysis requires no storage of tables, needs to be performed only once and can be incorporated in the knowledge base of a diagnosis system as a set of precompiled first-principles rules. These rules are physically correct and are completely general in that the rules are independent of the process under consideration. However, qualitative analysis may generate ambiguous results due to some loss of information. For instance, the addition of quantities of opposite sign results in ambiguity, since relative magnitudes are not known. Hence, a hybrid utilization of qualitative and quantitative analysis of the balance equations is a feasible alternative. Quantitative analysis can be used when qualitative reasoning results in ambiguity.

Qualitative analysis of Eqs. (4) and (5) is performed in the equivalent equations

$$[dM] = \left[\frac{\partial \rho}{\partial T} \right] \cdot [dT] + \left[\frac{\partial \rho}{\partial P} \right] \cdot [dP], \quad (6)$$

$$[dU] = \left[\frac{1}{\rho} \right] \left\{ \left[\frac{\partial \rho}{\partial T} \right] \cdot [dT] + \left[\frac{\partial \rho}{\partial P} \right] \cdot [dP] \right\} + \left[\frac{1}{h} \right] \left\{ \left[\frac{\partial h}{\partial T} \right] \cdot [dT] + \left[\frac{\partial h}{\partial P} \right] \cdot [dP] \right\}, \quad (7)$$

through qualitative algebraic operations with the trends of the quantities inside the bracket [·]. Given the signs or trends (increasing, decreasing, constant) in the partial derivatives and differentials of the right-hand-side of the equations, analysis is performed by applying the operations of qualitative algebra of product (·) and addition (+) among the brackets. The trends in the differentials dT and dP are readily available from the variations in T and P, respectively. The trends in the partial derivatives, $\partial \rho / \partial T, \partial \rho / \partial P, \partial h / \partial T, \partial h / \partial P$, are directly obtained from the equation-of-state tables and are illustrated in Table I for the steam tables. From this point on, the steam tables are used as an example of the equation-of-state, but the presented methodology is general and is not limited to water properties. All eight partial derivatives in Table I present a monotonic behavior with the exception of $\partial h / \partial P$ for subcooled liquid after about 523° K. After 523° K, $\partial h / \partial P$ becomes slightly negative. The monotonic behavior of the partial derivatives is fundamental in the qualitative analysis of the balance equations.

TABLE I

	Trends in the Partial Derivatives.			
	$\partial \rho / \partial T$	$\partial \rho / \partial P$	$\partial h / \partial T$	$\partial h / \partial P$
Subcooled Liquid	↓	↑ ^a	↑	↑ ^b
Superheated Steam	↓	↑	↑	↓

^anegligible changes due to water incompressibility until 523K

The operations of qualitative algebra of product and addition of a change ΔX in variable X and a change ΔY in variable Y are represented in Tables II and III, respectively. The trends in ΔX and ΔY can yield either increasing (↑), decreasing (↓), constant (~) or indeterminate (?) qualitative inferences. For instance, Table II shows that the product of an increasing trend in ΔX (↑) and a decreasing trend in ΔY (↓) yields a decreasing (↓) trend. The addition of similar trends in ΔX and ΔY, illustrated in Table III, results in an indeterminate (?) or ambiguous inference.

TABLE II

ΔX	Qualitative Product [ΔX]·[ΔY]		
	ΔY		
	~	↑	↓
~	~	~	~
↑	~	↑	↓

TABLE III

	Qualitative Addition [ΔX] + [ΔY]			
	ΔY			
ΔX	~	↑	↓	
~	~	↑	↓	
↑	~	↑	↓	

The qualitative analysis of the mass inventory of Eq. (6), for single-phase fluid, is illustrated in Table IV. The rows of Table IV correspond to the nine possible combinations in the trends of T and P, which are represented in the first and second columns of the table. The third and fourth columns correspond to the qualitative behavior of the mass inventory for subcooled liquid and superheated steam, respectively, as a function of the trends in T and P of the associated row. The qualitative behavior of the mass inventory for the first seven rows of the table are uniquely obtained by applying the information of Tables I, II and III into Eq. (6). For example, in the case of ΔT ↑ and ΔP ↓, represented by the sixth row of Table IV, the decreasing (↓) behavior of the mass inventory in both subcooled liquid and superheated steam conditions is obtained by substituting the trends of Table I into Eq. (6) and applying the qualitative operations of Tables II and III

$$[dM] = \left[\frac{\partial \rho}{\partial T} \right] \cdot [dT] + \left[\frac{\partial \rho}{\partial P} \right] \cdot [dP],$$

$$= [\downarrow] \cdot [\uparrow] + [\uparrow] \cdot [\downarrow]$$

$$[\downarrow] + [\downarrow]$$

TABLE IV

	Qualitative Analysis of Single-Phase Mass Inventory.			
	Variations		Mass Inventory (ΔM)	
	Temperature (ΔT)	Pressure (ΔP)	Subcooled Liquid	Superheated Steam
1	~	~	~	~
2	↑	~	↓	↓
3	↓	~	↑	↑
4	~	↑	~ ^a	↑
5	~	↓	~ ^a	↓
6	↑	↓	↓	↓
7	↓	↑	↑	↑
8	↑	↑	↓ ^b	?
9	↓	↓	↑ ^b	?

^aNegligible changes due to water incompressibility

^bFor $\left| \frac{\Delta P}{P} \right| \leq 100 \left| \frac{\Delta T}{T} \right|$

For the last two rows of Table IV, ambiguities in qualitative operations prevent a unique characterization of the behavior in the mass inventory for both subcooled liquid and superheated steam conditions. For instance, for the eighth row where ΔT ↑ and ΔP ↑ we obtain:

$$[dM] = \left[\frac{\partial \rho}{\partial T} \right] \cdot [dT] + \left[\frac{\partial \rho}{\partial P} \right] \cdot [dP],$$

$$= [\downarrow] \cdot [\uparrow] + [\uparrow] \cdot [\uparrow]$$

$$[\downarrow] + [\uparrow]$$

The quantitative addition of a decreasing first term with an increasing second term results in the indeterminate

(?) behavior of dM . Hence, the net result depends on the relative magnitude of the two terms. For subcooled liquid, parametric studies show that for reasonable changes in T and P the first term of Eq. (6) is the dominant one, due to the negligible compressibility of water, causing dM to decrease. An exception to this tendency would occur only when the relative change in P is about two orders of magnitude larger than the relative change in T . For superheated steam, a general trend cannot be obtained for the last two rows of Table IV. The net result of Eq. (6) oscillates between the two terms depending on the relative variations of T and P . In this case, quantitative analysis needs to be used to unambiguously determine the trend in dM .

A similar approach could be used to obtain the qualitative behavior of the energy inventory dU of Eq. (7). The problem with this approach is that the large number of qualitative addition operations generally results in an ambiguous inference. Instead, the analysis of the qualitative behavior of the energy inventory is obtained directly through parametric studies of T and P with the steam tables. The results of the analysis are presented in Table V, which has the same layout as that of Table IV. The table shows that a general qualitative behavior of the energy inventory can be obtained for almost all possible combinations of the variations of T and P . However, as in the analysis of the mass inventory, the last two rows of Table V for superheated steam are also indeterminate. In this case, as in Table IV, the ambiguity can be resolved only for specific changes of T and P , and quantitative analysis must be employed.

TABLE V

Qualitative Analysis of Single-Phase Energy Inventory.				
	Variations		Energy Inventory (ΔU)	
	Temperature (ΔT)	Pressure (ΔP)	Subcooled Liquid	Superheated Steam
1	~	~	~	~
2	~	~	~	~
3	~	~	~	~
4	~	~	~ ^a	~
5	~	~	~ ^a	~
6	~	~	~ ^b	~
7	~	~	~ ^b	~
8	~	~	~	~
9	~	~	~	~

^aNegligible changes due to water incompressibility

$$^b \text{For } \left| \frac{\Delta P}{P} \right| \cong 100 \left| \frac{\Delta T}{T} \right|$$

B. Two-Phase Treatment of Mass and Energy Balances

The analysis of mass and energy balances for a control volume containing two-phase fluid is restricted to components in which the liquid f and the vapor g phases are separable and assumed to be at their corresponding saturation conditions. Since under saturation conditions pressure and temperature are not independent thermodynamic properties, the trend in the measurable liquid level L is used in addition to the saturation pressure P , to determine the behavior of the total mass M and energy U inventories. As an extension for Eqs. (1) and (2), P and L can be related to the total M and U inventories of a given control volume V through the equations of state

$$\begin{aligned}
 M &= M_f + M_g \\
 &= \rho_f(P) V_f(L) + \rho_g(P) V_g(L), \\
 &= A\{\rho_f(P) L + \rho_g(P)(H - L)\},
 \end{aligned}
 \tag{8}$$

-continued

$$\begin{aligned}
 U &= U_f + U_g \\
 &= \rho_f(P) h_f(P) V_f(L) + \rho_g(P) h_g(P) V_g(L), \\
 &= A\{\rho_f(P) h_f(P) L + \rho_g(P) h_g(P)(H - L)\},
 \end{aligned}
 \tag{9}$$

where the $P V$ term in Eq. (2) has been neglected, A is the cross-sectional area and H is the total height of the control volume V , ρ_f is the saturated-liquid density, ρ_g is the saturated-vapor density, h_f is the saturated-liquid enthalpy and h_g is the saturated-vapor enthalpy.

The qualitative analysis of M and U in Eqs. (8) and (9), or the differential counterparts dM and dU , requires the utilization of the steam tables for extraction of the values of ρ_f , ρ_g , h_f and h_g as functions of the variations in P and L , plus the knowledge of the component total height H . The latter requirement stipulates a geometric dependency in the analysis of both equations and prevents the precompiled construction of the physical first-principles rules. Since our approach is intended to be generic and independent of the process being diagnosed, the physical rules describing mass and energy imbalances for two-phase fluid are generated on-line, through table lookup, as the process experiences a malfunction.

C. The Momentum Balance

The analysis of momentum balance in a control volume requires more information than does that of mass and energy. In addition to the knowledge of temperature and pressure for the control volume under consideration, momentum balance also requires information about the fluid velocity. The product of the fluid velocity v and the total mass M defines momentum \underline{M} , as described in Eq. (3). Since the fluid velocity v is generally obtained through measurements of the mass flow rate W , where $W = v \rho A$, with A being the cross-sectional area of the control volume, Eq. (3) can be rewritten in terms of W , with the use of Eq. (1).

$$\underline{M} = L W \tag{10}$$

where L is the length of the control volume. Since L is fixed for a given volume, the analysis of momentum balance is directly obtained through the differential

$$d\underline{M} = L dW. \tag{11}$$

Hence, momentum is added to a control volume if the associated measured flow rate W is increasing and it is subtracted from a control volume if the associated measured flow rate is decreasing.

Functional Classification of Components

The methodology for process diagnosis provided in this invention relies on the characterization of imbalances in the process components, as described in the foregoing paragraphs, along with the functional classification of the components. Each component type, e.g., pipe, pump and electric heater, is functionally classified according to the component influence in causing an imbalance in the conservation equations if and when the component fails. For example, a pump should be functionally classified as a source or sink of momentum because a pump failure causes an imbalance in the momentum conservation equation. This method differs from other approaches to functional characterization of components in that each component type is classified only once and that the classification is based on physical

laws, as opposed to multiple and judgmental classification based on the importance of the component in a given context.

Table VI illustrates the functional classification of some of the most common components present in industrial processes. For instance, the last component in the table, a valve, functions both as a sink or source of momentum. A valve leak or unexpected closure would cause a negative balance in the momentum conservation equation, yielding a functional classification for the valve as a momentum sink. On the other hand, an unexpected valve opening would cause a positive imbalance in the momentum equation, yielding classification as a momentum source. The classification presented in Table VI represents the major influence of a component in one of the three (mass, energy and momentum) balance equations. Each component type can, however, be hierarchically classified according to the component capability in disturbing each one of the three balances. A hierarchical component classification would increase the comprehensiveness of the diagnosis but it would, most likely, depend on the phase of the substance, e.g., liquid or vapor, being transported through the component.

TABLE VI

Functional Classification of Components.	
COMPONENT	FUNCTIONAL CLASSIFICATION
Pump	Momentum Source or Sink
Pipe	Momentum Source and Sink
Electric Heater	Energy Source or Sink
Valve	Momentum Source or Sink

Process Structural Representation

In addition to the functional behavior of the various systems and components of a process plant, plant operators also use their understanding of the structural arrangement of these components when faced with unexpected scenarios and being forced to diagnose the unfolding event and make corrective control actions. The operator's structural understanding of the process relates to graphical or schematic representations of the plant in the form of piping and instrumentation diagrams (P&IDs). Since the information content of a P&ID is essential for diagnosing process malfunctions and it is readily available, for a given process, it has been constantly used as part of the knowledge base of a process diagnosis expert system. In the first generation of expert systems, the information content of the P&IDs was embedded in the production rules. More recently, the P&IDs have been represented in a separate knowledge base which allows for complete independence between the diagnosis methodology and the plant process. The following paragraphs describe the representation of schematic diagrams within the context of the proposed diagnosis methodology.

In this work, the structural domain knowledge of schematic diagrams of a process is represented through directed graph structures and is compiled in a separate knowledge base. The description of a schematic diagram by a graph structure is achieved through a straightforward nodalization process. Each component or component part in a schematic diagram is a node of the graph, while each connection between two components corresponds to an edge. When the edges are directed, i.e., represented by ordered pairs, the graph is a directed graph. Furthermore, a graph structure can be

decomposed into loops, i.e., sub-graphs, just as one defines loops or circuits in a schematic diagram.

FIG. 1 illustrates the schematic diagram of a balance of plant (BOP) for a liquid metal nuclear reactor (LMR) plant. The nodalization of the components in FIG. 1 that fall inside the dashed lines is represented in FIG. 2. Each component or component part surrounded by the dashed lines in FIG. 1 corresponds to a node in FIG. 2, while the physical connections between components, i.e., the pipings, are represented by the directed edges or arcs of the graph structure in FIG. 2. The possible paths between two components and the distinction between heater tube and shell sides in the schematic diagram are characterized in the graph structure as distinct loops.

The knowledge base corresponding to the directed graph structure representation of a schematic diagram describes three kinds of information: component specific, intra-loop and inter-loop.

- (i) Component specific information—describes the characteristics of each component including: component name, type, fluid phase, value and trend of four plant parameters (temperature, pressure, liquid level and flows), and behavior (source or sink of mass, momentum and energy).
- (ii) Intra-loop information—describes all possible paths between any two components in a given loop.
- (iii) Inter-loop—describes which components of a loop are adjacent to components of another loop and all possible paths between any two components of distinct loops.

This knowledge base is the only process-dependent data of the proposed diagnosis methodology, and it can be easily improved or modified to accommodate any changes in the process.

DIAGNOSIS PROCEDURE

After the methods for estimating macroscopic imbalances, classifying components and describing the process schematics have been developed, diagnostic rules and procedures can be applied to identify the possible faulty components. In essence, the diagnostic procedure first identifies a component malfunction with respect to violations in the conservation equations and then relates unusual changes in these factors with appropriate component functionality and location. The diagnostic procedure assumes the occurrence of single faults and availability of validated sensor measurements in the process components. In addition, knowledge of the correct state of the process at the onset of the malfunction is also assumed to be known. The single-fault assumption, and that of complete availability of sensor measurements are not constrained by the proposed methodology and may be relaxed in future developments and implementations of the algorithm.

FIG. 3 is a simplified flowchart of a fault detection and diagnosis method in accordance with the present invention. The initiating process fault will cause one or more of the four monitored sensor measurements (temperature, pressure, liquid level and flow) to deviate from the expected state in one or more components. The diagnosis procedure for these misbehaving components involves the following four steps:

1. State deviations and corresponding increasing or decreasing trends are defined by establishing threshold values for each one of the four sensor measurements and comparing the expected component state with associated measurements.

2. Based on the trends of the varying measurements and the condition of the components (subcooled liquid, saturated, superheated steam), the precompiled physical rules of Tables IV and V and/or table lookup through the steam tables are used to characterize mass and energy imbalances in the components. Momentum imbalances are characterized through direct measurements of mass flow rates. The increasing or decreasing imbalance directions characterize the behavior of each component as a source or sink, respectively, of mass, energy or momentum.
3. A set of possible faulty component types, e.g., pump, pipe and electric heater, is generated by matching the type (mass, momentum or energy) and direction (source or sink) of estimated imbalances against a component functional database such as the one described in Table VI.
4. Faulty component candidates are hypothesized if the type of the misbehaving components matches one of the component types generated by step 3. The matching process is implemented through the knowledge base that describes the schematic diagrams of the process.

The diagnosis procedure can be better understood through an example. An unexpected reduction of the pump motor torque of the feedwater pump in FIG. 1 would cause a slight pressure increase upstream of the pump, a pressure decrease downstream and a decrease of the mass flow rate both up and downstream of the malfunctioning pump. These deviations cause the components up and downstream of the pump, which are transporting subcooled liquid, to behave as momentum sinks. The functional classification of pumps and valves as sources or sinks of momentum and the existence of these two component types in the group of misbehaving components flag the feedwater pump, check valve and the control valve as possible faulty components. Detailed diagnosis, to distinguish between a pump and a valve failure, can now be applied.

TEST PROBLEM

The methodology in the last two sections has been incorporated in a prototype expert system for on-line process diagnosis. The diagnosis system is written in Prolog and consists of three distinct knowledge bases and an inference engine. The knowledge bases for estimating the macroscopic imbalances in mass, momentum and energy and that describing the functional classification of components are based on physical principles and so are process-independent and are constructed once for analysis of any process. The third knowledge base, describing the process schematics, is created through a query session with the user that automatically generates Prolog procedures representing the process. This knowledge base is process-specific; however, it is isolated from the rest of the system and can be easily modified or reconstructed for different processes. The inference engine is also general and process-independent and consists of the diagnosis procedures of the previous section and rules for controlling the search.

To test the prototype expert system, a test case representing the BOP for a LMR plant as illustrated in FIG. 1 has been selected. The BOP contains subcooled water with the exception of the shell side of all heaters and in the line beyond the saturation point inside the steam generator. The entire LMR plant, from the reactor core (not shown in FIG. 1) to the waterside condenser, is

modeled with the SASSYS-1 system analysis code to simulate four malfunctions:

1. Reduction of the feedwater pump motor torque by 50%,
2. Closure of the feedwater check valve area to 10% of nominal,
3. Rupture of the piping connecting the tube side of heaters #1 and #2 at a constant rate of 30 kg/s, and
4. Rupture of the piping connecting the shell side of heaters #1 and #2 at an increasing rate of 0.2 kg/s.

All four process malfunctions are correctly hypothesized by the expert system within 11s into the transient. In the first two cases, however, both feedwater check valve and pump are selected as possible faulty component candidates. This is due to the fact that the two components, valve and pump, are functionally classified as source or sink of momentum, and the failure of either one would cause the components of the tube-side loop, from the deaerator to the steam generator, to behave as a momentum sink. In this case, a more detailed diagnosis, perhaps involving quantitative simulation, is required to distinguish between the two faults. The last two events characterizing pipe ruptures in the tube and shell sides, respectively, are uniquely hypothesized by the expert system. A tube rupture causes the upstream components to behave as momentum sources while causing the downstream components to behave as momentum sinks. Hence, by classifying a pipe as a sink and source of momentum and knowing which components are behaving as sources of momentum and which are behaving as sinks of momentum, the type and location of the malfunction is uniquely determined.

QUALITATIVE ANALYSIS OF THE MACROSCOPIC BALANCE EQUATIONS

In the inventive approach for nuclear power plant diagnostics, the plant structure is visualized as a network of flow paths representing the various components of the plant. Each plant component is associated with a control volume characterized by lumped thermal-hydraulic and thermodynamic properties such as temperature, pressure, and mass flow rate, and is described by macroscopic mass, energy and momentum conservation equations. A component fault will cause the properties of the associated control volume to vary, which in turn will cause imbalances in the conservation equations. Here, the variations of pressure P and temperature T are related through the equations of state to the total inventories of mass M and energy U for a control volume V containing single-phase fluid, and the mass flow rate W is related to the total momentum inventory \underline{M} of volume V through the definition of momentum, as set forth in Eqs. (1), (2) and (10) above.

A compact set of diagnostic rules relating the variations of pressure, temperature and mass flow rate to imbalances in macroscopic mass, energy and momentum can be obtained through a qualitative analysis of Eqs. (1), (2) and (10). The qualitative analysis approach consists of representing a large quantity space of a variable by a small quantity space. For instance, the large quantity space representing changes in the values of T , P and W is represented here by a small quantity space consisting of only three values (+, -, 0) representing the case when changes are positive, negative and zero, respectively. Although the transformation from quantitative to qualitative analysis allows the construction of a compact set of rules, some information is lost in the mapping process. This loss of information may cause

ambiguities in certain circumstances which may be resolved only by providing additional information.

The expressions for the qualitative analysis of imbalances in M , U and \dot{M} as a function of variations in P , T and W are obtained through a two-step transformation of Eqs. (1), (2) and (10). First, the associated differentials dM , dU and $d\dot{M}$ are obtained for a fixed control volume V . Then, the differentials are transformed into qualitative differential equations using DeKleer's methodology and notation as set forth in Eqs. (6) and (7), where the square brackets [•] represent the qualitative value (+, -, 0) of the argument, and the term PV in Eq. (2) has been neglected. Given the qualitative values (signs of the changes) of the differentials and partial derivatives of the right hand sides of the equations, diagnostic rules are obtained by applying the operations of qualitative algebra among the brackets. The values of $[dT]$, $[dP]$ and $[dW]$ are readily available from the variations of T , P and W , respectively, and the qualitative values for the partial derivatives are obtained through analysis of the equation-of-state tables such as previously discussed Table I. Table I illustrates the qualitative values of the partial derivatives for single-phase (subcooled liquid and superheated steam) water. The approach is, however, general and is not limited to water properties.

Substituting the qualitative values of the partial derivatives of Table I into Eqs. (6) and (7) and applying the operations of qualitative algebra, we obtain expressions for the qualitative analysis of changes in mass and energy inventories, respectively. Those qualitative expressions are solely dependent on the observed values of $[dT]$ and $[dP]$ and are used to obtain the diagnostic rules. For instance, the qualitative expression that represents changes in the mass inventory, for subcooled liquid, is given by:

$$[dM] = [-] \bullet [dT] + [+] \bullet [dP] = -[dT] + [dP] \quad (12)$$

For a positive $[dT]$ and a negative $[dP]$ Eq. (12) yields a negative change in the mass inventory,

$$[dM] = -[+] + [-] = [-] + [-] = [-],$$

which can be expressed as the following first-principles qualitative diagnostic rule characterizing a mass imbalance in a control volume:

if temperature is increasing and pressure is decreasing in a control volume containing single-phase fluid, then the total mass inventory of the control volume will decrease.

A summary of the qualitative analysis of the mass and energy inventories, for subcooled liquid and superheated steam, is presented in previously described Tables IV and V, respectively. The rows of the tables correspond to the nine possible combinations in the values of $[dT]$ and $[dP]$, which are represented in the first and second columns of the tables. The third and fourth columns correspond to the qualitative behavior of the mass in Table IV and energy inventories in Table V for subcooled liquid and superheated steam, respectively, as a function of the values of $[dT]$ and $[dP]$ of the associated row.

As mentioned earlier, the loss of information due to the use of a quantity space described by only three values can yield ambiguous results. For instance, the analysis of the mass inventory is ambiguous when $[dT]$ and $[dP]$ are both positive because the two terms of the right hand side of Eq. (12) have different signs and the

net result depends on the relative magnitude of the two terms. For this specific case, parametric studies yield a negative change in the mass inventory as long as the module of dP/P is smaller than the module of $100 dT/T$.

For the case of two-phase flow, the qualitative analysis of mass and energy inventories can be obtained, when the two phases are separable, as a function of the variation of the saturation pressure and liquid level. The analysis of momentum imbalances is directly obtained through Eq. (11). Momentum will increase in a control volume if the associated measured flow rate W is increasing, and it will decrease if W is decreasing.

Our approach for both fault detection and identification is based on the fact that a component fault affects the performance of the plant by causing imbalances of mass, energy and momentum in the process components. Fault detection, as described in the previous section, is obtained by mapping trends in pressure, temperature and flow into trends in the imbalances of the conservation equations. Fault identification is obtained by relating the detected imbalances with the function of the components. This is achieved through the generation of a library of component types, e.g., pipe, pump, electric heater, and functionally classifying them according to which of the three (mass, energy and momentum) conservation equations is most strongly affected when the component fails. For example, if we functionally classify a pipe as a source and sink of momentum, because a pipe failure primarily causes an imbalance in the momentum conservation equation, we could then relate a positive upstream and a negative downstream imbalance in the momentum conservation equation to a pipe failure.

The functional classification of the most common components present in a nuclear power plant is illustrated in Table VI. Each component type is classified as a source and/or sink of mass, energy and momentum. This abstract classification of components allows for the implicit representation of the failure modes of the components and addresses the issue of functional completeness of a diagnostic knowledge base. For instance, by classifying a valve as a source or sink of momentum, we are inherently accounting for the possible failure modes of the valve. A valve leakage, blockage, or unexpected closure are covered by the classification of the valve as a sink of momentum, since any one of these failures would cause a negative imbalance in the momentum conservation equation. An unexpected valve opening is covered by the classification of the valve as a source of momentum for analogous reasons. This method is in contrast with the event-oriented approach for diagnostics of pressurizer failures using macroscopic conservation equations, where every set of imbalances is explicitly associated with a component failure.

In addition to the functional classification of the components, the information describing the physical structure of the plant is also used in the identification of faults. This information, obtained from the plant schematics or piping and instrumentation diagrams, describes the structural arrangements of the plant components and is represented in a separate knowledge base. This knowledge base contains the only plant-dependent data of the proposed diagnosis methodology and is the only portion of knowledge that needs to be modified to accommodate changes in the plant or to diagnose component faults in another plant.

Detection and Diagnosis Procedure

In the following, we show how the methods for estimating macroscopic imbalances in the conservation equations, the functional classification of components, and the information about the plant schematics are combined to detect and identify faulty components in a nuclear power plant.

In essence, a component fault is detected and diagnosed through the four-step procedure described in FIG. 3. In step 1, the deviations of the monitored plant parameters (temperature, pressure and flow) from their expected values in each component are determined by violations of established thresholds. Next, based on the qualitative changes of the deviating plant parameters (e.g., positive [dT], negative [dW]) in each affected component and the physical state of the components (e.g., subcooled liquid, superheated steam) the rules of Table IV are used to characterize mass and energy imbalances in each one of the affected components. Momentum imbalances are characterized directly. The positive or negative imbalance directions characterize the behavior of each affected component as a source or sink, respectively, of mass, energy and momentum. In step 3, a set of possible faulty component types is obtained by matching the type (mass, energy or momentum) and direction (source or sink) of the characterized imbalances of the affected components against the functional classification of components in Table VI. Finally, faulty component candidates are identified by using the information of the plant schematics and matching the type of the affected components against the set of possible faulty component types obtained in step 3.

Power Plant Test Problem

The concepts presented in the foregoing sections have been synthesized in a prototype expert system for on-line power plant diagnosis. The diagnosis system is written in Prolog and consists of an inference engine and three distinct knowledge bases representing the qualitative imbalances in the three conservation equations, the functional classification of components, and the plant schematics. With the exception of the plant schematics, the developed expert system is completely general and can be applied to diagnose plant component faults in different systems.

The plant configuration selected as a test case for the prototype diagnostic expert system is diagrammed in previously described FIG. 1. The balance of plant (BOP) design for a liquid metal reactor (LMR) plant contains subcooled water, with the exception of the shell-side of all heaters and in the line beyond the saturation point inside the steam generator. The entire LMR plant, from the reactor core (not shown in FIG. 1) to the water-side condenser, was modeled with the SASS-YS-1 LMR systems analysis code to simulate four single-fault transients:

1. Reduction of the feedwater pump motor torque by 50%,
2. Closure of the feedwater check valve area to 10% of nominal,
3. Rupture of the piping connecting the tube side of heaters #1 and #2 at a constant rate of 30 kg/s, and
4. Rupture of the piping connecting the shell side of heaters #1 and #2 at an increasing rate of 0.2 kg/s.

Each transient was simulated for 80s, starting from a steady-state 100% nominal power condition, including a 20s null transient. The results of each one of the four

simulated single-faults was stored in a separate data file, with the values of temperature, pressure and flow for the various components of the BOP sampled at 1s intervals. The data files were then used to simulate on-line tests of the diagnosis expert system, which correctly identified the single-faults within a few seconds into the transient. The following describes the procedures used by the proposed approach to detect and identify the first transient, an unexpected 50% reduction of the feedwater pump motor torque.

A feedwater pump motor torque causes a slight pressure increase in the upstream piping connecting the pump to the deaerator, a pressure decrease in the downstream components up to the steam generator, and an immediate decrease in the mass flow rate through the components between the deaerator and the steam generator control valve. FIG. 4 shows the variation in pressure just upstream of the pump, and downstream in the tube side of heater #1. FIG. 5 shows the variation in flow in the piping connecting the deaerator to the pump and in the piping connecting the tube sides of heaters #1 and #2. The deviations of both pressure and flow from the expected values, corresponding to step 1 of the detection/diagnosis procedure in FIG. 3, trigger the expert system. In step 2, the system makes a list of the affected components, which in this case includes components between the deaerator and the steam generator, and associated imbalances. These two time-dependent steps are illustrated in Table VII at the onset of the transient. The first column of the table describes the affected components, while the second column shows the qualitative changes in the plant parameters for each one of the affected components. For example, at the onset of the transient the tube bundle in heater #1 is experiencing zero (0) temperature change dT, and negative (-) pressure dP, inlet flow dW_{in} , and outlet flow dW_{out} changes. The last column in Table VII shows a negative imbalance in momentum for all affected components. This imbalance is a consequence of a decrease in flow. Due to water incompressibility, a negative [dP] in the tube-side of heaters #1 and #2 does not cause imbalances in the mass or energy inventories in these components, as shown in row five in Table IV.

TABLE VII

Affected Components	Initial Effects of the Reduction of the Feedwater Pump Motor Torque by 50%						
	Plant Parameter Trend				Imbalance Type		
	[dT]	[dP]	[dW _{in}]	[dW _{out}]	[dM]	[dU]	[dM]
Deaerator	0	0	0	—	—	—	—
Feedwater Pump	NA ^a	NA	—	—	—	—	—
Check Valve	NA	NA	—	—	—	—	—
Tube Heater 1	0	—	—	—	—	—	—
Tube Heater 2	0	—	—	—	—	—	—
Control Valve	NA	NA	—	—	—	—	—

^aNA indicates data were not available.

In step 3 of the detection/diagnosis procedure, the expert system searches the knowledge base representing the functional classification of the components (as described in Table VI), to identify a pump and a valve as two component types that could be responsible for the behavior of the affected components as momentum sinks, i.e., negative [dM]. Finally, by matching the identified component types, i.e., pump and valve, with the list of affected components the expert system flags the

feedwater pump and the two valves as the possible faulty components. Detailed diagnosis, to distinguish between a pump and a valve failure, may then be applied through quantitative simulation or component-level reasoning mechanisms.

The uniqueness of the proposed method to identify system-level faulty component candidates during incipient off-normal operations of power plants relies on the use of mass, energy and momentum conservation concepts for both fault detection and diagnosis. This unique combination allows for the construction of a compact, yet robust plant-independent diagnosis system. Once a component type has been classified, the same rule used to classify the component can be used to detect the failure of that component type anywhere in the system or in any other system. In addition, there is no need to tackle the impossible task of formulating all possible events or combination of events, as is required in event-oriented approaches.

The present invention provides a powerful and effective approach for incorporating basic first-principles into the knowledge base of a general process diagnosis system. The methodology identifies faulty component candidates which can then be singled out with deep-knowledge reasoning. The use of basic physical principles produces a small, general and comprehensive set of diagnostic rules and methods which are physically correct. The generality of this approach is achieved through the clear separation of the process-dependent schematics representation from the remaining process-independent knowledge bases and inference engine. These factors produce a robust process diagnosis methodology which can be effectively verified and validated through standard techniques.

While particular embodiments of the present invention have been shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects. Therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of the invention. The matter set forth in the foregoing description and accompanying drawings is offered by way of illustration only and not as a limitation. The actual scope of the invention is intended to be defined in the following claims when viewed in their proper perspective based on the prior art.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method for diagnosing failures in the operation of a thermal-hydraulic system including detection of a malfunction of one or more components in said thermal-hydraulic system, said method comprising the steps of:
 assigning to one or more of the components of the thermal-hydraulic system a thermal-hydraulic control volume which characterizes the total mass, momentum and energy inventories of said one or more components during normal and off-normal operations;
 assigning to each thermal-hydraulic control volume its associated mass, momentum and energy conservation equations;
 assigning to one or more components a functional classification as a source or sink of mass, momentum or energy;
 monitoring operation of the components associated with the thermal-hydraulic control volumes for

detecting an imbalance in the total mass, momentum or energy inventories in any of the thermal-hydraulic control volumes; and

5 comparing a detected imbalance in mass, momentum or energy of the thermal-hydraulic control volumes with the conservation equations and the functional classification for each of the components and identifying a given component as faulty when a detected imbalance in mass, momentum or energy of the thermal-hydraulic control volume matches the classification of the component as a source or sink of mass, momentum or energy.

2. The method of claim 1 wherein the step of determining whether each component is a source or sink of its associated mass, momentum or energy inventory includes the steps of grouping the components by type of component and functionally classifying each component type in priority as a source or sink of mass, energy or momentum in accordance with how strongly each of the conservation equations is affected by a malfunction of the component.

3. The method of claim 1 wherein the step of comparing a detected imbalance in mass, momentum or energy of the thermal-hydraulic control volume with the conservation equations and the component classification includes the step of providing a set of possible faulty components, their imbalance type (mass, momentum or energy) and direction (source or sink) and comparing this information with the functional classification of the component types.

4. The method of claim 1 wherein the step of assigning to each thermal-hydraulic control volume mass, momentum or energy inventories representing normal operation includes establishing threshold values of pressure, temperature, level and flow for each thermal-hydraulic control volume and wherein a given component is determined as potentially faulty when the value of pressure, temperature, level or flow exceed said threshold values causing associated imbalances in mass, momentum or energy.

5. The method of claim 1 wherein the step of detecting imbalances in the conservation of mass, momentum and energy, and the step of classifying components as a source or sink of mass, momentum or energy are separated from each other and are independent of the thermal-hydraulic system.

6. The method of claim 1 further comprising the step of identifying the physical location of said given component in the thermal-hydraulic system for reducing the number of possibly malfunctioning components.

7. The method of claim 6 wherein the step of identifying the physical location of said given component includes constructing a nodalization graph wherein each component is represented as a node and each connection between two components is represented as an edge corresponding to piping components.

8. The method of claim 6 wherein the step of identifying the physical location of the components is separated from the step of detecting imbalances and the step of classifying components, and is the only system-dependent information of the method.

9. The method of claim 1 wherein the step of monitoring operation of the thermal-hydraulic control volumes for detecting an imbalance in mass, momentum and energy includes measuring pressures, temperatures, levels and mass flow rates.

10. The method of claim 9 wherein the step of monitoring operation of the thermal-hydraulic control vol-

umes for detecting an imbalance in mass, momentum or energy further includes the step of determining trends in imbalances in mass, momentum and energy in terms of trends in pressure, temperature, levels and mass flow rates.

11. The method of claim 10 wherein the step of detecting imbalances of mass and energy is performed through qualitative analysis of a plurality of equations of state relating pressure and temperature to fluid density and enthalpy, and wherein an imbalance in momentum is detected through qualitative analysis of the monitored mass flow rate.

12. The method of claim 11 wherein the step of determining trends in imbalances in mass and energy includes referring to the equations of state in the form of steam tables for water and other tables for other fluids and determining variations of fluid density and specific enthalpy as a function of variations in pressure and temperature.

13. The method of claim 12 wherein the step of determining variation of fluid density and specific enthalpy as a function of variations in pressure and temperature is performed for subcooled liquid as well as for superheated steam.

14. The method of claim 12 wherein the step of detecting trends in imbalances of mass and energy for two-phase flow is performed through qualitative analysis of the equations of state including a measurement of liquid fluid level.

15. A method for diagnosing the operation of a thermal-hydraulic system including detection of a malfunction of one or more components in said system, said method comprising the steps of:

assigning to one or more of the components of the thermal-hydraulic system a thermal-hydraulic control volume which characterizes the total mass, momentum and energy inventories of said one or more components during normal and off-normal operations;

assigning to each thermal-hydraulic control volume its associated mass, momentum and energy conservation equations;

determining whether each component is a source or sink of mass, momentum or energy and characterizing imbalances of the total mass, momentum and energy inventories of the thermal-hydraulic control volume through conservation equations, equations of state and tracking mass flow rate, wherein the step of determining whether each component is a source or sink of its associated mass, momentum or energy inventories includes grouping the components by type of component and functionally classifying each component type in priority as a source or sink of mass, energy or momentum in accordance with how strongly each of the conservation equations is affected by a malfunction of the component;

monitoring operation of the components associated with the thermal-hydraulic control volumes for detecting an imbalance in the total mass, momentum or energy inventories in any of the thermal-hydraulic control volumes;

identifying the physical location of said given component in the thermal-hydraulic system for reducing the number of possibly malfunctioning components; and

comparing a detected imbalance in mass, momentum or energy of the thermal-hydraulic control volumes with the conservation equations and the functional classification for each of the components and identifying a given component as faulty when a detected imbalance in mass, momentum or energy of the thermal-hydraulic control volumes matches the classification of the component as a source or sink of mass, momentum or energy wherein the step of comparing a detected imbalance in mass, momentum or energy of the thermal-hydraulic control volumes with the conservation equations and the component classification includes providing a set of possible faulty components, their imbalance type (mass, momentum or energy) and direction (source or sink) and matching this information with the classification of component types.

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UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 5,265,035
DATED : November 23, 1993
INVENTOR(S) : Reifman et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

<u>COLUMN</u>	<u>LINE</u>	
20	12	"source of sink of mass" should be --source or sink of mass--

Signed and Sealed this
Second Day of August, 1994

Attest:



BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks