# IMPLEMENTATION OF NEW PRODIAG ALGORITHM AND SIMULATION-BASED ACCEPTANCE TEST

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## ABSTRACT

This paper presents the improvement of an automated-reasoning computer program for nuclear power plant diagnosis, namely PRODIAG. PRODIAG, first developed at the Argonne National Laboratory, uses confluence-based reasoning to perform fault diagnosis in engineering systems that can be described by the conservation laws for mass, energy, and momentum. Therefore, unlike other plant configuration-dependent rule-based diagnosis algorithms, the code is generally applicable to a wide variety of plant configurations by simply replacing the plant instrumentation diagram (PID) database. The need for improvement was raised when the original PRODIAG failed to provide the requisite degree of extensibility and maintainability for new applications. These shortcomings have been addressed through a new code architecture that uses an objected-oriented logic-programming language in place of the original Prolog language and uses an open-source automated reasoning engine in place of the original hardwired rule-evaluation sequence. This paper presents the architecture and implementation details of the code transition. Verification and validation studies were performed for the new PRODIAG, which involved re-running the distinct fault cases defined at the time the code was originally developed

*Key Words*: plant fault diagnosis, expert system, artificial intelligence, object oriented program

## 1   INTRODUCTION

Computer-based diagnostic systems for detection and identification of component faults in nuclear power plants have been widely investigated in the past years. A common approach is event-oriented and process specific approach, where, given a particular process (system) in a plant and a set of predefined modes of component faults or transient events in the process, the diagnostic system is hardwired to detect and identify these component faults in that particular process. Such a method is however incapable of correctly diagnosing unanticipated transient events, and is not transferrable to a different plant process. On the other hand, a generically applicable, event- and process-independent diagnostic system, namely PRODIAG [1.2], was developed at ANL in the 1990's to perform automated diagnosis of component faults in T-H processes. PRODIAG is based on the fundamental physical principles of conservation of mass, momentum, and energy that governs the behavior of the process, which in conjunction with qualitative physics reasoning [3, 4] and the functional relationship between the behavior and the design objective of each component of the process yield the capability to 1) identify unanticipated component faults, and 2) be ported across different plants and processes.

However, the PRODIAG code implementation reflects the state of expert systems development in the mid 1990's. That is, the reasoning process is inextricably wedded to the execution of rules as opposed to the recent trend where the rules are defined separately and then presented for evaluation by a reasoning engine. The code is programmed in Prolog. Therefore, a developmental work has been conducted to re-design and re-write the PRODIAG code consistent with current-day best-practices for software

implementation of automated-reasoning algorithms. The objective was motivated by experience in adapting the original PRODIAG to new diagnosis applications different from the original application. While the heart of PRODIAG, the engineering-based confluence reasoning approach, has general applicability to many physical systems, the actual implementation realized in Prolog did not provide for ready extensibility and maintainability. Mainly, this was a consequence of 1) failure to program using objected oriented techniques (the Prolog language does not support object-oriented programming, and 2) the decision to imbed the confluence-derived rules in the diagnostics search sequence, as opposed to keeping the two separate.

This paper presents the architecture to implementation details of the code transition. Verification and validation studies were performed for the new PRODIAG. This involved re-running the distinct fault cases defined at the time the code was originally developed

## 2    OVERVIEW OF PRODIAG PROGRAM

### 2.1  PRODIAG Diagnostic Strategy

The methods of PRODIAG are described in [1, 2] and are summarized here. Unlike the traditional event-oriented approach for diagnostics, PRODIAG used function-oriented approach that does not require pre-specification of the possible process component faults. The unique capability of PRODIAG are attained through the systematic structuring of fundamental physical principles and basic general concepts into independent knowledgebase, a number of key abstractions, the use of function-oriented approach for diagnostics, and the use of qualitative physical reasoning.

The diagnostic strategy is carried out by separating the relevant information into three distinct but interacting knowledgebase: physical rules database (PRD), component classification dictionary (CCD), piping and instrumentation database (PIDB). Process symptoms are related to component faults through the three-step mapping illustrated in Fig. 1. Through this three-step mapping, the diagnosis is transformed into a function-oriented approach and confines the process-dependent information solely to the PIDB.
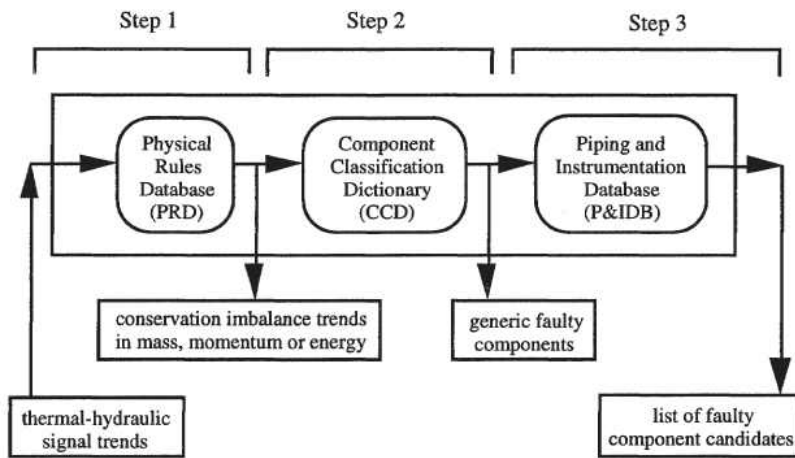


Figure 1. PRODIAG Diagnostic Process by Mapping of Sensor Signals into Faulty Components through the Three Knowledge Bases of PRODIAG

### 2.1.1  Piping an Instrumentation Database (PIDB)

To facilitate systematic application of physics rules for component level diagnostics in process independent manner, the T-H process is decomposed into basic elements or building blocks to form

generic geometrical configurations to which the rules of the PRD can be applied. A top-down tree like decomposition definition is established, accordingly a T-H system is decomposed into loops defined between two end boundaries, and components (including junctions) which belong to each loops. The plant specific system configuration is described in the P&ID database, which includes the loop-specific information, component-specific information, and inter-loop information.

### 2.1.2  Time Window Selector

To allow application of quasi-static version of the balance equations to the dynamic plant T-H systems, it is necessary to properly account for the process dynamics as transient event evolves in time. For example, different process variables of various components different time constants. The transient-induced dynamic effects are taken into account when determining the process variable trends by correctly synchronizing the T-H signals used in the rules of the PRD while accounting for the process time constants. Such synchronization is accomplished by introducing the concept of 'time window'. Triggered by two threshold values for each process variables, the primary time window opens to initiate the diagnosis process, and subsequently the secondary threshold opens the time windows for initiating the inclusion of individual process variables. The time windows close after certain period related to the time constants.

### 2.1.3  Physical Rule Database

PRODIAG' s physical rules are derived based on qualitative physics [3, 4] where a small number of qualitative trends, such as increasing, decreasing, and unchanging trends, are used to represent the values of continuous real-valued process variables applicable to process-independent basic elements, i.e. loops, control volumes, and components. First principle rules, mapping trends in T-H signals into imbalances of mass, momentum, and energy, were solely derived through the equations of state and the definitions of momentum, and applied to the relevant control volumes. Here, in addition, the basic mathematical description of the macroscopic conservation equations to construct qualitative rules that characterize imbalances in mass, momentum, and energy. The sensor readings associated with the control volume boundaries are used to identify the location of the imbalances, which indicate the malfunctions.

The qualitative physics rules of the PRD are of two classes: Q rules and CV rules. A Q rule indicates the type and trend of the imbalance in a control volume inferred from the trends in the T-H signals. Corresponding to the three balance equations of mass, momentum, and energy, there are there types of $Q$ rules: $Q_{m\ ass}$, $Q_{m\ om}$, $Q_{eng}$. The $Q$ status can have one of three trends: increasing ($\uparrow$), decreasing ($\downarrow$), and unchanging ($-$). A CV rule infers the trend status of unmeasured T-H signals in a process component from the other T-H signals of the component and the $Q$ status of the component.

As an illustration, consider the physics rule,

$$Q_{m\ ass} = W_{out} - W_{in} \ ,\tag{1}$$

where $W_{in}$ and $W_{out}$ are the control volume inlet and outlet mass flow rates, respectively, and $Q_{m\ ass}$ is the mass source/sink term in the mass balance. Transforming (1) into qualitative differential expressions, using De Kleer and Brown's methodology and notation [4], gives the following confluence:

$$[dW_{in}] - [dW_{out}] = -[dQ_{m\ ass}],\tag{2}$$

where the square brackets [·] represent the qualitative value or trend ($\uparrow$, $\downarrow$, $-$) of the argument basic quantity. Equation (2) represents the general confluence, from which $Q$ rules characterizing imbalances in $Q_{m\ ass}$ can be derived by applying the different trend combinations of $W_{in}$ and $W_{out}$ and using the operations of qualitative algebra. Thus,

$$\text{Rule (A)} \qquad \text{If } W_{in}^{\uparrow} \ \text{ and } W_{out}^{\downarrow}, \text{ then } \ Q_{m\ ass}^{\downarrow}\tag{3}$$

$$\text{Rule (B)} \qquad \text{If } W_{in}^{\downarrow} \ \text{ and } W_{out}^{\uparrow}, \text{ then } \ Q_{m\ ass}^{\uparrow}\tag{4}$$

Likewise, other Q rules are derived for defining momentum and energy with related process variables.

PRODIAG includes a comprehensive set of rule bases modules, which include various physical rules.

### 2.1.4  Component Classification Dictionary

Generic process components are fundamental building blocks of generic geometric configuration. As such, their misbehavior or malfunction causes changes in the Q status of s control volume. Hence, through the proper functional classification of generic components, the Q status of control volumes detected by the results of the PRD is linked with components whose failure could be responsible for the detected Q imbalances. Such classification of components is compiled in the component classification library (CCD). A small number of generic component types included in T-H processes are classified into predefined classes. For example, based on the three conservation equations, each generic component type, e.g. closed valve, open valve, and electrical heater, is functionally classified as a source or sink of mass, momentum, or energy.

## 2.2  Limitations of the Original PRODIAG

As a first step toward the software upgrade, the roughly 100,000 lines of the original Prolog code were analyzed into a flowchart. The line-by-line inspection of the code yielded findings of some limitations.

- The absence of object-oriented programming practices proved to be a significant limitation. The code was not structured in a way that made it easy to read. The code as written in Prolog read like a procedural-based program which results in execution in a way that is difficult to follow.

- PRODIAG by nature of its Prolog implementation performed a diagnosis through a rule-evaluation algorithm that is essentially hardcoded for the current PRODIAG rule set. This made maintenance of existing rules and the addition of new rules difficult.

- There was a significant amount of legacy code which under the procedural-based coding approach resulted in poor readability. A more structured programming approach was needed to bring order to this conglomeration that has evolved over time.

## 3    IMPLEMENTATION OF NEW PRODIAG EXPERT SYSTEM

## 3.1  Selection of Diagnosis Method

A survey of automated diagnosis and related software methods was performed with the objective of addressing the short comings identified in the previous section. Broadly, diagnosis methods can be classified into two categories: rule (expert)-based and model-based. The recent state-of-the-art approach is hybrid system that adopts model-based diagnosis with detailed physical model [5]. Such aspects were considered in the selection of a preferred software tool for the re-write of the PRODIAG software. Different programming languages and automated reasoning environments were judged for their suitability for use in the re-write.  Considered were support for 1) an inference capability, 2) an object-oriented capability, 3) a debugger, 4) a semi-natural English-type language, and 5) an integrated development environment (IDE).  The tools examined were the Max-SAT solver [6], the VisiRule package [7], PyKE [8], and Drools (JBoss) [9].

The final choice was made to adopt Drools JBoss [9], which is an open source tool with a Java-based rule engine.  It supports forward chaining rules via the Rete algorithm and also partially supports backward chaining rules. The main benefits of this tool are the wide user base, various functionalities and the Eclipse integrated development environment (IDE). It was determined that the Drools JBoss best meets the requirements identified in Section 2. Significant pluses are the capability for object-oriented code and the existence of a debugger in an integrated development environment. PRODIAG rules within the code can be formulated in forward-chaining reasoning form. The language is Java-based and consequently benefits from a large Java-user community. The Drools JBoss support for production rule (if-then) was found to be adequate.

## 3.2 New PRODIAG Software Architecture

The overall software architecture of the program is illustrated in Fig.2 and consists of four parts: 1) PRODIAG Expert system, 2) PID Construction Program, 3) Read Data Interface Program, and 4) Graphic User Interface.
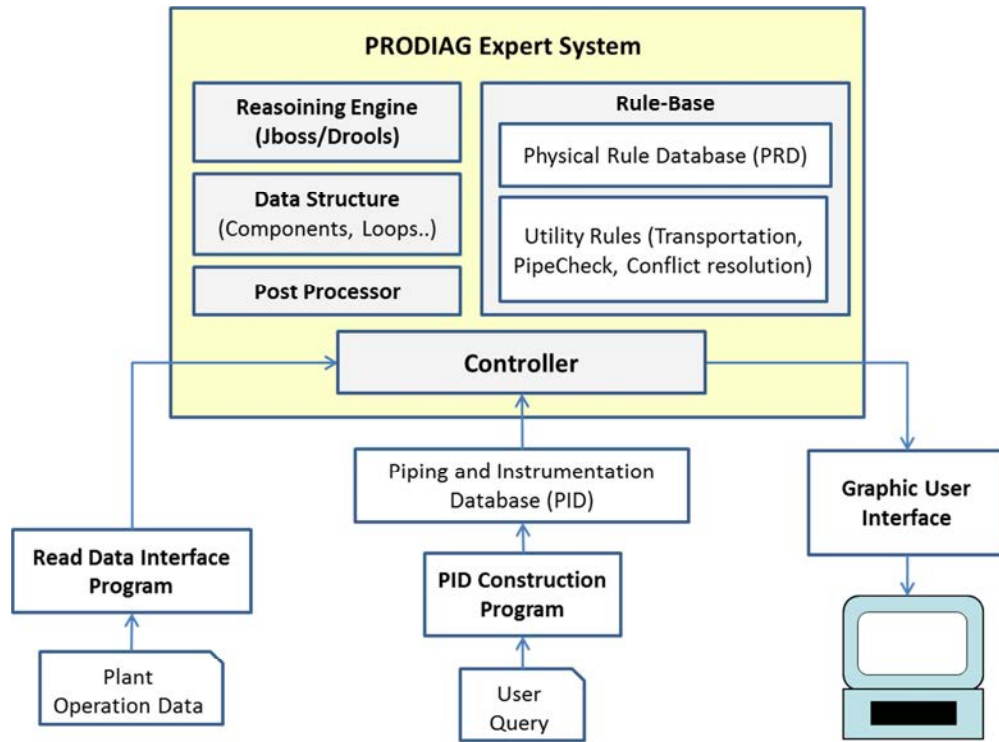


**Figure 2. Overall Software Architecture of New PRODIAG**

## 3.3 Data Structure

The new PRODIAG uses the following data structures to keep track of static information (e.g. PID) and process variables.

- *Component*: A Component object keeps track of the component properties (e.g. component type, volume type, relative pressure, fluid type, location). The following types are supported: bearing, closed_valve, demineralizer, filter, heat_exchanger_cold, heat_exchanger_hot, heater, junction, open_valve, pump, seal, seal_barrier, sump, system, tank, and turbine.

- *Loop*: A Loop object keeps track of the properties of the loop and the components in the loop. It also keeps track of intermediate diagnosis results, such as faulty component candidates, for later use in the final diagnosis in the post processing.

- *THProcess*: This is the *one instance* for the whole life-cycle of the expert system. It keeps track of all the Loop, Component and Q instances. It also holds a handle to the rule-base engine.

- *Sensor*: A Sensor object stores the initial value of a process variable, and keeps track of its raw trends during the following updates.

- Q: Q objects are imbalance indicators that keep track of the inference output of various Q-rules in the rule base. There are two subclass, Qcomp and Qloop, depends on the Q is associated with Component or Loop.

## 3.4 Rule-Base

A major objective of the PRODIAG redesign activity was to modularize the program so that it could be easily modified or extended. Currently there are 21 different modules organized as agenda groups. These modules have no direct interactions with each other, and the collaborations are achieved mostly through updating the inserted Java objects: Component, Loop and Q.

*Transportation*: The transportation module replicates the enthalpy transportation and constant flow transportation procedure to fill the unfilled process variables, esp. temperature and constant flow. The transportation happens along any given loop that meets the conditions. Transportation, as in original PRODIAG system, is executed right before the primary Q-rules.

*Module 00.00*: Module 00.00 is designed to detect certain instrumental errors. The design of the rules is straightforward: identifying a component with measurements that meet the rule condition, then report the error and stop the diagnosis.

*Modules 10.0, 20.00, 30.00, 40.00, 50.00, 90.00, 100.00*: defines the set of Q-rules of various categories.

*Module 60.00, 70.00, 80.00, 100.00, 120.00*: are the set of CV-rules designed to infer unmeasured variable trends for based on other measurements and Q trends.

*Pipe Check*: Pipe check is yet another undocumented module in the original PRODIAG program. This module is used to check the failure of a single pipe based on the immediate surrounding flow or pressure trends and their environment pressure attributes (relative pressure).

*Conflict Resolution*: This module includes all conflict resolution routines for conflicting Q assignments, so that other rules that with action items on Q do not need to worry about any potential conflicting assignments.

*Q Propagation*: This auto-focus group has only one rule, which will propagate the component Q trends into the loop Q. Every time a component Q trend is set with conflicts resolved, this group will be pushed on top of the stack and propagate the component Q trend to loop Q.

*Cleanup and Generic*: This module contain some general rules for the purpose of housekeeping, to make sure rules in other modules can be executed as expected. This group is also an auto-focus group, so that will be fired as needed.

## 3.5 Automated Reasoning Process

The core of new PRODIAG is a business rule management system Drools, which provides a powerful reasoning engine for performing diagnosis. Java objects can be inserted into the rule base as facts, and therefore become accessible by the reasoning engine. A registered rule in the rule base consists of a set of conditions and a set of associated actions. Once the conditions of the rule are met, the actions will be executed.

The rule base consists hundreds of rules in the form of standard Drool rules base. Each rule work independently, and the collaboration between rules are achieved through delicately conceived condition and action items. The effects of the rules are reflected in the modifications they made to the Java objects.

The diagnostic procedure works as follows: a new rule engine session is created, and data structures, such as Components, Loops, Qs, are initialized and registered as facts in the engine. A set of rules is also registered with a rule flow specification. Then during each iteration, a new batch of sensor reading is updated through TimeWindow selector, and rules are fired to perform diagnosis. The iteration continues until a conclusion is reached or the input data is exhausted. After each iteration, a post processing procedure is invoked to collect the inference results and present the final results.

In general, there is no direct way to control the order of rule execution once we fire up the rule engine. However, through the ruleflow facility of Drools, we can group rules into group and control the overall flow. Using the "ruleflow" keyword, as in the example above, we categorized the rules based on the module they serve in, and use a flowchart tool to specify the orders of the group.

Fig. 3. shows the rule flow for PRODIAG. It has three branches, the left branch replicates the general order of original PRODIAG work flow: Transportation -> Q-Rules -> CV-Rules -> Transportation -> Q-Rules -> Diagnosis; the two other branches will be executed in parallel with the main branch and taking care of some routine updates and conflict resolution. The detail of the ruleflow groups will be discussed in next section. Notice that the ruleflow is different from program flowchart. It only governs which set of rules should be activated after the rule groups before it has ceased fire, but it has no control over when an activated rule should be fired.
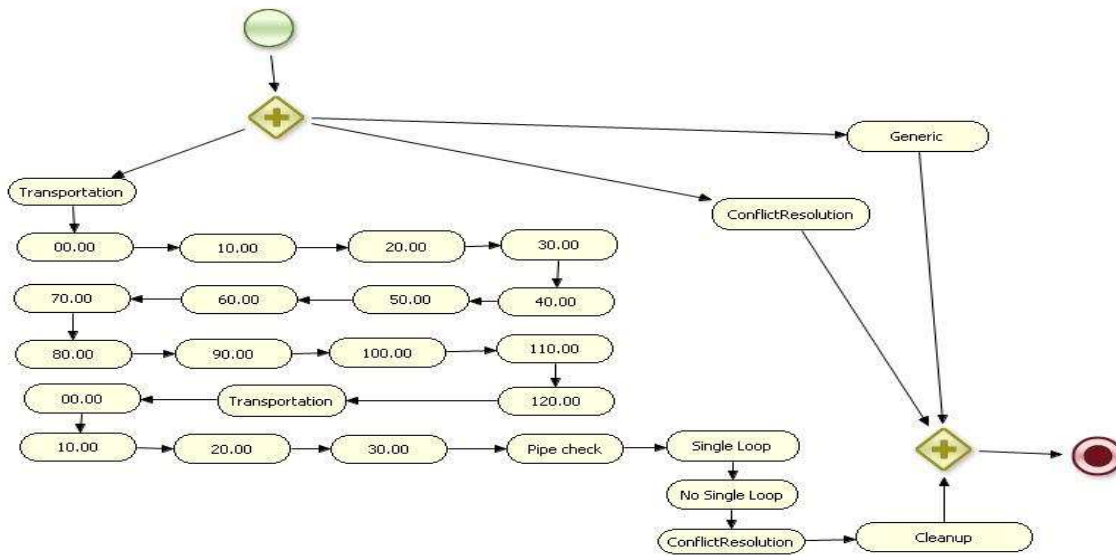


**Figure 3. Schematic of Diagnosis Procedure**

## 3.6 Post-Processing

After the rules cease firing, the reported faulty candidates are gathered and post processed in "ResultPool" (see ResultPool class). Because PRODIAG is a loop-based inference system, most faulty candidate information is stored in the class Loop. In general, there are nine categories of possible faults.

## 4    GRAPHIC USER INTERFACE

In order to give users a realistic interface for plant status monitoring and control, a graphic user interface is developed which displays the plant status and provides control interface for the

CVCS. The GUI is implemented based on the use of Control System Studio. The plant status panel of the CVCS is shown in figure 6.
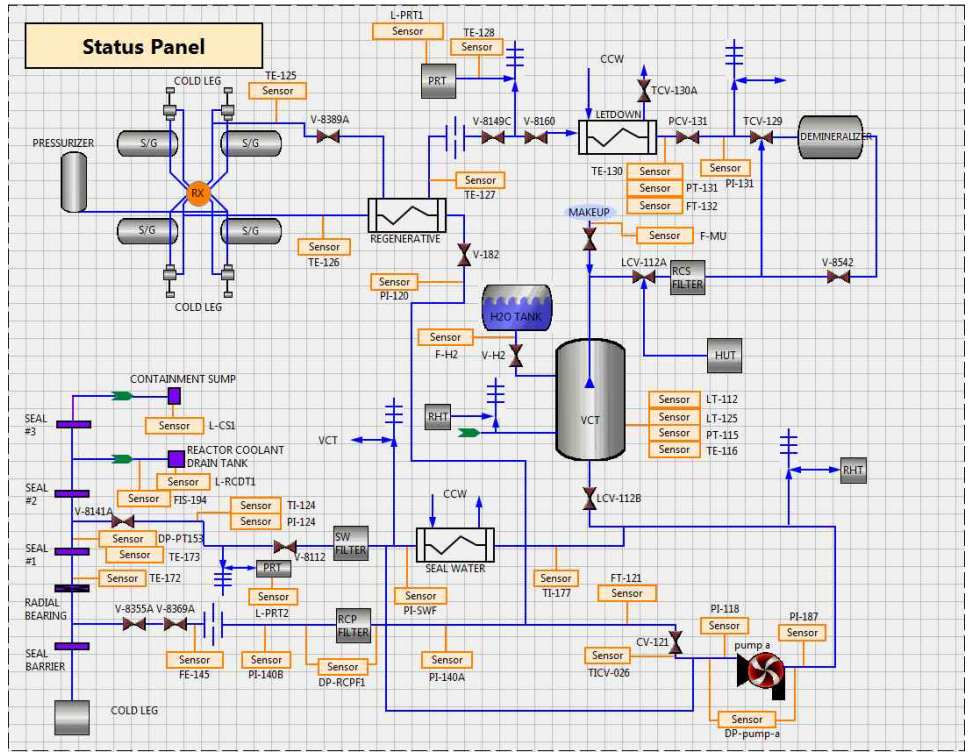


**Figure 4. Plant Status Panel of the Braidwood NPS CVCS**

Control System Studio [10]  is an Eclipse RCP (Rich Client Platform) application. It was originally designed as a GUI for another program called Epics (Experimental Physics and Industrial Control System). Epics stores the individual sensor values in a format called a process variable. Once Epics is configured with proper definition of process variables, it can begin to monitor any changes in the process variables.

In order to easily control the simulation, we designed a control panel in Swing. Fig. 5 provides a high level overview of how the control panel interfaces with the rest of the system in order to make these simulations possible.

The "Bridge Program" is the name given to the interfaces used to connect Epics and Prodiag. The interfaces for connecting Prodiag to Epics and vice versa are arbitrarily defined in Java. Since Prodiag itself is already part of the simulation, no third party libraries are required to connect to it. However, since Epics is separate from the simulation program, we have to use a third part Java library called JCA (Java Channel Access). JCA provides with a Java API for connecting to Epics.
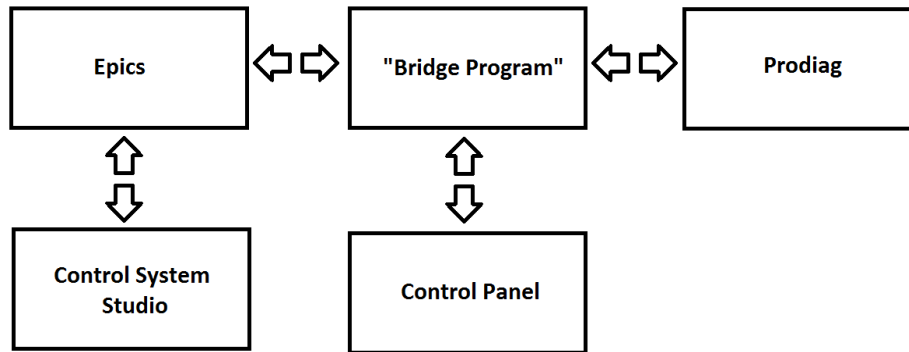
**Figure 5. Overview of the control panel interfaces with PRODIAG and plant simulator**

## 5    ACCEPTANCE TEST CASE RESULTS

For verification and validation purpose, the new PRODIAG was tested with a test date generated from a power plant simulator. The diagnostic results were compared with those of old PRODIAG. The Chemical and Volume Control System (CVCS) of ComEd's Braidwood pressurized water reactor was selected as the test bed. Figure 1 shows the PID of the Braidwood CVCS system under test. The test data was generated to represent transient conditions for a range of postulated failure conditions.

The test results are summarized in comparison with those of old PRODIAG diagnostic results on the same test cases.  Total 20 failure cases were tested and the results are shown in Table 1. The diagnostic results are classified into two categories: component failures and piping failures (clogging or break). In the old PRODIAG results, the piping failure results are displayed and one sentence including the most outer boundaries. On the other hand, in the new diagnostic results, each piping segment failure is indicated. When combined which makes up the old diagnostic results. The diagnostic results matched most cases for the component failures, except CV09-150 case which was sensor failure case. The piping failure diagnostic results matched in most cases, but with different levels of accuracies in terms of pin-pointing the faulty segments.  Table 2 shows a summary of comparison of diagnostics results.

**Table 2  Summary of Diagnostic Results Comparison**

| Diagnosis | Match | Predict Better | Predict Worse |
|---|---|---|---|
| Component Failure | CV04-100, CV05-310, CV06-100, CV07-100, CV08-480[a], CV10-100, CV12-65, CV14-65, CV16-95, CV18-70, CV21-50, CV24-65, CV27-150 | CV01-100 | CV09-150[b] |
| Piping Failure | CV04-100, CV24-65, CV25-45 | CV06-100, CV07-100, CV12-65 | CV01-100[c], CV05-310[c], CV13-45[c], CV22-65[c], CV23-65[c], CV26-20[c] |

[a] This fault was a sensor failure case. The diagnosis is not correct in this case.
[b] This is a sensor failure case. The diagnosis is indeterminate.
[c] Piping failure pipe-run localization correct, but piping run is longer than diagnosed by original PRODIAG.

# 6  DISCUSSION

PRODIAG is a function-based approach for nuclear power plant diagnostics. Compared to the traditional process-based diagnostic systems, it has advantage in terms of portability and capability to diagnose unanticipated faults. However, due to the dated software structure, it had difficulty in software expansion for new application. To this end, a software update was performed to transform PRDIAG to modern day software practice. The objective is to adopt object oriented software structure, and separation of rules from the inference mechanism.  The feasibility of the software is validated with simulation plat operation data. Despite the initial success, further validation of the code for robustness, and improvement toward model-based diagnostics is anticipated.

## ACKNOWLEDGEMENT

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