SAFETY INSTRUMENTED SYSTEM (SIS) FOR PROCESS OPERATION BASED ON REAL-TIME MONITORING

by Cen Kelvin Nan

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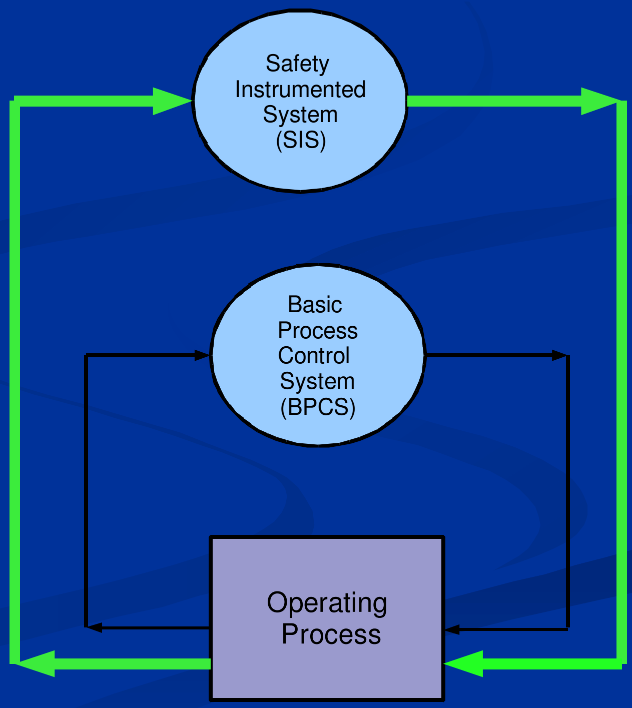
Background

Safety Instrumented System (SIS)

What is SIS ?

- A system independent of Basic Process Control System (BPCS), is designed to take action to maintain the process safety in the event of malfunction
- "a system composed of sensors, logic solvers and final-control elements for the purpose of taking the process to a safe state, when predetermined conditions are violated" *IEC 61508 (2000)*

IEC : International Electrotechnical Commission

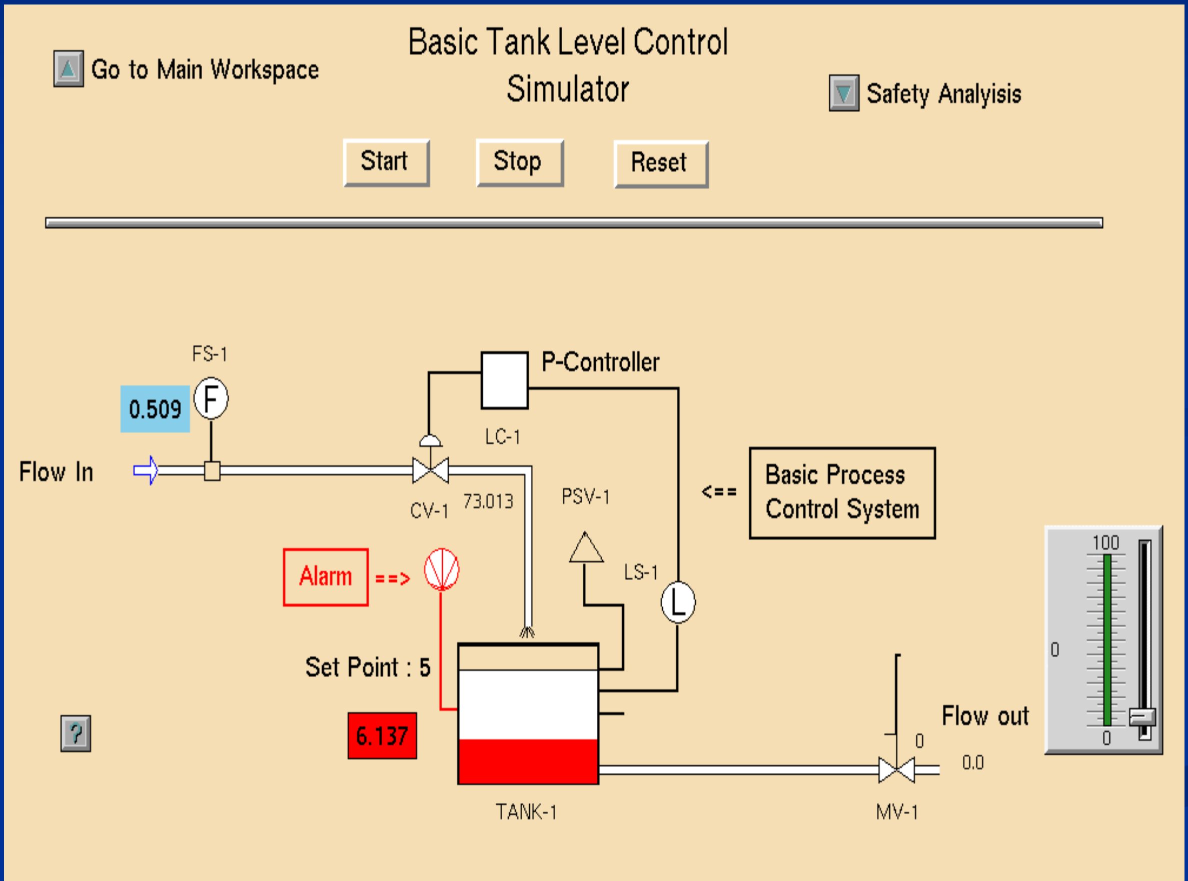


SIS VS BPCS

Background Cont

An example of SIS

- The flammable liquid is drawn from a process source into a tank (10 meters high)
- BPCS aims to maintain tank level below 5 meters
- An alarm will be activated if liquid level in tank reaches to 6 meters.
- An explosion will happen if the level control fails for any reason and tank becomes full

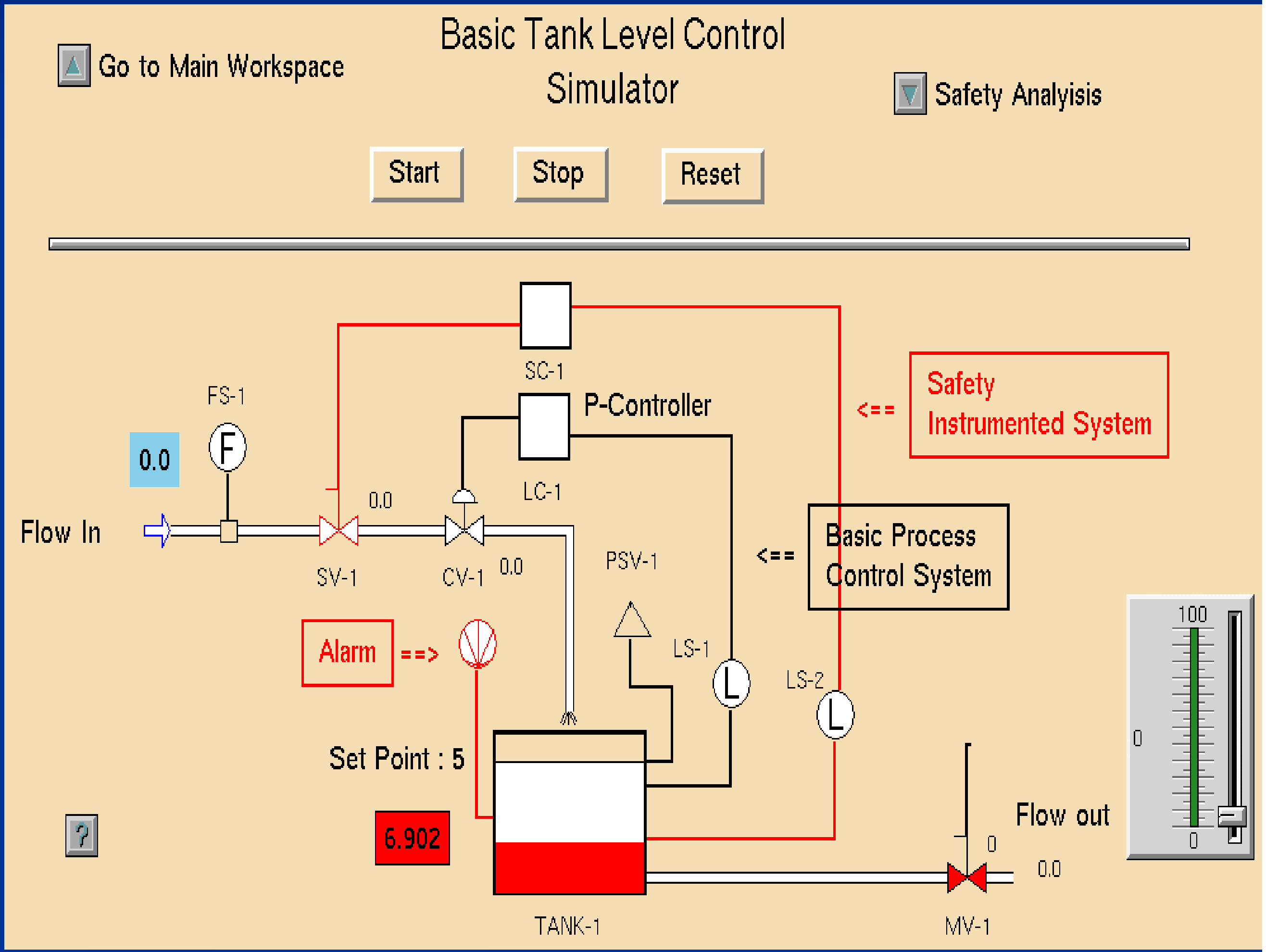


What Happen if no operator notice the alarm ???

Background Cont

An example of SIS

- A SIS, which is a simple shut down system is added
- SIS will automatically close valve SV-1 if alarm system fail
- As a consequence, whole system will be shut down until operator recognizes this hazard



Background Cont

Safety Function (SF)

What is Safety Function ?

- "Function to be implemented by a SIS, other technology safety-related system or external risk, reduction facilities, which is intended to achieve or maintain a safe state for the process, with respect to a specific hazardous event" (*IEC 61508 , 2003*)

- A set of specific actions to be taken under specific circumstances, which will move the chemical process from a potentially unsafe state to a safe state

  (*Edward and Kevin, 2003*)

- **A method to define the functional relationship between inputs and outputs in SIS**

- **Developing a SIS can be regarded as designing one or more corresponding safety functions**

Background Cont

Developing a safety instrumented system can be ... designing one or more correspond... general safety function which can... part of each SIS. This functio... **function**.

Goal: ***Propose a general methodology to develop the SIS through designing fault diagnosis function, which can be used in various process systems***

Fault Diagnosis Functio...

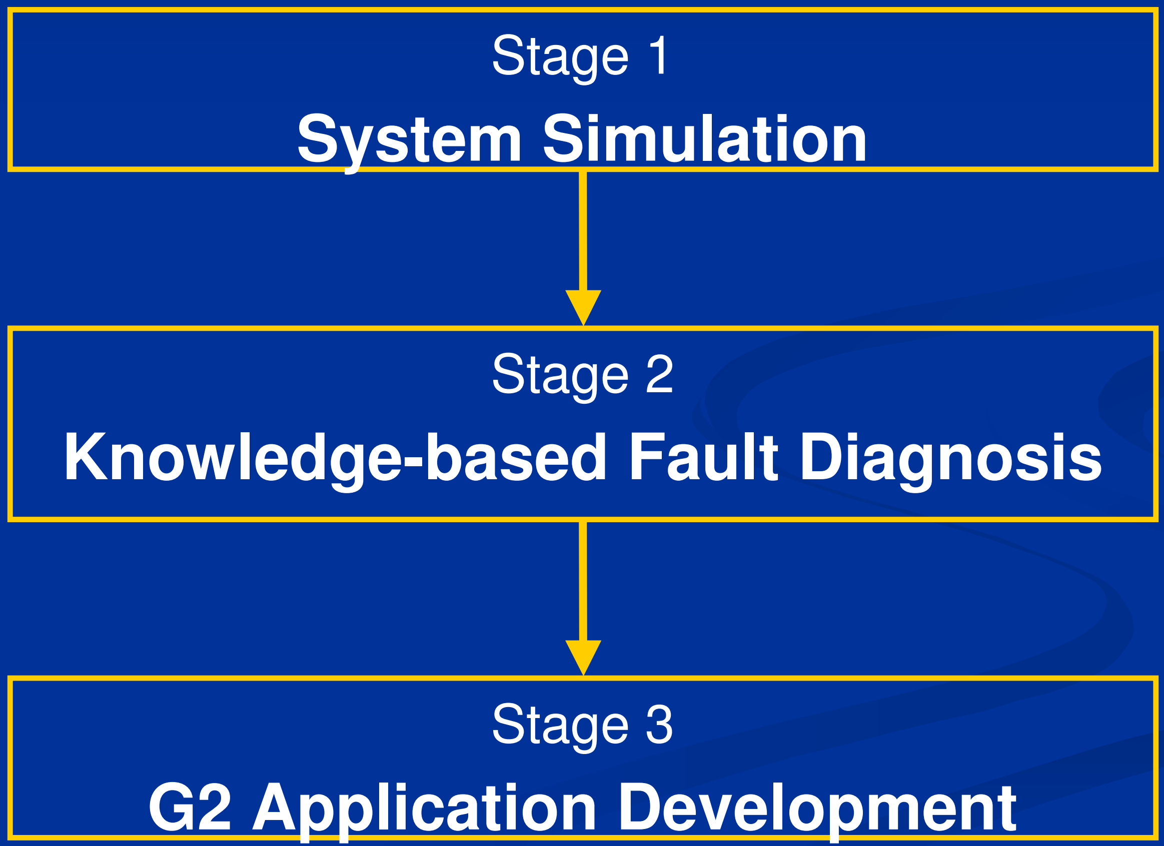
- is among the objectives... under a total process of sup... (Sharif and Grosvenor, 1998)
- is to monitor the process th... the real-time information from the lower ... (sensors) and take actions on higher level (co...llers)
- a common approach which can be applied to detect over-all faults and even faults in components

Research Contributions

- Propose a methodology for real-time fault diagnosis in process system and its use in developing real-time SIS
- Implement the proposed methodology by developing a computer based tool
- Study and evaluate the performance of the proposed methodology using developed tool.

Proposed Methodology

The proposed methodology implementation is divided into three stages



Stage 1: System Modeling and Simulation

Why use system modeling and simulation ?

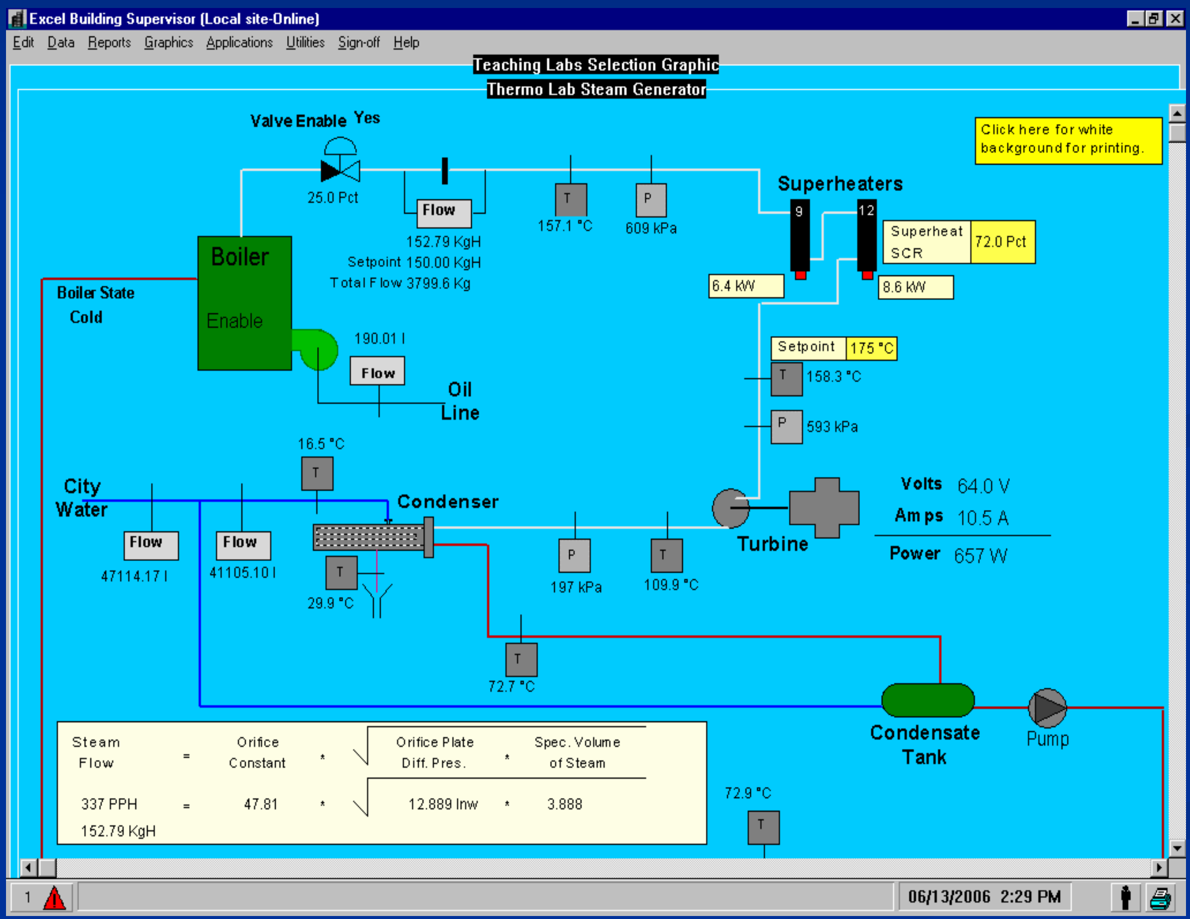
- It is a quantitative technique that examines the detailed execution of the process at a higher level
- More flexible and applicable for a developer to have a complete system simulator as a platform rather than trying to apply any extra system into real process system
- Provide a platform for designing and testing diagnosis function

Stage 1: System Modeling and Simulation Cont

System Selection: Micro Steam Power Unit in Thermal Lab

Stage 1: System Modeling and Simulation Cont

System Selection: Micro Steam Power Unit in Thermal Lab



Components of unit:

- Boiler
- Super heaters
- Steam Turbine
- Condenser
- Condense Tank
- Pump
- Other control system components

Stage 1: System Modeling and Simulation Cont

System Modeling

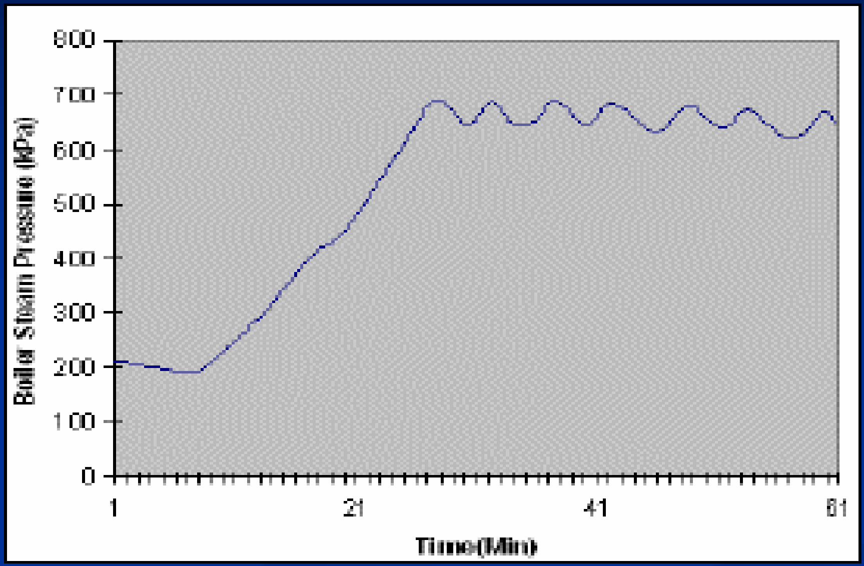
1. **Identify the order of the process model according to components of system**

- **Process Variables to Model**

  Pressure/Temperature/Flow Rate

- **Key Variable of the system**

  Steam pressure in the boiler



Trend Chart of Steam Pressure in Boiler

Second Order:

- Steam pressure in boiler
- Steam temperature in boiler
- Steam flow rate

First Order:

- Pipe time delay
- Valve Dynamic
- Super heater dynamic

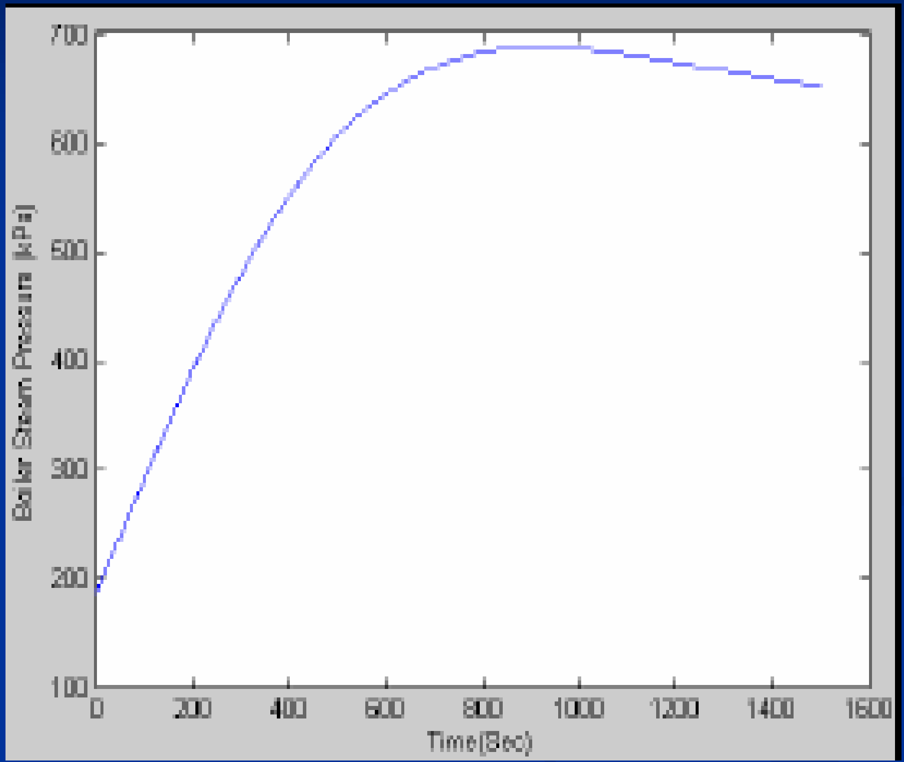
etc

Stage 1: System Modeling and Simulation Cont

System Modeling

2. **Determine model parameters based on historical trend log records**

- **Obtain system characteristics by analyzing trend log records**



Simulated steam pressure in boiler by Mat lab

Stage 1: System Modeling and Simulation Cont

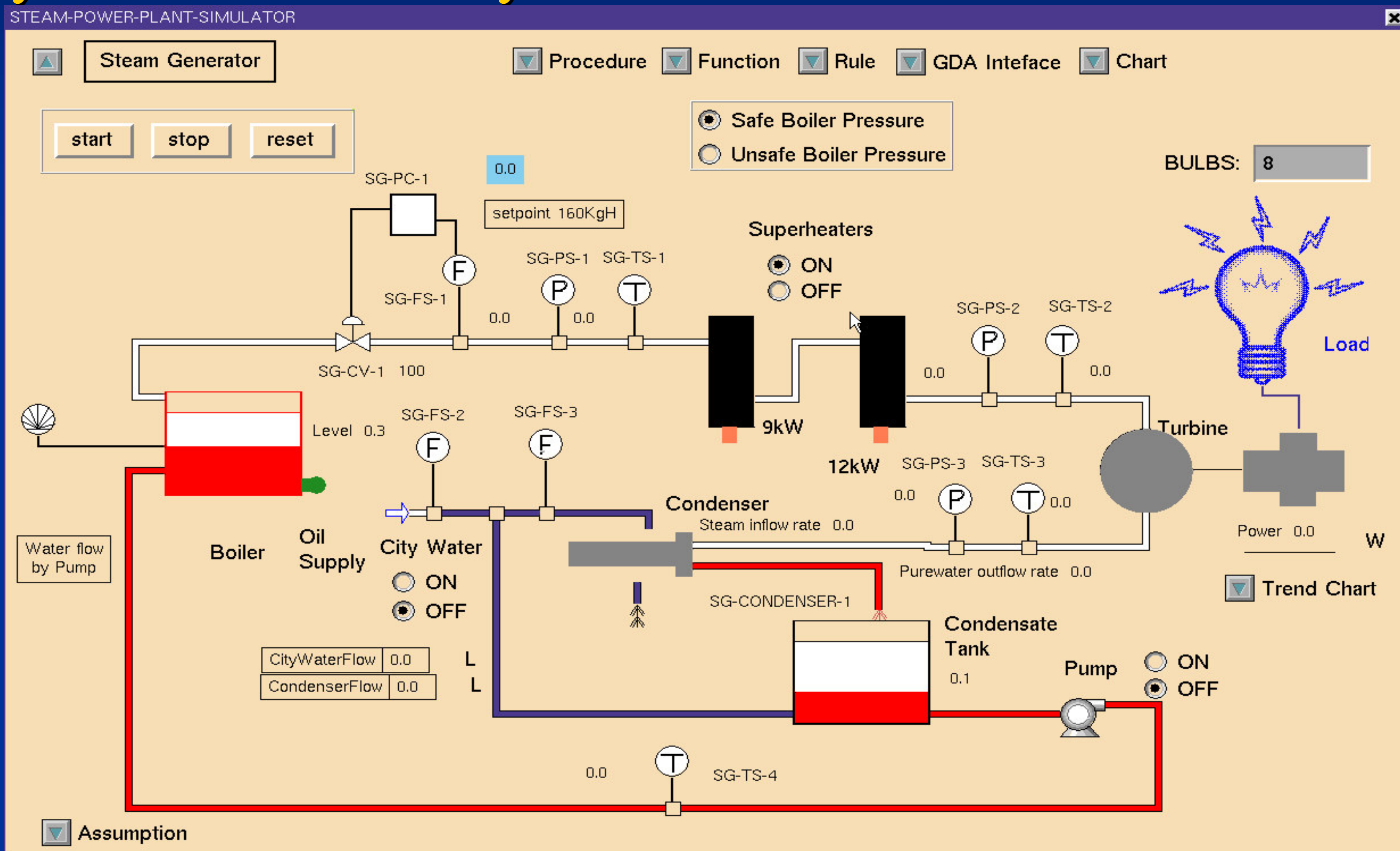
System Simulation by G2

Steps:

1. G2 Object Definition
2. G2 Equation Definition
3. G2 Procedure Development
4. G2 Rule Definition

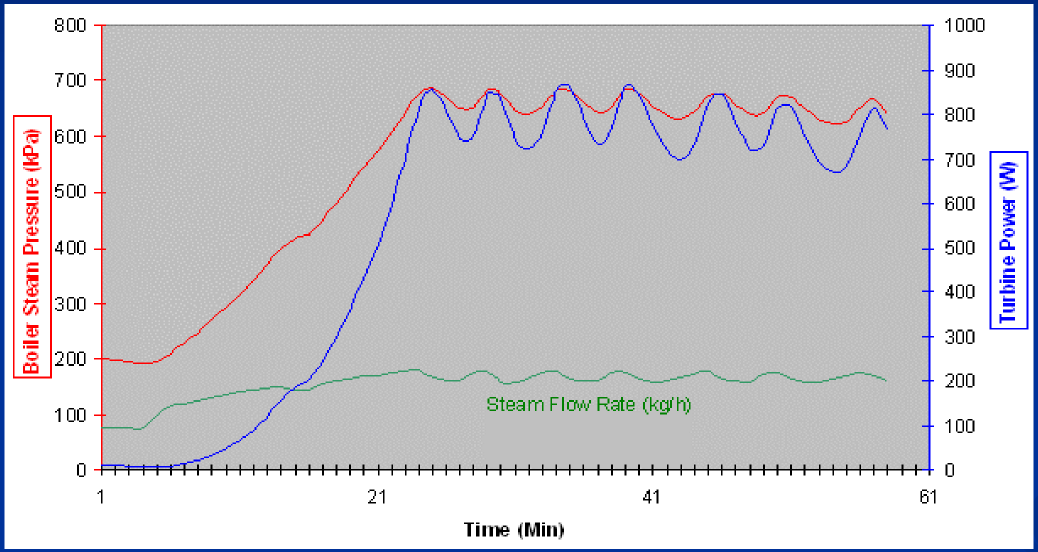
Stage 1: System Modeling and Simulation Cont

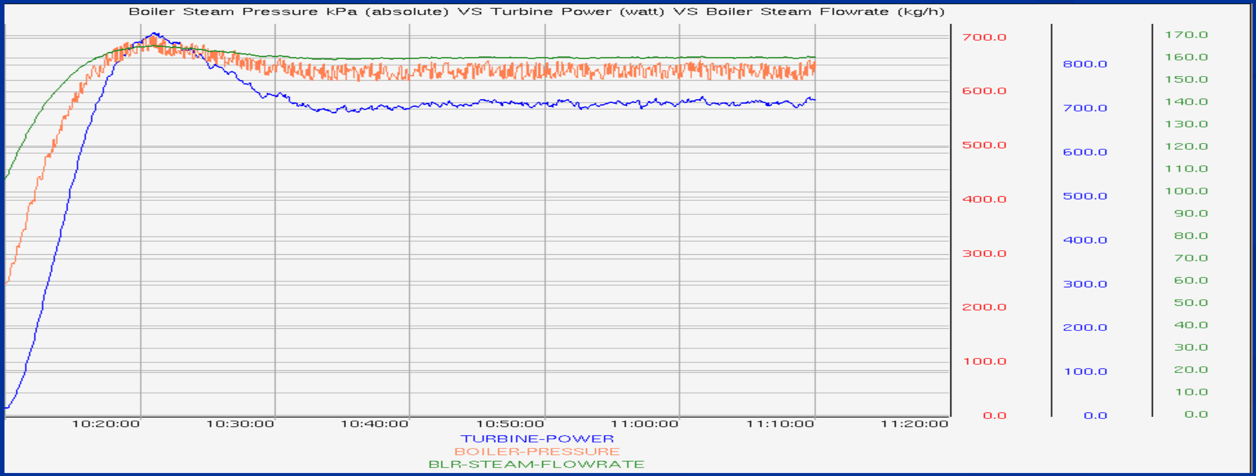
System Simulation by G2



Stage 1: System Modeling and Simulation Cont

System Verification : Daily Operations





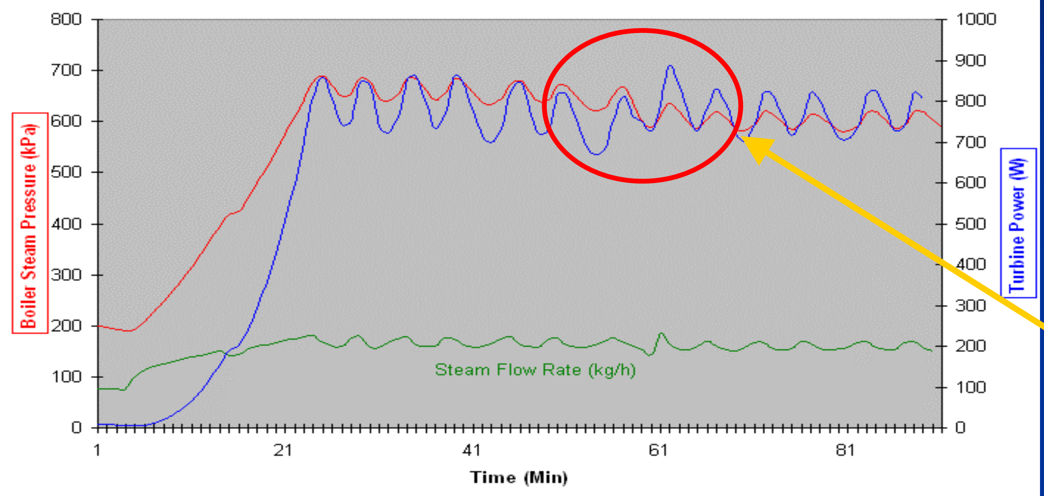
Boiler Steam Pressure (kPa)

Turbine Power (W)

Steam Flow Rate (kg/h)

Stage 1: System Modeling and Simulation Cont

System Verification: Non-Daily Operations



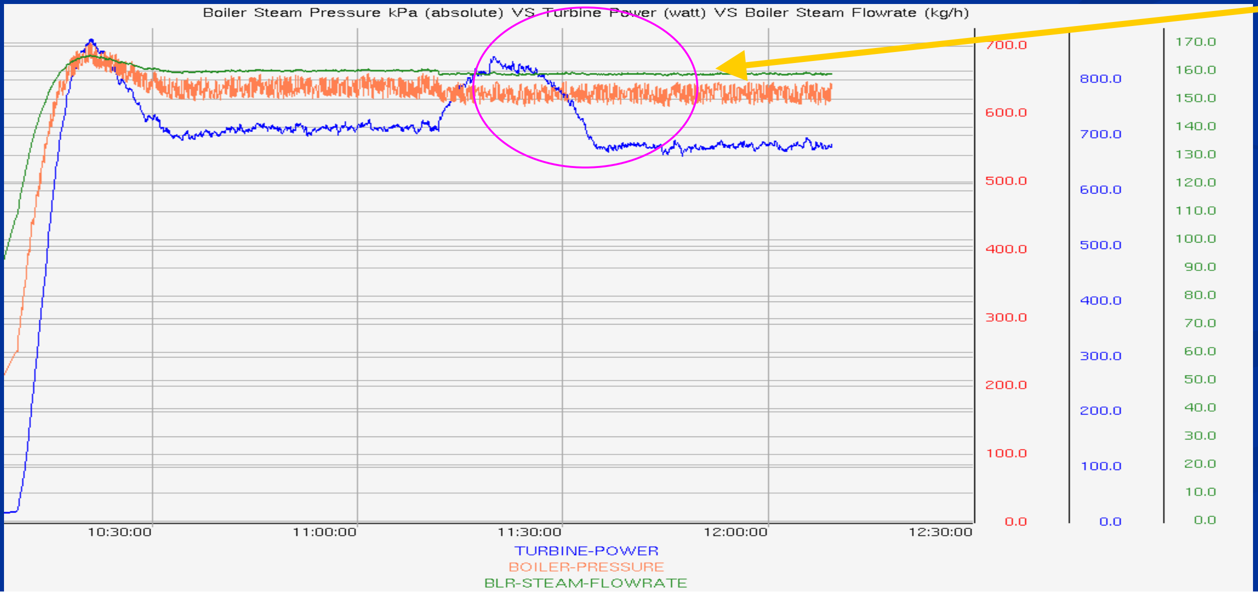
Reduce Power Load

Turbine Power (W)

Boiler Steam Pressure (kPa)

Steam Flow Rate (kg/h)

Unexpected Events



Stage 1: System Modeling and Simulation Cont

Summary

- The developed simulator is
  - Based on simplified process model
  - Built by G2 structured procedural language
- The result of the verification is acceptable for the next stage.

Stage 2: Knowledge-based Real-time Fault Diagnosis Method

What is Fault ?

- Also referred as any kind of malfunction in the actual dynamic system
- Could result from process variables, process components, or even basic control systems
- Could lead the entire process system to a critical state

- The detection and diagnosis of faults in process systems is of great significance
- Fault diagnosis method is implemented to realize the fault diagnosis function of developed safety instrumented system

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

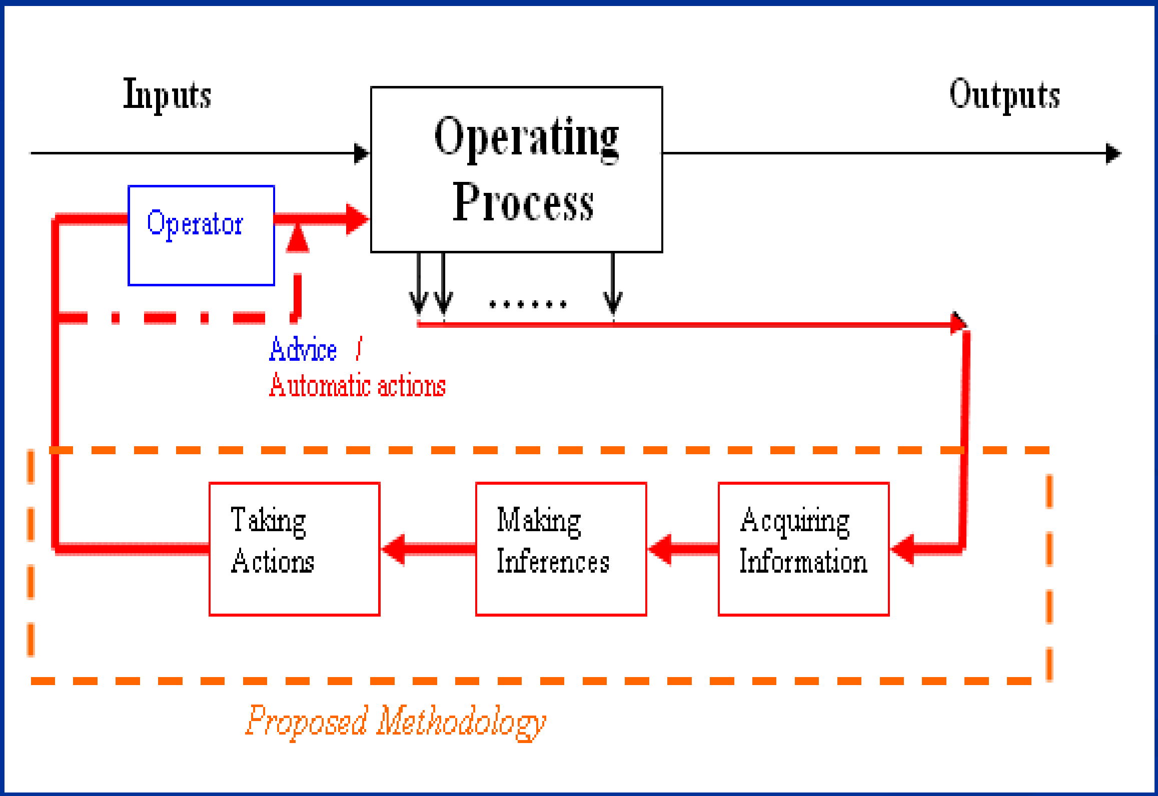
Why use Knowledge-based approach ?

- In practice it is almost impossible to obtain a model that exactly matches the process behavior
  (Lamiaa & Ibrahim, 2002)
- Knowledge-based approach is performed based on the evaluation of on-line monitored data according to a set of rules which the human expert has learned from past experience

  (Monsef et al., 1997)
- The operator and engineer's intelligence related to the specific process systems are implemented into this approach

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Proposed knowledge-based real-time fault diagnosis method



Three Steps:

1. Acquiring Information
2. Making Inferences
3. Taking Actions

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step1 : Acquiring Information

- The purpose of this step is to obtain real process data, which represents current process variables of system
- Process data contains valuable information about the state, operation, and behavior of the process plant, more so in case with limited available process knowledge

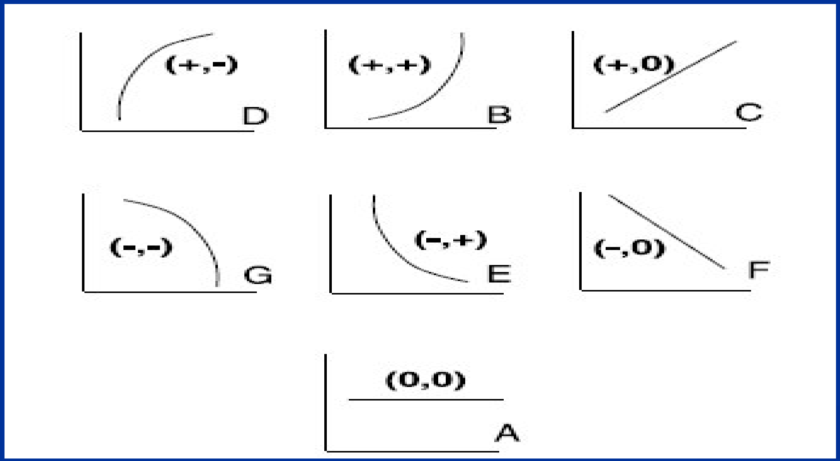
  (Sourabh et al., 2004)
- A simple and quick method is needed to extract the meaningful information from the sheer volume of real-time sensor data
- Process trend analysis is a useful approach to utilize real-time temporal patterns

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

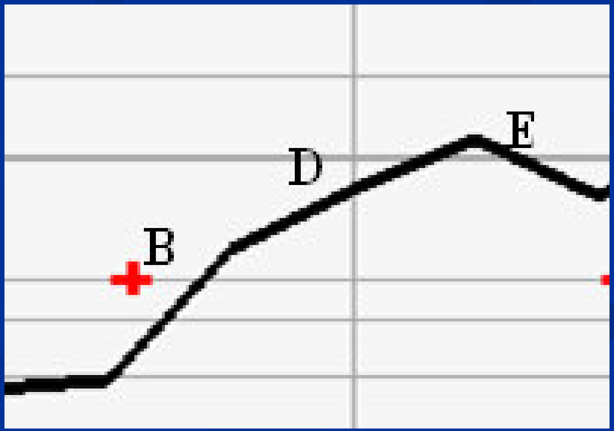
Step1 : Acquiring Information

Trend Pattern Recognition Approach

- A trend is represented as a sequence (combination) of these seven primitives
- Primitive is the fundamental element of trend description proposed by Janusz and Venkatasubramanian (1991)
- Seven Primitives : A(0,0), B(+,+), C(+,0), D(+,-), E(-,+),F(-,0),G(-,-) ,where the signs are of the first and second derivative respectively



Fundamental elements of trend: Primitives (Sourabh et al., 2003)



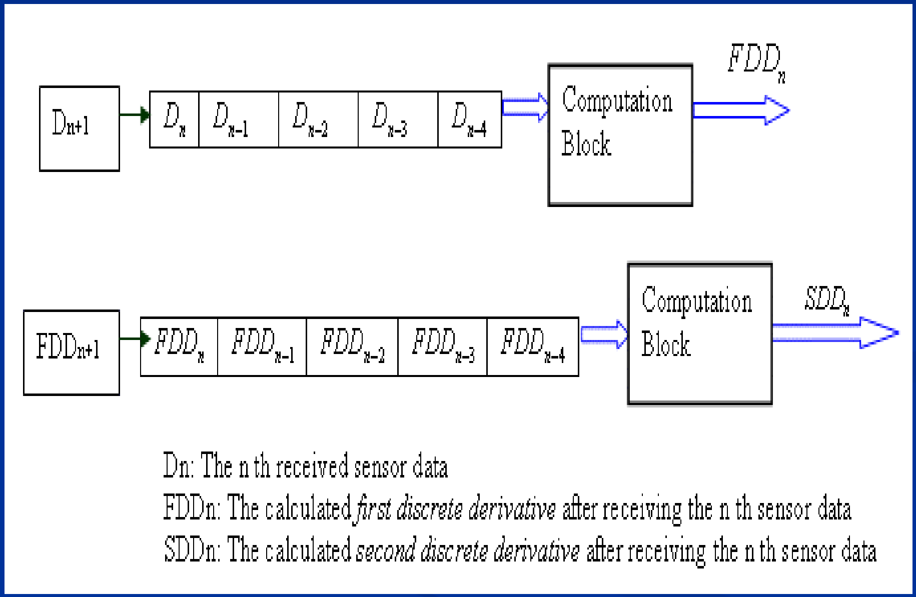
An example of BDE trend

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step1 : Acquiring Information

Primitive Identification

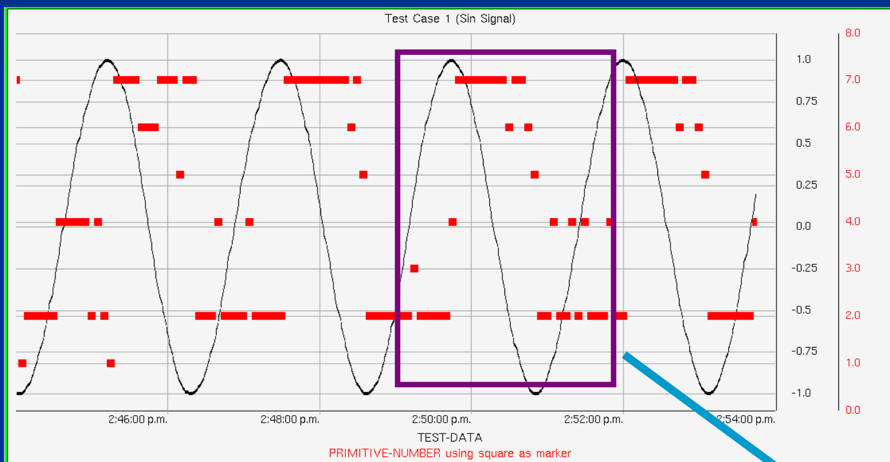
- Use Fix Window Discrete Data Primitive Identification Approach
- The discrete sensor data is collected by the fixed window and fitted by third order polynomials
- The instantaneous first discrete derivative (FDD) and second discrete derivative (SDD) are computed using general least squares fit method
- The fixed window size is specified as five and the computation is based on the new sensor data value and four most recent data value



Fixed window discrete data primitive identification approach.

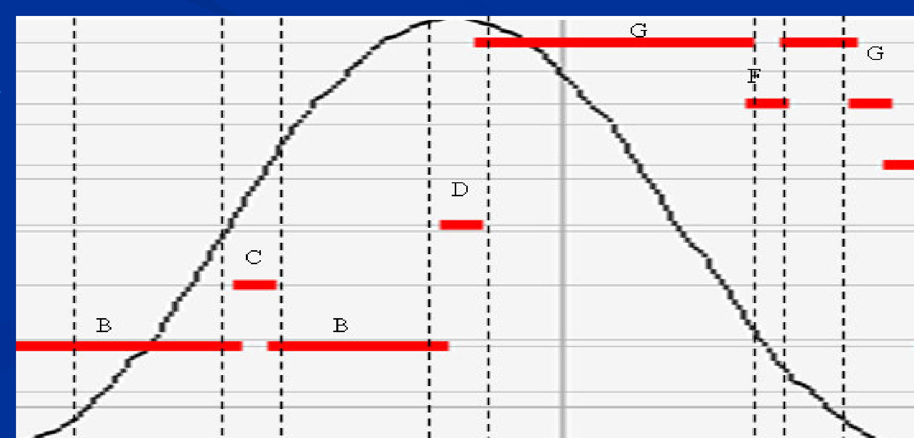
Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step1 : Acquiring Information



Result of primitive identification case study

Simulated sinusoids signal data is generated as the input of primitive identification system

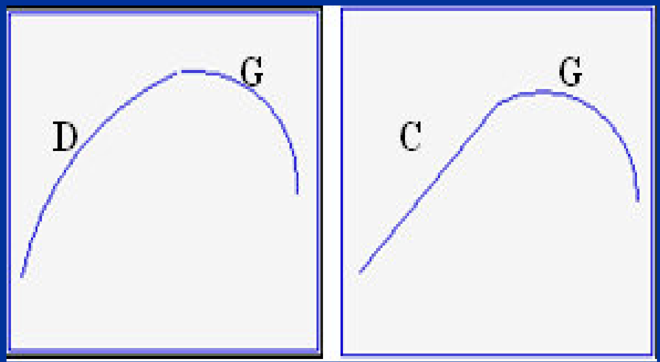


Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step1 : Acquiring Information

Trend Recognition

- Process trend is used to capture the pattern of fault event for future analysis
- Similarity Index (SI) (Sourabh et al., 2003) is used to quantify the process trends and represent the similar extent of two process trends



For example:
Trend DG, CG are similar to some extent since the shape of primitive D and primitive C are alike

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step1 : Acquiring Information

SI Computation

- The SI between two trends can be calculated by the equation below
- Table below shows the pre-defined similarity matrix between each primitive

$$SI = \frac{\sum_{i=1}^{N} Sp_i p_i^*}{N}$$

$Sp_i p_i^*$	A	B	C	D	E	F	G
A	1	0	0.25	0	0	0.25	0
B	0	1	0.75	0.5	0	0	0
C	0.25	0.75	1	0.75	0	0	0
D	0	0.5	0.75	1	0	0	0
E	0	0	0	0	1	0.75	0.5
F	0.25	0	0	0	0.75	1	0.75
G	0	0	0	0	0.5	0.75	1

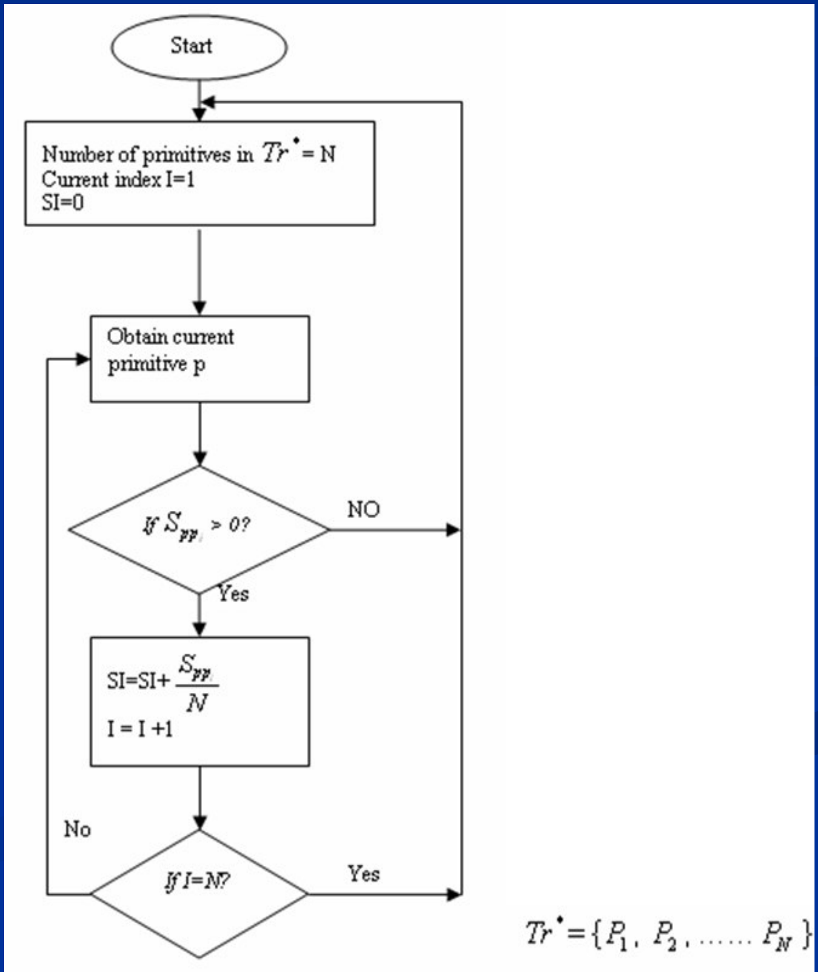
where $S_{P_i P_i^*}$ provides the similarity between P_i and P_i^*

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step1 : Acquiring Information

Algorithm of Computing SI

- First, knowledge-based trend must be determined, which includes the number and type of primitives
- Then similarity value is decided after comparing each received primitive with corresponding knowledge-based primitive
- If similarity value is not equal to zero, the current SI is calculated
- The SI computation ends when either index is equal to N or the next similarity value is zero.



Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step1 : Acquiring Information

Rate of Change (ROC)

- In addition to SI, the Rate of Change (ROC) is also used as the input of the analysis
- Represents the discrete rate of change
- Is obtained through computing the instantaneous slope for five individual input data using general least squares fit method
- Characterizes the input sensor data by determining whether and at what rate the input is increasing or decreasing
- Comparing with SI, ROC is capable of quantifying the temporal pattern of sensor data

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step2 : Making Inferences

Fuzzy Inference System (FIS)

- An inference system based on both expert knowledge and fuzzy logic
- Has the capability of converting the numeric data into linguistic variables
- Be able to handle the impreciseness of process trend
- Have been successfully applied in fields such as automatic control, data classification, decision analysis, etc (Marcellus, 1997)

For detail information about Fuzzy Logic, please refer to a paper (Zadeh, 1988) by Dr.Zadeh.

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step2 : Making Inferences

Application of Fuzzy Inference System

- Expert knowledge is mapped with the knowledge-based fault process trend (pattern) in the form of fuzzy if-then rules
- For example a rule might read :

  If sensor S1 shows Tr1 AND ROC of sensor S1 is large, then the fault F1 is most likely to happen

- This rule implies that if sensor S1 has been observed with process trend Tr1 and at the same time its value increases significantly, then the possibility of F1 fault event occurring is extremely high
- Tr1 is knowledge-based process trend, which has been recognized as a fact by the experts based on their experiences

Stage 2: Knowledge-based Real-time Fault Diagnosis Method Cont

Step 3 : Taking Actions

- The objective of this step is to guide the process back to normal in the case of abnormal conditions.
- Can be achieved by developing set of actions which include activating safety measures and higher layer of protection

Stage 3: G2 Application Development

G2 software is chosen as the developing platform

The aims of developing computer application is:

- To provide the platform for testing proposed methodology
- To enhance the performance of the safety system
- To decrease the response interval between detecting fault and taking further actions

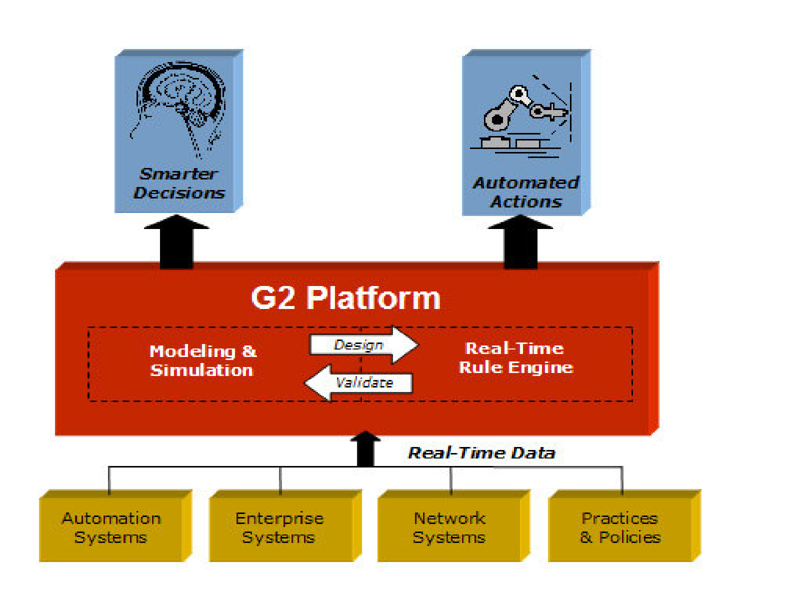
Developed c… applicatio… following ca…

- Rule-based reasoning
- Event detection
- Diagnosis capabilities
- Connectivity
- Integrated intelligent technologies

Stage 3: G2 Application Development Cont

G2 Real-time expert system from Gensym

- Gensym Corporation is a leading provider of rule engine software and services for mission-critical solutions that automate decisions in real time
- Gensym's flagship G2 software applies real-time rule technology for decisions that optimize operations and detect, diagnose, and resolve costly problems
- G2 is the world's leading real-time engine platform and uniquely combined real-time reasoning technologies including rules, object modeling simulation, and procedures in a single development and deployment environment



G2 platform (www.gensym.com)

For more information , please go to www.gensym.com

Stage 3: G2 Application Development Cont

GDA : G2 Diagnosis Assistant

GDA

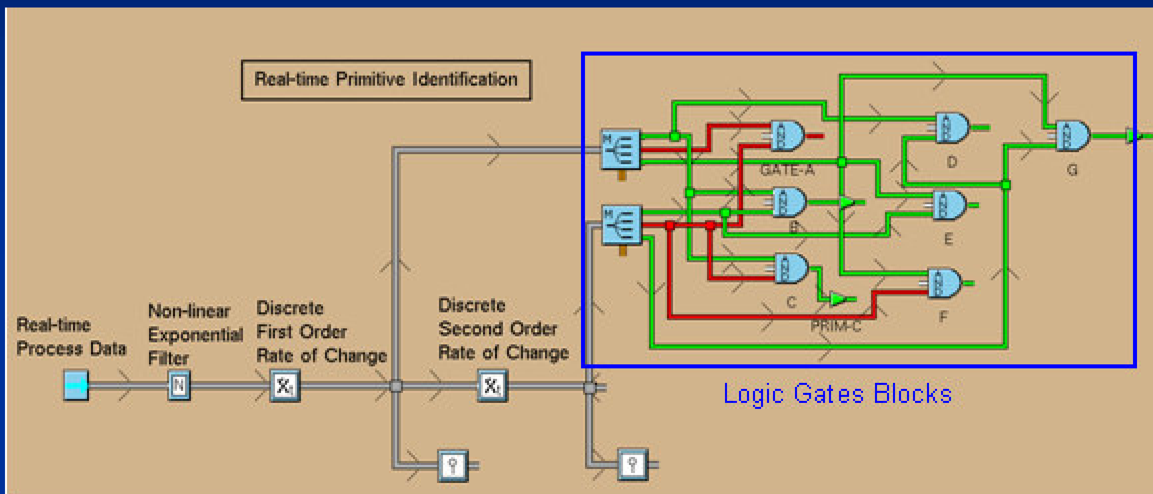
- Is an environment for developing and running intelligent operator applications
- Its principal component is a graphical language that lets user express complex diagnostic procedures as a diagram of blocks

A GDA application contains various schematic diagrams, which have capability of :

- Acquiring data from real-time processes
- Making inferences based on the data
- Taking actions based on the inference values, such as raising alarms, sending messages to operators, or concluding new set points

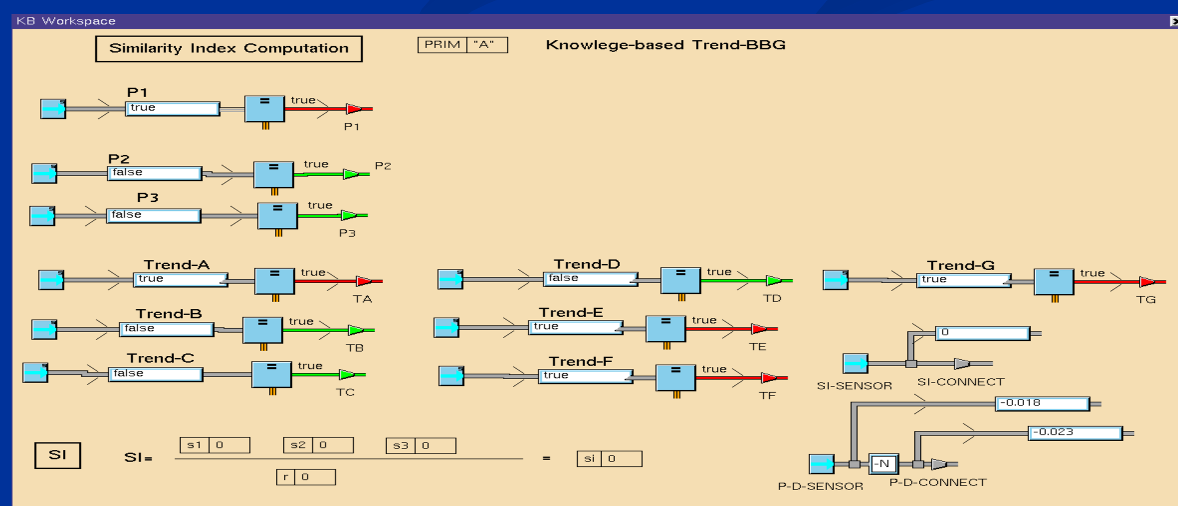
Stage 3: G2 Application Development Cont

Developing GDA Application



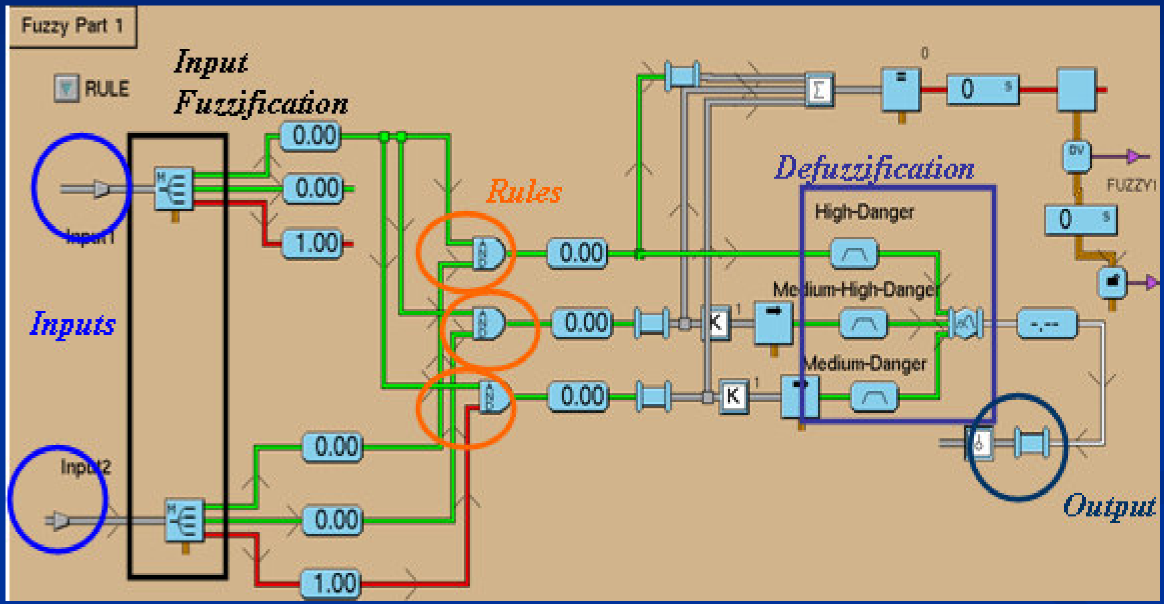
Primitive Identification

Similarity Computation



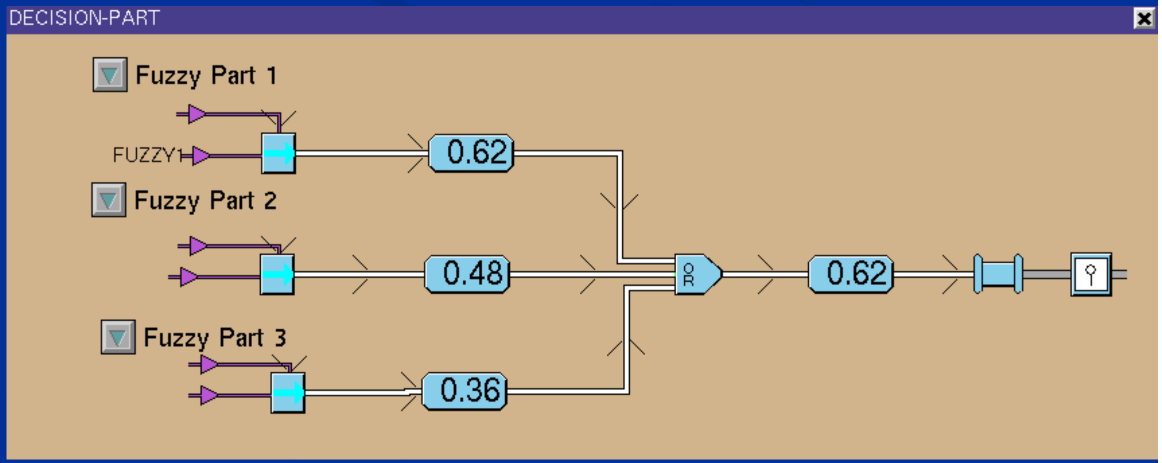
Stage 3: G2 Application Development Cont

Developing GDA Application



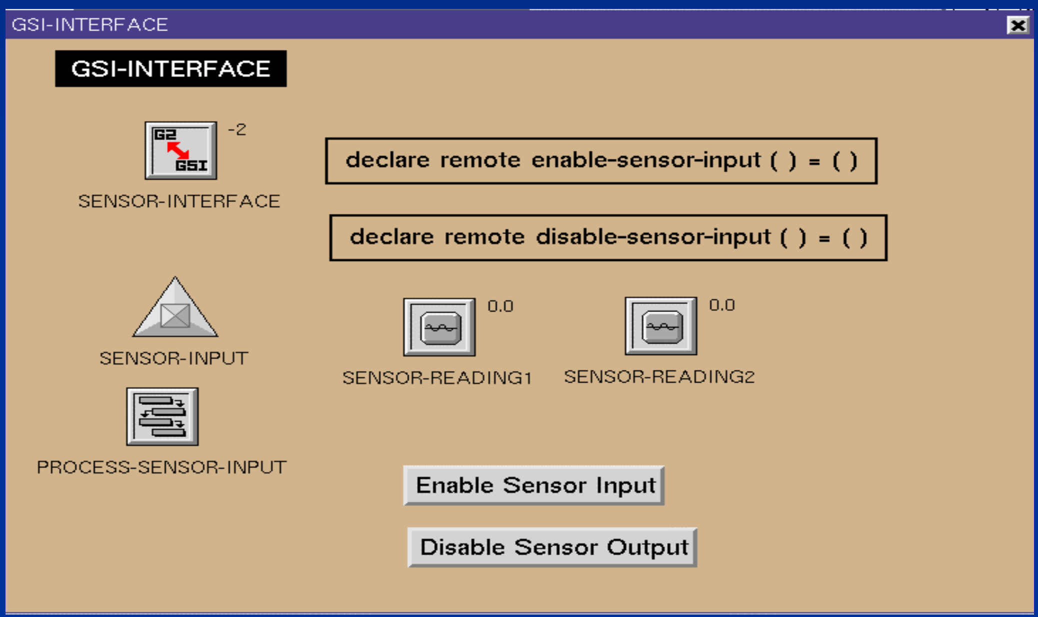
Fuzzy Logic System Implementation

Fuzzy Logic Final Output



Stage 3: G2 Application Development Cont

Developing GDA Application



- G2 Gateway Standard Interface (GSI) object needs to be generated to allow GDA application to communicate with external process sensors
- "C" compiled application is created in monitor workstation to obtain real-time sensor reading

Case Study

- In order to verify the capability and efficiency of the proposed methodology, two case studies are performed
- The developed GDA application with diagnosis function is demonstrated on a variety of situations

- Case Study 1: Fault Event Detection in a Micro Steam Power Unit Using Simulated Data
- Case Study 2: Abnormal Material Temperature Drop (real-time industrial data)

Case Study Cont

Case Study 1

- The input data is generated by the developed micro steam power unit
- The purpose of this case study is to test the performance of the developed GDA application before applying it into real process system

Fault Event Definition

1) The trend pattern of steam pressure in boiler during this specific event can be recognized as BBG
2) Steam pressure suddenly increase or decrease significantly

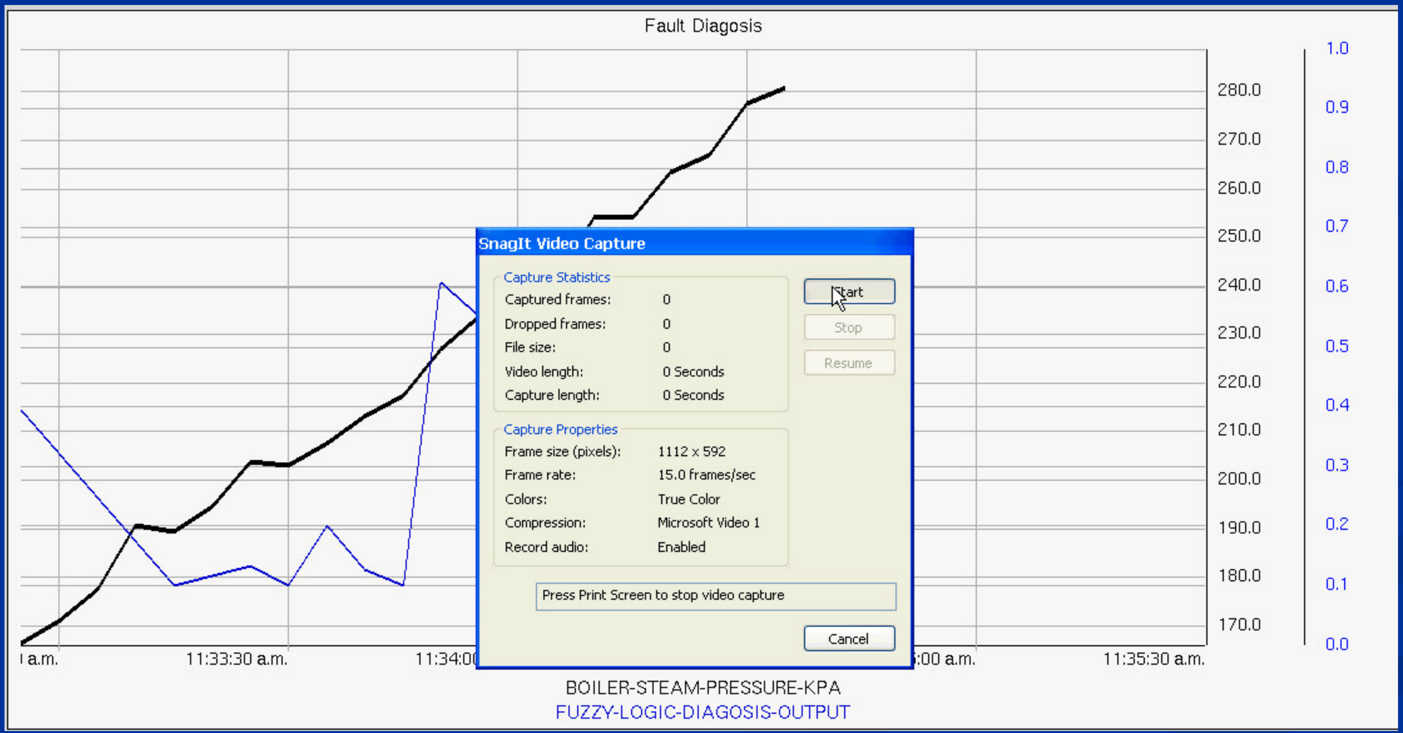
Critical Operation Condition

1) FIS output threshold is set to 0.85
2) The number of recurring outputs beyond threshold in 3 minutes is set to 3

Case Study Cont

Case Study 1: Testing Results

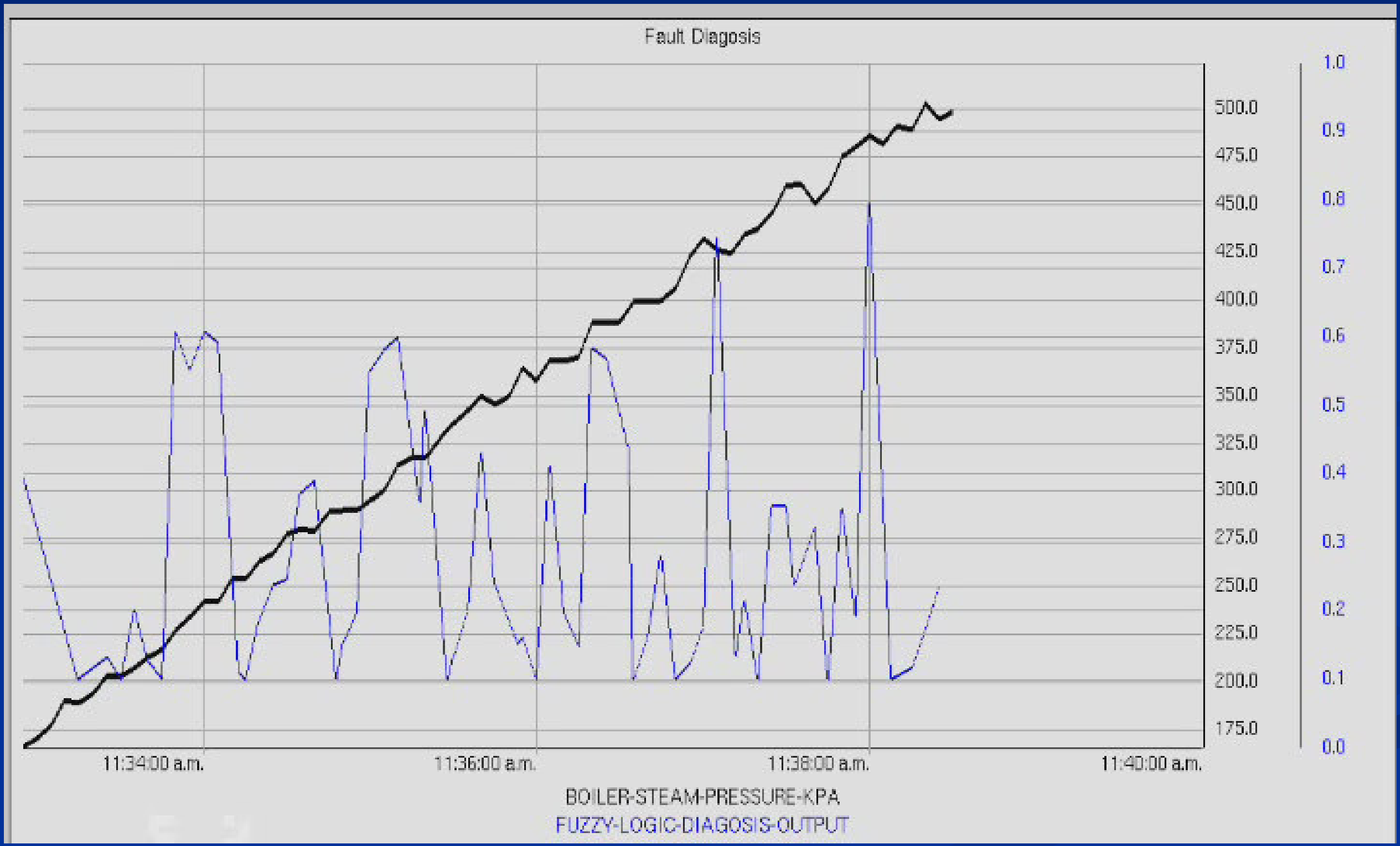
- Micro steam power unit simulator is activated under normal process conditions
- The identified fault event is also generated during the simulation



When it starts…..

Case Study Cont

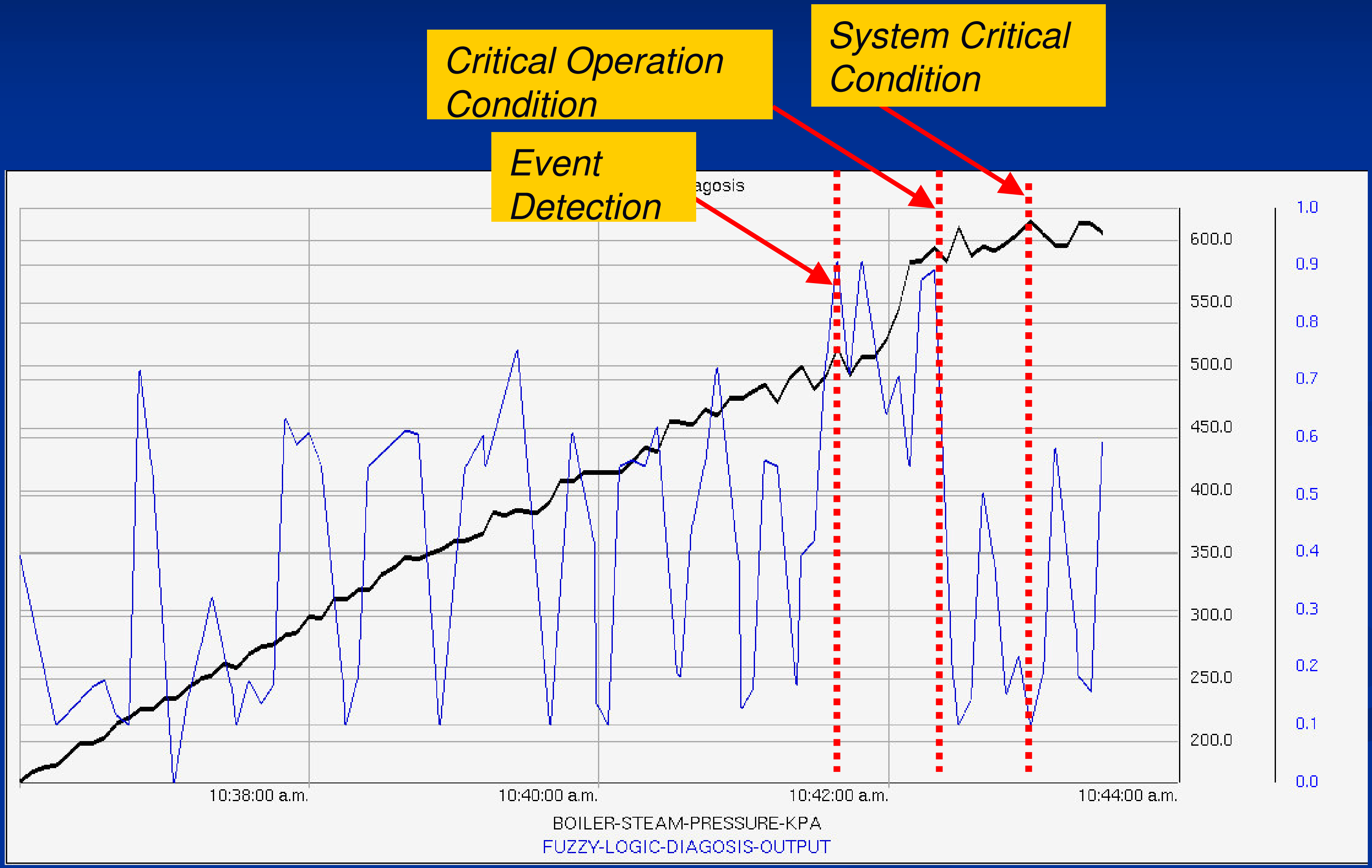
Case Study 1: Testing Results



When fault event happen

Case Study Cont

Case Study 1: Testing Results



Case Study Cont

Case Study 2

- The developed GDA application is tested in real process system
- Three fluid chemical samples are heated under high pressure
- When temperature reaches around 100 degrees Celsius, the heater will be suddenly shut down
- Due to this unexpected operation, the temperature of heated samples will start to reach beyond the normal operating level
- The test is performed using Advanced Reactive System Screening Tool (ARSST™) device

Case Study Cont

Case Study 2

ARSST

- is designed to simplify the acquisition of data necessary for thermal hazards analysis, runaway reaction evaluations, and the proper sizing of pressure relief vents
- is located in the Health, Safety and Risk Engineering Lab in the Inco Innovation Centre of Memorial University and is used for the purpose of graduate student experiments

The picture of ARSST standard containment vessel

Case Study Cont

Case Study 2

Three chemical samples, which are used in this case study are

- Water (H_2O)
- Sodium hydroxide solution
  ($NaOH$, 1.60 mg/ml)
- Methyl red
  ($C_{15}H_{15}N_3O_2$, 0.1%)

Fault Event Definition

1) Trend pattern of sample temperature during this specific event can be recognized as GGB
2) Sample temperature suddenly decreases significantly

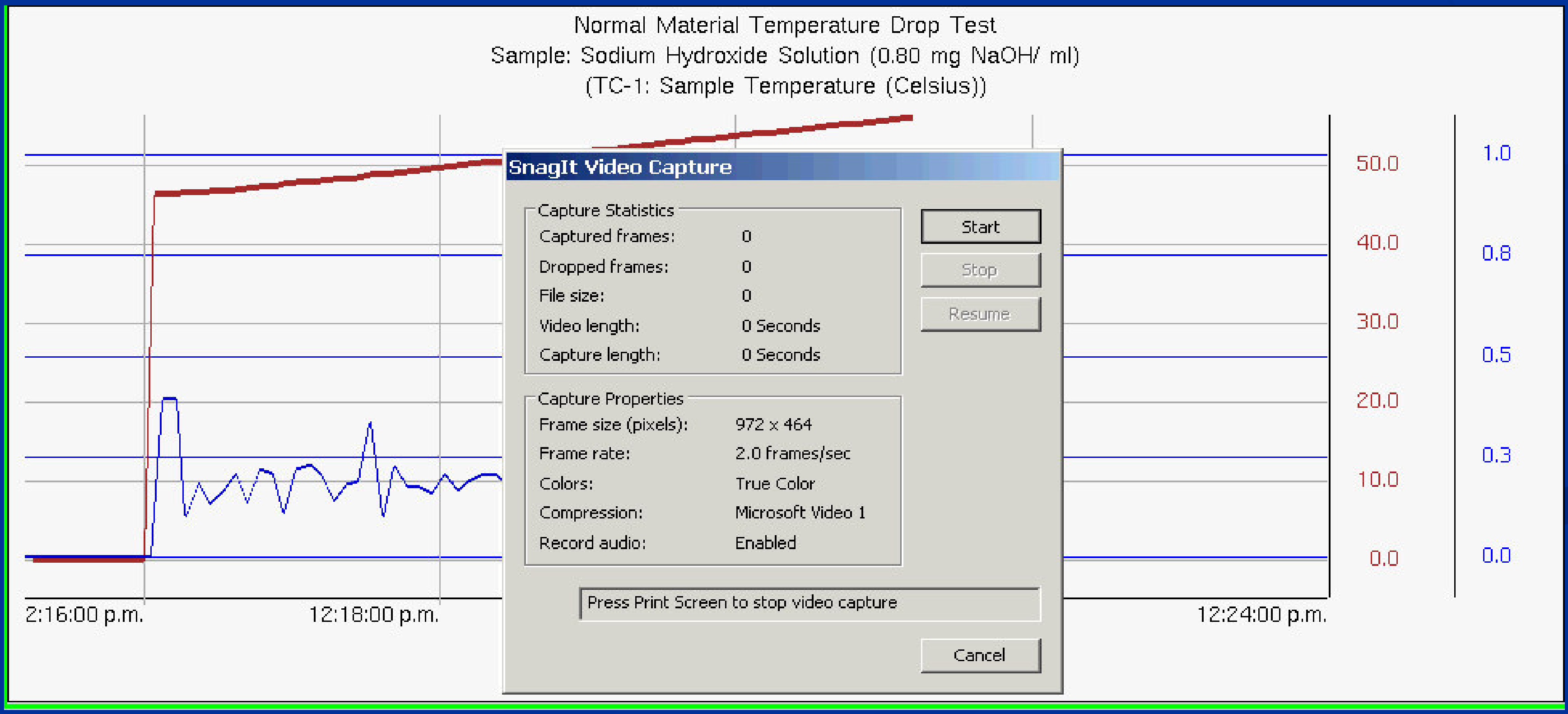
Critical Operation Condition

1) FIS output threshold is set to 0.88
2) The number of recurring outputs beyond threshold in 5 minutes is set to 4

Case Study Cont

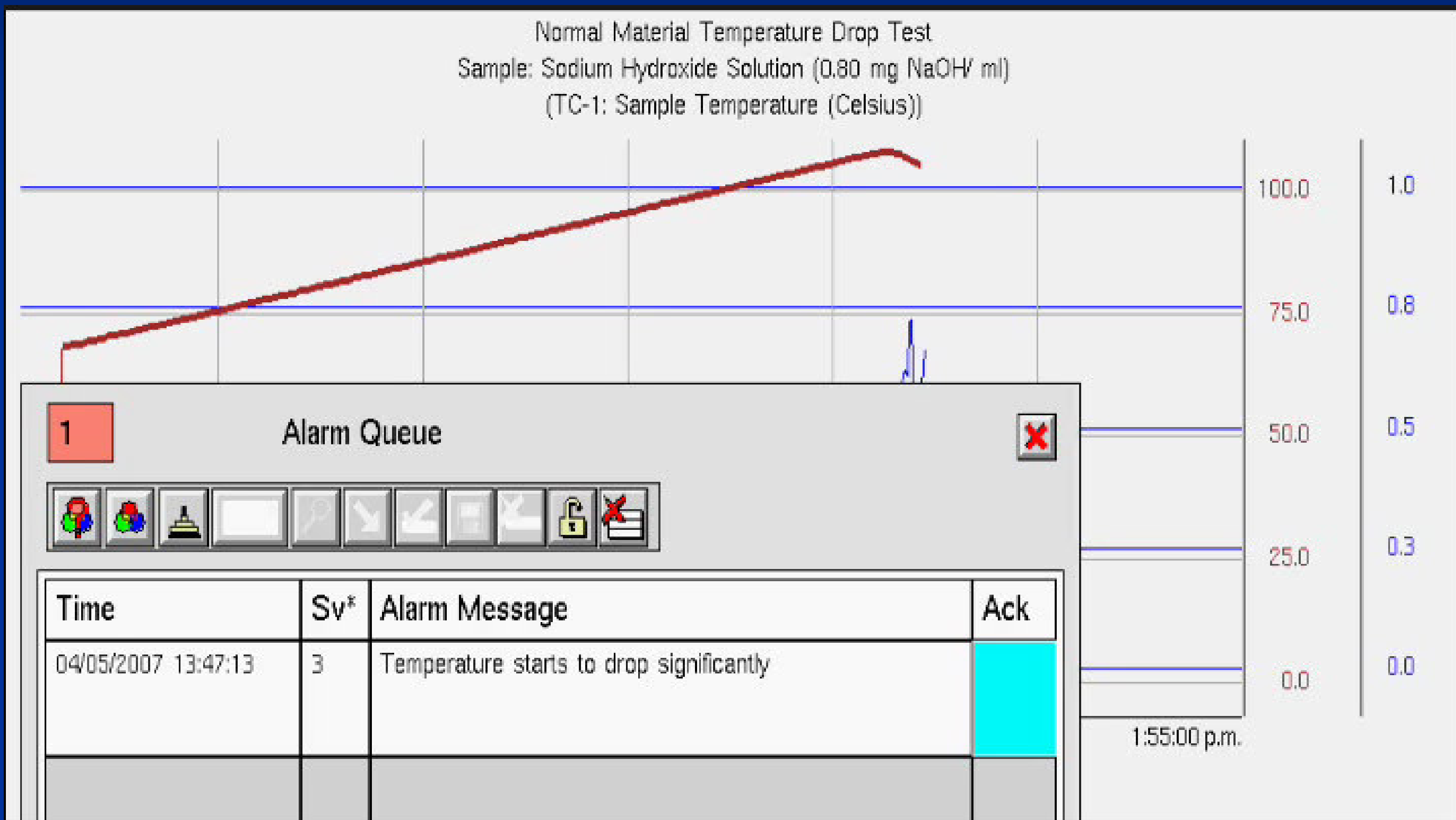
Case Study 2: Testing Results

- Three chemical samples are heated at a rate of 2 degrees Celsius per minute under pressure of 120 Psi using ARSST containment
- The output of thermal couple TC-1 is obtained through a DAS (Data Acquisition) card installed on the system monitor workstation
- the heater is turned off when sample temperature reached around 100 degrees Celsius



Case Study Cont

Case Study 2: Testing Results

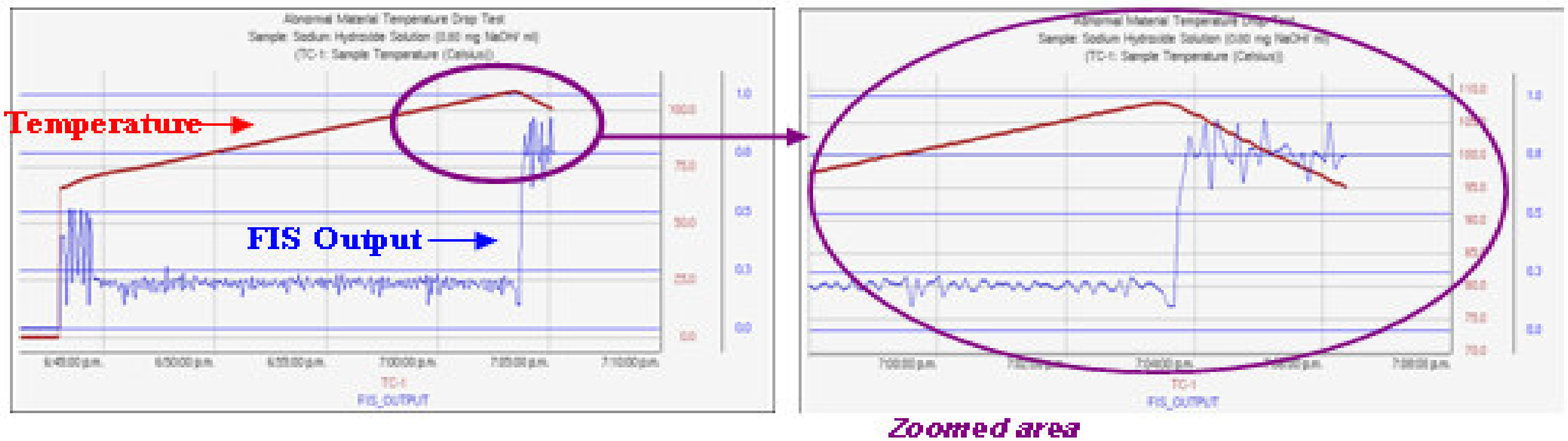


When fault event happen

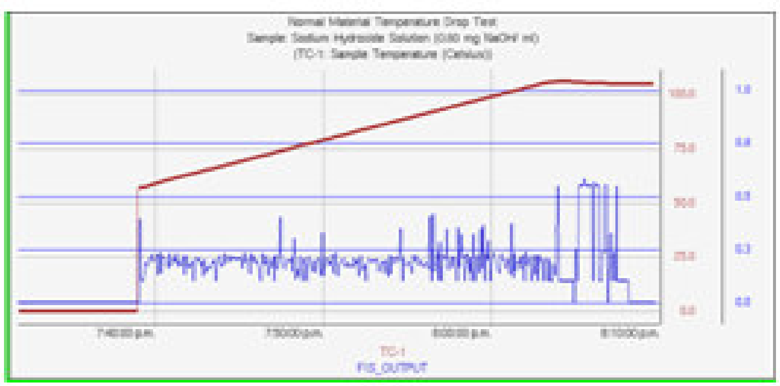
Case Study Cont

Case Study 2: Testing Results

Sodium hydroxide solution *fuzzy logic diagnosis output (Abnormal temperature drop)*



Sodium hydroxide solution *fuzzy logic diagnosis output (Normal temperature drop)*

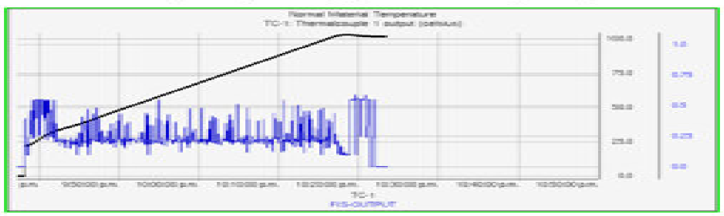


Case Study Cont

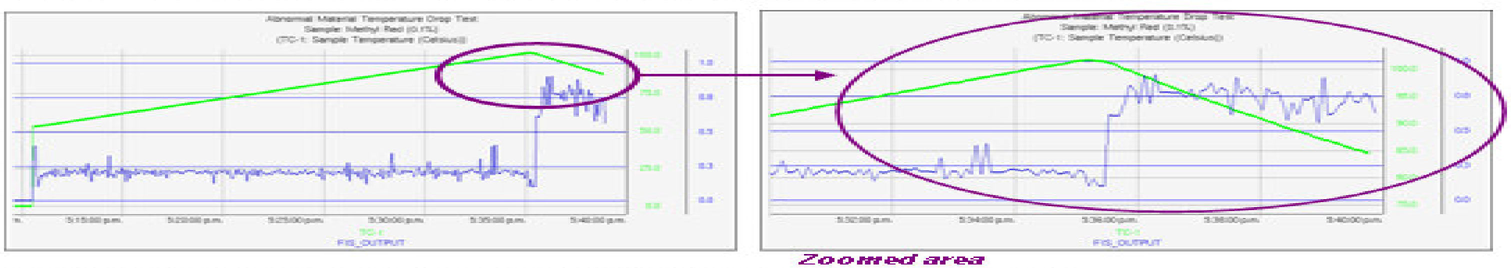
Case Study 2: Testing Results

Water *fuzzy logic diagnosis output (Abnormal temperature drop)*

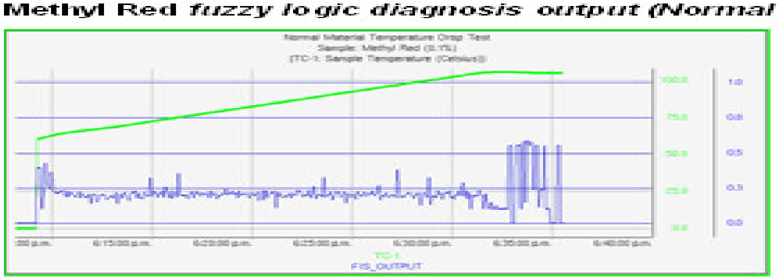
Water *fuzzy logic diagnosis output (Normal temperature drop)*



Methyl Red *fuzzy logic diagnosis output (Abnormal temperature drop)*



Methyl Red *fuzzy logic diagnosis output (Normal temperature drop)*



Conclusions

- Fault diagnosis function is a common safety function, which works as an approach to develop a general SIS suited to various process systems
- Proposed Methodology provides a fundamentally simply way to handle complex process systems without making itself exceedingly complex
- It is straightforward, flexible, and easy to develop and understand
- The performance can be enhanced by future works

Future Works

- The accuracy of primitive identification can be improved by introducing a redundancy majority voting system: Two-out-of-Three (2oo3)
- FIS method could be improved by defining more trend patterns
- As knowledge-based fault diagnosis method is data-driven, the performance is dependent on the quality of expert knowledge and frequency of data processing. This could be further strengthened by integrating such a data-driven method with a simple model-based method

Publications

- Nan, C., Iqbal, M.T., & Khan, F.I. (2006). Modeling and simulating a micro steam power unit using G2 real-time expert system. presented at IEEE NECEC 2006 , St.Johns, Newfoundland.

- Nan, C., Khan, F.I., & Iqbal, M.T.(2007). Abnormal process condition prediction (fault diagnosis) using G2 expert software . accepted for presentation at Canadian Conference on Electrical and Computer Engineering Vancouver 2007.

- Nan, C., Khan, F.I., & Iqbal, M.T.(2007). Real-time fault diagnosis using knowledge-based expert system. (in process)

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Thank You !

Q and A ?