COMPUTER BASED CORE MONITORING SYSTEM

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Abstract

Availability of powerful microprocessors enable on-line burnup calculation, reactivity balance calculation, thermal balance calculation, clad hot spot calculation, detection of flow blockage in coolant channel and coolant boiling. Fast Breeder Test Reactor at India is monitored by on-line computer systems. Flow in every fuel subassembly, clad hot spot and power excursion in the reactor core are monitored by an on-line Fault-tolerant Computer System. Entire hardware and software has undergone detailed verification and validation by an independent safety committee. Hardware and software design of computer systems for core monitoring are detailed in the paper. The design of on-line diagnostics is explained with the help of a “fault tree” diagram for computer system. The verification and validation methodology is outlined. The experience gained in the operation and maintenance of the system is discussed. The hardware and software feature to prevent “tampering” of the system is detailed. Configuration methodology is discussed with practical example encountered at the site.

Introduction

Normally reactor core is provided with in-core flux sensors, thermocouples, flow meters, acoustic sensors, etc. The signal from the in-core flux sensors needs to be processed for flux mapping, reactor power, period and reactivity. The outlet temperature from each fuel subassembly needs to be monitored for detection of flow blockage, clad hot spot and undesirable power excursion. On-line statistical analysis of the acoustic sensor signal is required for the detection of coolant boiling in the core. Availability of powerful computer systems enable on-line processing of in-core sensor signals.

Core monitoring

Fast Breeder Test Reactor at Kalpakkam, India is a loop type sodium cooled fast reactor (40 MWt, 13.5 MWe). A mixture of plutonium carbide (70%) and natural uranium carbide (30%) is used as fuel with nickel and stainless steel assemblies as radial reflectors. Since the power density is above 500 KW/l, any blockage of coolant may lead to fuel melt down. Hence, it is necessary to monitor the temperature rise in every fuel subassembly. The outlet temperature of the coolant from each fuel subassembly is measured by two Cr-Al thermocouples. Flow guides, connected to mobile core cover flat, guide five percent of the coolant to the thermocouple. Ungrounded thermocouples are used to overcome the effect of common mode ground voltage (noise). The temperature signals from the reactor core are scanned every second by Fault-tolerant Computer System (Figure 1). The temperature of the cold junction box is sensed separately by RTD sensors and are processed by the computer system every 20 seconds.

A non-linear look up table is used for conversion of electrical value to physical value. The outlet temperature signal of fuel subassembly is compared with the reactor inlet temperature for signal validation. When the reactor is at the shut down state, the computer print out of fuel subassembly outlet temperatures enable to identify the “static error” in the individual thermocouple signal.

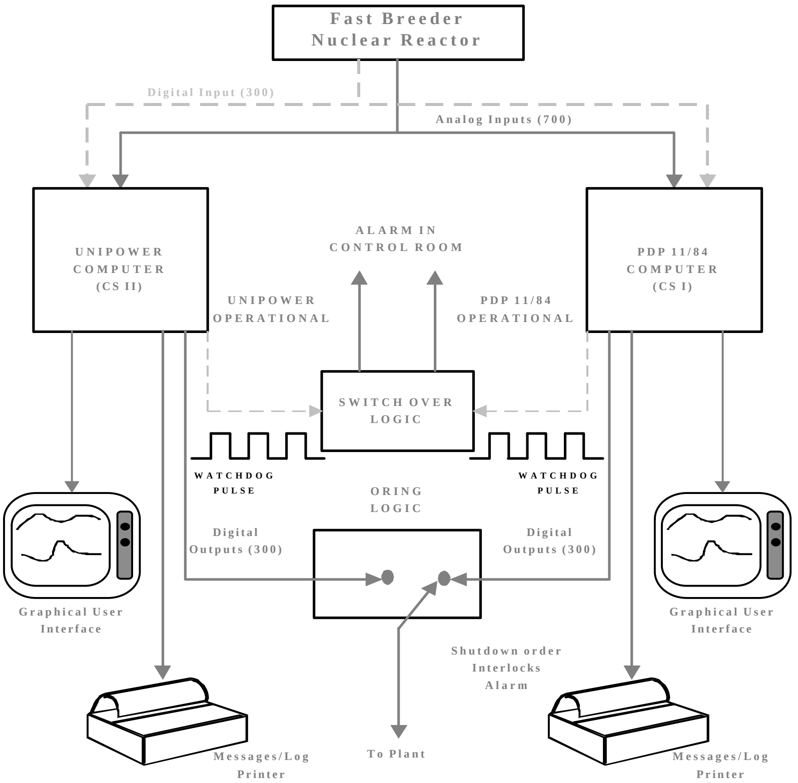
The fluctuation in the temperature signal is about 0.5°C at shut down state. However, the fluctuation increases to 2°C when the temperature rise in the reactor core (DT) raises to 150°C, which corresponds to 10.4 MWt. The response time of thermocouple, sensing the coolant temperature of central subassembly is 500 m sec.

The mean outlet temperature of all the subassemblies is calculated every second and is compared against alarm and trip limits. Similarly, the mean gradient (mean outlet temperature reactor-inlet temperature) is compared against alarm / trip limits.

If the mean value or mean gradient crosses the respective limit than corresponding action (alarm or trip) is initiated by the computer system. Relevant error messages are displayed in CRT terminal.

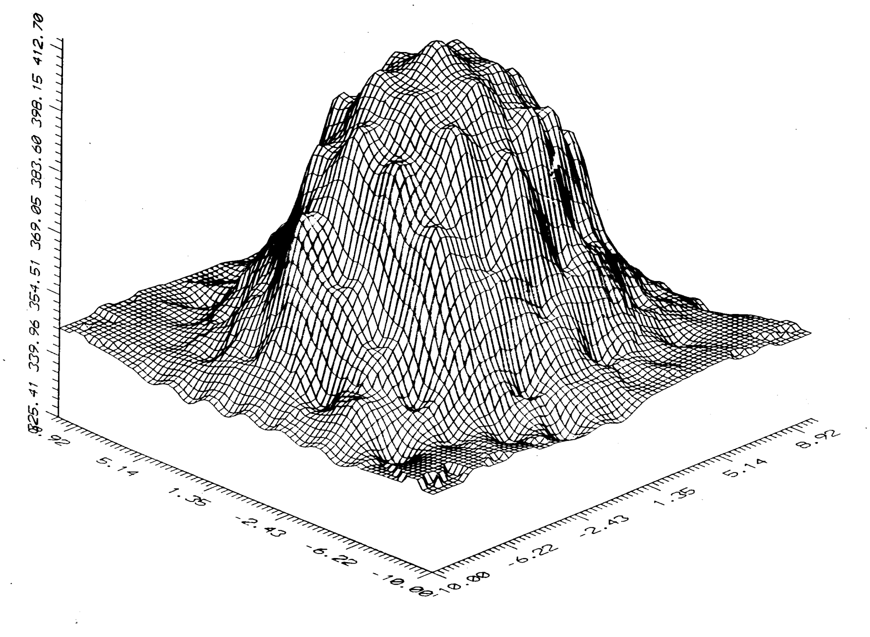
For every fuel subassembly a constant ‘ai’ is computed as the ratio of actual temperature rise and the mean temperature gradient. Normally ‘ai’ is greater than unity for the central fuel subassembly and is less than unity for the peripheral fuel subassembly. In spite of flow zoning, the temperature distribution is not uniform across the fuel subassemblies (Figure 2).

Figure 1. Architecture of fault tolerant computer system



- NORMALLY PDP 11/84 WILL BE SUPERVISING WITH UNIPOWER AS ACTIVE STANDBY
- IF BOTH PDP 11/84 AND UNIPOWER ARE NOT OPERATIONAL, SHUTDOWN WILL BE ORDERED TO THE PLANT
- SWITCH OVER LOGIC HAS 'MANUAL' AND 'AUTO' MODE FOR SWITCH OVER

Figure 2

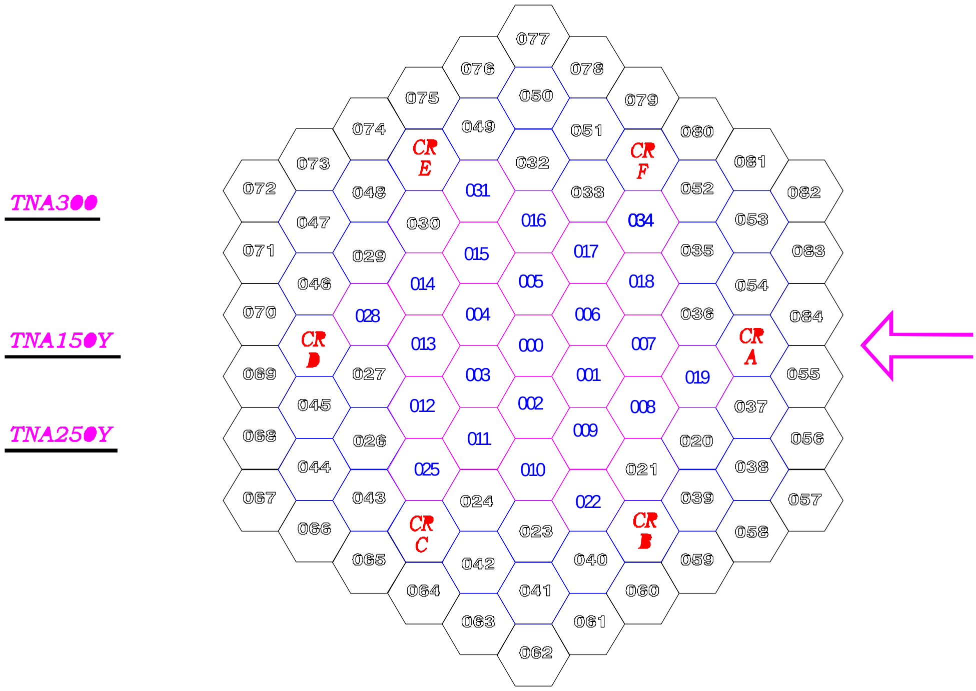


Assuming normal flow of coolant through the fuel subassemblies, the set of ‘ai’ is calculated for every fuel subassembly at different power levels and are stored in the computer as database. During reactor operation, Computer compares the actual temperature rise with the expected temperature rise. Difference between the two is compared against alarm limit (5°C) and trip limit (10°C).

Difference = Actual temp rise - ai x mean temp rise

If the difference exceeds the alarm or trip limit, corresponding action is initiated by the computer system. For minimising the spurious trip, the final trip action is initiated only if both thermocouples of the fuel subassembly cross the trip limit. During the signal validation stage, if a thermocouple is found faulty, then actual trip will be initiated if other thermocouple of the fuel subassembly crosses the trip limit. If both thermocouples of a fuel subassembly are found faulty, then trip is initiated, as it is not advisable to operate the Fast Breeder Reactor without core monitoring. The global temperature distribution, on-line trend, history of the signal, etc. are displayed in the colour graphic terminal housed in the control room (Figure 3).

Figure 3. Full core configuration



Thermal balance

The power generated in the core is calculated by the computer by summing up the thermal power of each fuel subassembly

$$\text{Core Power} = K\ F \times fi \times Ti$$

where

- F = Total flow of the coolant in the core
- fi = Flow fraction with respect to the subassembly
- Ti = Temperature rise in the subassembly
- K = Conversion Constant

Reactor vessel is surrounded by a biological shield (concrete) which is cooled by water. The radiated heat from reactor vessel is computed .This in turn is added with core power to obtain the reactor power. Triplicated compensated ion chambers are used for display of neutronic power. Computed thermal power is used for validation / calibration of neutronic power.

Reactivity balance

The on-line computer calculates the reactivity balance every 20 seconds and displays the result to the operator as per the following format.

Shut down margin	XXXX pcm
Reactivity added due to withdrawal of control rods	XXXX pcm
Reactivity change due to change in the coolant temp	XXXX pcm
Reactivity change due to change in reactor power..........	XXXX pcm
Reactivity change due to burnup....................................	XXXX pcm
Net Reactivity Balance	XX pcm

Shut down margin is the “input data” to the computer after every fuel handling campaign. Control rod level is scanned by the computer every second and the reactivity change is computed from the “look up table” (reactivity vs. position). If the reactivity balance exceeds 20 pcm, the operator is alerted, thus detecting any anomalous reactivity addition. For analysing the reactivity transient, related parameters (neutronic power, central subassembly temperature, coolant flow, reactivity) are scanned every 100 msec by a separate computer system.

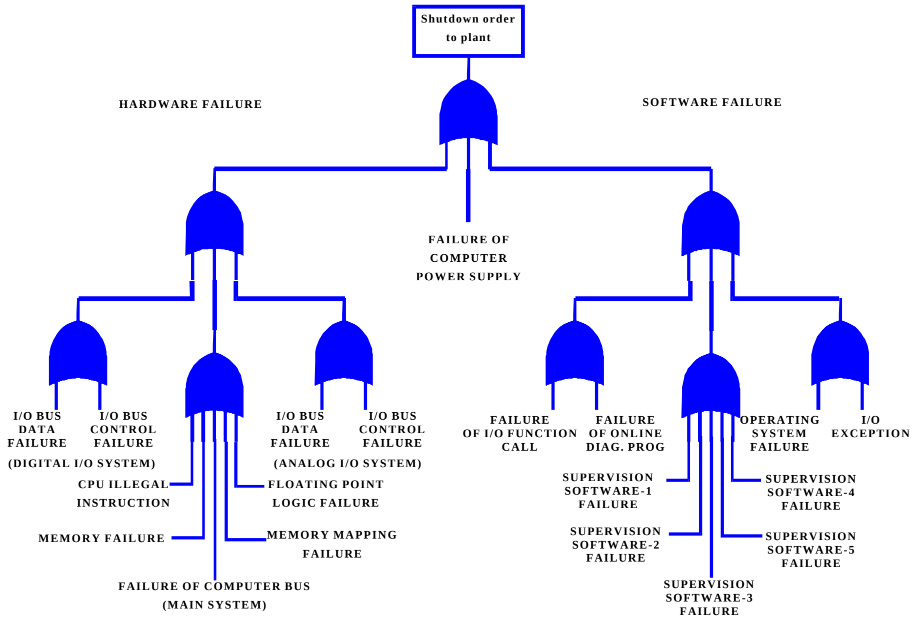
Health checking of neutronic system

In the Fast Breeder Test Reactor, triplicated neutronic channels are used for the measurement of power, period and reactivity. Trip orders from the neutronic channels are processed by 2/3 solid state voting logic system. The on-line computer is used to detect the discordance between the triplicated channels. The on-line computer diagnoses the health of 2/3 voting logic system by injecting the test pulse (2 m sec duration) and checking the propagation of the pulse up to the EM coil of control rod drive mechanism. The nature of the fault (safe fault, unsafe fault, mixed fault) is diagnosed and displayed to the operator.

On-line diagnostics

On-line diagnostics is designed to detect the malfunctioning of hardware (memory, analog input / output system, digital input / output system, bus transaction) and processing software routines (Figure 4).

Figure 4. Fault tree diagram for computer failure

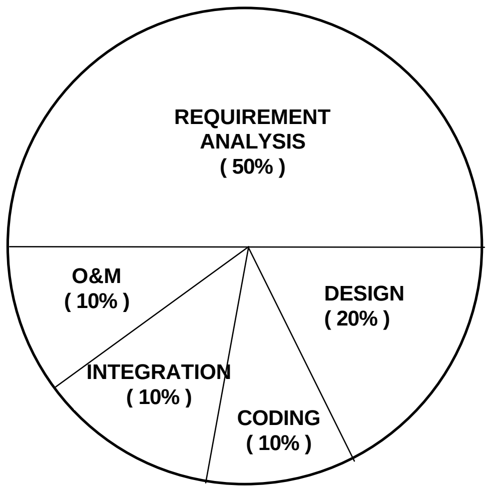


For checking the health of the analog input system, variable analog output voltage is scanned back through one of the input channels. In similar fashion, the digital input / output system is checked. Watchdog pulse is generated by on-line diagnostics only if all the hardware / software units are functioning properly. Absence of watchdog pulse will result in tripping of the reactor.

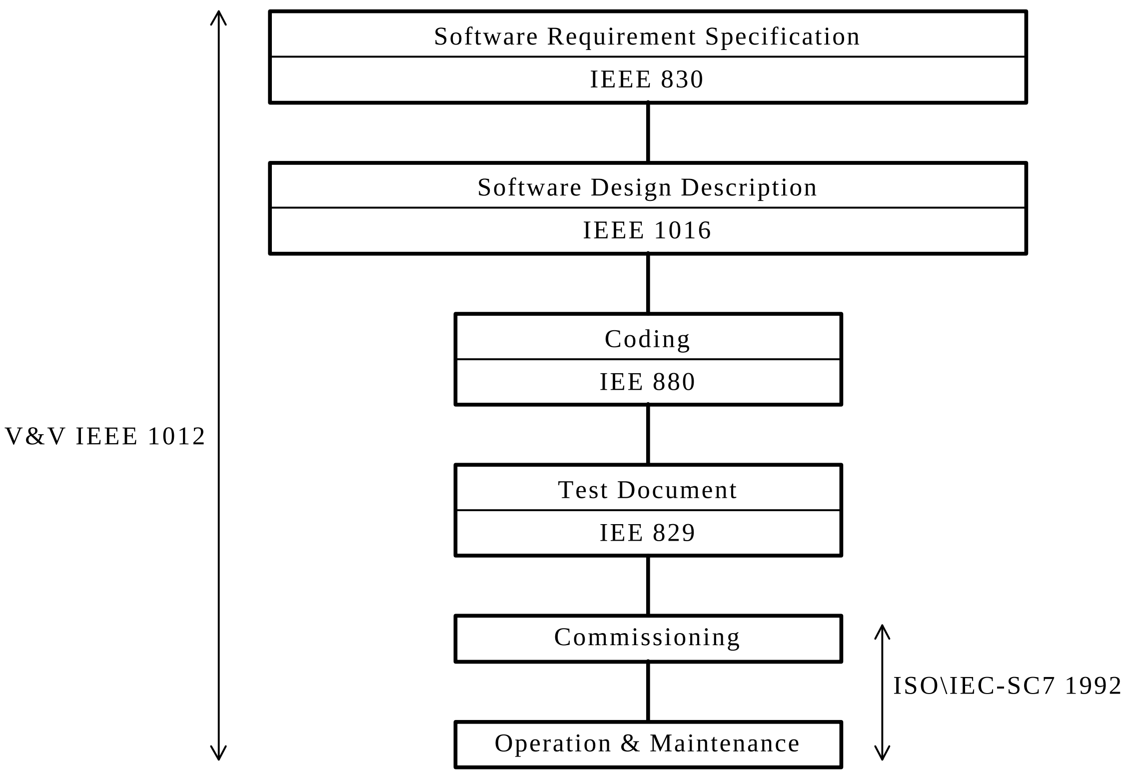
Reliability of the on-line computer system

To achieve high reliability, verification and validation are carried out by an independent agency at every life cycle stage of the Real Time System. Ground isolation technique is incorporated in the process I / O System. Cadmium coated mild steel racks are used for the Process I / O System as a shield against EMI. The error in software is mainly due to fuzzy specification (Figure 5).

Figure 5.



Software life cycle



To minimise the error, a detailed system requirement document, a system design document, a hardware requirement document, a hardware design document, a software requirement specification, a software design document and a test procedure document are prepared.

Static analysis and code walk-through are carried out for the source code. Test data is chosen such that all IF statements are checked. Test results are verified and validated. IEC / IEEE guidelines are followed at various stages of the Real Time System.

Configuration management

Errors normally creep into on-line computer system after hardware / software modifications, since these are carried out under a time constraint. Proper configuration modification procedure shall be followed for the safety-related computer system. In Fast Breeder Test Reactor, any hardware / software modification is analysed by the Station Operation Review Committee. With necessary work permits, authorised personnel carry out the modifications. The plant operator has no access to the operating system (unprivileged user). Hence safety-related supervision routines cannot be aborted from the console. Software data undergoes a rationality check. The updated documents and performance of the system is verified by a Safety Committee. Different levels of “check lists” are prepared for qualifying the operation and computer personnel.

Operational experience

Fast Breeder Test Reactor can be in any one of the following states:

- Shut down state (RSD)
- Start up of reactor (SUR)
- Reactor in operation (ROP)
- Start up of fuel handling (SUF)
- Reactor in fuel handling (RFH)

The state of the reactor is arrived at by conventional relay logic. The state of the reactor is available to the computer system as digital inputs. Due to the misbehaviour of the conventional relay logic, the reactor state was wrongly diagnosed by the computer. This led to bypassing of the core temperature supervision software.

When reactor was gradually shut down, the temperature distribution was distorted due to a variation in the response time of the core thermocouple signals. This resulted in the generation of spurious plugging detection alarms from the computer system. To avoid spurious alarms, core temperature supervision is enabled above 2 MWt.

Conclusion

The on-line computer systems at Fast Breeder Test Reactor, besides ensuring safe operation of the plant, provide valuable performance information of fuel, reactor assembly, neutronic system and heat transport system. This has led to the design of the Prototype Fast Breeder Reactor (PFBR, 500 MWe). Distributed Digital Control System is being developed for supervising different parts of PFBR. The reactor core will be monitored by triplicated computer systems, with the digital outputs routed through 2/3 voting logic.