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Special features of the safety and control systems of the *Dhruva* reactor

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Abstract. The prime requirement of reactor safety combined with the need for high availability of nuclear plants have, in recent years, led to considerable research and development efforts at the Bhabha Atomic Research Centre in the field of reactor safety and control engineering. The areas of special interest have been the development of a fast acting emergency shutdown system, on-line fault detection facility for the reactor protection circuits, enhanced instrumentation capability for measurement of critical plant parameters and computerised systems for plant protection, control, performance evaluation, disturbance analysis, and data acquisition and display with particular attention to the problem of man-machine interface. Some of these recent concepts have been incorporated in safety and control systems of the *Dhruva* reactor which is at present undergoing commissioning trials at Trombay. The special features of these systems are highlighted in the paper. The safety strategy adopted for the reactor and the consequent development of special safety systems are described in detail. The choice of the reactor control scheme and the methodology followed in the design of the automatic power control system are indicated. Campbell instrumentation for measurement of neutron flux or in other words reactor power, extensive use of microprocessors in safety related instrumentation and an improved man-machine interface through suitable design of control room have helped in achieving a high degree of reactor safety. The salient features of these systems are also included.

Keywords. Reactor safety; reactor control; control and instrumentation.

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1. Introduction

Dhruva is the latest addition to the family of nuclear research reactors in Trombay. Designed, constructed and presently being commissioned by engineers and scientists of the Bhabha Atomic Research Centre (BARC), the reactor will provide a thermal neutron flux of 180 trillion neutrons $\mathrm{cm}^2/\mathrm{sec}$ at the rated power of 100 MW(th). This high neutron flux makes the reactor a versatile nuclear facility for fundamental as well as engineering research, for conducting prototype tests on power reactor fuels and materials, and also for production of a variety of radioisotopes to be used in industry, medicine and agriculture.

Certain special features have been incorporated in the design of safety, control and instrumentation systems of *Dhruva*. These features, hitherto untried in other reactors of India, help in achieving a high degree of reactor safety and plant availability. The evolution of these new systems and their design features are presented.

This article has been specially prepared for commemorating the sixtieth birthday of Dr. Raja Ramanna, who has been a great source of inspiration and guidance to the *Dhruva* Project and through this we pay our tributes to this great nuclear scientist.

2. Brief description of the reactor

Dhruva is a natural uranium fuelled, heavy water moderated and heavy water cooled reactor. Fuel elements in the form of multipin clusters of uranium metal clad in aluminium are located in specially designed coolant channels made of zircaloy. The stainless steel reactor vessel houses the coolant channels and is placed in a concrete vault filled with demineralised light water. The vault acts as a shield against nuclear radiation emanating from the reactor core. The hot heavy water carrying the heat generated in the fuel rods is cooled by demineralised light water in a set of three heat exchangers. The light water in turn transfers its energy through another set of five heat exchangers to sea water, the sea being the ultimate heat sink. In order to maintain purity of heavy water the free space in the reactor vessel is filled with helium. Reactor power is controlled through suitable adjustment of moderator level. Provision has been made for on-power fuelling of the core through a specially developed fuelling machine. A simplified process flow diagram is shown in figure 1 and table 1 indicates the salient features of the reactor.

3. Safety strategy

The safety strategy adopted for *Dhruva* has evolved out of the general principles of reactor safety normally followed in the design of nuclear power plants.

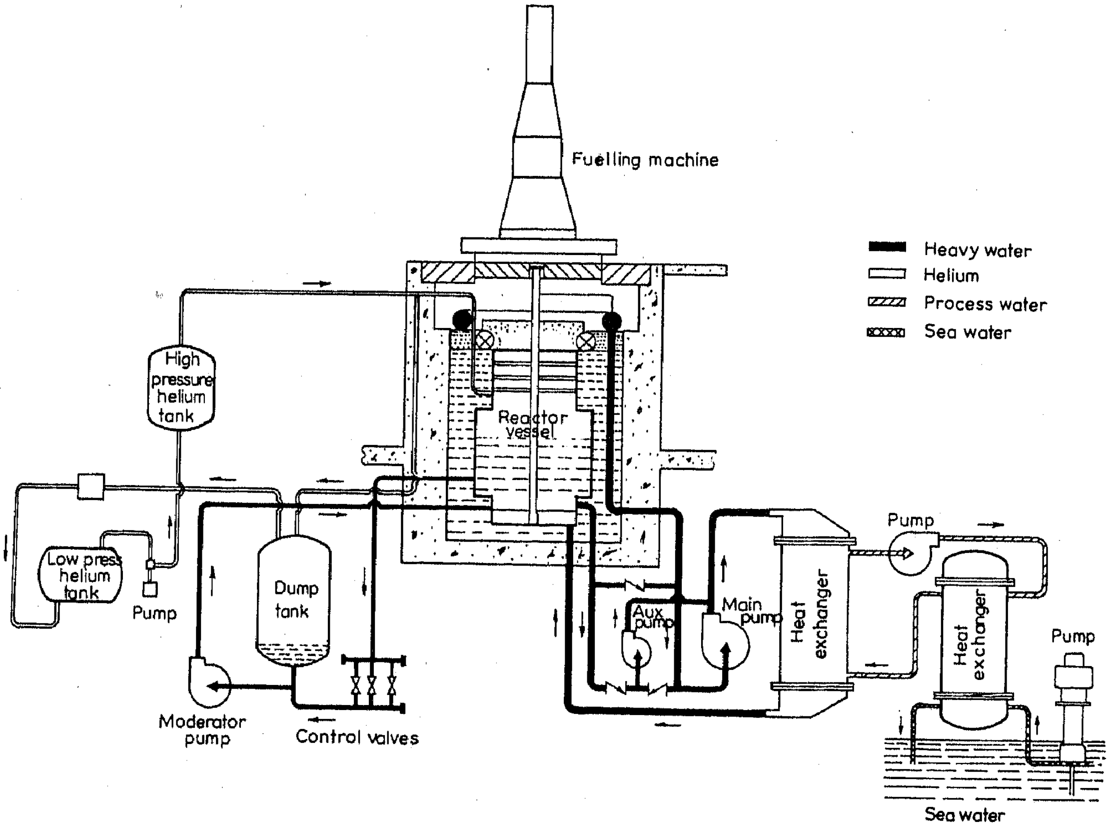

Figure 1. Simplified process flow diagram of *Dhruva*.

Table 1. Salient features of *Dhruva*

Item	Description
Reactor type	Thermal research reactor
Reactor power	100 MW (thermal)
Thermal neutron flux	1.8×10^{14} neutrons/cm^2-sec
Average specific power	15.2 kW/kg of uranium
Fuel assembly	7 pin clusters of natural uranium metal clad in aluminium
No. of fuel assemblies	129
Moderator and reflector	Heavy water
Primary coolant	Heavy water
Secondary coolant	Light water
Ultimate heat sink	Sea water
Shielding	Light water followed by high density concrete
Reactor control method	Adjustment of moderator level in reactor vessel
Primary shutdown system	Gravity drop of cadmium shutoff rods in the core
Emergency shutdown system	Injection of gadolinium solution in in-core tubes
Additional shutdown system	Dumping of moderator
Refuelling	On-power
Reactor block dimension	11.05 metres in diameter 11.94 metres in height
Reactor vessel dimension	3.76 metres in diameter 4.19 metres in height

3.1 *General principle*

The primary goal of reactor safety is to prevent any significant release of radioactive material from a nuclear facility to the general public outside the plant (Thompson and Beckerley 1964). In order to achieve this goal a defence-in-depth approach is normally adopted for the design of a nuclear reactor. This design approach involves two parallel principles. It is first assumed that a serious accident can take place and, therefore, means must be found to prevent the release of fission products out of the plant. This leads to the construction of multiple barriers against radioactive release like fuel sheath, primary heat transport system, containment etc. The second principle demands that accidents must not take place. This results in specially developed safety systems totally dedicated to accident prevention. These ensure that the reactor is automatically shutdown whenever minor plant upsets tend to become major. These also provide long-term cooling to the fuel elements and contain potential release of radioactivity.

The above features namely, provision of safety systems which prevent accidents in the first place, and multiple barriers to radioactive release which ensure public safety even in the event of a serious accident, have been incorporated in all reactors of India and they are largely responsible for the excellent record of reactor safety maintained in this country. However, constant effort for continuous improvement in the state of the art is an interesting feature of nuclear technology. The search for further improvement in reactor safety leads to the conclusion that defence-in-depth approach should be further extended to the design of the overall safety system itself. This has been tried in the *Dhruva* reactor.

3.2 *Defence-in-depth in safety system design*

Defence-in-depth design approach implies a need to ensure that accidents will be prevented even if any individual safety system fails to perform its safety functions. In order to meet this requirement it will be useful to have a reactor concept which by virtue of its intrinsic characteristics prevents accidents or minimises their consequence. It is also necessary to have sufficient redundancy in the safety systems so that failure of any individual system does not diminish the protection capability of the overall system. Since recent experience shows that identical systems can fail simultaneously due to common-mode faults (Moore and Hanauer 1972), redundant safety systems should be based on diverse principles of operations. Defence-in-depth philosophy also demands that individual safety systems must independently perform their safety functions whenever needed. This requirement of high availability can be largely met by employing fail-safe design philosophy. However, it is to be recognised that an absolute fail-safe feature is nearly impossible to achieve in practice. Preparedness for unsafe failures is, therefore, an important aspect of defence-in-depth safety strategy. An on-line fault-checking facility helps in immediate detection of unsafe failures and this feature, if incorporated, will improve the protection capability of safety systems.

The safety strategy adopted for *Dhruva* thus departs from the traditional approach in its special emphasis on: (i) intrinsic safety features of the plant, (ii) diversely functioning safety systems and (iii) continuous on-line fault-detection facility.

4. Special safety features

The primary cause of practically all reactor accidents is a mismatch between the energy liberation rate within the core and the energy removal rate of the coolant. Accidents can be prevented to a great extent if reactor power is always restricted within the heat transport capability of the cooling systems. The disturbances which tend to upset the power-coolant balance are many and can be classified under two broad categories. These are: (i) externally or internally induced reactivity transients (ii) failures of the heat transport systems. Since the possibility of a major power-coolant mismatch cannot be ruled out, it is necessary to ensure a positive reactor shutdown during such an occurrence.

For *Dhruva* the inherent characteristics of the plant as well as the special features incorporated in the reactor shutdown systems help in achieving this goal.

4.1 *Intrinsic characteristics*

A sudden loss of coolant from the reactor core is the most severe of all credible causes of a major power-coolant imbalance. Although a failure of this kind is highly improbable in a nuclear plant, public safety needs to be ensured even for such eventualities. Loss of coolant accident (LOCA) poses a serious safety problem due to its adverse impact on both reactor power and the heat transport system. This situation not only leads to a total loss of heat transport capability but also tends to increase reactor power due to the resultant positive reactivity effect. It has been estimated in the case of *Dhruva* that the gain in reactivity on a total coolant loss can be as high as 8.7 milli K. Undesirable though it is from the safety standpoint, positive reactivity feedback from a LOCA is an inherent nuclear characteristic of all pressure tube type of reactors. This nuclear limitation has been overcome in the *Dhruva* reactor by an ingenious engineering design of the primary coolant system.

The primary coolant circuit of *Dhruva* is divided into three independent loops, each consisting of an operating pump, a heat exchanger, valves and interconnecting piping. Figure 2 shows a simplified flow diagram of a single loop. It may be seen that cool heavy water from the inlet plenum flows upwards through the coolant channels containing the reactor fuel and then joins the outlet header. Each of the coolant loops draws hot heavy water from the header and after cooling in the respective heat exchangers discharges the same to the inlet plenum, thus completing the cycle. A part of the cool heavy water at heat exchanger outlet is diverted to the top of reactor vessel for cooling the top tube sheets and other internal structural assemblies. This heavy water after cooling the internal components of the reactor vessel falls on the free surface of the moderator. Thus at every instant heavy water from the closed main coolant loop enters into the free moderator region of the vessel. In order to maintain dynamic equilibrium, it is necessary to return an equal quantity of heavy water from the moderator to the coolant system. This has been achieved by connecting the reactor vessel to the suction side of the coolant pump in each loop by suitably sized lines. In this arrangement the reactor vessel acts as a surge tank for the coolant and consequently moderator becomes the source of coolant make-up during a LOCA. Thus a break in the coolant circuit automatically increases the moderator return flow and loss of coolant heavy water is continuously replenished by moderator heavy water. It is clear that fuel cooling will continue so long as moderator inventory in the reactor vessel is not completely lost. The integrated coolant-moderator circuit of *Dhruva* ensures that a loss of coolant is necessarily preceded by a total loss of moderator which results in an automatic reactor shutdown. Also, a rupture in the coolant circuit does not immediately affect the heat transport capability of the cooling system and this provides sufficient time for actuation

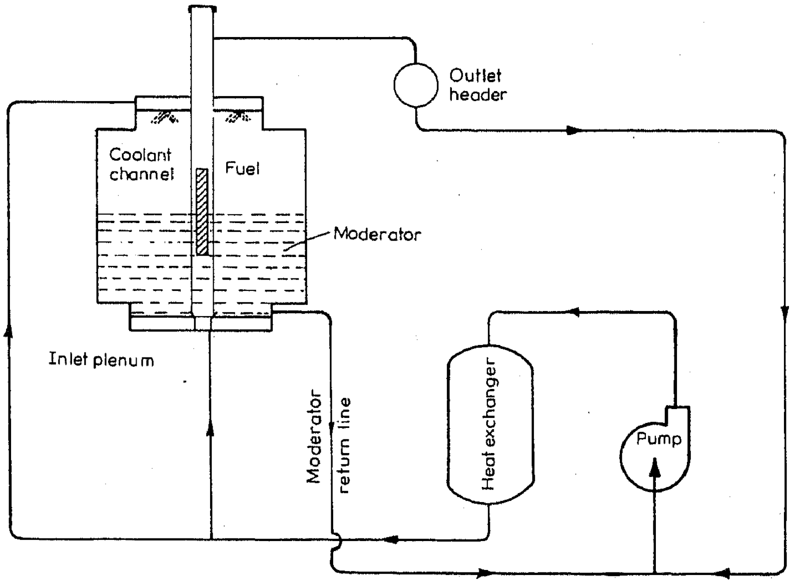

Figure 2. Simplified primary coolant flow diagram (single loop).

of the emergency core cooling system. These two factors enable preservation of fuel integrity even after a double ended rupture of the largest coolant pipe. LOCA in *Dhruva*, therefore, does not pose any problem of fission product release even within the plant.

4.2 *Emergency shutdown system*

The provision of two diversely functioning high speed shutdown systems, either of which is capable of causing a rapid reactor shutdown for the entire spectrum of credible accidents, is a special feature of *Dhruva*. The primary shutdown system utilises the traditional method of inserting a set of neutron absorber elements, called shutoff rods, into the reactor core. There are nine shutoff rods in *Dhruva* which use cadmium as the neutron absorbing material. The drive mechanisms of these rods are of electromechanical type and follow the popular clutch and drum arrangement. In this design, the rod is attached to a steel wire rope which in turn is wound on a drum. An electromagnetic clutch, if energised, connects the drum to a motor through an irreversible gear train. When the reactor is in operation, the rod is parked above the core region and is held in position by the energised cluth. On a reactor shutdown signal, the clutch is deenergised and the rod drops freely into the core. Although the shutoff rod assemblies are independent of one another, they are identical in design and construction. Thus, in spite of built-in redundancy the primary shutdown system is vulnerable to common-mode failures. To guard against such failures a diversely functioning emergency shutdown system has been provided. This system, specially developed for *Dhruva*, injects a neutron absorbing liquid solution (poison) into a set of empty tubes located in the reactor core.

4.2*a System description* The system, shown in figure 3 comprises essentially of:

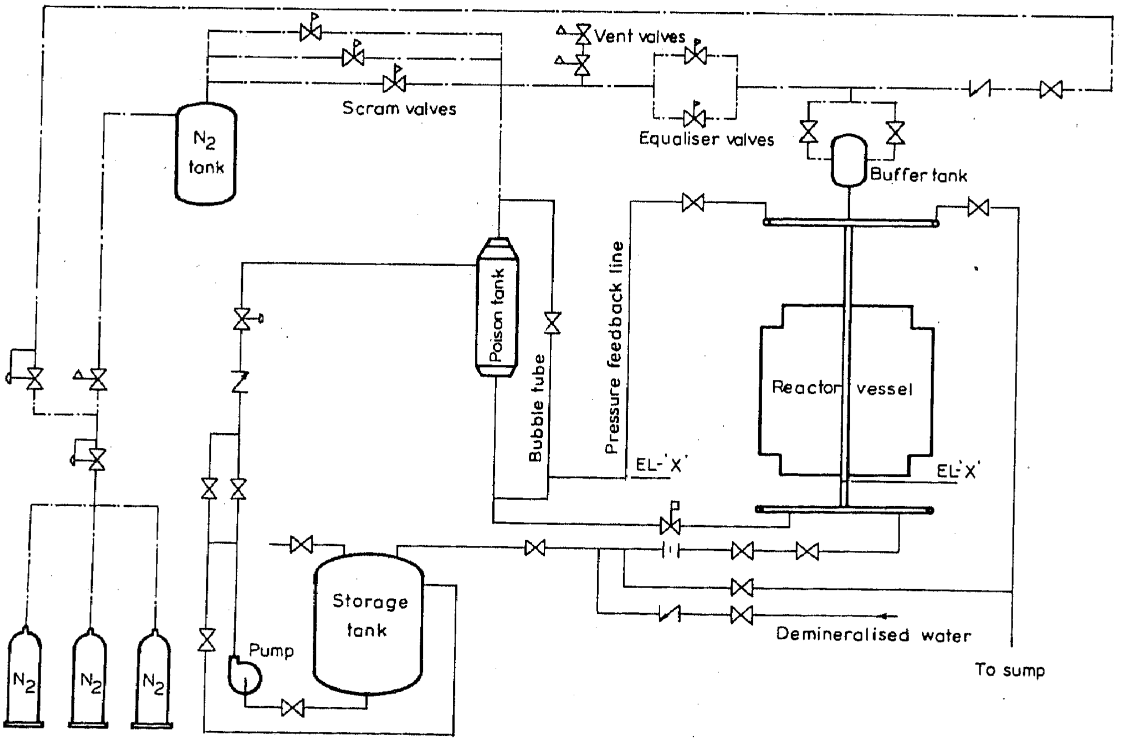

Figure 3. Emergency shutdown system.

(i) twenty tubes passing through the reactor, termed as poison tubes, and the connecting headers at top and bottom ends; (ii) a 50 litre capacity liquid poison tank containing solution of gadolinium nitrate in demineralised water, (iii) a 60 litre capacity nitrogen tank; (iv) a 20 litre capacity buffer tank; (v) a 400 litre capacity poison storage tank; and (vi) nitrogen cylinders, a pump, connecting pipes and valves.

The poison tank containing liquid neutron absorber is connected to the lower header and also to the nitrogen tank through three fast-acting solenoid valves (scram valves) operating in parallel. The nitrogen tank is maintained at a pressure of 15 kg/cm^2 (g) by the nitrogen cylinders. The upper header is connected to the buffer tank which in turn is connected to the poison tank through two fast acting solenoid valves (equaliser valves) operating in parallel. Two more fast acting solenoid valves (vent valves) operating in series, connect the poison tank to an air plenum which is always maintained at near atmospheric pressure. These valves play an important role during the poison injection process. Other valves in the system facilitate post-injection operations like dumping, washing and refilling of poison, and they remain in their deenergised fail-safe states prior to and during the injection process.

4.2*b* *Principle of operation* When the reactor is operating, the liquid level in the poison tubes is maintained below the reactor vessel by applying suitable nitrogen pressure to the buffer tank and venting the poison tank to the air plenum. In this condition the scram and equaliser valves are in energised close states and the vent valves are in energised open states. On an emergency shutdown signal these valves are deenergised, thus pressurising the liquid in poison tank. This initiates rapid injection of poison solution into the poison tubes. The time required to fill the tubes is approximately 0·8 second. The high velocity liquid front is damped by the compressed nitrogen in the buffer tank which creates a counter pressure on the moving mass. The motion is found to be oscillatory. However, the oscillation is contained well above the active core and as such there is no variation in reactivity.

In order to ensure a high degree of stability of the poison level in the reactor operating mode, a novel feature utilising the principle of pressure feedback has been incorporated in the system. It may be seen from figure 3 that the upper header pressure is fed back to the so-called 'bubble tube' through a feedback line. The junction of these lines, marked as point 'x' in the figure, is kept at the same elevation as the desired level in the poison tubes. The normal levels in the poison tank and the poison tubes have an elevation difference of 5·4 meters. Thus a differential pressure equivalent to 5.4 meters of solution head is to be maintained between the tubes and the tank. The upper header is, however, kept at a pressure somewhat higher than the above requirement, so as to maintain a steady flow of gas through the pressure feedback line and the bubble tube. A rise in the poison tube level reduces the gas flow rate, thereby increasing the pressure in the poison tubes. This immediately pushes down the liquid to the original elevation. Similarly, a fall in the level increases the gas flow rate. This reduces the pressure in the poison tubes which again restores the original level.

4.2*c* *Post-injection operations* During the poison injection process the nitrogen supply system is isolated from the nitrogen tank. After the injection is completed, vent valves are opened. This releases the pressure built up in the system. For a restart of the reactor, the poison from the core is brought back to the storage tank. The poison tubes are then flushed with demineralised water to remove any residual poison that may stick to the tube walls. After the completion of flushing, the system is once again filled with poison.

4.2*d* *Performance under failure* The dynamics of the poison injection process was analysed through a detailed mathematical model which was verified by actual tests on a scaled prototype of the system. The process simulation was carried out on the BESM-6 computer of BARC. Using the model, the behaviour of the system under normal condition as well as under various modes of failure were determined. This study reveals that poison can be injected in less than one second even if two of the three scram valves and three of the four equaliser and vent valves simultaneously fail to operate. Therefore, satisfactory operation of one scram valve and any of the vent and equaliser valves ensure adequate system performance. Since these valves operate on fail-safe principle, the probability of not meeting the above requirement is extremely small and the same is estimated to be less than 1 in 10^6. Even in the case of three scram valves failing simultaneously, poison is still injected though at a considerably slower rate. The injection time under such failure is approximately 8 seconds. Figure 4 shows the post-injection rise in poison level as a function of time for the normal mode as well as the extreme condition of all scram valves failing.

4.3 *On-line fault detection facility*

The failures in a safety system are normally classified under ‘safe’ and ‘unsafe’ categories. A safe failure inadvertently actuates a safety system thereby causing a

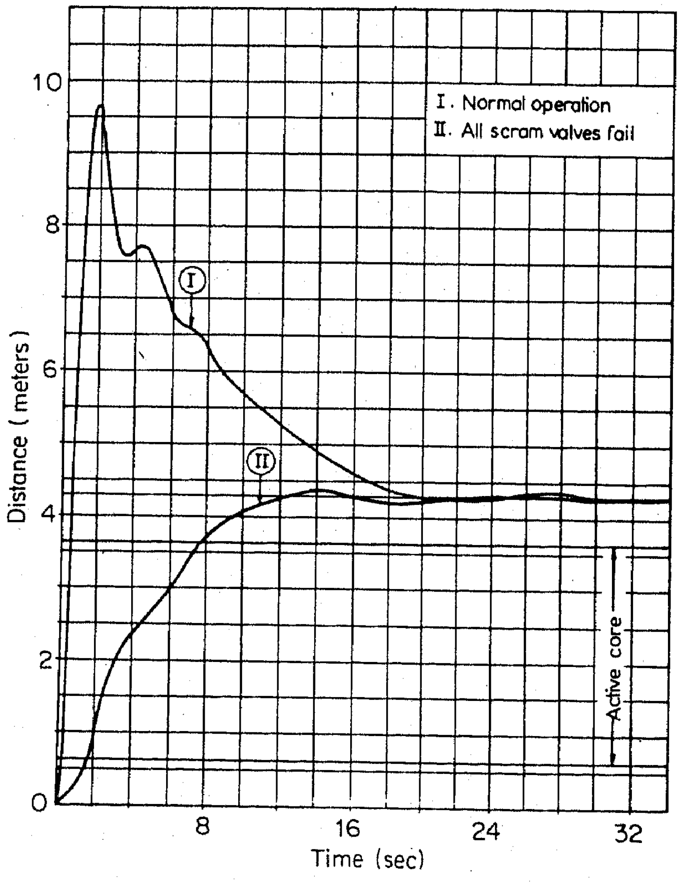

Figure 4. Poison level transients.

spurious reactor shutdown. Although such failures reduce plant availability they have no adverse effect on safety. An unsafe failure decapacitates a safety system and, therefore, is of great concern. Periodic functional testing of safety systems helps in reducing the probability of unsafe failures. The fractional dead time (D) of a safety system which represents the fraction of operating time that the system may remain decapacitated is given by

$$D = \tfrac{1}{2} f_u T$$

where f_u is the unsafe failure rate and T is the interval between two successive tests. It is clear that greater the frequency of tests lesser is the probability of an unsafe failure. Manual testing of systems involves considerable time and effort on the part of the operators and makes it difficult to achieve rapid rates of testing. High speed automatic test facilities are, therefore, required to overcome the problem of unsafe failures. This has been attempted in some of the critical areas of the *Dhruva* safety system.

The fine impulse test (FIT) facilities of *Dhruva* continuously search for unsafe failures in the safety logic systems which generate safety signals and actuate safety mechanisms. Each safety function is generated in three independent logic channels and the relevant mechanism is actuated whenever two or more of these channels demand a safety action. The FIT system is based on a 8-bit Intel microprocessor. It may be seen from figure 5 which represents the system block diagram, that fine impulses are injected into each logic channel as simulated input signals. These pulses represent the conditions which will prevail during an emergency. Sufficiently short pulses used for this purpose ensure that the output devices do not respond to these stimuli. The outputs of the logic channels for the simulated inputs are read by the central processing unit (CPU) through digital input data cards and get checked for any possible fault. When faults are encountered, the system analyses the faults to the card level and displays the address of

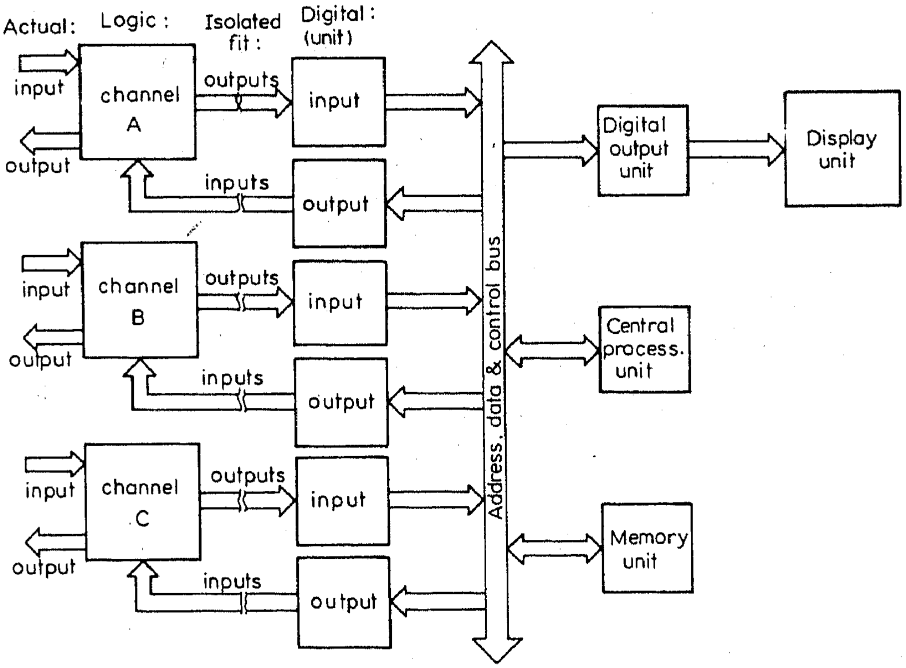

Figure 5. Fine impulse test facility.

the defective cards on the display panel. The system takes less than one second to check all components under its purview. A watch dog timer and other self-checking facilities have been incorporated in the system to improve its reliability.

The FIT facilities of *Dhruva* can carry out checks a million time faster than the manual testing rate normally followed in operating plants. Since the probability of a failure is inversely proportional to the frequency of testing, these facilities provide an extremely effective protection against unsafe failure.

5. Control and instrumentation systems

The control and instrumentation (C & I) systems of *Dhruva* are designed to achieve a high degree of automatation in plant operation. This reduces the routine work load of the operating staff, providing increased opportunity to concentrate on unusual occurrences. The C & I systems also assist the operator in high level monitoring of plant performance, thereby enhancing both safety and availability of the reactor.

5.1 *Automatic power control system*

Reactor power in *Dhruva* is regulated through suitable variation of moderator level in the reactor vessel. As shown in figure 6, the moderator level is changed by varying the rate of flow of heavy water into and out of the vessel. The speed of the moderator pumps in the inflow line and the opening of control valves in the outflow line are controlled to achieve the required flow variation. This method of reactor control offers certain safety advantages. It enables rapid draining of moderator from the core by opening of the control valves and tripping of the moderator pumps, thereby causing a reactor shutdown. The control system can, therefore, be used as an additional shutdown system of the reactor.

The dual control of both inflow and outflow rates of heavy water is a special feature of *Dhruva*. This scheme results in low equilibrium flow in the core which restricts the

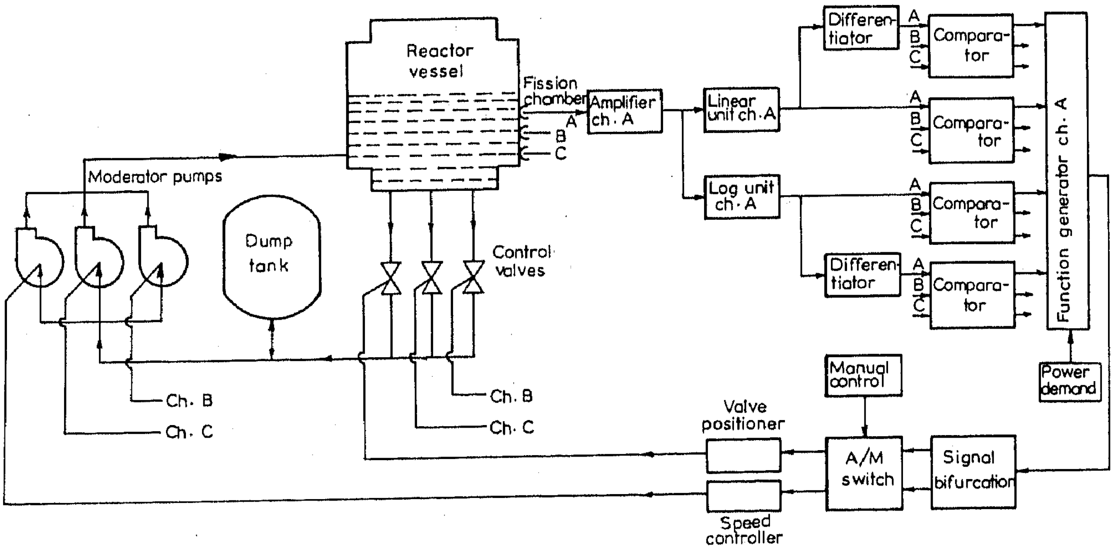

Figure 6. Automatic power control system.

flow-induced vibrations of in-core components. This also reduces the power consumption by the pumps. Added to these the large reactivity range of this scheme enhances the control capability of the system.

To achieve high availability and adequate safety, triplicated control channels are provided. Each channel is essentially independent of the other two and controls one valve and one pump. The system is so designed that control capability is preserved even on failure of one complete channel. However, the possibility of such failures is low since the functioning of the various sub-systems is continuously monitored by a number of signal comparator units incorporated for this purpose. The control signal for the pump or the valve is derived through suitable processing of the power demand signal set by the operator, and the feedback signals provided by the neutron power detecting instruments.

The system design was optimised through a parametric study of the system behaviour under various steady state and transient conditions. Detailed mathematical models were developed for this purpose. The reactor was described by the point kinetics equations with six groups of delayed neutrons. Accelerations in fluid flow were calculated through incompressible one-dimensional fluid flow equations. Individual models were also developed for the electronic units, moderator pumps and control valves. The integrated model was found to be highly nonlinear with 29 state variables. The steady state stability of the system which is valid for small perturbations, was evaluated through the linearised version of the model. It was established that the control system was stable with adequate gain and phase margins. The transient performance was, however, analysed with the help of a detailed computer code which included all the non-linearities of the model.

5.2 *Wide range monitoring of reactor power*

Neutron flux which is proportional to reactor power, is normally measured by processing a neutron detector output in either pulse mode or d.c. mode. In pulse mode individual pulses from the detector are counted and the count rate represents neutron flux or reactor power. This technique is employed for low level flux upto a maximum of 10^6 nv. At high flux values individual pulses overlap and the resultant current is measured in the d.c. mode. The d.c. current is proportional to neutron flux and hence, reactor power. In recent years, a third technique for the measurement of neutron flux has been developed. This is based on the noise theories of Campbell. Applying this theory it can be shown that the mean square of the current from a source of random current pulses is proportional to the pulse rate and square of the pulse height, provided that the d.c. portion of the current is cut off by capacitive coupling and the fluctuating a.c. component is used exclusively. Therefore, the mean square of a.c. components of the detector current is proportional to neutron flux. The Campbell technique provides certain advantages. Since only the variations in current are measured, d.c. leakage currents of cables do not result in significant error. Also, the mean square output being proportional to the square of pulse height smaller pulses contribute less to the total signal, thereby improving the gamma discrimination capability of the system. A proper integration of pulse and Campbell techniques enables wide range monitoring of reactor power through a single neutron detector. Such a system has been developed for *Dhruva*. This system, shown in figure 7, monitors reactor power over a range of 10 decades using a single fission chamber. It has been, thus, possible to use a few detectors and yet have

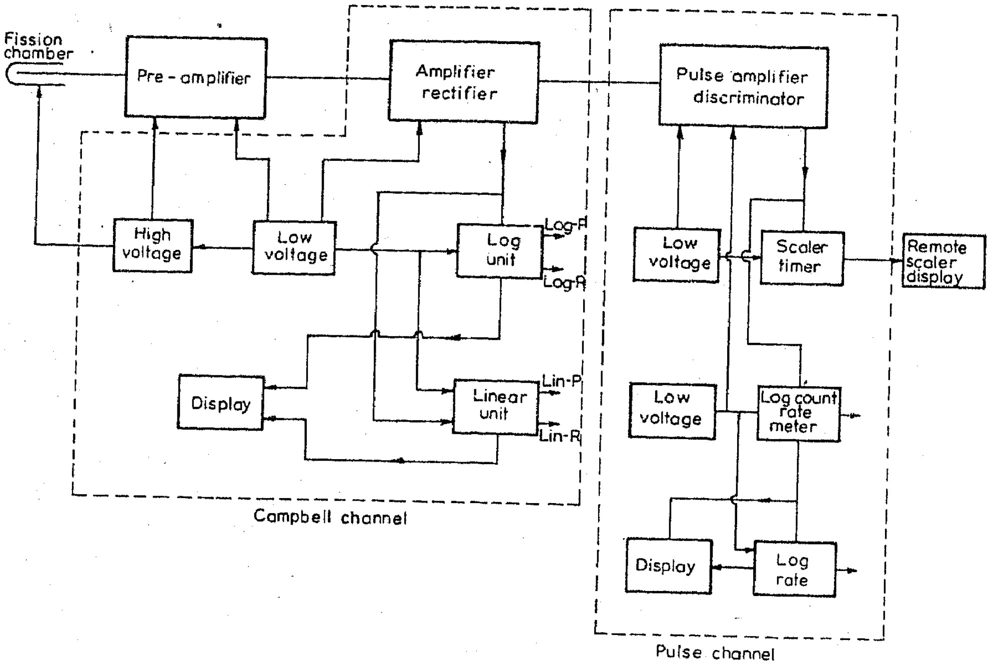

Figure 7. Integrated Campbell-pulse channel.

wide range monitoring capability. A ten decade coverage of reactor power by the regular instrumentation system is a special feature of *Dhruva* and this enables normal reactor start-up even after a very long shutdown without the help of additional instrumentation.

5.3 *Instrumentation for operator support*

A number of microprocessor-based systems assist the operator in high level monitoring of plant performance. These enable early detection of minor plant upsets and guide the operator in taking corrective actions. The data acquisition and display system, coolant channel surveillance systems and alarm annunciator system are provided for this purpose. These systems were specially developed to meet the high reliability requirements of reactor instrumentation.

The data acquisition and display system is configured around a 16-bit Intel microprocessor and employs two-colour cathode ray tubes (CRTS) for data display. The system exploits the advantages offered by colour CRT terminals and presents plant data in easy-to-grasp formats like mimics, graphs, tables, bar charts etc. This leads to enhancement of operator's comprehension of plant behaviour and therefore to a better man-machine interaction. The functions carried out by the system include alarm annuciation with detailed instructions for operator action, display of plant status in mimic and tabular forms, system performance calculations and graphic presentation of the trend in various process variables during routine transients like start-up, manual shutdown, raising or lowering of power etc. Facilities are also available for routine or demand logs of plant parameters.

The coolant channel surviellance systems monitor the health of fuel elements in the reactor core. The coolant flow, outlet temperature and radioactivity level in each coolant channel are continuously monitored by three independent microprocessor-based systems and the relevant information is displayed in the control room. Whenever any of these parameters exceeds the operational limit the system provides an alarm and indicates the address of the affected coolant channel. In the normal mode process status is displayed on a demand by the operator.

The alarm annunciator system provides audio-visual warning to the operator when minor perturbations occur in operating parameters. In order to achieve high reliability a dual computer scheme has been adopted for this system. In this scheme each computer is entirely capable of performing all functions of the annunciator. Only one computer system is normally active and the second one is a standby. In the event of a malfunction of the active computer system the control is automatically transferred by the watchdog to the standby system.

Extensive self-checking features have been incorporated in all computerised systems of *Dhruva* and they are responsible for the high reliability of these systems. Apart from the reduction in size and cost, these systems offer an additional advantage of flexibility which facilitates system modification during commissioning.

6. Control room

The control room provides all the information and controls required for safe operation of the plant. Considerable efforts were made to evolve an optimum design of the control room, especially the sizing and layout of panels and consoles as well as the arrangement of control and display devices. The main emphasis was on achieving an optimum integration of the operator with the process through appropriate human factor engineering. This was considered to be essential, since many of the abnormal occurrences in the operating plants can be attributed to operator errors resulting from deficiencies in control room design.

In view of the multitude of tasks to be performed from the control room, it is necessary to have functional grouping of different tasks. The *Dhruva* control room consisting of nine panels and one console having a total length of approximately 30 meters can be subdivided into three functional areas. Routine reactor start-up and shutdown is carried out at the console. Reactor cooling and other process systems which are unaffected by reactor shutdown, are controlled from the central five panels. The extreme panels, two on each side, provide the information which is to be periodically logged by the operator.

In order to facilitate identification of different controls, operational mimic diagrams are extensively used. These diagrams display the flow of a process medium in a system and include the major components like pumps, valves, tanks, etc, which are represented by symbols. The control switches of an equipment are incorporated within the corresponding symbol. These switches are of lighted push button type and thus equipment status is always indicated on the corresponding symbol. This enables the operator to immediately determine the effect of a control action taken by him. As a further aid to the operator the status of relevant process variables are displayed through suitable indicators. Mimic diagrams are structured in different colours, each colour representing a specific system. This helps in highlighting different systems.

Two colour CRTS located on the console display detailed information on the plant status. This facility enables the operator to gather all data from a single instrument. Individual instruments like recorders and meters also provide standby indications.

7. Conclusion

The safety and control systems of *Dhruva* were entirely designed, developed and fabricated at BARC. The special features of these systems reflect the current trends towards diversified safety systems, increased use of computer power in C & I functions, enhancement of existing instrumentation capability and improved man-machine interaction through advanced control centres. These concepts are likely to be employed in future nuclear plants of our country.

References

Moore V A and Hanauer S H 1972 *Proc. Nuclear power plant control and instrumentation* (Vienna: IAEA) p. 1.

Thompson T J and Beckerley J G 1964 *The technology of nuclear reactor safety* (eds.) T J Thompson and J G Beckerley (Cambridge, Massachusetts: MIT Press) Vol. 1, Chapter 1.