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IAEA SAFETY STANDARDS

for protecting people and the environment

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Instrumentation and Control and Software Important to Safety for Research Reactors

DRAFT SAFETY GUIDE

DS 436

New Safety Guide

IAEA

International Atomic Energy Agency

IAEA SAFETY RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish standards of safety for protection against ionizing radiation and to provide for the application of these standards to peaceful nuclear activities.

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Information on the IAEA's safety standards programme (including editions in languages other than English) is available at the IAEA Internet site

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OTHER SAFETY RELATED PUBLICATIONS

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FOREWORD

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1. INTRODUCTION

BACKGROUND

1.1 This safety guide is part of the set of publications developed within the framework of the IAEA research reactor safety programme, which covers all of the important areas of research reactor safety. It supplements and elaborates upon the safety requirements for design and operation of the instrumentation and control system for research reactors that are established in Section 6 and 7 of Ref. [1].

1.2 The rate of ageing and obsolescence of research reactor instrumentation and control systems has increased due to the technological advancements in the field of electronics. During the lifetime of a research reactor one or more refurbishments of instrumentation and control system can be predicted. There are different reasons demanding instrumentation and control modernization projects such as improvement of maintainability and reliability, new utilization or experiments in research reactors, enhancement of safety, etc. The advances in technology will require special attention to the safety classification of instrumentation and control systems, to the development in the use of computer based instrumentation and control systems, to the significant structural changes of instrumentation and control systems caused by the intelligent devices, and to the software development including verification, validation and quality assurance.

OBJECTIVE

1.3 The objective of this safety guide is to provide guidance on the instrumentation and control systems important to safety of research reactors, including all instrumentation and control components, from the sensors allocated to the mechanical systems to the actuated equipment, operator interfaces and auxiliary equipment. This safety guide is intended for use by all organizations involved in the design and operation of research reactors including the operating organization, the regulatory body and other organizations involved in a research reactor project.

SCOPE

1.4 This safety guide provides guidance on the design, safety classification, qualification and operation of instrumentation and control systems important to safety for research reactors to achieve compliance with Ref. [1].

1.5 The guidance applies to both, the design of instrumentation and control systems for new research reactors and to the modernization of the instrumentation and control of existing facilities.

1.6 This safety guide also provides recommendations for human factor engineering and human-machine interface and for computer based systems and software for use in instrumentation and control systems important to safety, digital data communication equipment, and the software measures needed for instrumentation and control functions.

1.7 This guide also provides recommendations for the configuration management of both, instrumentation and control systems for new research reactors and for the modernization of the instrumentation and control of existing facilities.

STRUCTURE

1.8 Section 2 discusses the identification of instrumentation and control functions and systems, the method and the basis of safety classification into safety and safety related functions and systems. Section 3 describes how instrumentation and control systems are arranged into a hierarchy. Section 4 and 5 gives an overview of general and specific design requirements of instrumentation and control systems, while section 7 expands on the guidance given in section 4 in the area of human-system interfaces. The operation aspects of instrumentation and control systems are presented in section 6. Section 8 provides guidance on design, and other aspects of computer based systems and Software. Section 9 deals with instrumentation and control systems configuration management. Section 10 presents the instrumentation and control systems modification and modernization aspects.

PERCEPTION OF NEEDS FOR INSTRUMENTATION AND CONTROL MODERNIZATION

1.9 One major reason to decide for an instrumentation and control modernization at a given facility is obsolescence of the present instrumentation and control system, the unavailability of spare parts and an increased failure rate of the instrumentation and control system leading to frequent reactor shut downs, long repair periods and therefore resulting in high unavailability of the facility. Recommendations for ageing management for research reactor systems are given in Ref. [8]. Additional aspects supporting a positive decision for modernization is evidently the technological progress in instrumentation and control systems leading to higher reliability of instrumentation and control systems, improvement of human-system interface and extensive and fast data collection and processing. Besides such technically based decisions also other aspects (such as new regulatory requirements) may influence the final decision for modernization of the instrumentation and control system

Forecasting problems and limits in the nearest future

1.10 Before entering the modernization project, it is advisable to collect information on needs and limitations in the current instrumentation and control system. Such information can be found from past failures and incidents as collected by event recording systems as used in the facility. Other weaknesses can be identified from regular self-assessment of operational performance, including analysis of even small deviations from normal operation. In addition to identifying current problems and limits with the current instrumentation and control system the decision maker should assess and attempt to foresee possible future problems and limits of the current instrumentation and control system.

2. SAFETY CLASSIFICATION OF INSTRUMENTATION AND CONTROL SYSTEMS

GENERAL CONSIDERATIONS

2.1 For the purposes of this guide the following classification scheme is used to grade recommendations according to safety significance:

- All instrumentation and control functions, systems, and components fit into one of two categories: items important to safety or items not important to safety (see Fig.1);
- Functions, systems, and components important to safety are further categorized as either safety systems or safety-related items;
- The main safety functions for a research reactor are:

    i. Control of reactivity;

    ii. Cooling of radioactive material; and

    iii. Confinement of radioactive material.

- Instrumentation and control systems important to safety are those instrumentation and control systems used to accomplish functions important to safety.
- Functions, systems, and components important to safety are those which contribute to:

    i. Safely shut down the reactor and maintain it in a safe shutdown condition during and after appropriate operational states and accident conditions;

    ii. Remove residual heat from the reactor core after shutdown, and during and after appropriate operational states and accident conditions;

    iii. Prevent or reduce the potential for the release of radioactive material and to ensure that any releases are within prescribed limits during and after operational states and within acceptable limits during and after accidents; and

    iv. Permit the safe operation of the reactor.

2.2 Safety systems consist of the protection system, the safety actuation systems and the safety system support features. Components of safety systems may be provided solely to perform safety functions or may perform safety functions in some facility operational states and safety related functions and/or non-safety functions in other operational states. The design premise should be to prevent the addition of any component or function not strictly required by the highest safety classification.

2.3 Safety related systems are systems important to safety performing other safety functions not mentioned in paragraphs 2.2 as monitoring the availability of safety systems or diminishing the needs of a safety system to actuate performing other smooth actions in advance.

2.4 Systems not important to safety are those systems that do not belong to systems important to safety.

2.5 For instrumentation and control systems important to safety, graded approach to the requirements of Ref. [1] can be applied but the extent of grading should be clearly justified in the safety analysis report (see paragraph 1.14 of Ref. [1]).

2.6 Additional guidance on the application of a graded approach can be found in Ref. [2].

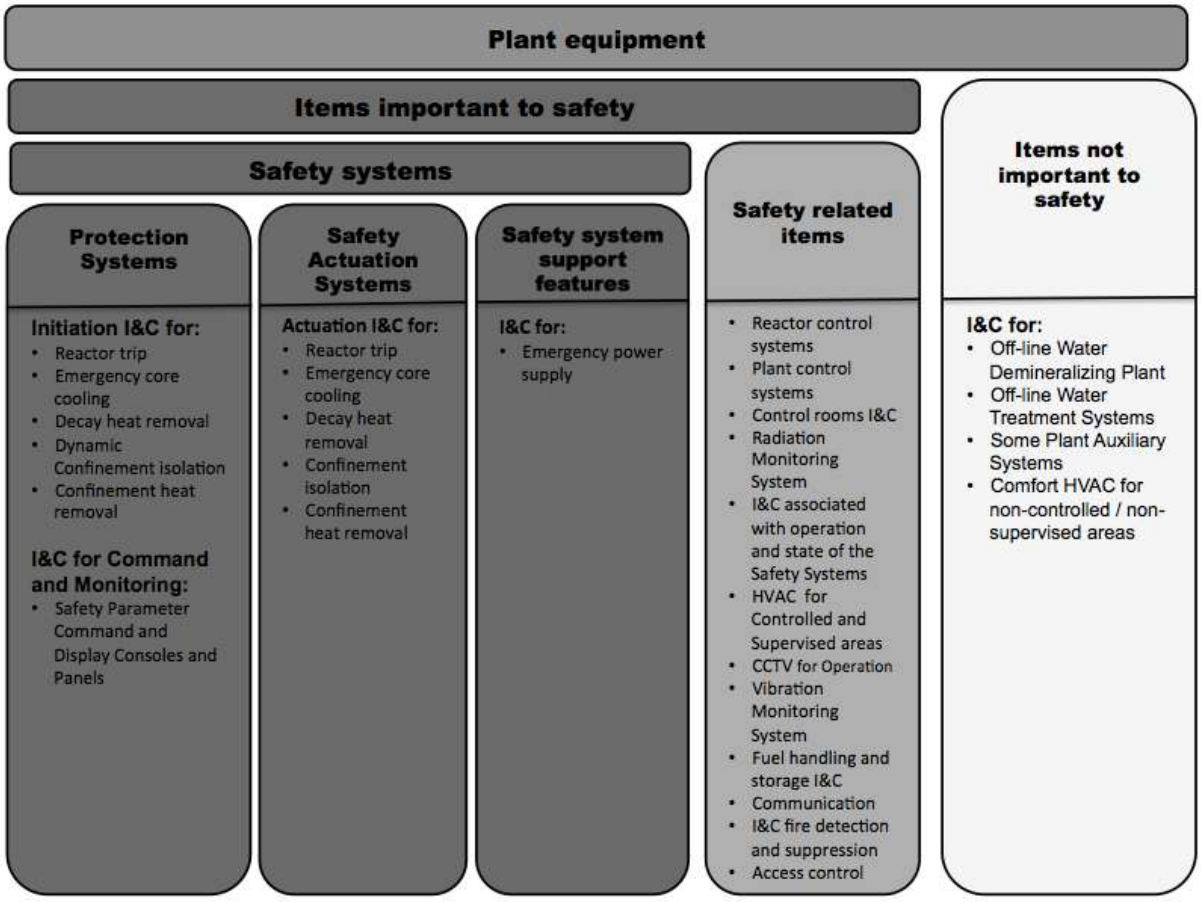

FIG. 1: Examples of instrumentation and control systems classified in connection to their importance to safety. See also Annex I.

SAFETY SYSTEMS

2.7 Functions of safety systems are to ensure timely detection of violations of limits and conditions for safe operation of research reactor and automatically initiate reactor shutdown, emergency core cooling and residual heat removal, and confinement of radioactive materials and/or limitation of accidental releases.

2.8 Safety systems perform a number of functions to ensure the safe operation of a research reactor such as:

- Shut down the reactor as necessary to prevent anticipated operational occurrences from leading to design basis accident conditions;
- Maintain the reactor in a safe shutdown condition after all shutdown actions;

- Remove residual heat in appropriate operational states and design basis accident conditions;
- Confine radioactive materials and limit accidental releases;
- Mitigate the consequences of beyond design basis accidents; also can be considered the new terminology introduced by IAEA for this conditions as design extension conditions[1]. See Ref. [14].

2.9 The safety system should automatically initiate the required protective actions for the full range of postulated initiating events to terminate the event safely.

2.10 The examples of instrumentation and control safety systems are:

- Initiation instrumentation and control for:
  - Reactor trip, initiated by the reactor protection system, which includes:
    - Sensors and instruments which monitor neutron flux, flow rates, temperatures, pressures, and other safety variables and by demand, safety variables from experimental devices; and
    - The system which processes these signals compares them against the safety system settings and initiates the reactor trip if any of these settings has been exceeded.
  - Emergency core cooling;
  - Residual heat removal; and
  - Confinement of radioactive material.

- Instrumentation and control for Command and Monitoring:
  - Safety parameter command and display consoles and panels; and

- Actuation instrumentation and control for:
  - Reactor trip;
  - Emergency core cooling;
  - Decay heat removal;
  - Confinement of radioactive material.

- Instrumentation and control for safety interlocks, and

[1] Design extension conditions: Accident conditions that are not considered for design basis accidents, but that are considered in the design process of the facility in accordance with best estimate methodology, and for which releases of radioactive material are kept within acceptable limits. Design extension conditions could include severe accident conditions.

- Instrumentation and control for:
  - Emergency Power Supply.

SAFETY RELATED SYSTEMS

2.11 Safety related systems perform a number of functions to ensure the safe operation of a research reactor such as:

- Provide for reactivity control within safe limits;
- Remove heat from the core;
- Maintain sufficient coolant for core cooling in normal operational states and following any postulated initiating event;
- Maintain the integrity of the cladding for the fuel in the reactor core;
- Maintain integrity of barriers;
- Minimize the radiation exposure of personnel;
- Prevent degradation of reactor safety originating from experimental devices and facilities; and
- Provide information to the operator regarding the state of the facility.

2.12 Control functions assure that the research reactor facility is controlled and kept within its operating limits and conditions, thereby contributing to nuclear safety by minimizing the demand on safety system.

2.13 Monitoring and display functions provide the interface between the reactor facility, reactor operators and maintenance personnel. These functions are related to safety as they allow the facility personnel to intercept transients and maintain the reactor within the operating limits and conditions.

2.14 Some examples of safety related instrumentation and control systems are:

- Reactor control systems;
- Control rooms instrumentation and control;
- Radiation monitoring system;
- Instrumentation and control associated with operation and state of the safety systems;
- Instrumentation and control for humidity ventilation and air conditioning for controlled and supervised areas;
- Instrumentation and control for close circuit television for operation;
- Vibration monitoring system;
- Fuel handling and storage instrumentation and control;
- Communication;
- Instrumentation and control for fire detection and suppression systems; and
- Instrumentation and control for access control.

SYSTEMS NOT IMPORTANT TO SAFETY

2.15 Systems not important to safety support operation of the facility while having no impact on the reactor's safety.

2.16 Some examples of instrumentation and control systems not important to safety are instrumentation and control for:

- Off-line water demineralizing facility;
- Off-line water treatment systems;
- Some facility auxiliary systems;
- Instrumentation and control of experimental devices and irradiation installations that do not affect reactor safety; and
- Comfort humidity ventilation and air conditioning for non-controlled/non-supervised areas.

METHOD OF CLASSIFICATION

2.17 The method for classifying the safety significance of a structure, system or component should be based primarily on deterministic methods and engineering judgment, complemented where appropriate by available probabilistic safety assessment. The basis for such classification should consider:

- The safety function(s) to be performed by the instrumentation and control system;
- The consequences of the instrumentation and control system's failure (failure or faulty performance of the function(s));
- The estimated frequency or probability (if available) that the instrumentation and control system will be called upon to perform a safety function; and
- Following a postulated initiating event, the time at which or the period for which the instrumentation and control system will be called upon to operate.

2.18 In addition to considering the factors mentioned above, the following factors should also be taken into account in determining the class of the instrumentation and control system:

- The estimated frequency or probability (if available) of postulated initiating events and the potential severity of their consequences if the instrumentation and control system provided fails (e.g.: high, medium or low probability, with high, medium or low consequences (e.g. radiological consequences));
- The potential of the instrumentation and control system itself to cause a postulated initiating event (i.e. the instrumentation and control system's fail-safe modes) and the combination of the probability and consequences of such a postulated initiating event (i.e. frequency of failure and radiological consequences);
- The timeliness and reliability with which alternative actions can be taken; and
- The timeliness and reliability with which any failure in the instrumentation and control system can be detected and remedied.

2.19 The criteria, should be chosen so as to provide a quantitative and/or qualitative indication of the relative importance to safety of the instrumentation and control system being classified.

2.20 Once each of the factors has been considered and analysed for each instrumentation and control system a decision should be made by the operating organization on system's classification (after considering relevant inputs, for example from designer or regulatory body).

DESIGN, CONSTRUCTION AND MAINTENANCE OF INSTRUMENTATION AND CONTROL SYSTEMS

2.21 All instrumentation and control systems and equipment should be designed constructed operated and maintained in such a way that their specification, verification and validation process, quality and reliability are commensurate with their safety classification.

2.22 All instrumentation and control systems and equipment performing functions important to safety should have appropriately designed interfaces with systems and equipment of different classes, in order to ensure that any failure in a system classified in a lower class (less stringent requirements) will not propagate to a system classified in a higher class. Equipment providing the function to prevent the propagation of failure should be treated as being of the higher class.

2.23 Instrumentation and control system or equipment safety class should have the same safety class as the system or equipment they control/monitor. If an instrumentation and control system or equipment controls or monitors several systems or equipment, its safety class should be the one of the highest safety class of these systems or equipment.

3. OVERALL INSTRUMENTATION AND CONTROL SYSTEM ARCHITECTURE

GENERAL

3.1 The research reactor should be provided with sufficient instrumentation and control systems in the form of an architectural design for a safe operation of the research reactor during normal operation, shut down, refuelling, maintenance and, to automatically initiate reactor shutdown, emergency core cooling, residual heat removal, and the confinement of radioactive materials and/or limitation of accidental releases during and after accident conditions.

3.2 Instrumentation and control system architecture should fulfil paragraphs 2.2 to 2.7; 6.1 to 6.43; 6.61 to 6.64; 6.94 to 6.105 and 6.136 to 6.144 of Ref. [1]. Instrumentation and control system architecture should support all instrumentation and control functions needed to ensure the safety of the facility.

3.3 The overall instrumentation and control system architecture provides high level definition of the instrumentation and control systems, the assignment of instrumentation and control functions to these systems, and the communications (interfaces) between instrumentation and control systems with the facility operators.

Modern instrumentation and control systems are more highly integrated than were the last generations of instrumentation and control systems. The architecture of highly integrated systems should be carefully considered to ensure proper implementation of the defence in depth concept. A well designed architecture can reduce the complexity of instrumentation and control systems by a rational allocation of functions only in the systems where they are needed. The identification of all the different and individual instrumentation and control ssystems of a research reactor that can be included in a particular facility depends on the type of reactor, the purpose and its operation modes. They are shown and described in Annex I.

DEFENCE IN DEPTH

3.4 As it is stated in Ref. [1], paragraph 2.5 "...*the application of the concept of defence in depth throughout design and operation provides a graded protection against a wide variety of transients, anticipated operational occurrences and accidents, including those resulting from equipment failure or human action within the installation, and events that originate outside the installation*".

3.5 The facility design should incorporate the defence in depth. The levels of defence should be independent as far as is practicable. See also Ref. [6].

3.6 The implementation of the defence-in-depth concept for instrumentation and control is mostly achieved at the level of the overall instrumentation and control architectural design as a mean to achieve independence between levels of defence in depth.

3.7 The overall instrumentation and control architecture should:

- Implement a defence in depth concept. For instrumentation and control, defence in depth includes implementing successive instrumentation and control functions designed to limit the consequences of a postulated initiating event despite the failure of instrumentation and control functions designed to respond first.
- Not compromise the defence in depth strategy of the facility design.

INDEPENDENCE

3.8 The independence is intended to prevent the propagation of failures from the item affected by the failure to other redundancies, or from a system to other system independently to the safety class that they belong.

3.9 The overall instrumentation and control architecture should neither compromise the independence of the structure, system and component safety classes, nor the independence implemented at the different levels of defence in depth.

3.10 Safety systems should be independent from systems of lower safety classification as far as practicable to ensure that the safety systems can perform their safety functions during and following any postulated initiating event that requires these functions without any interference or degradation from those systems of lower safety classification.

3.11 Items important to safety should be environmentally qualified for the effects of the design basis accidents to which they must respond.

3.12 The failure of the support features of safety systems should not compromise the independence between redundant portions of safety systems or between safety systems and systems of lower safety classification.

CONSIDERATION OF COMMON CAUSE FAILURE

3.13 A common cause failure is defined as the concurrent failure of two or more structures, systems or components due to a single event or cause. Common cause failure might happen, for example, because of human errors, errors in the manufacturing process, inadequate specification, qualification for, or protection against internal or external hazards, high voltages, data errors, data communication errors, or failure propagation between systems or components.

3.14 Latent failures and common failure modes which potentially might result in a common failure of the redundancies should be identified, and justification should be provided for any which the operating organization does not consider as credible sources of common cause failure between systems or individual components. Justification that a common cause failure need not be considered may, for example, be based on the component dependability, technology, or feedback gained over its wide usage. The consequences of a postulated initiating event in combination with a common cause failure that prevents necessary reactor protection system response to the postulated initiating event should be no greater than those tolerated for design basis accidents. The accident sequences and consequences resulting from the combination of a postulated initiating event and common cause failure of the reactor protection system may be analysed using best estimate methods.

3.15 The design of equipment should take due account of the potential for common cause failures of items important to safety to determine how the concepts of diversity, redundancy, physical separation, electrical and functional isolation have to be applied to achieve the necessary reliability.

3.16 Often it is necessary to provide a diverse actuation system to limit the consequences of the postulated initiating event in conjunction with common cause failure in one or more protection system functions.

3.17 Justification should be provided for accepting identified vulnerabilities, if any, of instrumentation and control systems and architecture that are not addressed. Instrumentation and control systems performing functions on level of defence 3 (e.g. safety systems, reactor protection systems) should completely eliminate all vulnerabilities of instrumentation and control systems and its architecture to common cause failures.

OVERALL ARCHITECTURAL DESIGN OF THE INSTRUMENTATION AND CONTROL SYSTEM

3.18 The overall instrumentation and control architecture should:

- Provide all instrumentation and control functions needed to ensure the safe operation of the facility and manage anticipated operational occurrences and accident conditions;
- Provide systems necessary to support the defense in depth concept of the facility;

- Provide preferably a hierarchical system design where instrumentation and control safety systems keep the highest priority to perform the safety functions for which they have been designed;
- Divide the overall instrumentation and control system into individual systems as necessary to:
    a) Support design basis requirements for independence between functions in different levels of the defense in depth concept;
    b) Adequately separate systems and functions of different safety classes;
    c) Establish the redundancy needed to fulfill design basis reliability requirements;
    d) Support the compliance of safety systems with the single failure and fail safe criteria;
    e) Provide necessary information to the main control room and supplementary control room (if applicable);
    f) Provide necessary operator controls in the main control room and supplementary control room (if applicable); and
    g) Provide automatic controls necessary to maintain and limit the process variables within the specified normal operational ranges.
- define the interfaces between the individual instrumentation and control systems

3.19 The inputs to the overall instrumentation and control architecture design process should refer to the facility safety design basis documents, which should provide the following information:

a) The defense in-depth concepts of the facility;
b) The groups of functions to be provided to address postulated initiating event sequences;
c) The safety classification and the functional and performance requirements of the facility functions important to safety;
d) The role of automation and prescribed operator actions in the management of anticipated operational occurrences and accident conditions;
e) The assignment of functions to operators and to automatic means;
f) The information to be provided to the operators;
g) The priority principles between automatically and manually initiated actions;
h) National requirements including those for instrumentation and control licensing; and
i) Research reactor operating organization requirements with respect to operational features (i.e. the instrumentation and control design as it affects the interface with facility operators) for systems important to safety.

3.20 The instrumentation and control systems should be architecturally designed in a top-down approach (see Figure 3.1) having different monitoring, processing, acquisition/actuation and sensors/actuator driver levels. The monitoring functions

should be allocated at the supervision level; the calculation, algorisms, safety and process functions should be located at the control level; the acquisition and actuation functions should be allocated at the field level and sensors and actuator drivers should be located at the facility level.

3.21 The instrumentation and control system top-down approach requires the inclusion of three independent communication levels namely:

a) Supervision communication level;

b) Control communication level; and

c) Field communication level,

to establish a communication interface between the different top-down approach architectural levels and the reactor and facility systems.

3.22 The use of diversity, redundancy, physical separation, electrical and functional isolation, in the overall architectural design of the instrumentation and control instrumentation and control system, should be consistent with the safety classification of each instrumentation and control system and the defence in depth concept, both for the overall facility and for the instrumentation and control system. In case of redundancy, other factors as availability of instrumentation and control systems should be considered.

3.23 The use of the same features (those mentioned in 3.22) should be applied in the design of the different architectural levels to reduce the probability of dependant failures of the levels.

3.24 The instrumentation and control system should have a fail-safe design such that no malfunction within the system caused solely by variations of external conditions within the ranges detailed in the design basis, will result in an unsafe condition or failure.

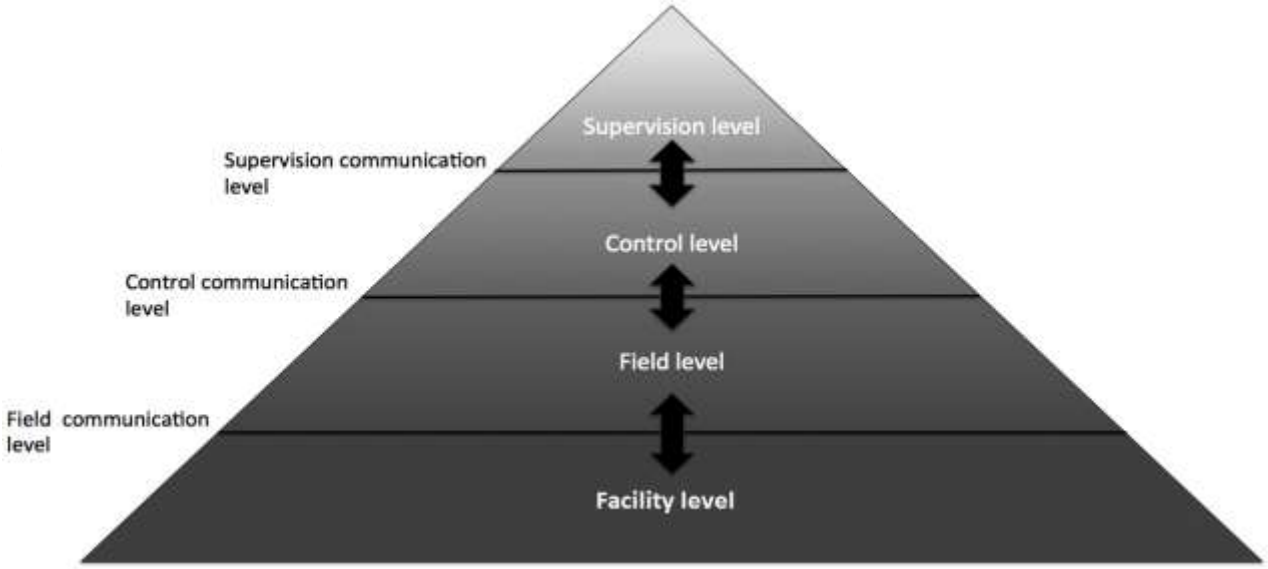

Figure 3.1: Top-down architectural approach design

4. DESIGN GUIDELINES

GENERAL

4.1 Instrumentation and control systems should fully implement the requirements of their design bases. The origin of and rationale for every requirement should be defined, to facilitate verification, traceability to higher level documents and as a demonstration that all relevant design requirements have been accounted for.

4.2 Unnecessary complexity should be avoided in the design of instrumentation and control systems. The intent of avoiding complexity is to keep the instrumentation and control system as simple as possible but still fully implement its safety requirements. Examples of complexity to be avoided are the inclusion of functions not important to safety, architectures involving overly complex communication or system interactions, use of design and implementation features not amenable to sufficient analysis or verification, and use of implementation platforms that are too complex to facilitate an adequate safety demonstration. Careful review of the rational for each requirement is one effective means for avoiding inessential complexity.

DESIGN BASES

4.3 Each research reactor instrumentation and control system important to safety should have design bases that specify the following:

a) The facility states (operational states and accident conditions) in which the system is required;

b) The various facility and experimental configurations that the instrumentation and control system must accommodate;

c) Functionality requirements for each facility state including extended shutdown;

d) for each manual protective action the points in time and the plant conditions during which manual control is allowed;

e) Postulated initiating events to which the system must respond;

f) The variables, or combination of variables, to be monitored, the control actions required, and identification of actions to be performed automatically, manually or both;

g) The ranges, rate of change, required accuracy of input and output signals of the system;

h) Constraints on values of process variables;

i) Requirements for periodic testing, self-diagnostics, and maintenance;

j) System reliability levels. These levels may be specified using, deterministic criteria, probabilistic criteria or both;

k) Security and operational constraints;

l) The range of transient and steady state environmental conditions under which the system is required to perform functions important to safety;

m) The range of environmental conditions, including those arising from natural phenomena hazards under which the system is required to perform functions important to safety; and

n) Conditions with the potential to functionally degrade the performance of systems important to safety and the provisions to be made to retain the capability.

4.4 In addition the design bases for protection and reactor shutdown systems the following should be specified as well:

a) The limiting values of actuation for safety systems;

b) Variables that must be displayed so that the operators can confirm the operation of protective system functions or enable them to decide manual actions; and

c) The conditions under which bypass of safety functions are to be permitted to allow for changes in operating modes, testing, or maintenance.

DESIGN CRITERIA

DESIGN FOR RELIABILITY

4.5 The level of system reliability should be commensurate with the safety importance of the system. A comprehensive strategy that uses various complementary means (including an effective regime of analysis and testing) at each phase of development of the system and a validation strategy to confirm that the design requirements for the system have been fulfilled should be established and implemented to substantiate the claimed reliability.

4.6 All instrumentation and control systems important to safety regardless of technology should be developed using a defined development process that includes verification and validation. In case of safety systems the verification and validation process should be independent (see paragraph 8.36).

Redundancy

4.7 The principle of redundancy should be considered as the provision of alternative (identical or diverse) structure, system or components, such that any of them can perform the required function regardless of the state of operation or failure of any other structure, system or components. The principle of redundancy is an important design principle for improving the safety and reliability of systems important to safety. The design should ensure, on the basis of analysis that the redundancy will provide a backup to assure that no single failure could result in a loss of the capability of a system to perform its intended safety function.

4.8 The single failure approach is a deterministic method to determine the necessary degree of redundancy for items important to safety and it should be applied.

Single failure

4.9 A single failure is a failure which results in the loss of capability of a component to perform its intended safety function(s), and any consequential failure(s) which result from it. The single failure could occur prior to, or at any time when the safety task is required.

4.10 Instrumentation and control systems important to safety have a critical role in achieving the main safety functions, shutting down the reactor, providing cooling, in particular for the reactor core, and confining radioactive material. In the design of instrumentation and control safety systems the single failure criterion should be applied so that the system is capable of performing its safety function in the presence of any single failure.

4.11 The design of instrumentation and control systems important to safety should include provisions for detecting all identifiable failures in the system by means such as anomalous indication, alarm, or periodic testing.

4.12 No single failure could result in a loss of a system to perform its intended safety function

4.13 Multiple sets of equipment that cannot be tested individually should not be considered redundant.

4.14 The degree of redundancy should depend upon the potential for failures that could degrade reliability. For all instrumentation and control systems important to safety redundancy should be applied to the extent necessary to meet reliability and unavailability requirements of the design basis. For instrumentation and control safety systems redundancy should also be applied to the extent needed to comply with the single failure criterion when equipment is removed from service for planned surveillance or testing.

4.15 As far as practicable, redundant safety systems should be physically separated from each other and from systems of lower safety classification. Moreover, the concept of independent equipment should be used.

Common cause failure

4.16 The design of instrumentation and control system important to safety should minimize the possibility of common cause failures by means of independence, physical separation and diversity of equipment. Especially, safety systems should be designed in such a way that occurrence of common cause failures are safely prevented.

Independence

4.17 The principle of independence (e.g. functional independent, electrical isolation, physical separation by means of distance, barriers or a special layout for reactor components as well as independent of communication) should be applied, as appropriate and as far as reasonably practicable, to enhance the reliability of systems.

4.18 Examples of events caused by common cause failures which may be avoided by physical separation should include failures resulting from: fire, flooding, and other abnormal, or accident environments. Physical separation also reduces the likelihood of inadvertent errors.

4.19 Design of certain areas of the facility such as containment penetrations, cable spreading rooms, equipment rooms, control rooms etc. should consider the extent to which independence might be lost after a postulated initiating event.

4.20 Different safety functions should be performed by different modules, components or systems to avoid the effect of the failure of these items on each other.

4.21 Electrical and data connections between redundant systems and connections between safety systems and systems of a lower safety classification should be designed so that no credible failure in one system will prevent the other system(s) from meeting their performance and reliability requirements.

4.22 Electrical isolation should control or prevent adverse interactions between equipment and components caused by factors such as electromagnetic interference, electrostatic pick-up, short circuits, open circuits, grounding, and among others application of the maximum credible voltage (alternating or direct current). Examples of provisions for electrical isolation are electronic isolating devices, optical isolating devices (including optical fibre), relays, cable or component shielding, separation, distance, or combinations thereof.

4.23 When isolation devices are used between safety systems and systems of a lower safety classification, the isolation devices should be part of the safety system having higher classification.

4.24 When it is not feasible to provide adequate physical separation or electrical isolation between safety systems and systems of a lower safety classification, the lower safety classification system should be:

a) Identified as part of the safety system which it is associated;

b) Independent from other lower safety classification systems; and

c) Analysed or tested to demonstrate that the association does not unacceptably degrade the safety system with which it is associated.

4.25 If data communication channels are used in safety systems they should satisfy the recommendations for independence (functional isolation, electrical isolation and physical separation).

Diversity

4.26 Diversity is the presence of two or more redundant systems or components to perform an identified function, where the different systems or components have different attributes so as to reduce the possibility of common cause failure, including common mode failure. Examples of such attributes are: different operating conditions, different working principles or different design teams (which provide functional diversity), and different sizes of equipment, different manufacturers, and types of equipment that use different physical methods (which provide physical diversity).

4.27 Diversity in instrumentation and control systems is the principle of monitoring and processing parameters using different methods or technologies, different logic or algorithms, or different means of actuation in order to provide more than one way to detect and respond to a specific event.

4.28 Both the scope and the type of the diversity provided should be considered. The level of conservatism may be achieved by providing diversity to protect against the more frequent postulated initiating event, without extending full diversity to cover very unlikely postulated initiating events or low consequence postulated initiating events, since the risk of such events may be acceptable despite the possibility of common cause failure.

4.29 Diversity provides defence against common cause failures, increasing the probability that safety actions will be performed when necessary.

4.30 In any application, it should be ensured that diversity is achieved in the implemented design and preserved throughout the life of the facility.

4.31 Where independence is claimed between two systems (for example a research reactor's main reactor protection system and its second diverse reactor protection system) through multiplying their failure probabilities within the probabilistic safety assessment, then their diversity should be substantiated considering the full instrumentation and control chain from the facility sensors, calculators to actuators drivers.

4.32 Diversity applied to instrumentation and control systems should include:

- Functional diversity: could be achieved by systems providing different physical functions or means resulting in the same safety effects; and
- Equipment diversity: achieved by sensors and systems using different technology.

4.33 In assessing claimed diversity, attention should be paid to the equipment's components to ensure that actual diversity exists. For example, different manufacturers might use the same processor or license the same operating system, thereby potentially incorporating common failure modes. Claims for diversity based only on a difference in manufacturers' names are insufficient without consideration of this possibility. To minimize common failure modes, the design should preferably consider the option of different processors with different operating systems.

Failure modes

4.34 The failure modes of instrumentation and control components should be known and documented.

4.35 The failure modes of instrumentation and control systems important to safety should be known and properly documented using failure mode and effect analysis methods. The more probably failure modes should neither place the system in an unsafe state nor cause spurious actuation of safety systems.

4.36 Failures of instrumentation and control components should be detectable by periodic testing or self-revealed by alarm or anomalous indication.

Fail-safe

4.37 The principle of fail-safe design should be considered and adopted as appropriate in the design of instrumentation and control systems to fail into a safe state, with no necessity for any action to be initiated for any system in failure.

DESIGN TO COPE WITH AGEING

4.38 The service life of electrical and electronics systems and components might be considerably less than facility life. Ageing degradation that impairs the ability of a qualified safety component to withstand and function under severe environmental conditions may exist well before the functional capabilities under normal conditions are noticeably affected.

4.39 Ageing mechanisms that could significantly affect instrumentation and control components and means for following the effects of these mechanisms should be identified during design. Ageing is most commonly due to heat, and radiation exposure. Nevertheless, the possibility that other phenomena (e.g., mechanical vibration, or chemical degradation) might be relevant to a specific component must be considered.

4.40 Significant ageing effects (e.g., thermal and radiation ageing) should be addressed to show the required functionality is maintained up to the end of service life. Further conservatism should be provided, where appropriate, to allow for unanticipated ageing mechanisms.

4.41 Examples of means to address ageing impacts include:

- Component replacement before the end of its qualified service life;
- Adjustment of functional characteristics (e.g., recalibration) to account for ageing effects; and
- Changes to maintenance procedures or environmental conditions that have the effect of slowing the ageing process.

DESIGN FOR SECURITY

4.42 The purpose of security applied to instrumentation and control systems of research reactors is to prevent, detect and, in case of detection, eliminate or mitigate vulnerabilities that could be exploited either from outside or inside of the area of the protected equipment.

4.43 As the instrumentation and control system is, in general, a combination of hardware and software modules that execute the overall functional and performance requirements to keep the research reactor in safe status in all of its plant states, the architectural and functional vulnerabilities and their consequences on the instrumentation and control system should be assessed and quantified.

4.44 The design of the instrumentation and control system should include a security perspective to prevent malicious interventions or exploitations of the system.

4.45 Many design principles and components in the overall architectural design contribute to enhance both safety and security simultaneously, nonetheless an assessment should be performed to identify when one objective can be detrimental to the achievement of the other.

4.46 The recommended safety design guidelines of the instrumentation and control design, as far as feasibility possible, should not create adverse effects to the security system.

4.47 Security provisions should be implemented into the instrumentation and control system from the beginning of the system design. One of the primary security considerations from a design perspective is the potentiality of an instrumentation and control system failure or manipulation due to an adversary, external of internal, with malicious intent.

4.48 End User organizations and designers should consider principles of security and cyber security in all phases of the project, namely, requirements specifications, conceptual, preliminary and detail design, fabrication, integration, installation, commissioning, operation and maintenance of the instrumentation and control systems.

4.49 Regulatory bodies should verify that principles of security and cyber security were applied during all phases of the project (whole project life cycle) as stated in paragraph 4.48.

EQUIPMENT QUALIFICATION

4.50 Instrumentation and control systems and components important to safety should be qualified for their intended function. The qualification should provide a degree of confidence commensurate with the system or component's safety classification. The basis for qualification should be documented.

4.51 The design should provide qualification programme(s) addressing all topics affecting the suitability of the system or component for its intended functions important to safety, including:

a) Suitability and correctness of functions and performance for systems and components;

b) Environmental qualification for components (including radiation endurance qualification if applicable);

c) Seismic qualification for components; and

d) Electromagnetic compatibility qualification for systems and components;

4.52 Qualification should be based upon a combination of methods, including:

a) Use of engineering and manufacturing processes in compliance with recognized standards;

b) Reliability demonstration;

c) Past experience in similar applications;

d) Testing of supplied equipment;

e) Analysis to extrapolate test results or operating experience under pertinent conditions; and

f) Ageing analysis as applicable.

4.53 Traceability should be established between each installed system, structure and component important to safety and the applicable evidence of qualification. This includes traceability not only to the component itself, but traceability between the tested configuration and the installed configuration.

4.54 The equipment qualification programme should demonstrate that the as-built instrumentation and control systems and installed components correctly implement the qualified design.

Suitability and correctness

4.55 The design of instrumentation and control systems and components should meet all functional, performance, and reliability requirements important to safety contained in the design bases and equipment specifications.

4.56 Examples of functional requirements should include: functionality required by the application, support system or equipment operability, operator interface and input /output range requirements.

4.57 Examples of performance requirements should include: accuracy and response time requirements.

4.58 Examples of reliability requirements should include: requirements for fail-safe behaviour, conformance with the single failure criterion, independence, failure detection, maintainability, and service life.

Internal and external hazards

4.59 Instrumentation and control systems and components should be protected against or designed and qualified to withstand internal and external hazards including seismic hazards, they may be subjected to.

Environmental qualification

4.60 In this guide environmental qualification means qualification for temperature, pressure, humidity, chemical exposure, radiation, and ageing mechanisms that might affect the proper functioning of components under those conditions.

4.61 Systems and components should be designed to withstand the effects of, and be compatible with the environmental conditions associated with normal operation and anticipated or postulated accidents when they are required to function.

4.62 Components should be shown to meet all design basis requirements when subjected to the range of environmental conditions specified in the design basis.

Electromagnetic compatibility qualification

4.63 The undisturbed operation of electrical and electronic systems and components depends upon their electromagnetic compatibility with components located nearby or with which they are connected.

4.64 Significant sources of electromagnetic interference should include, for example, fault current clearance by switchgear or circuit breaker or fuse operation, electric fields caused by radio transmitters, natural sources such as lightning strike, and other man-made sources internal or external to the facility.

4.65 Electromagnetic qualification of instrumentation and control systems and components depends upon a combination of system and component design to minimize the coupling of electromagnetic noise to electrical components. Testing should be done to demonstrate that components can withstand the expected levels and testing to demonstrate that electromagnetic emissions are within tolerable levels. Instrumentation and control systems and components already qualified should be accompanied with the corresponding qualification certificate.

4.66 Systems and equipment, including associated cables, should be designed and installed to withstand the electromagnetic environment in which they are located.

4.67 The types of electromagnetic interference to be considered in the design of instrumentation and control systems and components should include:

- Emission of and immunity to electromagnetic disturbances;

- Emission and conduction of electromagnetic disturbances via cables; and
- Electrostatic discharge.

4.68 The emission characteristics of wireless systems and devices used at the facility as well as those of repair, maintenance and measuring devices should be taken into consideration. Wireless systems and devices should include, for example, mobile phones, radio transceivers, and wireless data communication networks.

4.69 Any electrical or electronic equipment in the facility will contribute to the electromagnetic environment. Instrumentation and control systems important to safety must be capable to perform safety functions in such environment. The contribution of electromagnetic emissions from all equipment, not only equipment important to safety, must be evaluated as to its impact on the performance of instrumentation and control systems important to safety.

4.70 Equipment and systems, including associated cables, should be designed and installed and qualified to appropriately limit the propagation (both by radiation and conduction) of electromagnetic interference among facility equipment.

TESTING AND TESTABILITY

4.71 The design of all instrumentation and control systems important to safety should include provisions that allow performance of the required testing during reactor operation, or, if justified, during shutdown only, supporting implementation of the guidance given in Ref. [11]. Many of the research reactors are operated on relatively short operating cycles therefore provisions for testing during operation on those research reactors may be not necessary.

Test provisions

4.72 Provisions for testing instrumentation and control systems and components important to safety should:

a) Have appropriate test interfaces and status indication. Test interfaces should include, for example, the capability to introduce simulated process conditions or electrical signals;

b) Operate such that faults in the equipment are readily detectable;

c) Have features to prevent unauthorized access;

d) Be located such that test equipment and the components to be tested are readily accessible;

e) Be located such that neither the testing nor access to the testing location exposes staff to hazardous environments;

f) Have communications facilities as needed to support the tests; and

g) Auxiliary test equipment should be appropriately calibrated.

4.73 The design should ensure that the system cannot be unknowingly left in a test configuration. Inoperability or bypass of safety system components or channels should be indicated in the control room. For frequently bypassed items these indications should be auto-announcing.

4.74 Self-checking features of instrumentation and control systems important to safety should be considered and applied by the design as applicable. It is necessary to balance the provision of self-checking features and the need for simplicity.

4.75 Built-in test facilities should themselves be capable of being checked at regular intervals to ensure continued correct operation.

Preserving instrumentation control functions during testing

4.76 Arrangements for testing include: procedures, test equipment interfaces, installed test equipment and built in test facilities. Testing should neither compromise the safety function nor introduce the potential for common cause failures.

4.77 Test facilities that are permanently connected to safety systems should be considered as part of the safety systems.

Test considerations

4.78 Examples of considerations should include:

- Location of sensors such that testing and calibration can be performed preferably at their location;
- Location of test devices and test equipment in areas convenient to the equipment to be tested;
- Layout or administrative features;
- Convenience of component status indication and test connections; and
- Have communications facilities as needed to support the tests.

4.79 Where equipment to be tested is located in hazardous areas, the design should consider the provision of facilities to allow testing from outside the hazardous area.

4.80 Design of instrumentation and control systems important to safety should include provisions to automatically alert operators that channels or components are in test mode. Operator notification that channels or components are in test mode is often accomplished by alarms.

Test programme

4.81 The design of instrumentation and control systems should include identification of a testing and calibration programme. The scope and frequency of testing and calibration should be designed and justified as consistent with functional and availability requirements.

4.82 A test programme should include:

- A description of programme objectives;
- Identification of systems and channels to be tested;
- A master test schedule;
- The reasons and justification for the tests to be conducted and test intervals;

- A description of required documentation and reports;
- A requirement for periodic review of programme effectiveness; and
- Specification of the individual test procedures that will be used during the conduct of tests.

4.83 The tests defined in the test programme should ensure that, during and after completion of the tests:

- The overall functional capabilities of the systems are not degraded; and
- The instrumentation and control safety systems continue to meet their design basis requirements of functionality and performance.

4.84 The test programme should arrange tests into a sequence such that the overall condition of the system or component under test can be immediately assessed without, as far as practicable, further testing of other components or systems.

4.85 The test programme should define processes for periodic tests and calibration of systems that:

- Specify overall checks of all functions from the sensors to the actuators, capable of being performed in situ and with a minimum of effort;
- Confirm that design basis functional and performance requirements are met;
- Test all inputs and output functions, such as alarms, indicators, control actions, and operation of actuation devices;
- Ensure the safety of the facility during the actual testing; and
- Minimize the possibility of spurious initiation of any safety action and any other adverse effect of the tests on the availability of the research reactor.

4.86 Conduct of the test programme should not cause deterioration of any system or component.

4.87 It is necessary to evaluate and document the reasons for, root causes of, and actions taken after a failed test before the results of a repeated test can be used to demonstrate operability of the system or component involved.

4.88 Corrective actions may, for example, include maintenance or repair of components, or changes to test procedures. If corrective actions are determined to be unnecessary the reasons should be documented.

4.89 Where temporary connections are required for periodic testing or calibration, connection and use of such equipment should be subject to appropriate administrative controls.

4.90 For testing purpose, temporary modification of computer code in systems and components is not allowed.

4.91 The time interval during which equipment is removed from service should be minimized and each sensor should be individually tested to the extent practicable.

4.92 Test of a safety system channels should preferably be single online. When a single online test is not practicable, the test programme may combine overlapping tests, to

achieve test objectives. For safety system channels tests it is necessary to provide documented justification for the use of overlapping tests.

4.93 Test of a safety system should independently confirm the functional and performance requirements of each channel of sensing devices, command, execution, and support functions.

4.94 Test of a safety system should include as much of the function under test as practical (including sensors and actuators).

4.95 Wherever possible, test of a safety system should be accomplished under actual or simulated operating conditions, including sequence of operations.

MAINTAINABILITY

4.96 The design should consider provision of means for the maintenance of instrumentation and control systems. The design of instrumentation and control systems should include maintenance plans for all systems and components.

4.97 Instrumentation and control systems and components should be designed so as to minimize risks to maintenance personnel and to facilitate necessary preventive maintenance, troubleshooting, and timely repair.

4.98 Design to facilitate maintenance, troubleshooting and repair includes:

- Avoiding locating equipment in areas of extreme temperature or humidity, and where risk of high radiation levels exist;
- Considerations of human factors in performing the required maintenance activities; and
- Leaving sufficient room around the equipment to ensure that the maintenance staff can perform their tasks.

4.99 If components must be located in inaccessible areas other solutions should be considered by the design. Examples include:

- Installation of spare redundant devices in cold or hot standby; and
- Provision of facilities for remote replacement, repair and to put back in operation again.

DESIGN ANALYSIS

4.100 Safety analysis in design is used to support the design of a new instrumentation and control system or modifications to the design of an existing one. Design analyses, including the following specific activities, they should be performed to confirm that instrumentation and control systems fulfil their design basis requirements, Ref. [3]:

a) Verification that safety systems comply with the single failure criterion;

b) Failure mode and effects analysis to confirm compliance with the single failure criterion, and to confirm that all known failure modes are either self-revealing or detectable by planned testing;

c) Verification that the design of instrumentation and control systems includes adequate test provisions;

d) Verification that the overall instrumentation and control system supports the facility defence-in-depth concept;

e) Verification that common cause failure vulnerabilities of instrumentation and control safety systems are known and have been adequately addressed. Common cause failure vulnerabilities may be addressed by eliminating the vulnerability, providing diverse means of achieving the safety functions subject to the common cause failure, or justifying acceptance of the vulnerability;

f) Diversity analysis to investigate vulnerabilities of safety systems to common cause failure;

g) Verification that design basis reliability requirements are met. This demonstration may be based on a balance of application of deterministic criteria and quantitative reliability analysis that considers design features such as, for example, redundancy, testability, failure modes, and rigour of qualification. For complicated systems a combination of qualitative analysis, quantitative analysis, and testing is usually needed to verify compliance with design basis reliability requirements;

h) Test facilities that are part of the safety system must be considered when determining system availability;

i) Confirmation that all system requirements have been implemented and validated;

j) Typically traceability analysis to confirm implementation and validation of requirements;

k) Confirmation of correct system behaviour following power interruptions and restart or reboot; and

l) Verification that the effects of automatic control system failures will not exceed the acceptance criteria established for anticipated operational occurrences;.

4.101 The methodology for any analysis conducted should be thoroughly defined and documented together with analysis inputs, results, and the analysis itself.

4.102 Each assumption of an analysis should be stated, and justified in that analysis.

SAFETY SYSTEM SETTINGS

4.103 The requirements and operational limits and conditions established in the design for the facility should include limiting settings for safety systems. The limits and conditions for safe operation include safety system settings for instrumentation and control systems.

4.104 Determination of instrumentation and control safety system setting usually considers the following values:

- Safety limits – limits on certain operational parameters within which the operation of the reactor has been shown to be safe;
- Analytical limit (of safety system setting) - limit of a measured or calculated variable established by the safety analysis to ensure that a safety limit is not exceeded; and
- Allowable value - the limiting value that a safety system setting may have when tested periodically, beyond which appropriate action must be taken. The allowable value for a specific safety system setting specifies the value at which it is acceptable to find that a trip would occur when testing the corresponding channel. If the point at which a

protective action would be initiated is found to be beyond the allowable value, corrective action is necessary.

Figure 4.1 illustrates the relationship between these terms and the types of measurement uncertainties that are normally considered in establishing the basis for trip safety system setting and allowable values.

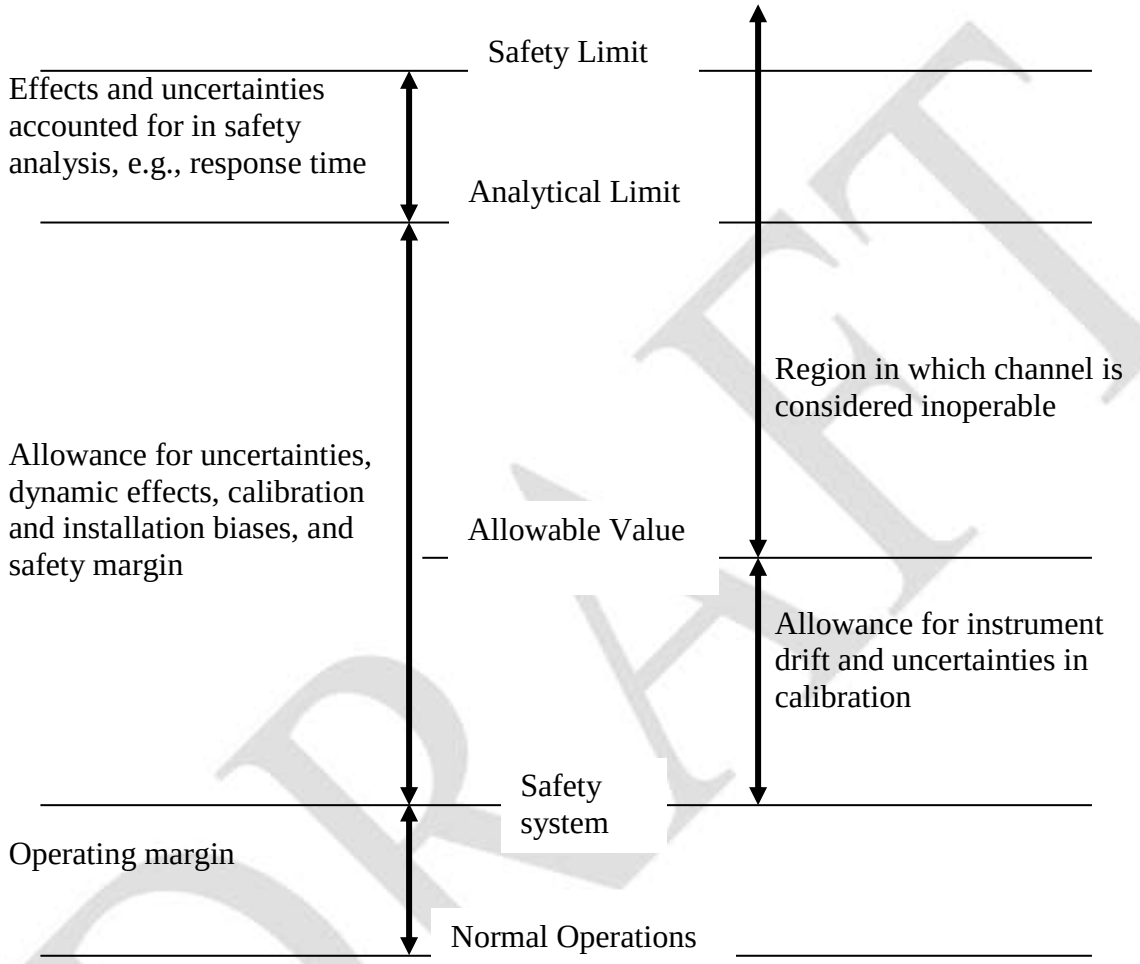

FIG. 4.1 Safety system setting terminology and errors to be considered in safety system setting determination

IDENTIFICATION OF ITEMS IMPORTANT TO SAFETY

4.105 A consistent and coherent method of naming and identifying all instrumentation and control components should be determined and followed throughout the design, construction, installation and operation phases of the reactor facility as well as for the labelling of controls, displays and indications. Clear identification of components is necessary to reduce the likelihood of inadvertently performing maintenance, tests, repair or calibration on an incorrect channel. Components or modules mounted in

equipment or assemblies that are clearly identified may not themselves need identification.

5. SYSTEM SPECIFIC DESIGN GUIDELINES

SENSING DEVICES

5.1 Measurements of research reactor variables should be consistent with the requirements of the design basis. These measurements include both detection of the present value of a variable within a range, and detection of a discrete state such as it is detected by limit or on/off switches (i.e. temperature, pressure, flow or level limit switches and main supply availability, control system normal operation or interlock on/off switches).

5.2 The measurements of variables may be made directly or indirectly such as calculation of the value performing multiple measurements, or by measuring other data having a known relationship to the desired variable.

5.3 To the extent practicable, the reactor conditions should be monitored by direct measurement rather than being inferred from indirect measurements.

5.4 The sensor for each monitored variable and its range should be selected on the basis of the accuracy, response time, and range needed to monitor the variable in normal, and accident conditions.

5.5 No identified common cause failure vulnerability of sensing devices should have the potential of denying operators the information and parameters that they need to control and mitigate accident conditions. An example is the saturation of radiation monitors.

5.6 If more than one sensor is necessary to cover the entire range of the monitored reactor parameter, a reasonable amount of overlap from one sensor to another should be provided. Examples include source range, intermediate range and power range of nuclear instrumentation.

5.7 If the monitored variables have a spatial dependence (i.e., the measured value of a parameter depends upon sensor location), the minimum number and locations of sensors, such as flow measurement elements, should be identified by the design and justified.

REACTOR PROTECTION SYSTEM

5.8 The reactor protection system should comply with all of the general guidance for design of instrumentation and control systems given in the section 4 where applicable.

5.9 The design of the reactor protection system should include provisions to bring the reactor into a safe condition and to maintain it in a safe condition even if the reactor protection system is subjected to a credible common cause failure (e.g. hardware failure or failure due to ageing or human factors).

5.10 The reactor protection system should, as a minimum, include a function to initiate shutdown of the reactor. The reactor protection system could also provide other safety functions such as initiation of emergency core cooling, confinement functions and maintaining the reactor in a safe and stable condition (acting in this case as extended engineered safety features instrumentation and control system).

5.11 The appropriate protective actions should be started automatically for the full range of postulated initiating events to terminate the event safely.

5.12 As part of the defence in depth the need for a second protection system, with all or part of the functions of the primary protection system should be considered. Where two independent reactor protection systems are provided, these two systems should be independent and diverse from each other.

5.13 The action initiated by the reactor protection system should be latched so that once an action is started, it will continue even if the initiating state ceases to be present. Functions added to latch safety actions should not reduce the reliability of the safety action below an acceptable level.

5.14 In some cases, manual operator action may be considered to be sufficient provided that:

- The operator has sufficient and clearly presented information to make reasoned judgements on the need to initiate the required safety actions;
- The operator is allowed sufficient time to evaluate the status of the reactor facility and to complete the required actions;
- The operator is provided with sufficient means of reactor control to perform the required actions, and;
- The diagnosis is simple and the action is clearly defined.

5.15 In addition to any automatic actions, means should be provided to manually initiate reactor trip and any other safety actions of the reactor protection system. It is preferable that the manual actuation function act directly on the final actuation devices (e.g. reactor trip breakers) rather than being an input to the reactor protection system logic.

5.16 Functions that inhibit protection system trip functions, including the means for activating and deactivating these inhibit should be part of the protection system. Sometimes it is necessary to inhibit the action of protection system functions to allow changes in reactor conditions. For example, the trips that limit reactor power during start-up must be inhibited at some point to allow power increase past the low power trip safety system setting. Another example would be the necessity for inhibition of certain functions in case of pulsed operation of a research reactor. In this guide such reactor protection system inhibit functions are called safety interlocks and are classified as components/functions of safety systems.

5.17 During facility operation, the operator should be provided with suitable warnings or alarms when the facility is approaching a state where operational interlocks should be enabled or disabled.

5.18 The protection system should prevent enabling of an operational interlock when the applicable permissive conditions are not met. If conditions change such that an enabled operational interlock is no longer permissible the protection system should automatically accomplish one of the following:

- Disable operational interlock; or
- Initiate appropriate protective actions.

5.19 Paragraph 4.80 gives recommendations on temporary connections used for maintenance and testing. This recommendation should be strictly applied to reactor protection systems.

5.20 The design should ensure that Safety System Settings can be established with such a margin between the initiation point and the safety limits where the action initiated by the Reactor Protection System will be able to control the process before the safety limit is reached. In addition, these margins should take in account the following:

- Inaccuracy of instrumentation;
- Uncertainty in calibration;
- Instrument drift; and
- Instrument and system response time.

5.21 If a computer based system is intended to be used in reactor protection system the following requirements should be applied:

- Hardware and software of high quality and best practices should be used;
- The whole life cycle of the system should be systematically documented and reviewed; and
- Independent verification and validation process should be applied.

5.22 Where the necessary reliability of a computer based system that is intended for use in a reactor protection system cannot be demonstrated with a high level of confidence, diverse means of ensuring fulfilment of the protection functions should be provided. The diversity may be provided:

- Internal to the reactor protection system or by a separate and independent system; and
- By a diverse system which may be hardwired or computer-based as long as adequate diversity can be justified.

5.23 Diversity may be provided internal to the reactor protection system or by a separate and independent system, as long as the design bases are met.

5.24 Diverse systems may be non-computer based systems, including hardwired or other technology backups or computer-based systems as long as the existence of diversity can be justified. Normally, it is easier to justify diversity between computer-based and hardware-based systems than between two computer-based systems.

5.25 "*To confirm the reliability of the computer based systems, an assessment of the computer based systems should be undertaken by expert personnel who are independent of the designers and the suppliers."* Ref. [1], para. 6.104, (c)

5.26 For computer based reactor protection systems, the system design should include computer security.

OTHER INSTRUMENTATION AND CONTROL SYSTEMS IMPORTANT TO SAFETY

5.27 The reactor operator should be provided with sufficient instrumentation for monitoring the operation of the reactor process systems during normal operation, shut-down, refuelling and maintenance, including the recording all variables important for safety.

5.28 The reactor operator should be provided with sufficient indicating and recording instrumentation to monitor relevant reactor parameters during and following anticipated operational occurrences and accident conditions.

5.29 The design should take into account the requirements of start-up neutron source and dedicated start-up instrumentation, for conditions in which they are needed.

5.30 Audible and visible alarm systems should provide an early indication of changes in the operating conditions of the reactor if these conditions could lead to a reduction in safety.

5.31 The safe normal operation of a research reactor, intended to cover all normal modes of operation, should be considered in the design process. The design process should establish a set of requirements and limitations on the normal operation of the instrumentation and control systems as necessary for safe operation of the facility. These requirements should cover:

- The information necessary to establish the safety system settings;
- Control system constraints and procedural constraints on process variables and other important parameters;
- Maintenance, testing and inspection of the facility to ensure that systems, structures and components function as intended; and
- Clearly defined operating configurations, including operational restrictions in the event of safety system outages.

These requirements and limitations are the bases for establishing the operational limits and conditions under which the reactor is authorized to operate.

Control rooms

5.32 In the main control room, supplementary control room (if required – see paragraph 5.38), and other areas where staff are expected to monitor and control facility systems the necessary provisions should be implemented to ensure satisfactory conditions in the working environment, and to protect against hazardous conditions.

5.33 Normal working environments to be considered include: lighting, temperature, humidity, noise, and vibration, for normal, abnormal and accidental conditions. The design of the main control room and supplementary control room (if required - see paragraph 5.38) should take into account conditions resulting from internal hazards (e.g. fire smoke or toxic substances in the atmosphere) and external hazards (e.g. earthquakes, flooding, extreme meteorological conditions, man-made hazards).

Main control room

5.34 The principal location for safety and safety related control actions is the main control room. A control room should be provided from which the reactor facility can be safely operated in all its operational states and from which measures can be taken to maintain the research reactor in a safe state or to bring it back into such a state after the onset of anticipated operational occurrences and accident conditions..

5.35 The design should consider the layout of instrumentation and the mode of presenting information to operating personnel with both, an adequate overall picture of the status

and performance of the facility, and detailed information, where necessary, on specific systems or equipment status or performance.

5.36 The functional design of a control room should provide the operating personnel with accurate, complete and timely information on the status of facility equipment and systems for all operational states and accident conditions, and to optimize the activities of the operator in monitoring and controlling the facility.

5.37 The information displayed should allow operators to:

- Take specific manually-controlled actions for which no automatic control is provided;
- Confirm facility critical safety functions availability and performance of automatic safety actions;
- Determine the potential for or actual breach of a fission product barrier;
- Confirm performance of safety systems, auxiliary supporting features, and other systems necessary for mitigation of accident conditions or maintaining of safe shutdown; and
- Determine the magnitude of any release of radioactive materials and ~~to~~ continually assess such releases.

Supplementary control room

5.38 A remote reactor shutdown capability should be provided if the safety analysis identifies events that could inhibit the operators' ability to shutdown the reactor from the main control room. A supplementary control room or emergency control console should be provided if operators are required to perform safety actions and the safety analyses identifies events where the main control room could be unavailable or operations from the main control room could be inhibited.

5.39 Events that could inhibit the operator's ability to shutdown the reactor from the control room should include, for example, fire in the control room or fire in a location that affects connections between the control room and devices elsewhere in the facility.

5.40 A suitable provision outside the main control room should be considered and applied as appropriate for transferring priority control to a new location and isolating the equipment in the main control room whenever the main control room is abandoned.

5.41 Sufficient instrumentation and control equipment should be available, preferably at a single location that is physically and electrically separate from the main control room, so that the reactor can be placed and maintained in a shutdown state, residual heat can be removed, confinement functions can be performed and the essential facility variables can be monitored in the event of a loss of ability to perform these essential safety functions in the main control room.

5.42 The parameters displayed in the supplementary control room may differ from those displayed in the main control room if the supplementary control room does not need to respond to the same range of anticipated operational occurrences and accident conditions as the main control room. In any case the information available at the supplementary control room or emergency control console should allow for putting the facility in a safe condition during and after accident conditions and mitigate the consequences of the accident.

5.43 The design of supplementary control rooms should take into account ergonomic factors and include suitable provisions for preventing unauthorized access and use.

Irradiation and experiment facility control systems

5.44 In many research reactors there are special control consoles for running irradiation and experimental devices. They are located in the main control room and/or in other rooms.

5.45 The operator of experimental devices should have communication links with reactor operator to share information on experience and reactor status and make each other aware of the expected actions (e.g. in special, situations that requires shut-down of the reactor).

5.46 The irradiation and experimental devices control consoles should be devoted exclusively to the facilities to keep a functional separation with the reactor activities.

5.47 Important alarms of the facilities related to the reactor operation should be included in the reactor alarm system. Other alarms of experimental devices should be presented with a functional separation from reactor's alarms.

Voice communication system

5.48 Communications systems should be provided for staff to securely interface between the main control room, supplementary control room, other locations internally within the facility, the operators of experimental devices, associated facilities, the on-site emergency centre, and to external emergency organizations without having to leave the control room.

5.49 Both the main control room and the supplementary control room should have at least two diverse communications links with:

- Areas where communications are needed during anticipated operational occurrences or accident conditions;
- Off-site emergency services; and
- Associated facilities.

5.50 The diverse communications links should be routed such that they will not both be affected by loss of the primary communications links, whatever its origin (including external events), and should be capable of operating independently of both the facility power systems and offsite power systems.

Provisions for fire detection and extinguishing

5.51 The nature of the fire alarm system, its layout, the necessary response time and the characteristics of its detectors should be determined by the fire hazard analysis.

5.52 The detection system should provide detailed annunciation in the control room about the location of the fire by means of audible and visual alarms.

5.53 Local audible and visual alarms, as appropriate, should also be provided in facility areas that are normally occupied. Fire alarms should be distinctive and should not be capable of being confused with any other alarms in the facility.

5.54 The fire detection and alarm system should be energized at all times and should be provided with non-interruptible emergency power supplies, including fire resistant cables where necessary.

5.55 Fire detectors should be sited so that the flow of air due to ventilation or pressure differences necessitated for contamination control will not cause smoke or heat energy to flow away from the detectors and thus unduly delay actuation of the detector alarm.

5.56 If the environment does not allow detectors to be placed in the immediate area to be protected (e.g. owing to increased radiation levels or high temperatures), alternative methods should be considered, such as the sampling of the gaseous atmosphere by remote detectors with automatic operation.

5.57 When items such as fire pumps, water spray systems, ventilation equipment and fire dampers are controlled by fire detection systems, and where spurious operation would be detrimental to the facility and the personnel, operation should be controlled by two diverse means of detection operating in series. The design should allow the operation of the system to be stopped if the actuation is confirmed to be spurious.

5.58 Wiring for fire detection systems, alarm systems or actuation systems should be:

- Protected from the effects of fire by a suitable choice of cable type, by proper routing, or by other means;
- Protected from mechanical damage; and
- Constantly monitored for integrity and functionality.

POWER SUPPLIES OF INSTRUMENTATION AND CONTROL SYSTEMS

5.59 The power supply for instrumentation and control systems should have classification, reliability provisions, qualification, isolation, testability, maintainability, and indication of removal from service, consistent with the design basis reliability requirements of the instrumentation and control systems they serve.

5.60 Instrumentation and control systems that are required to be available for use at all times in operational states or design basis accident conditions should be connected to uninterruptible alternate current power supplies that provide the systems with power within the tolerances specified by the instrumentation and control design bases[2].

5.61 Power supplies can provide a transmission path for electromagnetic interference which might originate outside the instrumentation and control systems or might arise from other instrumentation and control systems that are connected directly or indirectly to the same power supply. Such interference sources include electrical fault clearance associated with other equipment on the same supply. These interferences should be analysed and avoided to the extent possible.

[2] Modern instrumentation and control systems can be powered directly from direct current power sources. This is advantageous for systems that need non-interruptible power because it eliminates the need for inverters, motor-generators, or power transfer devices in the electrical power system.

6. OPERATION

OPERATIONAL LIMITS AND CONDITIONS

General

6.1 Paragraphs 7.29 and 7.30 of Ref. [1] respectively define:

- "*A set of OLCs (operational limits and conditions)important to reactor safety, including safety limits, safety system settings, limiting conditions for safe operation, requirements for inspection, periodic testing and maintenance and administrative requirements, shall be established…*"; and
- "*The OLCs shall be used to provide the framework for the safe operation of the research reactor…*"

6.2 The design of the instrumentation and control systems of the reactor should assure that, during the operational states of the reactor, the instrumentation and control systems contribute to keep the settings and values of the original selected operational limits and conditions.

Safety limits

6.3 The instrumentation and control systems should include those safety functions and safety related functions that prevent the exceeding of safety limits during the operational states of the reactor, during design basis accident and, as far as reasonably practicable, during beyond design basis accident.

Safety system settings

6.4 For each parameter for which a safety limit is required and for other important safety related parameters, an instrumentation and control system should monitor the parameter and provides a signal that can be utilized in an automatic mode to prevent that parameter from exceeding the set limit. The required instrumentation and control systems to provide these functions should include the capability of storing these safety systems settings.

Limiting conditions for safe operation

6.5 Acceptable margins between normal operating values and the safety system settings should be considered in the functions of the instrumentation and control systems to assure safe operation of the reactor and avoid frequent actuation of safety systems.

CONTROL OF ACCESS TO SYSTEMS IMPORTANT TO SAFETY

6.6 All reasonable precautions shall be taken to prevent persons from deliberately carrying out unauthorized actions that could jeopardize safety when accessing instrumentation and control systems or performing tasks on instrumentation and control systems.

6.7 Instrumentation and control systems, classified as important to safety, should be controlled to prevent unauthorized access. Access control methods should include physical restrictions or barriers, special embedded devices and limited access to functions important to safety using hardware or software access keys, access alarms and proper administrative controls.

6.8 Access to the safety systems settings and calibration adjustments should be restricted by physical and administrative means.

6.9 On the basis of the security policy that has been defined for the computer based system environment, appropriate security procedures - for instance password management - should be implemented (for example to guard against unauthorized access and viruses).

6.10 Secure storage arrangements and procedural controls should ensure that only authorized software versions are loaded into the facility equipment. The correct performance of the computer based system should be demonstrated before it is returned to service.

6.11 Electronic access to software and data of computer based systems via external network connections should be prohibited.

6.12 A hierarchical access method should be implemented in order to restrict authorised users to only access data and commands for which they are enabled.

6.13 The security policy should implement suitable measures in place to prevent intentional or unintentional intrusion or corruption of the software or data, the introduction of malicious code, incorrect connection to external networks, or hacking attacks.

MAINTENANCE, TESTING, SURVEILLANCE AND INSPECTION OF INSTRUMENTATION AND CONTROL SYSTEMS AND COMPONENTS IMPORTANT TO SAFETY

6.14 Inspection, periodic testing, surveillance and maintenance of the instrumentation and control systems should be conducted to ensure that all their components function in accordance with the design intent and with the requirements, in compliance with the operating limits and conditions and in accordance with the long term safety of the reactor.

6.15 The instrumentation and control systems should include, when reasonably applicable, on-line testing functions and capabilities to facilitate and reduce the time of periodic testing preserving the availability of the reactor.

PROVISIONS FOR REMOVAL FROM SERVICE FOR TESTING OR MAINTENANCE

6.16 Removal from service of any single safety system, component or channel should not result in loss of the required minimum redundancy unless the acceptably reliable operation of the system can be adequately demonstrated.

6.17 If use of equipment for testing or maintenance can impair an instrumentation and control function, the interfaces should be subject to hardware interlocking to ensure that interaction with the test or maintenance system is not possible without deliberate manual intervention.

6.18 In safety systems it is important that design features ensure that during periodic tests of part of a safety system those parts remaining in service can perform the required safety task.

EXTENDED SHUTDOWN

6.19 A research reactor facility may have a period of extended shutdown pending decisions on its future.

6.20 The operating organisation should assess and define the minimal instrumentation and control systems required for safety to be kept operational during that extended shutdown.

7. HUMAN FACTORS ENGINEERING AND HUMAN-MACHINE INTERFACE

GENERAL CONSIDERATIONS

7.1 Human factors and human-machine interfaces considerations should be embedded throughout the entire design process.

7.2 Effective human-machine interfaces should be applied for systems which should provide the operator with accurate, complete and timely information on the research reactor status and should enable proper operation of the instrumentation and control systems.

7.3 In the design of instrumentation and control systems the human factors should be taken into account. During the design of the human-machine interfaces special attention should be paid to the duties and responsibilities of the operating personnel (e.g. operators as well as the maintenance staff, experimenters and emergency response staff) in order to achieve an effective interface between the operating personnel and the research reactor systems. Particular requirements of the operation organization should be taken into account from the early stages of the design.

7.4 All human-machine interfaces should be designed according to ergonomic principles. The operational philosophy should determine which information is convenient to be displayed using conventional displays (e.g. panel instruments, alarm annunciators, etc.) and which information is convenient to be displayed using video screens. To assist in the establishment of design principles for information display and controls the different roles of the operating personnel such as operator, maintenance staff, systems manager and accident management should be taken into account.

7.5 The requirements specification for human-machine interfaces design should include the information to assess the general state of the facility, in whichever condition it may be, and confirmation that the designed automatic safety actions are being taken.

7.6 Verification and validation of human factors should be included throughout the design process to confirm that the design adequately accommodates all necessary operating actions and operating organization organizational arrangements.

7.7 Careful attention should be paid during the design of the human-machine interfaces to ensure that all the necessary information is available to the operator when and wherever it necessary. At the same time, the operator should not be overwhelmed by large

amounts of data that could be difficult to grasp owing to the limitations on human perception, cognition and memory. This is particularly important in the case of the treatment of alarms.

7.8 In the case where only a portion of the instrumentation and control system is modernized, careful consideration should be given to the design, compatibility and human interaction of the modernized portion of the instrumentation and control system to the existing systems to ensure proper and continued operation with the considerations given in paragraphs 7.1 through 7.7.

PRINCIPLES FOR HUMAN FACTORS ENGINEERING AND HMI DESIGN

7.9 The human-machine interfaces design should retain useful features and avoid human factors engineering problems and issues experienced in previous designs.

7.10 Instrumentation and control functions necessary to achieve facility safety objectives should be identified and allocated to human and system resources according to a defined methodology.

7.11 The human-machine interfaces characteristics need to support tasks assigned to operators should be identified and documented according to a defined methodology. All aspects of the human-machine interfaces (e.g. formats, terminology, sequencing, grouping, and operator's decision-support aids) should be designed in accordance with the task requirements.

7.12 The instrumentation and control system should provide operators with the information necessary to detect changes in system status, diagnose the situation, and verify manual or automatic actions.

7.13 The instrumentation and control system design should ensure take due account of the time needed by operators to perform their expected tasks.

7.14 The instrumentation and control system should be designed to detect operator errors, offer simple, comprehensible notification of the error, and simple, and effective methods for recovery.

7.15 Allocation of functions between manual and automatic actions should be made early in the design process.

7.16 Where a function is carried out automatically, the instrumentation and control system should provide operators with information necessary to monitor the function. The information should be provided at a rate and level of detail that the operator can monitor effectively.

7.17 The instrumentation and control system should alert the operator of the failure of an automatic control system.

7.18 The instrumentation and control system characteristics should be identified as necessary by a task analysis.

7.19 The relationship of each display, control, and data-processing aid to the associated tasks and functions should be clear.

7.20 The human-machine interfaces should provide an effective overview of the facility status.

7.21 The presentation of information should be integrated into a harmonized arrangement that optimizes the operator's understanding of the facility's status and the activities necessary to control the facility.

7.22 The operation and appearance of the human-machine interfaces should be consistent across information and control locations, reflect a high degree of standardization, and be fully consistent with procedures and training.

7.23 The human-machine interfaces should provide the capability to display recorded information where such displays will help operators to: identify patterns and trends, understand the past or current state of the system, or predict future progressions.

7.24 The instrumentation and control systems should provide sufficient instrumentation for monitoring its operation and process systems in normal operation and for recording all variables important to safety.

7.25 The instrumentation and control systems should provide sufficient indicators and recording instrumentation to monitor important reactor parameters during and following anticipated operational occurrences and accident conditions.

7.26 Audio and visual alarm systems should be provided for the early indication of changes in the operating conditions of the reactor that could affect its safety.

Control Rooms

7.27 Requirements for functional isolation and physical separation as well as ergonomic principles should be taken into account in the design of the control rooms.

7.28 In control room design human factors engineering as workload, possibility of human error, operator response time and minimization of the operator's physical and mental efforts should be taken into account, in order to facilitate the execution of the operating procedures specified to ensure safety in all operational states and accident conditions.

8. COMPUTER BASED SYSTEMS AND SOFTWARE

GENERAL CONSIDERATIONS

8.1 Computer based systems are of increasing importance to safety in research reactors as their use in both new and older facilities is rapidly increasing. They are used both in safety related applications, such as some functions of the process control and monitoring systems, as well as in safety applications, such as reactor protection systems.

8.2 Computer based systems reliability could be predicted and demonstrated with a systematic, fully documented and reviewed engineering process. This process should include the evaluation of operating experience with pre-existing software.

8.3 Since software faults are systematic and not random in nature, potential common mode failure of computer based safety systems employing redundant subsystems using identical copies of the software should be systematically considered.

8.4 Depending on the complexity of experimental devices in the research reactor, it should be considered to functionally split the Computer based system in reactor system and

experimental devices system. In that way, both systems could be treated with its own set of requirements and objectives.

COMPUTER BASED SYSTEMS AND SOFTWARE DESIGN CONSIDERATIONS

8.5 In safety systems implementation all unnecessary complexity should be avoided both in the functionality of the system and in its implementation, by complying with a structured design, following a programming discipline.

8.6 For safety systems, the functional requirements that have to be fulfilled by a computer system should all be essential to the achievement of safety functions. Functions not essential to safety should be isolated to avoid any impact to safety functions.

8.7 For computer based system applications, top-down decomposition, levels of abstraction and modular structure are important concepts for coping with complexity. The logic behind the system modularization and the definition of interfaces should be made as simple as possible.

8.8 A top-down design and development process for the system and its associated software should be used to facilitate the assessment of whether design objectives are achieved. The computer system should meet the criteria for the highest safety class of the functions it is implementing.

8.9 When the use of a computer involves two or more functions that fall into different safety classes, the computer system should meet the requirements of the higher safety class.

8.10 The use of diverse functions and system components at different levels of the design should be considered. The reliability of computer based systems can be enhanced by using diversity to reduce the potential for software common cause failures. Diversity of methods, languages, tools and personnel should also be taken into consideration. However, it should be noted that although diverse software may provide improved protection against common mode software failures, it does not guarantee the absence of coincident errors. The choice of type of diversity or the decision not to use diversity should be justified in the system design stage.

8.11 System fail-safe features, supervision and fault tolerant mechanisms should be added into the software, but only to the extent that the additional complexity is justified by a demonstrable global increase in safety.

8.12 Fault detection and self-supervision features should not adversely affect the ability of computer system to perform its safety function, or cause spurious actuations of the safety function.

8.13 It should be demonstrated that measures have been taken to protect a computer based system throughout its entire lifetime against physical attack, unauthorized access, fraud, viruses and so on. Safety systems should not be connected to external networks.

8.14 The use of external memory devices such as pen drives should be prevented. If the design contemplates its use, it should be restricted or strongly controlled in both, the operational and development environments. If allowed, any such device should be actively scanned for viruses or other malware prior to use on the system and its use logged.

8.15 A computer based system should be designed for maintainability to facilitate the detection, localization and diagnosis of potential or actual failures so that the system can

be repaired or replaced efficiently. Software that has a modular structure can be easier to repair, to review and analyse, since the design can be easier to understand. Software maintainability also includes the concept of making changes to the functionality. The design of a computer based system should allow, as far as practicable, that changes are confined to a small part of the software.

8.16 When the use of a computer involves two or more functions that fall into different safety classes, the computer system should meet the requirements of the higher safety class.

8.17 Computer systems that perform safety functions should have deterministic (real-time) behaviour with regard to functions and timing.

8.18 Sample rates and processing speed should be consistent with accuracy and timing requirements.

8.19 Data communication channels important to safety should satisfy the recommendations for independence from each other.

8.20 The design should ensure that errors and failures of transmission and data communication equipment are detected and that suitable alarms are provided to the operators and records made for analysis of performance.

8.21 The communication technology should be chosen and suitably configured to ensure that it is capable of meeting the requirements for time response under all possible conditions of data loading.

8.22 Appropriate consideration should be given to the use of redundancy in the data communication.

8.23 The data communication network topology and network interface should be designed and implemented to avoid common cause failures of independent systems or subsystems.

8.24 Data flow from lower to higher classified safety systems should be prevented.

8.25 The design should explicitly handle all possible cases of logic and timing, and all operating modes of the system such as reset, power-on and normal operation.

8.26 The selection of pre-developed items to be included in the final product should follow a defined and documented process to guarantee their suitability.

8.27 Software tools could be used to support all aspects of the instrumentation and control life cycle where benefits result through their use and where tools are available. These tools should be verified and assessed consistent with the reliability requirements, the type of tool, and the potential of the software tool to introduce errors.

PROJECT PLANNING

8.28 The development process should be carefully planned and clear evidences should be provided that the process has been followed in order to facilitate the independent assessment of systems important to safety.

8.29 Part of the project planning and management stages should be the identification, assessment and management of project risks. Also, a verification and validation plan should provide procedures for evaluating risks in each development activity.

8.30 The development plan should identify and define the development process that will be used on the particular project. Other aspects of the project which should be planned are quality assurance, verification and validation, configuration management, installation and commissioning.

8.31 All phases of the development process should be identified. Each phase consists of specification, design and implementation. The design activity of one phase sets the requirements for the next phase. Verification should be performed across each phase of the development and before starting the next phase

8.32 The methods to be used in the development should be identified. This selection should be related to the quality assurance programme description, in which standards and procedures are established.

8.33 A quality assurance programme should be prepared and implemented before the project begins. A software quality assurance plan should be produced at the start of the project.

Verification and validation plan

8.34 Verification and validation activities should be performed to demonstrate that the computer system achieves its overall safety and functional requirements. Techniques and explicit validation procedures should be identified in the verification and validation plan.

8.35 Verification and validation management planning should include the listing and collection of applicable standards, procedures and conventions that guide the verification process.

8.36 The teams performing verification and validation should be independent of the development team. Independence is usually ensured by having different line management for the verification and validation and development teams.

8.37 The verification and validation plan should include a mechanism for recording all instances of noncompliance found during the analysis and ensuring that they are properly resolved by means of an approved change control process.

Configuration management plan

8.38 All items of software development, such as compilers, development tools, configuration files and operating systems, should be under configuration management control. All identifiable items, such as documents, components of the software or data structures, should be given a unique identification, including a version number. These items should include both developed items and existing items that are being reused or reapplied.

8.39 A procedure for change control should be defined. The change control procedure should maintain records of the problems that were identified during the development process, which required changes, how the problems were analysed, which items were affected, which specific changes were made to correct the problem and which versions and baseline were produced to solve the problems.

8.40 The change control procedure should also identify responsibilities for approving changes.

Installation and commissioning plan

8.41 The installation and commissioning plan should cover the following:

- The sequence of steps for proper integration of the system into the facility and the corresponding facility states needed for safe introduction of the new or changed system;
- the required interactions with the regulatory body, including any approvals, hold points and reports that should be respected before the system can be put into operation;
- the commissioning test cases and sequence and the corresponding facility states needed to confirm proper functioning of the system in the facility environment; and
- a description of the records and reports that will be generated to describe the results of commissioning.

COMPUTER BASED SYSTEM REQUIREMENTS

8.42 The computer system requirements specification should define, as a minimum, the functional and non-functional properties of the computer system that are necessary and sufficient to meet the facility requirements.

8.43 Safety analyses, for example accident analyses, transient analyses or facility safety analyses (based on postulated initiating events and safety criteria), should be an essential part of this design. In addition to safety requirements, some additional requirements not directly associated with safety are added at this stage of the design, such as: requirements for availability.

8.44 An accurate and clear description of these requirements should be written before starting the next stage of the project. This description should be understandable to independent reviewers involved.

8.45 A safety analysis should also be made for safety related systems to determine functional safety requirements.

8.46 Non-functional requirements should specify the following:

- The relevant dependability attributes, such as reliability, availability and security, required of the system behaviour;
- The security requirements derived from the security policy that has been defined for the computer based system environment including security procedures;
- Whether and where physical separation is needed (for example between safety and control functions); and
- That the requirements not directly associated with safety (such as availability) will not adversely affect the ability of a safety function to be performed when required.

Software requirements

8.47 The software requirements should include the description of the allocation of system requirements to software, with attention to safety requirements and potential failure

conditions, functional and operational requirements under each operation mode, performance criteria, timing and constraints, failure detection, self-supervision, safety monitoring requirements and security requirements.

8.48 The software requirements should include description and consideration of software hazards and associated software safety analyses.

Software design

8.49 In systems important to safety, unnecessary complexity should be avoided at all levels of design. The simpler the design, the easier is to achieve and to demonstrate all other attributes. It also gives greater confidence that the software is fully understood.

8.50 To facilitate the tracing of requirements, each design element, such as a software module, a procedure, a subroutine or a file, should have a unique identifier.

8.51 The design should contain no contradictions and no ambiguities. The description of the interfaces between modules should be complete.

8.52 The design and its description should be such that it is possible to demonstrate that each software requirement has been met and to verify that the implementation is correct with respect to the detailed design.

8.53 The documentation on software design should provide technical information on the overall architecture of the software and on the detailed design of all software modules. Relevant implementation constraints should also be specified.

8.54 Each software module identified in the software architecture should be described in the detailed design.

8.55 Diagrams and flow charts could be used as long as the meaning of the elements of the diagrams is well defined. Other common techniques used for describing design should include data flow diagrams, structure diagrams or graphical methods.

Software implementation

8.56 The production of software code should be verifiable against the software specifications. The code should be readable, adequately commented and understandable. Validated software tools could be used to facilitate the code verification process.

8.57 A system for requesting formal change and controlling modifications should be in place in the implementation phase to deal with omissions and inconsistencies. Up to date records of these changes should be kept available for reviews and audits.

8.58 The code of each programme of a module should be kept simple and easy to understand, both in its general structure and in its details.

8.59 Data structures and their naming conventions should be used uniformly throughout the whole system.

8.60 Techniques for verification and analysis should be used to provide assurance of product quality.

8.61 Records of the numbers and types of anomalies should be maintained. These records should be reviewed to determine whether or not any lessons can be learned, and appropriate process improvements should be made.

8.62 Techniques such as reviews, inspections or audits should be applied to the verification of all life cycle phases. The means by which the verifiers are to record the results of their reviews should be stated in the verification plan together with a justification of the chosen method.

8.63 Review of the documentation on software design and software implementation should be undertaken prior to the design of the software test cases. The test case specifications should be fully documented and reviewed.

8.64 Test plans should be designed so as to facilitate regression testing, by ensuring that tests are repeatable and require minimal human intervention.

8.65 Any anomalies in test performance should be reviewed and, if it is determined that there is a need for a modification to the test procedure, an appropriate procedure for change control should be applied.

COMPUTER SYSTEM INTEGRATION

8.66 The computer system integration phase should encompass at least three sequenced activities: software tests, hardware integration and hardware-software integration.

8.67 The hardware-software integration should consist of three parts: Loading of all software into the hardware system, testing that the software–hardware interface requirements are satisfied, and testing that all the software can operate in the integrated software–hardware environment.

8.68 During the verification of the system evidence should be generated which will demonstrate that the system integration has been properly controlled.

8.69 A documented traceability analysis should be performed as part of the verification activity to demonstrate that the system integration requirements are complete with respect to the computer system design specification.

Integrated computer system tests

8.70 A software test plan should be developed, covering all testing to be done, including unit level, integration, factory and installation.

8.71 The integrated computer system tests should be performed before the system is transferred to site and installed. The final integrated computer system test is often combined with the factory acceptance test to form a single test activity.

8.72 In constructing test cases, special consideration should be given to the following:

- Coverage of all requirements (including robustness tests and security features);
- Coverage of full ranges (including out-of-range values for input signals);
- Exceptions handling (for example demonstration of acceptable behaviour when input failure occurs);
- Timing related requirements (such as response time, input signal scanning, synchronization);
- Accuracy;
- All interfaces (such as the hardware–software interface in system integration and external interfaces during validation);
- Stress and load testing; and
- All modes of operation of the computer system, including transition between modes and recovery after power supply failure.

8.73 A traceability analysis should be performed to demonstrate that the validation requirements (for test or evaluation) are complete with respect to the computer system requirements.

Validation and commissioning tests

8.74 Validation and commissioning tests should be carried out to verify that the computer system has been connected correctly and to confirm the correct functioning of the system.

8.75 The validation and commissioning tests should be usually combined with the site acceptance test, which includes verification of the operation and maintenance of the equipment.

8.76 Strict configuration control of the computer system (hardware and software) should be maintained during the commissioning programme. Any changes required in this phase should be subjected to a formally documented change process.

8.77 Sufficient documentation should be produced to demonstrate the adequacy of the commissioning programme for the installed computer based safety system.

OPERATION, MAINTENANCE AND MODIFICATION

8.78 During the operation, maintenance and modification phases the following main activities should be considered:

- Periodic tests, performed in order to verify that the system is not degrading;
- Perform regression testing due to modifications, implemented to enhance or change the functionality or to correct errors;
- Change of parameters;
- Diagnosis activities, e.g. the execution of special diagnostic programs;
- Hardware components replacement due to failures;

8.79 The life cycle of the systems should include the processes for implementing of modifications. This life cycle should contain the phases of the main development, including verification and validation. These activities together with an impact analysis and regression testing will be necessary to ensure that the modifications have been correctly implemented and no new errors introduced.

8.80 After failure of a hardware component, corrective actions should be limited to one-for-one replacements of hardware and to the reloading of the existing software modules. These actions should not include any modification unless analysis of the failed components reveals such a need.

Computer security

8.81 Ref. [13] provides guidance on concerns, requirements, and strategies for implementing computer security programmes at nuclear facilities.

8.82 The failure modes of computer security features and the effects of these failure modes instrumentation and control functions should be known, documented, and considered in system hazard analyses.

8.83 Neither the operation nor failure of any computer security feature should adversely affect the ability of a system to perform its safety function.

8.84 If computer security features are implemented in the Human Machine Interface, they should not adversely affect the operator's ability to maintain the safety of the facility.

8.85 Where practical, security measures that do not also provide a safety benefit, should be implemented in devices that are separate from instrumentation and control systems.

9. CONFIGURATION MANAGEMENT

9.1 A full set of documentation reflecting the configuration and status of instrumentation and control systems in the facility should be available prior to the commissioning of the facility and maintained up to date throughout the lifetime of the facility.

9.2 A baseline database of systems/components of the instrumentation and control systems should include the following information:

- General information (e.g. system identification, serial number, manufacturer, supplier support, location, safety class);
- System summary (e.g. functionality, configuration, safety impacts caused by the system, current performance, loss of operational availability due to the unavailability of the system, interfaces, security, documentation);
- Physical characteristics (e.g. number of cabinets, detailed component inventory, limits);
- Boundaries (environment, power supply, grounding, margins in the cabinets and the rooms for power supply, amount of information exchanged between other systems);
- System constraints (e.g. licensing conditions, technical specifications, design constraints, operating characteristics);

- Obsolescence issues (e.g. maintenance costs, replacement parts, performance degradation);
- Measures for improvements (e.g. functionality, configuration, performance, maintenance); and
- References.

9.3 Operational and maintenance staff should collaborate with the improvement and the updating of instrumentation and control configuration control documentation.

9.4 A process of verification and update of the existing documentation should be undertaken prior to commencing any modernization activities.

9.5 Operational and maintenance staff should collaborate on the update of existing documentation to ensure all modernization activities are completely captured in the instrumentation and control configuration control documentation.

10. MODIFICATION AND MODERNIZATION OF INSTRUMENTATION AND CONTROL SYSTEMS

10.1 Upgrade and modification of instrumentation and control systems should be performed in accordance with the guidance provided in Ref. [4] on planning, organizational aspects, safety assessment, implementation and post implementation, training, and documentation of facility modifications.

10.2 A modification to a reactor system may or may not include a complete replacement of the system components. Modifications to existing systems should account for any considerations that were addressed by the original equipment. The typical considerations when designing instrumentation and control systems are discussed in chapter 4.

10.3 Modification to instrumentation and control equipment is expected during the life of the facility. Regardless of the reason, thought should be given to the functional intent of the equipment being modified. For example, when changing from one technology to another (e.g. analogue system to a digital system).

10.4 When the decision is made to follow through with a modification to existing instrumentation and control equipment, careful consideration of the possible effects on reactor safety should be considered and assessed.

10.5 Special assurance is needed to verify that every modification has been properly assessed, documented and reported in terms of potential effect on safety, and that the reactor is not restarted without formal approval after the competition of modifications of instrumentation and control systems.

10.6 The design documentation for older legacy systems might be incomplete or inaccurate. Consequently major modifications to or replacement of such systems might require some degree of ‘reverse engineering’ to recreate the original design bases and specifications. A full set of documentation reflecting the current states of instrumentation and control systems in the facility should be available. A process of verification and update of the existing documentation should be undertaken prior to commencing any modernization activities.

10.7 A baseline database of systems/components of the existing instrumentation and control systems should be updated or created following the recommendations at 9.2.

10.8 Verification and update of existing documentation should start at a high-level functional description of the instrumentation and control system architecture, preferably in the form of a diagrammatic representation with an accompanying list of all instrumentation and control systems. If such a representation exists, it should be verified for accuracy.

10.9 There should be a designated responsible designer that will be responsible for the design, integration, documentation and maintenance as well as training facility personnel in the use of the new equipment. Refer to Ref. [5] for details on the responsibilities that the responsible designer should assume.

10.10 Modifications to any instrumentation and control system should take into consideration the duties and the responsibilities of the operating personnel, e.g. operators as well as the maintenance staff, experimenters and emergency response staff in order to achieve an effective interface between the operating personnel and the research reactor systems.

10.11 The effect the modification will have on how the facility personnel interact with the system should be considered. Particular requirements of the end-user should be taken into account from the early stages of the project. (Refer to section 7 for details on human factors considerations).

10.12 The reliability of the new or modified equipment should be considered as well as the effect the modification will have on overall system reliability. The performance of a qualitative analysis (e.g. failure modes, effects and criticality analysis) may be helpful in determining which parts of the system may be affected by the modification and what the implication is on the ability of the system to perform its safety function.

10.13 When modifying an existing safety system, the effect on the current defence-in-depth implementation should be considered.

10.14 When modifying any instrumentation and control system, consideration on design guidelines should be considered.

10.15 Generally, when modifying any system, the complexity of the modification plays a major role in the difficulty of analysing the effects on the overall system. In particular, careful consideration should be given to the addition of any new functions and/or the ability to expand the capabilities of the existing safety systems in the future.

10.16 Safety systems are required to be independent, as far as reasonably practicable, of other reactor systems. The designated responsible designer together with the operating organization should determine the need for, as well as the effect on independence during the initial design phase of the modification.

10.17 The effect on system environmental qualification should be considered. Environmental qualification should be based in recommendation of equipment qualification.

10.18 When an instrumentation and control system is modified or is part of an upgrade, the level of rigor applied in justifying and executing the change should be established based upon its role and function in ensuring the safety of the facility, in association with the existing systems and any of them that will remain in operation after the work. This also applies to software based systems.

10.19 Change control procedures should be in place, including appropriate procedures and organizational structures for the review and approval of the safety aspects of the modification.

10.20 The design of instrumentation and control upgrades and modification should consider:

- The limitations due to the physical characteristics of the installed facility, which effectively restrict the design options for instrumentation and control systems;
- The possible need to maintain consistency between the design of replacement equipment and existing instrumentation and control equipment to, for example, reduce the complexity of the overall operator interface and maintenance tasks of the facility; and
- Practical considerations with respect to the equipment or technology commercially available when required by the project programme and the prospects for securing support of such equipment and technology by manufactures or third parties for the installed life of the equipment.

10.21 The benefits of changes should be weighed against potential negative safety consequences and this assessment documented as part of the justification for the changes. For instance, enhancements to the operator interface features might increase errors by operations and maintenance personal for some time after the change.

10.22 When an instrumentation and control system is replaced, the new instrumentation and control system may, when appropriate, be run in parallel with the old system for a probationary period, i.e. until sufficient confidence has been gained in the adequacy of the new system.

10.23 The consequences of a tool update or change may be significant and should be subject to impact assessment (for example a compiler upgrade could invalidate previous analysis or verification results concerning the adequacy of the compiler).

10.24 Installation of the equipment should be performed by qualified personnel under the supervision of the designer.

10.25 Once complete, and before start-up of the reactor, the installation should be functionally tested following the recommendations of Ref. [4].

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ANNEX I

GENERAL

1.1. The instrumentation and control (I&C) systems of a research reactor involve many systems that can be identified in a particular facility and they may vary depending on the type of reactor, the purpose and its operation modes. Usually it could include those systems identified in section 2 as examples of I&C systems. Typical set of I&C systems and their interrelations is shown on Fig. AI.1

1.2. This annex identifies all the I&C systems that can be included in a research reactor considering that some or several of these I&C systems could not be present in a particular facility as they are not required for that specific application.

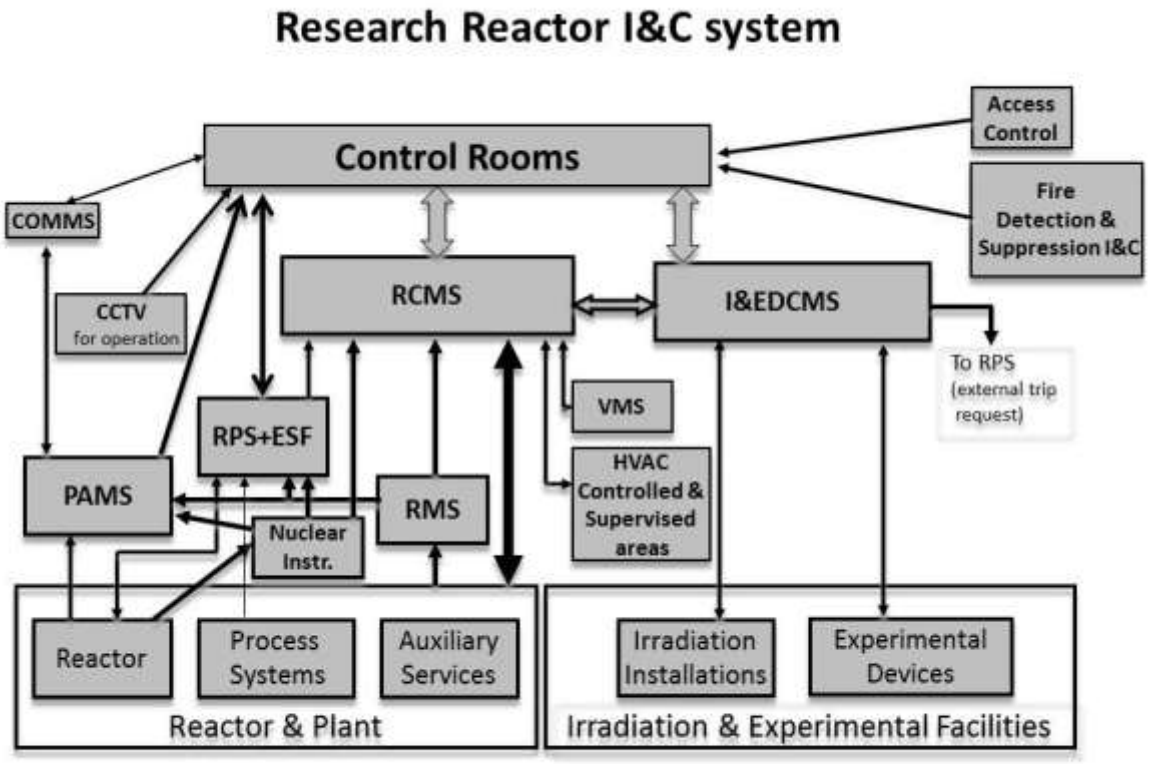

Fig AI.1 Research reactor I&C systems – Block diagram

Acronyms and abbreviations:

CCTV: Close Circuit Television;

COMMS: Communication System;

ESF: other Engineering Safety Features initiation I&C;

HVAC: Humidity Ventilation and Air Conditioning for Controlled and Supervised areas;

I&EDCMS: Irradiation & Experimental Devices Control and Monitoring System;

Instr.: Instrumentation;

PAMS: Post Accident Monitoring System;

RCMS: Reactor Control and Monitoring System;

RMS: Radiation Monitoring System;

RPS: Reactor Protection System; and

VMS: Vibration Monitoring System.

MAIN I&C SYSTEMS DESCRIPTION

Reactor Protection System (RPS)

1.3. The reactor protection system is a set of components designed to monitor reactor operation parameters (neutron power and period, coolant flow rate, inlet and outlet temperatures, pressure drop in reactor core, etc.), compare them with allowable values and automatically initiate actions of the reactor shutdown system when the parameters reach or exceed the safety system settings. Each parameter should be measured by two or more independent channels. The automatic actions are initiated on the basis that the logic arrangement for the protective action initiations comply with the single failure criteria and, when three independent channels are available, the logic arrangement of two out of three should be used to prevent the initiation of protective actions by spurious signals. A reactor protection system also could be actuated manually by the operator, the experimenters or from irradiation & experimental devices control and monitoring system. A trip of the RPS results in shutdown of the reactor.

Other Engineering Safety Features Initiation I&C (ESF)

1.4. The engineering safety features initiation I&C is a set of components designed to, upon request, initiate the action of the emergency core cooling, decay heat removal, confinement isolation and confinement heat removal systems. Also, it could be actuated manually by the operator. A trip in the ESF results in the initiation of one or more of the actions mentioned before. The functions of the ESF could be included in the RPS.

Post-Accident Monitoring System (PAMS)

1.5. Post-accident monitoring instrumentation is becoming an important feature of nuclear facilities. Its purpose is to provide the operators and their backup teams with necessary accident management information and to ensure that the sources of this information are, and remain, trustworthy. Under accident conditions, the operators require information so that they can:

(a) Perform those preplanned manual control actions for which automatic control is not provided and which are necessary to prevent or mitigate the consequences of the accident. Such actions, specified in the safety analysis report, are compiled in the post-accident operating procedures;

(b) Determine whether critical safety functions related to reactivity control, core cooling, reactor coolant system integrity, heat sink, containment integrity and radioactivity surveillance are challenged and are being accomplished by the RPS, the engineered safety features system and/or their essential support systems.

Nuclear instrumentation

1.6. The nuclear instrumentation follows the value and evolution of the neutron flux of the reactor in all its operational states as this parameter if of the highest relevance to assure

a safe operation of the reactor. Also bring the means to establish a suitable control strategy to start up the reactor and to keep it in a stable operation at different power levels.

Reactor Control and Monitoring System (RCMS)

1.7. At the root of the I&C systems resides the process instrumentation (detectors, sensors, switches) which measure process parameters and actual state (position) of actuators, and are connected to the reactor control & monitoring system.

1.8. Reactor control and monitoring system is intended for reliable following-up of the reactor performance and its safe operation. RCMS provides start-up, automatic adjustment of power, compensates fuel burn-up, and provides interlocks for safe operation. RCMS is built using fail-safe and redundant devices to receive and process signals from a large amount of sensors, actuate the corresponding control drivers as well as to present the reactor status information for the operator in the main console of the reactor (the main human machine interface).

Radiation Monitoring System (RMS)

1.9. The radiation monitoring system is designed for continuous radiation monitoring of nuclear facilities as well as surrounding areas to identify the possible release of radioactive materials or radiation due to a failure of the technological equipment, the integrity of protective barriers, the effectiveness of water purification systems, confinement isolation, filters, and ventilation systems among the most relevant systems or components.

Humidity Ventilation and Air Conditioning (HVAC)

1.10. Heating, ventilation and air conditioning systems are used for assuring and maintaining consistent operable environments for both personnel and equipment by providing ventilation, air quality and temperature control. The ventilation system also helps in maintaining the radiological conditions by pressure gradients, use of appropriate filters, etc. Modern electronic equipment generates much less heat than older types but, nevertheless, excess temperature can degrade performance and air-conditioning, as a means of removal of excess heat from I&C safety systems, should meet the requirements specified for safety system support features. In regions with a tropical climate or high humidity, the proper design of ventilation systems (physical separation, redundancy and closed cycle) may be the only way to eliminate a source of common mode failure in I&C equipment.

Vibration Monitoring System (VMS)

1.11. Vibration monitoring system provides a means of monitoring and detecting abnormal vibration conditions on reactor main rotary equipment.

Control Rooms

1.12. Sufficient controls, indications, alarms and displays are provided in main control room (MCR) to initiate, supervise and monitor normal reactor operation and reactor shutdown to a safe state and to provide assurance that a safe state has been reached and maintained.

1.13. The minimum set-up of the MCR includes the human system interfaces that operator needs to:

- Safely operate the reactor in all its operational states
- Monitor the safe operation of the reactor;
- Monitor the appearance of alarms
- Perform and confirm a controlled shutdown;
- Actuate safety-related systems;
- Perform and confirm a reactor trip;
- Perform and confirm the actuation of the ESFs
- Monitor the status of fission product barriers;
- Bring the reactor to a safe shutdown; and
- Implement emergency operating procedures.

1.14. The alarm annunciators show status of systems. Safety systems have audible and visible alarms on operator's console or control panel to provide warning on violation of limits and conditions of safe operation. Operators can access all signals through the main console of the reactor control and monitoring System. Also consoles and displays for the experimental and isotope production facilities are located in the main control room.

1.15. Supplementary control room, if it is applicable, provides remote reactor shutdown possibility if it cannot be done from the main control room. Sufficient controls, indications, alarms and displays should be provided in the supplementary control room to initiate, supervise and monitor a reactor shutdown to a safe state and to provide assurance that a safe state has been reached and maintained.

Irradiation & Experimental Devices Control and Monitoring System (I&EDCMS)

1.16. The primary use of a research reactor is the production of neutrons for research and for neutron irradiation of materials. Irradiation installations include equipment that is used to place, move, and organize samples to be irradiated. A dedicated and tailored I&C system is designed to control and monitoring those operations. Experimental and irradiation installations may have an impact to the reactor safe operation, so main parameters of the experimental devices that affect the safety of the reactor should be displayed in the main control room. Also trip signals from IEFCMS to RPS could be provided as demanded.

Communication System (COMMS)

1.17. Communication systems is the link for the operators of the main and supplementary control rooms, reactor hall, process areas, staff of the experimental and associated facilities, other internal locations within the facility and for external emergency organizations, A voice announcement system is used for making announcements that can be heard by all personnel on site and in the facility or to report an emergency or unforeseen circumstances requiring immediate response.

Close Circuit Television (CCTV)

1.18. Close circuit television is a useful aid, which allows operator and security staff to monitor and supervise relevant controlled or supervised area tasks and other outer approaches (i.e. control room entrance, reactor hall and restricted areas where radioactive sources are stored).

Fire detection and suppression I&C

1.19. This independent system has the capability to identify the presence of fire in the facility and, upon this event, initiate automatic fire suppression in the affected areas. Fire detection panels should be located in the control rooms to provide information to the reactor operators.

Access control

1.20. Access control system belongs to the physical security system and has the capability to supervise and manage the movement of the personnel in the facility. Access control panels should be located in the control rooms to provide the reactor operators with relevant information.

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