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INPRO ASSESSMENT OF AN INS IN THE AREA OF SAFETY OF FUEL CYCLE INSTALLATIONS

B. Raj*, Y. Busurin, F. Depisch****

*Indira Gandhi Center for Atomic Research

KALPAKKAM 603102,
Tamil Nadu, India

Tel: +91 (-044) -27480234 Fax: +91 (-044) -27480301
Email: dmg@igcar.gov.in

**International Atomic Energy Agency (IAEA)

Wagramerstrasse 5, P.O.Box 100, A-1400 Vienna, Austria

Tel: +43-1-2600-21392, Fax: +43-1-2600-29598,
Email: y.busurin@iaea.org

ABSTRACT

INPRO has defined requirements organized in a hierarchy of Basic Principles, User Requirements and Criteria (consisting of an indicator and an acceptance limit) to be met by innovative nuclear reactor systems (INS) in six areas, namely: economics, safety, waste management, environment, proliferation resistance, and infrastructure. If an INS meets all requirements in all areas it represents a sustainable system for the supply of energy, capable of making a significant contribution to meeting the energy needs of the 21st century.

Draft manuals have been developed, for each INPRO area, to provide guidance for performing an assessment of whether an INS meets the INPRO requirements in a given area. The manuals set out the information that needs to be assembled to perform an assessment and provide guidance on selecting the acceptance limits and, for a given INS, for determining the value of the indicators for comparison with the associated acceptance limits. Each manual also includes an example of a specific assessment to illustrate the guidance. This paper discusses the manual for performing an INPRO assessment in the area of safety of fuel cycle installations.

The example, chosen solely for the purpose of illustrating the INPRO methodology, describes an assessment of an MOX fuel fabrication plant based on sol-gel technology and illustrates an assessment performed for an INS at an early stage of development. The safety issues and the assessment steps are presented in detail in the paper.

INTRODUCTION

International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was established to help to ensure that nuclear energy is available to contribute, in a sustainable manner, to the energy needs in the 21st century. In six different areas – economics, safety (Reactors and fuel cycle facilities), waste management, proliferation resistance, environment, and infrastructure – requirements to be met by innovative nuclear energy systems (INS) have been identified. A methodology has also been developed to assess whether an INS complies with the requirements[1].

The success of the nuclear program greatly depends on the strengths of the country in nuclear fuel cycle activities. Development of processes for fuel cycle facilities - mining, milling, enrichment, fuel fabrication, interim spent fuel storage, transport, reprocessing and waste management has been a core activity, which has significantly contributed to the growth of nuclear energy. It is however necessary to emphasize that global success in the growth of nuclear energy to a large extent, depends on the safe and economical operation of the fuel cycle facilities as much as it depends on a safe and economical operation of nuclear reactors themselves. Indeed, the public acceptance of the safety of nuclear fuel cycle facilities and waste management options needs to be addressed in a comprehensive fashion for the nuclear energy to register a significant growth in the coming decades.

It is realized that the experience with respect to nuclear fuel cycle facilities in various countries has not been collated and harmonized to the extent that has been done for the reactor systems. Documentation and harmonization of safety issues under the auspices of IAEA facilitates a convergence of views on the desirable goals for these processes, and an early advancement of technologies required to achieve these, through efficient use of resources and knowledge from a wide range of international expertise. It is thus appropriate that under the INPRO project, a manual dealing with the safety of nuclear fuel cycle facilities is prepared. The INPRO manual has thus arisen out of the commitment of the IAEA to achieve nuclear energy growth through innovations in key factors related to safety of Nuclear Fuel Cycle Facilities.

INPRO SAFETY BASIC PRINCIPLES, USER REQUIREMENTS AND CRITERIA

In the area of *safety of nuclear installations*, INPRO recognizes that extensive work has been done prior to INPRO to establish safety requirements included in documents such as IAEA Safety Standards Series, e.g., Safety Guides, and INSAG documents. The safety basic principles and user requirements developed within INPRO are based on extrapolation of current trends and seek to encompass the potential interests of developing countries and countries in transition. For nuclear reactors, the fundamental safety functions are to control reactivity, remove heat from the core, and confine radioactive materials and shield radiation. For fuel cycle installations, they are to control sub-criticality and chemistry, remove decay heat from radio-nuclides, and confine radioactivity and provide radiation shielding.

To ensure that INS will fulfil these fundamental safety functions (Fig.1), INPRO has set out four Basic Principles(BP):

An INS shall

1. Incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations.

2. Excel in safety and reliability by incorporating into their designs, when appropriate, increased emphasis on inherently safe characteristics and passive systems as a part of their fundamental safety approach.

3. Ensure that the risk from radiation exposures to workers, the public and the environment during construction/commissioning, operation, and decommissioning, shall be comparable to that of other industrial facilities used for similar purposes.

Further, the development of Innovative Nuclear Energy Systems shall:

4. Include associated RD&D work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment to at least the same confidence level as for existing plants.

For each basic principle defined above, the corresponding User Requirements(UR) are set out [2]. To confirm that a user requirement is met, it is necessary to define the criteria for each aspect of the fuel cycle facilities. Corresponding indicators (IN) and acceptance limits are described for these criteria, to facilitate assessment. In total fourteen user requirements were derived from these basic principles. The outcome should be the prevention, reduction and containment of radioactive releases to make the health and environmental risk of INS comparable to that of industrial facilities used for similar purposes so that for INS there will be no need for relocation or evacuation measures outside the plant site, apart from those generic emergency measures developed for any industrial facility. RD&D must be carried out before deploying INS, using, e.g., large scale engineering test facilities including, possibly, pilot and prototype plants, to bring the knowledge of plant characteristics and the capability of codes used for safety analyses to the same level as for existing plants. The development of INS should be based on a holistic life cycle analysis that takes into account the risks and impacts of the integrated fuel cycle.

ASSESSMENT IN THE AREA OF SAFETY OF FUEL CYCLE INSTALLATIONS USING INPRO METHODOLOGY

The INPRO manual on Safety of Fuel Cycle Facilities [3] deals with safety issues related to design and operation of mining, milling, refining, conversion, enrichment, fuel fabrication, fuel storage and fuel reprocessing facilities and the application of INPRO methodology in terms of identifying indicators and acceptance criteria for these facilities.

It is clear that the fuel cycle operations are more varied in the processes and approaches, as compared to reactor systems. Nuclear Fuel cycle comprises a number of activities other than reactor operation, the possible combinations of which provide the various fuel cycle options (see Fig.2). Depending upon the requirements and perceptions of the individual country, either open or closed fuel cycle option is followed.

Safety Issues in Fuel Cycle Facilities

Whereas the reactor core of an NPP presents a very large inventory of radioactive material at high temperature, pressure, and within a relatively small volume, an NFCF operates at near ambient pressure and temperature and with comparatively low inventories at each stage of the overall process. In nuclear waste repositories, the total nuclide inventory will progressively increase to a maximum over the operating period of the facility.

Usually in NFCFs, there are long timescales involved in the development of accidents except in the case of criticality and less stringent process shutdown requirements are required to maintain the facility in a safe state, as compared to reactors. Such facilities also often differ from reactors with respect to the enhanced importance of ventilation systems in maintaining their safety- even under normal operation. This is because materials in these facilities are in direct contact with ventilation or off-gas systems.

The robustness of barriers between radioactive inventories and the operators as well as the environment must be ensured more stringently as compared to reactor systems. Fire protection and mitigation assume greater importance in NFCFs due to the presence of larger volumes of organic solutions and combustible gases.

From safety point of view, NFCFs are characterized by a variety of physical and chemical treatments applied to a wide range of radioactive materials in the form of liquids, gas and solids. Accordingly, it is necessary to provide correspondingly a wide range of specific safety measures as inherent parts of these activities, as in chemical plants. In addition, radioactivity release and criticality issues warrant more attention in NFCFs compared to NPPs.

For existing NFCFs, the emphasis is on the control of operations using administrative and operator controls to ensure safety, as opposed to engineered safety features used in reactors. There is also more emphasis on criticality prevention in view of the greater mobility (distribution and transfer) of fissile materials. Because of the intimate contact with nuclear material in the process, which may include open handling and transfer of nuclear material in routine processing, special attention is warranted to ensure worker safety. Potential intakes of radioactive material require control to prevent and minimize contamination and thus ensure adherence to specified operational dose limits. In addition, releases of radioactive material into the facilities and through monitored and unmonitored pathways can result in significant exposures.

The number of physical barriers in a nuclear facility that are necessary to protect the environment and people depends on the potential internal and external hazards, and the potential consequences of failures; therefore the barriers are different in number and strength for different kinds of nuclear installations. For example, in a fuel fabrication facility, safety is focused on preventing criticality in addition to contamination via low-level radioactive material. It is possible to enhance safety features in an INS by co-location of front end (e.g. mining and enrichment facilities) and back end (reprocessing and waste management) facilities. This would have benefits through minimal transport and avoiding multiple handling of radioactive materials in different plants of the fuel cycle facility. It is recognized that for innovative fuel cycle facilities, releases of radioactive material from all components of the system should be considered and optimized for a given concept. Ideally, the impact of the whole fuel cycle (including the associated waste disposal facilities and decommissioning activities) should be evaluated.

APPLICATION OF INPRO METHODOLOGY TO A MOX FUEL FABRICATION PLANT BASED ON SOL-GEL TECHNOLOGY

Sol-gel technique is an important route for the preparation of MOX fuel in the form of micro-spheres which can then be used to fabricate fuel pins either by vibro-compacting into a fuel pin or by palletizing the micro spheres and loading the pellets in the fuel pin. Sol-gel based fuel fabrication methods offer several advantages over the conventional powder-pellet route: elimination of problems associated with radioactive dust such as radiation exposure to personnel, amenability for automation and remote handling in view of the fluid like behaviour of the sol-gel derived micro-spheres, much better micro-homogeneity in case of mixed oxides, suitability for dove tailing to the reprocessing plant, significantly higher throughputs and lower scrap recycle requirements. Sol-gel based fabrication methods are also proliferation resistant, since the uranium, plutonium mixed nitrate solutions from the reprocessing plants can be used as the feed, obviating the need for partitioning of uranium and plutonium.

In view of these advantages, INPRO assessment in the area of **safety of fuel cycle installations** is discussed for a hypothetical INS- MOX fuel fabrication plant based on sol-gel technology- to illustrate the application of the INPRO Methodology in this area through the evaluation of selected indicators to determine whether or not they comply with the associated acceptance limits. The plant is based on the internal gelatin process [3].

Criticality accidents, accidental release of hazardous materials, fire and explosion are the major safety issues in MOX fuel fabrication plants. Some of the design principles are prevention of criticality by design (the double contingency principle is the preferred approach) and confinement of chemical hazards (includes the control of any route into the workplace and the environment). Shielding would be needed for protection of the workers due to higher gamma dose rates.

At the outset, it must be emphasized that safety analysis of a sol-gel based fuel fabrication plant has not been discussed in detail in open literature. Also, there is no report on operation experience on a plant based on this process. Hence, the purpose of this exercise is two fold: to provide an illustration of the elements of innovation in fuel fabrication and a methodology for their assessment based on INPRO, and to indicate typical areas where further work is necessary to evolve a robust and safe fuel fabrication technology based on sol-gel process. In this paper, only a few significant User Requirements (UR) and the corresponding indicators (IN) and acceptance criteria are given, as examples. For a detailed analysis, see Ref. [3].

UR1.1: *Installation of innovative nuclear energy systems (INS) should be more robust relative to existing designs.*

IN1.1.1: Robustness of design (simplicity, margins).

The sol-gel fuel fabrication facility is designed for withstanding earthquakes.

For fire prevention, use of fire resistant materials for primary confinement system and use of passive cooling systems for high temperature operation is envisaged. Minimum use of flammable materials is ensured.

For prevention of explosion, Ar-H2 or N2-H2 gas mixtures are used for calcinations and sintering instead of pure hydrogen. Mixing of nitric acid or nitrate solutions with HMTA/ Urea under low pH and high temperatures is avoided.

Maintenance of differential pressure in glove boxes and operating areas, easy access of the equipment in operating areas, automation for process operations, zoning in layout of the plant for hazardous operations, single port entry and exit for personnel and equipment and multiple levels of filtration are used for control of contamination.

Mass control of fissile material, on-line nuclear material accounting (NUMAC), use of ever-safe geometry, layout with sufficient separation between equipment as well as fissile material storage tanks, minimization of hydrogenous materials in process and use of neutron absorbing materials are ensured for criticality control.

IN1.1.2: High quality of operation.

The distinctive feature of the fuel fabrication facility is the presence of large inventories of mixed oxide. Automation/Remote control of all the process steps is ensured to minimize exposure of personnel to radiation. Every operator is made to undergo training in the normal operation and emergency procedures every six months.

IN1.1.3: Capability to inspect.

Monitoring systems are installed to provide information on the levels of liquids in process vessels, temperature, flow of cooling water and gas flow /vacuum in furnaces, radiation levels in glove boxes and operating areas and pressure drops across filters. Fire detectors are installed in all glove boxes.

IN1.1.4: Expected frequency of failures and disturbances.

Temporary loss of power leading to premature gelation which in turn can lead to choking of feed lines, leakage of solutions, ventilation failure, and loss of cooling water flow to furnace are the possible events of failures. Based on operating experience and available literature, it can be concluded that the frequency of occurrence of these failures and disturbances will be <10-2 per year.

IN1.1.5: Grace period until human actions are required.

In the event of ventilation failure (e.g. due to loss of electrical power), a grace period of one hour would be available to restart the ventilation systems. In the event of loss of flow of cooling water to the furnace, the gravity fed cooling water supply would be able to supply cooling water for a period of at least two hours, within which the furnace can be brought to a safe shutdown in case the pumped cooling water does not get initiated. The operation manual lists the anticipated incidents, action plan and time before which the actions have to be completed so that the incident does not escalate into an emergency.

IN1.1.6: Inertia to cope with transients.

Adequate flow of cooling water to the furnace is ensured, combined with a flow monitoring system, to ensure that in the event of transient reduction in coolant flow rate, the temperature of the furnace shell will not rise above safe limits. The leak tightness of the glove box (usually <0.5% box volume/hr when inside of glove box is at a pressure of +100mm water column) is such that in the event of temporary loss of the glove box ventilation or under slight positive pressure, the radioactivity level in the operating area would not exceed regulatory limits.

UR1.2: *Installations of an INS should detect and intercept deviations from normal operational states.*

IN1.2.1: Capability of control and instrumentation system and/or inherent characteristics to detect and intercept and/or compensate such deviations.

The fuel fabrication facilities incorporate several critical systems such as glove boxes, furnaces, vacuum systems etc, whose safe operating conditions indicating different limits for alarm and shutdown conditions are clearly defined. Furnaces are equipped with power supply shut down feature to prevent escalation of temperature.

UR 1.3: *The frequency of occurrence of accidents should be reduced.*

IN 1.3.1 Calculated frequency of occurrence of design basis accidents.

A typical sequence of events leading to criticality is given in Fig.3. The individual events leading to the failure are estimated to have a probability of 10-3, 10-3 and 10-2 per year respectively. Hence the overall probability will be 10-8/year.

IN1.3.2: Grace period until human intervention is necessary:

The design basis criticality event can occur in silicone oil tank. Action to terminate criticality can be taken by injecting a solution of neutron poison into this tank. Since this can be carried out by instrumented actions, the criticality event can be handled in a matter of a few minutes. A large release of radioactivity into the operating area can take place due to an explosion resulting in breakage of glove box panel and spillage of solution into working area. However, while this would increase air activity in the environment, it can be safely handled by trained staff with adequate precautions including use of respirators. The most important safety related action would be the evacuation of the laboratory area, which can be completed in about 15 minutes. No escalation of the incident is expected in this time period.

IN1.3.4: Number of confinement barriers maintained.

The most important safety feature of the fuel fabrication facility is the barrier for release of radioactive material into the environment. Pu based materials are handled in glove boxes, whose panels and gloves constitute a barrier. Further, additional barriers such as trays to collect the leaks from glass column of silicone oil are also kept inside the glove box to increase safety. It is ensured that inside the glove boxes the active solutions are always inside closed vessels so that presence of minimum two barriers is always maintained.

IN1.3.6: Sub-criticality margins.

The choice of plutonium amount and concentration, design of the process vessels and the lay out of the vessels in the glove boxes will be such that the k_{eff} will be less than 0.90. It will be ensured by design that even under moderated conditions the value will not exceed 0.95, thus providing a sub-criticality margin of 0.05. All process equipments in material handling area are designed to eliminate criticality for submerged conditions and fully reflected conditions.

Further discussion on the indicators and acceptance criteria for the UR corresponding to the four BPs are given in Ref.[3].

CONCLUSIONS

The Agency's International Project on Innovative Nuclear Reactors and Fuel Cycles is addressing the identification of full spectrum of user requirements for innovative technologies as well as the development of methodologies and guidelines for the comparison of different innovative approaches taking into account variations in potential demands across countries. The final result of INPRO Phase 1B (first part) is a tested and validated methodology for assessing innovative nuclear energy systems to ascertain whether they are sustainable.. Thus, Phase 1B (first part) was a decisive step toward INPRO's first objective of "ensuring the availability of nuclear energy in a sustainable manner in the 21st century". In the ongoing Phase 1B (second part) the holistic assessments of complete INSs ("cradle to grave") will represent an important step towards fulfilling INPRO's second objective "bringing together all MS, to consider jointly the international and national actions required to achieve desired innovations".

The success of the nuclear programme greatly depends on the strengths of the country in nuclear fuel cycle activities. The global success of the growth of nuclear energy to a large extent, depends on the safe and economical operation of the fuel cycle facilities and the public acceptance of the safety of nuclear fuel cycle facilities. The manual on the Safety of nuclear fuel cycle facilities is a significant document that facilitates the MS to fulfill this objective.

The work in the second part of Phase 1B and in the following Phase 2 will include all stakeholders in nuclear energy. In this way INPRO will meet its third objective "*to create a process that involves all relevant stakeholders*" by providing a forum where experts and policy makers from industrialized and developing countries can discuss technical, economical, environmental, proliferation resistance and social aspects of nuclear energy planning as well as the research, development and deployment of Innovative Nuclear Energy Systems in the 21st century.

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NOMENCLATURE

INS :	innovative nuclear energy system
MS:	Member State
RD&D:	research, development and demonstration
UR:	User Requirement
IN:	Indicator

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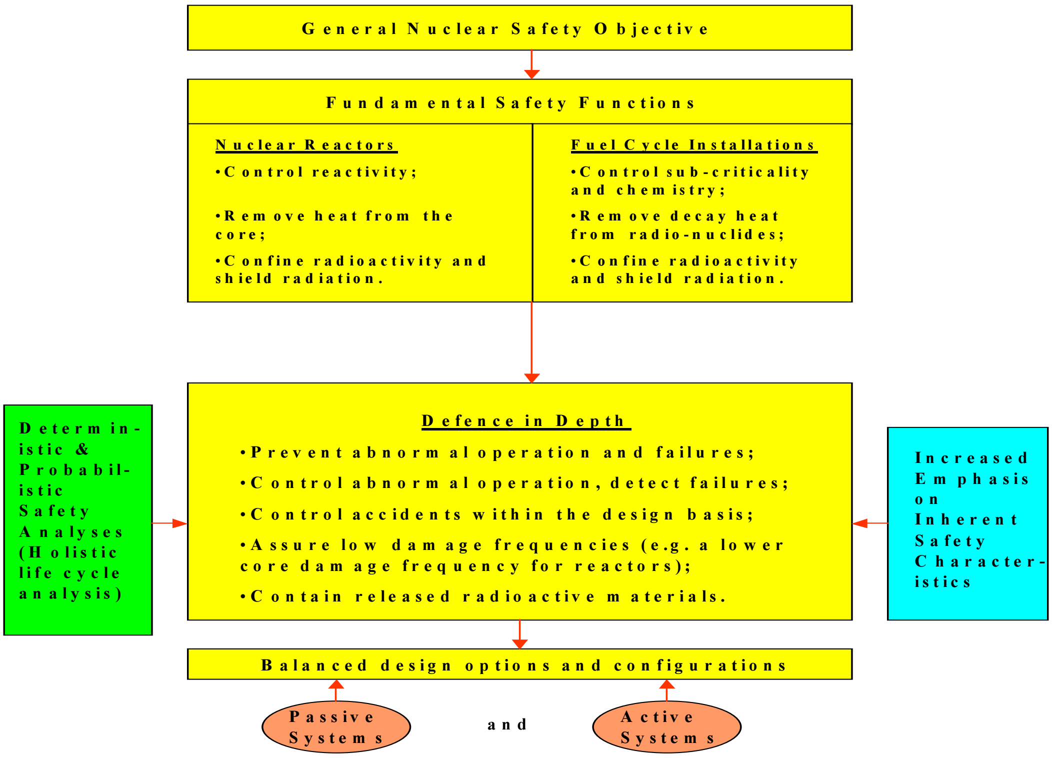

Figure 1: Framework for development of requirements for safety of INS

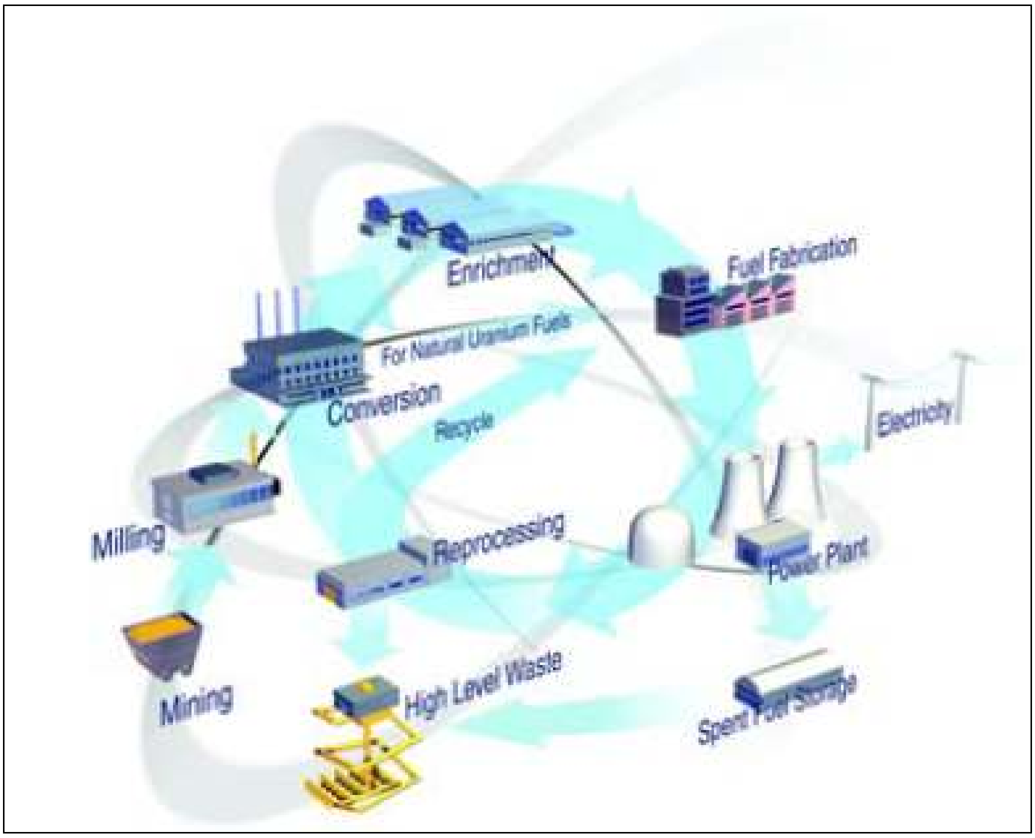

Fig.2 Schematic diagram of fuel cycle

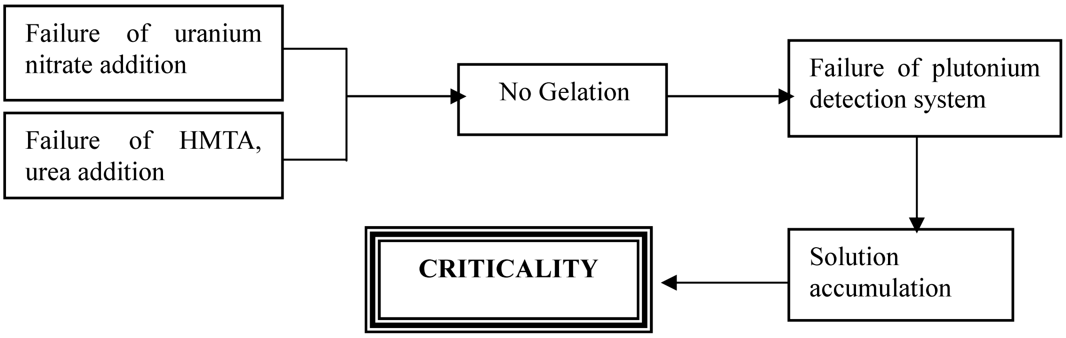

Fig. 3. Sequence of events that can lead to criticality