Chapter 1

Introductory Chapter: Safety Aspects in Nuclear Engineering

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.76818

1. Introduction

In principle, engineering is the application of scientific knowledge to optimize production processes and product applications where the whole production life cycle is considered starting from design phase and ending by closure phase. Recent scientific knowledge of radiation phenomenon backs to more than a century, since then efforts were directed to understand and utilize this phenomenon to support human civilization [1]. Currently, radiation uses have been extended to support primary, secondary, and tertiary economical sectors; this includes but not limited to applications in oil and gas extraction, medical diagnosis procedures, power generation, and sterilization and gauging activities in health, industrial, and agricultural fields all over the globe [1, 2]. Ensuring optimum production and utilization of natural and induced radioactive materials to serve these sectors over extended periods of time was the reason to support the development of nuclear engineering sciences. In this respect, the output of the nuclear industry could be classified into four main products, namely, fission energy, radioisotopes, radiological detection instruments, and fusion energy. Subsequently, nuclear engineering could be viewed as the engineering field that is concerned with optimization of the processes that utilize and apply nuclear, fission and fusion reactions. Within all these processes, nuclear safety is addressed to guarantee safe and sustainable optimized productions and applications.

Research efforts that support the nuclear industry, as in any other industry, could be classified based on the maturity of the technology either commercial or innovative. These efforts are directed to improve the performance of the first class, whereas they aim at getting the second class into wide scale commercial applications [3]. Nuclear engineering research areas that cover the four identified industrial outputs could be listed as follows:

1. Fission technologies which are concerned with design and optimization of nuclear research or power reactors, associated nonradiological systems and nuclear fuel cycle technologies.
2. Radioisotope production technologies, these include accelerators, irradiation facilities and their nonradiological systems, and radioisotope applications and associated waste management.
3. Radiological detection and nuclear instruments technologies, which include detection instruments that help in dose monitoring to ensure personal and facility safety.
4. Fusion technologies, which are innovative technologies that aim at engineering fusion energy.

Figure 1 shows different scientific bases that were used to establish nuclear engineering sciences and the areas that are covered within nuclear engineering studies. Specialized studies emerged from the integration of these scientific bases that include but not limited to neutronics, radiation protection, radiological detection, and nuclear waste management. This chapter focuses on introducing the role of nuclear safety in ensuring the sustainability of nuclear industry with special reference to nuclear waste management, where disposal activity is used as an example to illustrate this role. The reason for this selection is the nature of the disposal concept that relies on passive safety functions to ensure radiological hazard containment and confinement. Within this context, basic safety concepts and principles and nuclear waste management activities will be introduced. The role of nuclear safety in supporting decision-making process in the industry will be presented by highlighting this role for nuclear disposal project. Requirement for safety case and safety assessment for radioactive waste disposal

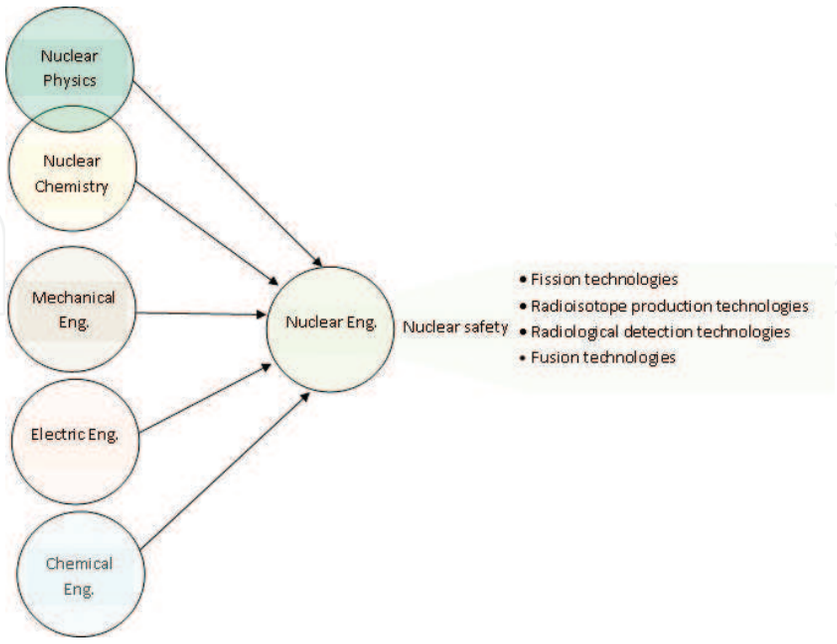

Figure 1. Nuclear engineering basis and major research areas.

project will be reviewed and the development of safety case throughout the disposal project life cycle will be introduced.

2. Safety concepts and principles

In principle, safety aims at ensuring protection from unwanted consequences. So, in workplaces that contain hazards, safety aims at controlling hazards to ensure acceptable risk. In facilities that handle radioactive materials, aside from the radiological hazard, that is, radiation and criticality, there could be several types of chemical and physical related hazards, that is, chemical toxicity, flammability, explicability and corrosivity [2]. These hazards and their classifications are listed as follows:

1. Radiation hazard: caused due to exposure to radioactive materials/radiation source, this exposure can lead to radiation health effect. The extent of these effects is dependent on the radiation type, absorbed dose, and duration of exposure and is initiated when living tissue absorbs some of the radiation energy that lead to changes in the cells [1, 4].
2. Criticality: in nuclear engineering, it refers to the capability of sustaining chain fission reaction; induced criticality should be assessed in workplaces that contain fissile materials [4].
3. Chemical toxicity: caused due to exposure to chemicals that can develop adverse reaction in living organisms [5]. Exposure could be classified based on the type, that is direct and indirect, or duration of exposure, that is acute, chronic [1, 5, 6].
4. Flammability, it is the ability of the material either solid or liquid or gas to ignite. Gas flammability is defined at standard pressure (101.3 kPa) and temperature (20°C). However, flammable liquids are classified based on their flash and boiling points (flashpoint <93°C). Solid flammable materials are those cause fire through friction [7].
5. Corrosivity, material that can damage metals or nonmetals, and it is classified based on the produced corrosion rate.
6. Explicability, materials that are chemically active producing gases at pressure rate that cause damage to its environment.

In this chapter, only nuclear safety will be discussed, where IAEA defined nuclear safety as "*the achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards*" [4]. The acceptable levels of protection from radiological hazard is usually derived based on the recommendation of International Commission on Radiological Protection (ICRP) to keep the exposure probability and magnitude as low as reasonable achieved (ALARA) taking into account the economical and social factors [1, 4]. It should be noted that radiological protection should be ensured under both normal and incidental conditions, where low probability incidents with considerable radiological consequences should

be considered. Safety measures should be taken to prevent and mitigate the consequence of incidents. Consequently, nuclear safety is only concerned with technical aspects to ensure protection from radiological hazard.

A decade ago, 3S (safety-security-safeguard) concept was introduced to ensure successful peaceful utilization of nuclear technology, where the areas of interaction between the three subconcepts, that is, safety, security, and safeguard, should be carefully addressed among concerned stakeholders [3, 8–10]. In this context, nuclear security is related to "prevention and detection of and, response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involve nuclear material, other radioactive substances or their associated facilities" [4]. Safeguards are agreements between IAEA and member states that target fissile materials, where these materials should be declared and controlled.

International Atomic Energy Agency (IAEA) identified 10 principles to achieve the radiological protection objectives of nuclear safety under normal and incidental situations, as follows [9]:

1. Safety responsibility rests with operator either personal, or facility that might cause radiological risk.
2. Effective sustainable legislative framework should be established.
3. Effective sustainable leadership and management for safety should be established.
4. Benefits associated with any radiological practice should be balanced with associated risks.
5. Radiological protection must be optimized to provide the highest level of safety that could be reasonably achieved.
6. Radiation control measures must limit radiological risks to individuals.
7. Protection of environment and people from anticipated radiological risks should be ensured.
8. All safety measures should be placed to prevent and mitigate accidental radiological consequences.
9. Emergency preparedness and response for radiological incidents should be addressed.
10. Reduction of unregulated radiological risks should be ensured.

3. Nuclear waste management activities

Safe management of nuclear wastes is vital to ensure the sustainability of the nuclear industry in some countries and/or to end legacy practices in other countries. Historical waste management strategies relied on identifying two options to deal with the generated wastes, namely dilute and disperse and contain and confine [2, 11]. These options aimed at ensuring radiological protection

http://dx.doi.org/10.5772/intechopen.76818

for worker, public and the environment. Currently, nuclear wastes are managed according to contain and confine option. The objective of this option is to prevent radiological hazard by isolating the waste for sufficient periods that allow the decay and limit release of short- and long-lived radionuclides, respectively [2, 12, 13]. To reach this end point, the wastes should be subjected to volume reduction (pre-treatment, and treatment), conditioning, and disposal in engineered facility [1, 2, 12, 14–32]. **Figure 2** illustrates an example of radioactive waste management scheme, and all the activities performed within the scheme should be complementary. It should be noted that these activities are divided as predisposal and disposal activities, where transport, characterization and segregation, transportation, pre-treatment, treatment, conditioning, and storage are pre-disposal activities. Waste acceptance criteria (WAC) are applied at each facility to ensure integrated safe performance of the overall management schemes [27]. Each activity in this scheme should be authorized by the regulatory body according to national legislative system [28, 33]. Different technological options could be applied in each activity; the selection of any is bounded by different technical and nontechnical factors [2, 27]. Technical factors include the waste characteristics (chemical, physical, radiological, and biological), technology maturity, robustness, and flexibility, and site characteristics [2]. However, nontechnical factors include socio-economical impacts, legal framework, and financial and technical resources availability [2, 27].

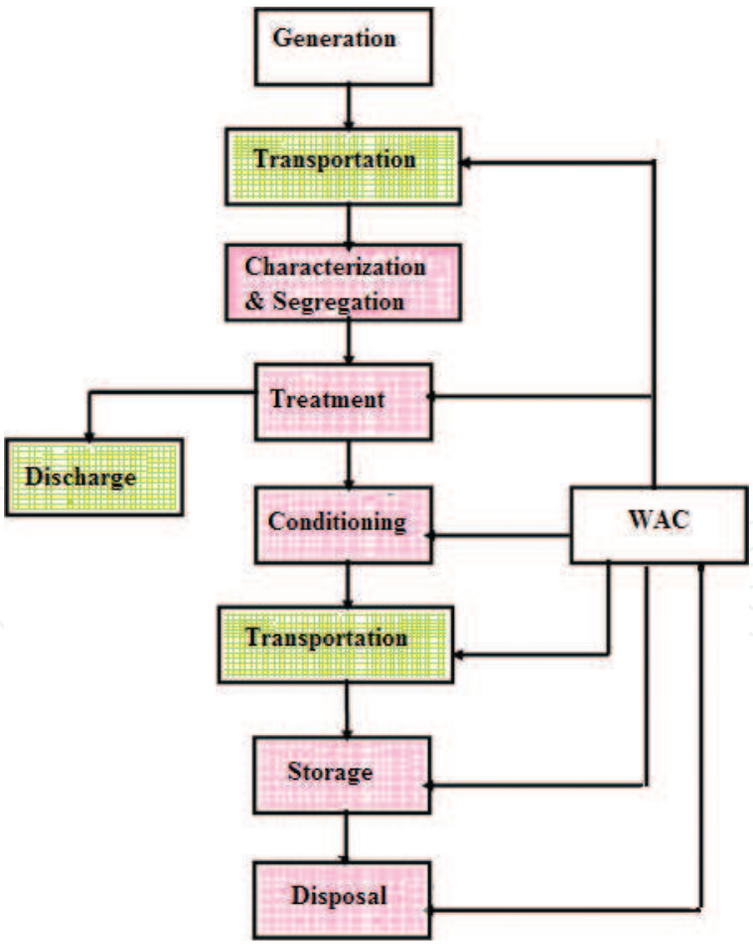

Figure 2. Radioactive waste management scheme.

4. Decision-making in nuclear industry

In the nuclear industry, decisions should be made based on sound scientific reasons that build confidence in the outputs of the industry [1, 33]. So, decisions are taken after ensuring effective improvement in safe design and operation of a facility/practice [34]. To support decision-making process, safety case (SC) is used to confirm the implementation of the required improvements. Safety case defined as a collection of all arguments that ensure achieving the highest level of quality in assessing radiological and nonradiological safety of the practice. These arguments include safety assessments, statement of confidence, and management system documentations. SC is prepared by dividing the studied system into subsystems that are analyzed and assessed, different terms are being used in this context, as follows [1, 4]:

Performance analysis: study of the system/subsystem/ process behavior and calculation of intermediate point of interest.

Safety analysis (*SA*): is directed to understand an overall system relevant to the protection against hazard.

Performance assessment (*PA*): determination of the performance acceptability that is conducted in comparison with certain design criteria or indicator.

Safety assessment (*SA*): aims at judging the overall system safety in comparison with regulatory safety limits, indicators and targets.

Indicators are characteristics that reflect possible impact of the system on the people/environment as a result of fault in a safety function or group of safety functions. Examples of safety functions for nuclear reactor and radioactive waste storage facility are listed in **Table 1** [9]. Based on the study types, indicators could be classified as performance or safety indicators. Performance indicators are usually used to assess the quality, reliability, or efficiency of the studied subsystems, whereas safety indicators are used to assess the performance of the overall system. **Table 2** lists the indicators classes and examples of these classes for radioactive waste disposal [34].

Hazard	Safety function in nuclear reactor	Safety function in radioactive waste storage facility
Criticality	Shut down and maintain shut down conditions of the reactor	Maintain subcriticality for fissile inventory
Thermal	Residual heat removal after shut down	Decay heat removal
		Control chemical process heat
Radiological	Confine radio-contaminants	Confine radioactive waste
		Shield radiation sources

Table 1. Safety functions in nuclear reactor and radioactive waste storage facility [9].

Indicator class	Indicators	Methods
Measurable	Spatial distribution of radionuclides in groundwater	Monitoring program in the site
Estimated	Lifetime of container	Derived from understanding the system
Calculated	Dose or risk	Modeling long-term evolution

Table 2. Examples of indicator classes in radioactive waste disposal system [34].

For radioactive waste disposal project, many decisions should be made at different milestones of the project lifecycle, that is, site selection, engineering design and construction, operation, closure, and post closure [35]. To support the decision-making process, the integration of assessment and analysis studies to produce radioactive waste disposal safety case should be conducted. **Figure 3** shows this integration, where the overall disposal system is divided into two main subsystems, near- and far-field that are analyzed and assessed. These subsystems are further divided into their main components, which are analyzed and assessed using relevant indicators. It should be noted that SC is a living document that is developed through the project lifecycle to reflect changes in the studied system, that is aging, operating experiences, and modifications. This is achieved by periodical safety review, where updated SC is submitted for revision on regular basis. IAEA identified the following requirements for safety case (SC) for radioactive waste disposal [36]:

1. SC is prepared by operator and reviewed and approved by regulator.
2. SC describes all safety relevant aspects of the site and facility, it includes SA and managerial control measures.
3. Adequate defense in depth is provided by applying several physical barriers and administrative procedures to ensure protection goal.
4. Site assessment should include present and natural evolution of the site and consider human plans and action in vicinity of the facility.
5. Facility development throughout its life cycle should preserve the identified safety function for the project.

Safety assessments represent a major part in safety case, as illustrated in **Figure 3**, safety assessment requirements for radioactive waste disposal facility include [36]:

1. SA should start at early stage of the disposal project and should be updated throughout the project lifecycle.
2. SA should conclude about compliance with safety objectives as required in the legislative framework.
3. Normal, anticipated and accidental conditions should be addressed in SA.

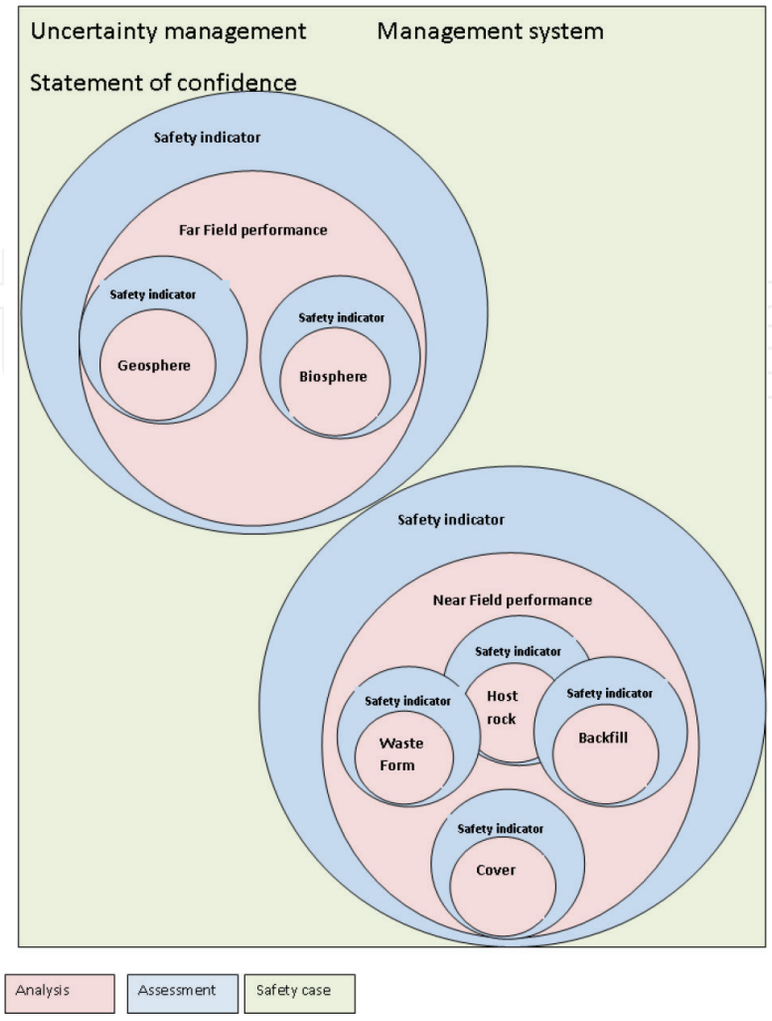

Figure 3. Integration of performance and safety assessment in radioactive waste disposal safety case.

4. Measures to control radiation risks that might arise under aforementioned conditions should be considered.
5. Radiation risks to individuals and population groups should be addressed for present and future generation.
6. SA could be conducted via deterministic and probabilistic approaches, and the scope of these analyses is determined according to the graded approach.

The outcomes of the decision-making process should assure [33, 34, 37]:

1. Maintenance of defense in depth and safety margins.
2. Consideration of good engineering and organizational practices.
3. Acknowledgement of the lesson learned from operational experience, research and development and state of the art.

4. Insurance of the integration of 3S concept.

5. Comply with relevant regulations.

5. Safety case development for radioactive disposal sites

Since the early establishment of radioactive/nuclear waste disposal practice, disposal was decided based on the output of performance and safety assessments. Both modeling and experimental assessments were carried out; **Table 3** lists the type of used assessment, studied subsystems, and performance indicators for three historical disposal practice [2, 38]. It should be noted that marine disposal is currently prohibited, hydro-fracture grouts are not used, whereas deep well injection license is renewed periodically [38].

Modeling radionuclide transport in near- and far-field is considered as the critical step in assessing the safety of the disposal practice. In modeling, processes that are important to the safety of the facility and site are linked together to predict the facility and site performances [39]. Modeling starts with system description, where information about important features, events, and processes is identified, then conceptual and mathematical models are developed. A typical scheme of a modeling process is illustrated in **Figure 4**. For an anticipated condition, conceptual model for disposal facility failure in a bathtub scenario is illustrated in **Figure 5**. The root cause of this scenario is the failure of the engineering barriers due to natural evolution of the system [39]. For each subsystem (waste form, engineering barriers, geo-sphere and bio-sphere), geometry, dimensionality, initial and boundary conditions, time dependence and relevant process are identified [40]. Then scenario consequences are determined using mathematical models. The level of mathematical model complexation is dependent on the stage of the disposal project. Within the design phase, three subphases are distinguished, namely,

Early disposal practice	Assessment type	Subsystems	Indicators
Marine	Modeling releases due to canister corrosion and package	Near field: waste form, package	Radionuclide concentration
	Monitoring release data		
	Modeling radionuclide transport	Far field: bottom sediment, benthic boundary layer, open oceans	Radionuclide concentration
	Monitoring transport		Doses
Hydro-fracture grout	Monitoring releases from experimental injection wells	Near field at monitoring wells	Radionuclide concentration
Deep well injection	Modeling transport		
	Monitoring releases from experimental injection wells		

Table 3. Methods to assess the performance of historical disposal practice [38].

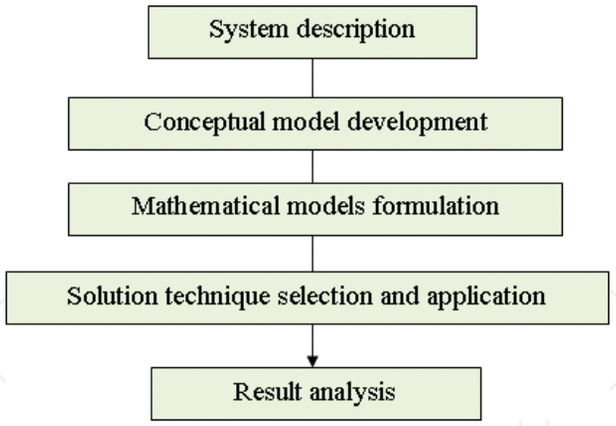

Figure 4. Steps in modeling process.

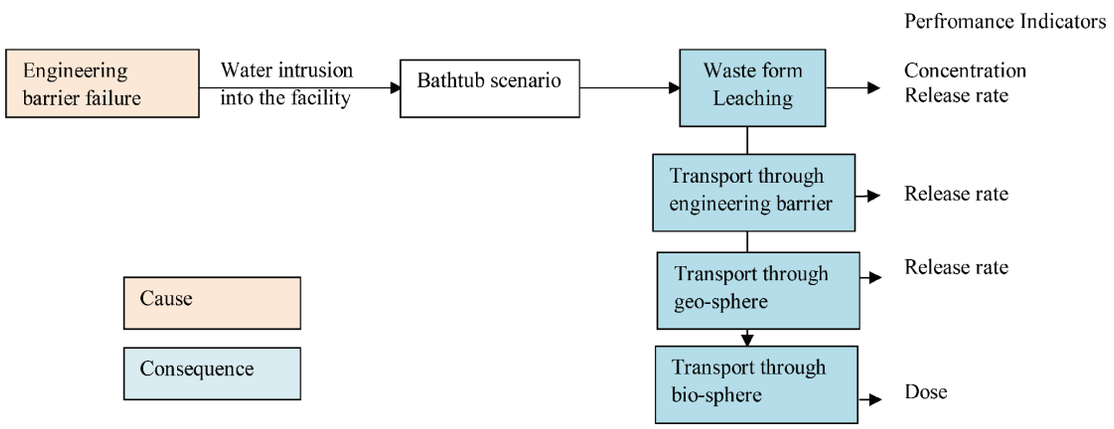

Figure 5. Conceptual model of disposal facility in a bathtub scenario.

conceptual design, basic design, and detailed design. The aim of the conceptual design is to select the disposal option; at this stage, data availability and its corresponding quality are respectively limited, so estimated radioactive waste inventory and generic site characteristics are used to model the system [2, 41]. As the project proceeds, modeling becomes more sophisticated where site-specific information and technical feasibility of engineering barrier materials become available. It should be noted that the development of the modeling efforts for each subsystem throughout the disposal lifecycle ensure the achievement of the sixth requirement for SA and third requirements for SC are addressed.

6. Conclusion

Nuclear engineering sciences emerged based on the integration of chemical, physical and engineering knowledge to serve the increased needs to optimize processes that utilizes radioactive, nuclear, and fusion reactions. The main objective of nuclear engineering is to ensure safe and sustainable production and application of nuclear/radioactive materials. This work

introduced the role of nuclear safety in ensuring the sustainability of nuclear industry. It could be concluded that:

1. Safety case is used to support decision-making process, and it contains all the technical and managerial arguments that ensure safe operation of nuclear facility/practice under normal, anticipated, and accidental conditions.
2. The nature of safety case as a living document should be emphasized.
3. Safety case should assure the maintenance of the defense in depth and safety margins throughout the project life cycle.
4. Modeling is the core of safety case, and the level of modeling complicity should be proportional to the imposed risks and level of development of the project.

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