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## Annex V

# SAFETY ASPECTS OF THE DESALINATION OF SEA WATER USING NUCLEAR ENERGY*

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### Abstract

The nuclear plants for desalination to be built in the future will have to meet the standards of safety required for the best nuclear power plants currently in operation or being designed. Some specific characteristics of desalination plants such as siting and coupling require particular consideration from a safety point of view, and further safety studies will be needed when the type and size of the reactor are determined. The current safety approach, based on the defence in depth strategy, has been shown to be a sound foundation for the safety and protection of public health, and gives the plant the capability of dealing with a large variety of sequences, even beyond the design basis. The Department of Nuclear Safety of the IAEA is involved in many activities, the most important of which are to establish safety standards, and to provide various safety services and technical knowledge in many Technical Co-operation assistance projects. The department is also involved in other safety areas, notably in the field of future reactors. The IAEA is carrying out a project on the safety of new generation reactors, including those used for desalination, with the objective of fostering an exchange of information on safety approaches, promoting harmonization among Member States and contributing towards the development and revision of safety standards and guidelines for nuclear power plant design. The safety, regulatory and environmental concerns in nuclear powered desalination are those related directly to nuclear power plants, with due consideration given to the coupling process. The protection of product water against radioactive contamination must be ensured. An effective infrastructure, including appropriate training, a legal framework and regulatory regime, is a prerequisite to considering use of nuclear power for desalination plants, also in those countries with limited industrial infrastructures and little experience in nuclear technology or safety.

## 1. INTRODUCTION

Several desalination methods are technically feasible and available. Three are currently used on a large scale (Multi-stage Flash, Multi-effect distillation and reverse osmosis), although they have different production throughputs and require different quantities of thermal and electrical energy. Reverse osmosis requires only electrical power (5-7 kWh/m$^3$); while the other processes require electrical and thermal energy (4.5-24 kWh/m$^3$).

Nuclear energy has proved to be a viable energy source for desalination, although the economics of the option need to be further investigated, taking into account the infrastructure necessary for nuclear power activities.

There has been a recent resurgence of interest in nuclear powered desalination in North African countries; indeed, the 1996 IAEA General Conference reaffirmed its importance and indicated further activity was needed in this area. In the light of this, it is important to review recent developments in the safety of nuclear power plants and to address some general safety issues and regulatory aspects, as well as some specific safety issues pertinent to this application.

The general approach to safety of nuclear reactors supplying heat or electrical power to desalination plants is equivalent to the approach used for nuclear power plants producing of

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electricity. The nuclear plants for desalination to be built in the future will have to meet the standards of safety required for the best nuclear power plants currently in operation or being designed, and for this reason the safety aspects are common with those related to new generation reactors for which a dedicated programme exists at the IAEA. Most of the general safety considerations reported in this paper have been discussed and analysed during the development of this programme. Some specific characteristics of desalination plants such as siting and coupling which require particular consideration from a safety point of view, and further safety studies will be needed when the type and size of the reactor are determined.

## 2. GENERAL SAFETY ASPECTS OF NUCLEAR POWER PLANTS

Application of the defence in depth strategy will continue to be the overriding approach for ensuring the safety of workers and the public, and for protecting the environment. This strategy is effective in compensating for human and equipment failures, both potential and actual. The concept is based on several levels of protection, including successive barriers that prevent the release of radioactive material to the environment. However, its efficacy depends on rigorous implementation. This implies a determined effort to make the defence effective at each level, particularly for accident prevention and accident mitigation. There is not a unique way to implement defence in depth, since there are different designs, different safety requirements in different countries, different technical solutions and varying management or cultural approaches. Nevertheless, the strategy represents the best general framework to achieve safety for nuclear power plants and, thus, nuclear powered desalination plants. In general, strong implementation of defence in depth requires a determined and constant effort from the design phase, to construction and operation in order to provide graded protection against a wide variety of transients, abnormal occurrences and accidents, including human error and equipment failures within the plant, and events initiated outside the plant.

### 2.1. Design basis approach and severe accident treatment

Operating nuclear plants are largely designed according to the design basis accidents approach. This means that the plant is deterministically designed against a set of hypothetical accident situations according to well established design criteria in order to meet the radiological targets. The current design basis approach has been shown to be a sound foundation for the safety and protection of public health, in part because of its broad scope of accident sequence considerations, and because of its many conservative assumptions which have the effect of introducing highly conservative margins into the design that, in reality, give the plant the capability of dealing with a large variety of sequences, even beyond the design basis. Often, probabilistic targets for core damage frequency and for containment performance are established. Experience and analysis have shown, however, that some sequences beyond the design basis (i.e. severe accidents) may need to be considered explicitly in the design, providing it with additional safety features to further prevent and mitigate such severe sequences. In this regard probabilistic safety assessment is recognized as a very efficient tool for identifying those sequences and plant vulnerabilities that require specific design features (elimination by design of the most challenging sequences to the containment). This, together with an effective containment system including good control of potential containment by-pass, ensure minimum radiological impact, with an extremely small chance of any off-site radioactive releases. For a nuclear powered desalination plant, the design basis may need to also include some transients or abnormal occurrences that might originate in the desalination unit itself.

### 2.2. Human error

The contribution of human error to events in the past has been significant. Human errors are a potential source of impairment of defence in depth because human activity is involved at all levels of defence. Therefore, the objectives are that new designs are simpler, and therefore easier to operate, and that specific design provisions are taken to make these plants more tolerant to human failure, as well as to reduce the potential for human interference initiating abnormal plant conditions.

The potential for a deterioration in defence in depth through human failure can be drastically reduced by introducing the following improvements, proposed for new reactors, to make these plants more operator friendly:

(a) Major system simplification through better design and greater inherent design margins that reduce the need for overly complex control systems and procedures;
(b) A greatly improved man-machine interface, with priority given to clear and unambiguous indications of plant parameters, and simpler and more forgiving controls with direct feedback on the results of actions taken;
(c) Prolonged grace periods by providing of increased time constants for the reactor system, or by a higher degree of automation;
(d) Use of symptom based procedures to complement event based procedures for emergency/accident situations;
(e) Greater automation to prevent human error.

### 2.3. Shutdown and low power states

Recently, increased emphasis has been placed on consideration of non-power states. INSAG-3 and INSAG-10 state that, during normal power operation, all levels of defence should be available at all times. During other plant conditions, an appropriate number of levels have to be available in order to maintain an adequate level of safety. This is because, during certain shutdown conditions, radiological barriers may be rendered ineffective (e.g. reactor coolant pressure boundary, containment) for maintenance or other reasons. Future plants will ensure that the concept of defence in depth can be implemented appropriately under these specific shutdown conditions. Specifically, new reactor designs have explicitly addressed safety in non-power states, primarily through improved defences that reduce the probability and safety significance of loss of decay heat removal events. This is often a design specific determination.

## 3. SPECIFIC SAFETY ASPECTS OF DESALINATION PLANTS

Simple energy considerations based on a survey of possible sites in North Africa and for different desalination methods show that the total power (electrical and thermal to supply potable water to a medium sized town) needed varies from a few to several hundred megawatts, and thus any proposed reactor falls into the small or medium sized category. Larger sizes would be required for the combined production of water and electrical power.

The nuclear power plants used for water desalination have several characteristics that are similar to those power plants used for district heating reactors (e.g. siting, power size, possibility of combined production), and the experience gained with these plants should be considered in designing nuclear powered desalination plants.

### 3.1. Coupling

The overall safety of an integrated complex composed of a nuclear reactor plant coupled to a desalination plant is predominantly dependent on the safety of the nuclear reactor plant and the effect of coupling, or rather the interaction between the desalination plant and the nuclear plant. This interaction should be analysed in various coupling situations to assess its effect on the safety of the reactor and on the overall nuclear desalination system, either in normal operation or in an accident situation.

Coupling will not pose any new safety concern if desalination uses only electrical power.

In thermal processes, the energy to be supplied is mainly low temperature process steam or water. Coupling is accomplished via a heat transfer circuit. Since radioactivity exists in the primary steam or hot water, the risk of contamination of product water exists and must be avoided. This can be done by adding intermediate loops maintained at values of pressure such that any leakage would not produce transfer of contamination to the distributed water. These simple measures, together with appropriate instrumentation and monitoring should be effective in preventing contamination of the distributed water. They do not seem to present any particular technical difficulty.

All the information available from the operating experience accumulated on an existing plant (ABTA, Kazakhstan) and from conventional desalination plants will also provide a valuable source of information for design and operation purposes. Operational transients in a desalination plant would have direct feedback into the reactor system. Such transients could have safety implications and need to be assessed.

### 3.2. Siting

For obvious reasons, the siting of a nuclear powered desalination plant raises some safety concerns, mainly because of the site selection restraints. The plant has to be built on a coastal site and near to populated areas to limit the cost of potable water distribution. The choice of site raises problems related to oceanography (tides, plant elevation) and very often to seismicity (frequent presence of faults on coasts).

The proximity of the nuclear desalination complex to population centres and its implication on the design and to the emergency planning and water supply should be examined.

If the site is in a remote area an important aspect to consider is the availability of adequate external electric power grid or supply for safe operation of the nuclear plant.

## 4. LEGAL AND REGULATORY ASPECTS OF NUCLEAR SAFETY

There are certain prerequisites for the safe utilization of nuclear power:

(1) To establish a legislative and statutory framework for the regulation of nuclear facilities;

(2) To establish a regulatory body that is independent of the organizations or bodies charged with the promotion or utilization of nuclear energy;

(3) To insure that this regulatory body has the responsibility for authorization (licensing), assessment, inspection and enforcement, and adequate authority, competence and

resources to discharge its assigned responsibilities; no other responsibility assigned to the regulatory body should jeopardize or conflict with its responsibility for regulating safety;

(4) To ensure that there is a clear delineation and separation of responsibilities between the regulatory body and the operating organization.;

(5) To ensure that adequate provision is made for the safe management of radioactive waste;

(6) To establish governmental emergency response capabilities;

(7) To ensure adequate physical protection arrangements;

(8) To provide the technological infrastructure necessary to support the safety of facilities and the radiation related activities.

These basic requirements need to be established well in advance of constructing any nuclear facility and will need considerable resource commitment from any country currently without a nuclear power plant.

In several cases, nuclear desalination plants may be proposed for countries with very little experience of nuclear technology and in particular of nuclear safety. The necessary creation of the infrastructure requires time, human resources and a great deal of training.

There are a large number of new designs that have been proposed for small or medium sized reactors. Although they are mainly based on existing proven technology, they include innovative solutions and systems that require a careful a safety evaluation, safety review and demonstration of licensability which, in some cases, cannot be done by the operator or the local licensing authority because of lack of experience or capability. Licensing of nuclear power plants involves considerable effort and expertise, and good communication between the nuclear authority, the operator and other national authorities. In the case of nuclear powered desalination this will involve additional responsibilities dealing particularly with water use. Joint effort and co-ordination are envisaged between the designer, the utility and the local authorities.

## 5. THE ROLE AND ACTIVITIES OF THE IAEA

The Department of Nuclear Safety is involved in many activities, the most important of which are to establish safety standards, and to provide various safety services and technical knowledge in many Technical Co-operation assistance projects. The department is also involved in other safety areas, notably in the field of future reactors. The newly established Convention on Nuclear Safety was developed under the auspices of the IAEA.

The IAEA produces many publications related to nuclear safety, the most important of which are those now to be included in the Safety Standards Series (SSS), formerly the Safety Series, which included the NUSS programme. The SSS will comprise three levels: Fundamentals, Requirements and Guides. They will be produced under the authority of the Advisory Commission for Safety Standards (ACSS) and its four subcommittees. These standards are written primarily for national regulatory bodies, which may wish to impose them upon licensees or other related organizations. They are, however, non-binding unless a Member State is receiving assistance or has an agreement with the IAEA, in which case they are mandatory.

### 5.1. Safety fundamentals (SFs)

Currently, there are three SF publications, but in the long term aim is to combine these into a single publication. These are the first publications in the hierarchy; they present basic objectives, concepts and principles to ensure safety in the development and application of atomic energy or radioactive material for peaceful purposes. The SF publications constitute the reasons why activities must fulfil certain requirements; they do not state what these requirements are, they are self-sufficient and do not include a list of references. In the SF on Safety of Nuclear Installations (SS-110) there are 25 fundamental principles grouped into four main areas, related to the Legislative and Regulatory Framework, the Management of Safety, the Technical Aspects of Safety and the Verification of Safety.

### 5.2. Safety Requirements (SRs) and Safety Guides (SGs)

Supporting the SFs are Requirements (formerly termed Codes, Standards or Regulations). In the nuclear safety area there will be four main areas: Siting, Design and Operation of thermal neutron nuclear power plants and the Research Reactor Series which has two SR publications. Previously, also Quality Assurance and Governmental Organization were included in the NUSS programme. These have been removed into a ‘general safety’ category and will be dealt with by the ACSS. All the existing NUSS codes (except QA, which was published in October 1996) are now subject to a comprehensive revision process, which is being overseen by the Nuclear Safety Standard Safety Committee (NUSSAC). This revision will ensure that all the relevant principles in the SF are systematically addressed, thus enabling a coherent set of publications to be produced. The SRs will set out in more detail what is required of Member States to ensure safety in a particular area, and they are governed by the content of the SFs. SRs do not generally present recommendations on or explanations of how to meet the requirements. This more detailed aspect is covered by the third level in the hierarchy, namely, the Safety Guides. The SGs present recommendations on the basis of international experience, of the measures to be followed to meet the requirements set out in the SR publications.

The category of Safety Practice has now been abandoned and these detailed publications will form part of the new Safety Reports Series.

Safety Series publications also deal with Radiation Safety and Waste Safety; they also need to be used as references for national regulations.

### 5.3. Experience with existing power plants

Over recent years, the IAEA has carried out many missions to operating nuclear power plants, some of which were to reactors of Eastern European countries often used for combined electrical power generation and district heating. A mission was also conducted on the BN-350 plant at ABTA, which is coupled to a desalination plant.

The BN-350 is a sodium cooled fast reactor used to produce electricity and heat. The plant is operated by the Mangyshlak Power Generation Company and its output supplies a large industrial complex, which is relatively isolated from the rest of the Kazakstan electrical grid.

The plant design output is 1000 MW(th), but the current operation is limited to 520 MW(th). The reactor itself is technically separated from the electricity/desalination/heat plant, which takes the steam output and returns feedwater to the nuclear part of the installation.

Therefore, the nuclear safety aspects discussed during an IAEA mission carried out in March 1995 were limited to the nuclear reactor and its cooling system, and did not involve the desalination plant. The topics discussed included detection and control of sodium fires, component ageing, sodium corrosion, vessel in-service inspection, seismic safety and accident analysis.

With the independence of Kazakstan, a new nuclear regulatory body has been created. However, the Kazakstan Atomic Energy Authority still needs assistance in establishing a regulatory body in accordance with current international practice. The IAEA has approved a technical co-operation project to provide this assistance.

Several nuclear plants in the world provide heat for nearby communities. This is a common procedure in WWER plants (Bohunice, Paks, Kola) and other LWRs in cold regions.

Generally, the heated water (or steam) is generated in a separate heat exchanger using part of the steam extracted between the high pressure and low pressure turbines. The pressure in the hot water (steam) distribution system is high enough to ensure that any leaks in the heat exchanger will be into the plant system and not into the water (steam) distribution system. This provision prevents the transfer of possible contamination from the nuclear plants to the heat distribution network.

The technical decision on the amount of diverted steam for district heating purposes depends on economic factors and on the distances involved between a given plant and the nearby towns and villages. No specific safety concerns related to the district heating aspects have been raised during the safety review missions carried out by the IAEA at these plants.

### 5.4. Current experience accumulated on research reactors

Nuclear desalination plants have been proposed for various Member States, in particular, those that are located in arid areas of Africa, Asia and elsewhere. Many of these countries have no experience at all with nuclear reactors, while a few have one or more research reactors.

Reviewing the experience gained with research reactors in several developing countries the following points can be made that may be applicable to a desalination project:

(1) Experience with a research reactor facility may be quite useful as it usually means that the country already has: a nucleus of a regulatory authority; some infrastructure in radiation protection and waste effluent control related to nuclear reactors; group of knowledgeable personnel in the areas of reactor operations and maintenance; programmes for the training of personnel; and experience with IAEA sponsored projects.

(2) A research reactor facility (especially a larger reactor) can be used to simulate or experiment with some of the processes associated with a desalination plant, and can also be used as a school for training the new staff needed for the new project.

(3) Developing countries vary greatly in their political stability, economic wealth, technological infrastructure, logistical infrastructure, and general technical and safety related attitudes. The following problems have been observed in various countries:

   (a) The lack of ability to obtain fresh fuel or spare parts for the reactor because of political instability;
   (b) Negligence of important reactor systems that are out of order (for lack of resources, or a proper attitude, or both, in order to replace or repair them)
   (c) Lack of an adequate operating budget;
   (d) Failure to make use of IAEA assistance (e.g. the equipment procured lies unused for years);
   (e) Inadequate security arrangements around the facility (even in riot prone countries);
   (f) The lack of any central inspection (e.g. licensing, radiation protection), which is in conflict with the statement made in the previous section;
   (g) Unreliable technical and logistical support (electricity, communications, general equipment and spare parts);
   (h) The inability to prepare and implement a priority based operational programme.

While gaining experience with a research reactor is expected, in general, to be useful as a first step before introducing nuclear power (or desalination), this same experience can shed light on the deficiencies that may undermine the prospects for such a project unless, in particularly serious cases, adequate international support can be provided.

### 5.5. IAEA activities on new generation nuclear power plants

The IAEA activities on the safety of new generation reactors, which were formally initiated after the Conference on the Safety of Nuclear Power: Strategy for the Future held in September 1991, are being carried out under the project Safety Approaches to the New Generation of Nuclear Power Plants, foreseen to continue for the next 2 years. The main objective of this project is to foster an exchange of information on safety approaches to new generation nuclear power plants with a view to promoting harmonization among Member States and contributing to the development and revision of safety standards and guidelines for nuclear power plant design. The revision is already in progress and relevant indications have been provided. If is expected that the new standards will have an impact on the design of all nuclear power plants, including those for desalination, constructed in the coming years.

In June 1995, following INSAG's review and comments, the IAEA published a technical publication, Development of Safety Principles for the Design of Future Nuclear Power Plants (IAEA TECDOC-801). The work tried to incorporate the lessons learned from recent operational experience, research and development, design, testing and analysis, as well as from attempts to reflect current trends in reactor safety design. It provides a basis for the development of safety objectives and principles for new generation nuclear power plants and for the revision of safety standards. The key proposal is that severe accidents beyond the existing design basis will be systematically considered and explicitly addressed during the design process for future reactors. The design features provided to address severe accidents are not expected to meet the same stringent requirements (redundancy, diversity and conservative acceptance criteria) used for the safety features to cope with design basis accidents; however, they will be engineered in such a way as to give reasonable confidence that they are capable of achieving their design intent. The publication also emphasizes the need to further lower the risk of any serious radiological consequences and to ensure that the potential need for prompt off-site protective actions can be reduced or even eliminated (good neighbour concept).

Other safety areas that are specifically addressed in TECDOC-801, and for which new or modified principles were suggested, are:

(1) In the area of safety prevention
- Clarification of the use of probabilistic safety analysis;
- Consideration of modes of operation other than full power (low power and shut down);
- Spent fuel handling and storage;
- Multiple unit sharing equipment.

(2) *In the area of accident mitigation*
- Confinement to mitigate addressed severe accidents.

(3) *In the area of proven engineering safety practices*
- Classification of the safety systems;
- Standardization;
- Consideration of the passive systems;
- Plant security.

(4) *In the area of human factors*
- Design to be user friendly and to avoid complexity;
- Design to reduce dependence on operator action;
- Consideration of operating and maintenance procedures since the design phase;
- Plant security.

Additional effort has been made to prepare a technical publication on the implementation of defence in depth for new generation Nuclear Power Plants. The work was based on the report on defence in depth prepared by INSAG, and the main objective was to bring together the relevant aspects of existing publications on both defence in depth and future reactor designs, and then to apply recent defence in depth formulations specifically to ongoing developments in future plant designs.

Particular attention has been focused on identifying and addressing those factors that have the potential to affect multiple levels of defence in depth. This provides high confidence that appropriate actions will be taken to ensure the effectiveness of the defence in depth concept against failures that have the potential to impact multiple levels of defence in depth. (Human failure, internal and external hazards, etc.).

The report provides a good general framework for a safety evaluation and also gives some indication as to how the defence of each level could be enhanced.

## CONCLUSIONS

Use of the nuclear option as an energy source for the desalination process is feasible. The safety, regulatory and environmental concerns in nuclear powered desalination are those related directly to nuclear power plants, with due consideration given to the coupling process. It is important, however, to maintain a progressive approach and to take advantage of state of the art knowledge and techniques; for this reason it is expected that any reactors used for desalination purposes will be designed, constructed and operated in accordance with internationally recognized safety standards.

IAEA missions to operating nuclear power plants coupled to heat production and desalination plants have not revealed any serious specific safety concerns related to the interaction of the nuclear plant with the heat distribution plant or desalination plant, but they have shown that any safety concerns are related to the reactor itself.

Nuclear safety and environmental considerations in nuclear desalination are those arising from the use of nuclear reactors as energy sources. Nuclear safety and regulatory actions should be based on relevant IAEA safety standards. In addition, as a specific requirement, the design, operation and performance of an integrated nuclear desalination complex must ensure the protection of product water against radioactive contamination.

The most serious concern, as experience with research reactors has shown, arises from the fact that very often countries that need water are developing countries, with limited industrial infrastructures and little experience in nuclear technology or safety. An effective infrastructure including appropriate training, a legal framework and a regulatory regime, is a prerequisite to considering use of nuclear power for desalination plants.

Investing in safety, which includes upgrading the national infrastructure, developing competent staff, strengthening the regulatory regime and establishing a positive safety culture, is an essential requirements.

Another relevant aspect is the social and political instability of some countries where nuclear facilities could be possible targets of external attack; the plant would require comprehensive physical protection arrangements.

With respect to existing international safety standards and guides, they also seem to be appropriate covering desalination plants. There seems to be no need to prepare any specific guidance for the safety of nuclear powered desalination plants.

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