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SAFETY GUIDES

safety series

Design and Operation of Radioactive Waste Incineration Facilities

INTERNATIONAL ATOMIC ENERGY AGENCY VIENNA 1992

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DESIGN AND OPERATION OF RADIOACTIVE WASTE INCINERATION FACILITIES

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FOREWORD

A substantial portion of the low and intermediate level radioactive wastes generated in the various parts of the nuclear fuel cycle, in nuclear laboratories and other places where radionuclides are used for research, and in industrial, medical and other activities, is combustible. Incineration of such radioactive wastes provides a very high volume reduction and converts the wastes into radioactive ashes and residues that are non-flammable, chemically inert and much more homogeneous than the initial wastes. With more stringent safety requirements and the increasing cost of final disposal, the incineration of radioactive waste has thus become a very important part of the waste management strategy. In particular, as a rather complex high temperature process, the incineration procedure has to meet certain specific safety requirements.

As had been recommended by several Member States, the IAEA has prepared this publication to provide safety guidance for the design and operation of radioactive waste incineration facilities. This Safety Guide emphasizes the design objectives and system requirements to be met and provides recommendations for the selection of the process used, and for the design and operation of the equipment.

This publication was drafted by the Secretariat and four consultants (R. Kohout, Ontario Hydro, Canada; S. Carpentier, Société générale pour les techniques nouvelles, France; W. Wurster, Kraftanlagen AG, Germany; L.C. Oyen, Sargent & Lundy Engineers, United States of America). The draft guide was reviewed by 16 experts from 11 Member States and one representative from the Commission of the European Communities at two Advisory Group Meetings held during 1987 and 1988. It was revised by the same consultants at three consultants meetings during the period from 1987 to 1989. The guide was finalized by R. Kohout in 1991. The officers responsible for this work at the IAEA were V.M. Efremenkov and A.F. Tsarenko of the Division of Nuclear Fuel Cycle and Waste Management.

The IAEA wishes to express thanks to all those who took part in the preparation of this Safety Guide.

CONTENTS

1. INTRODUCTION

BACKGROUND

101. A wide range of incineration techniques can be employed for radioactive waste processing depending on the characteristics and the volumes of waste to be treated. In comparison with other methods for the treatment of radioactive waste, incineration is a rather complex high temperature process, and its utilization demands that certain specific safety requirements shall be met. This Safety Guide deals with safety considerations for the design and operation of incineration systems and facilities dedicated to processing radioactive waste.

102. Several IAEA Safety Standards and Safety Guides [1-4] have been published to provide Member States with guidance and recommendations regarding which safety requirements in the management of the radioactive wastes shall be met. The present Safety Guide is addressed specifically to safety requirements for the incineration of radioactive waste and is complementary to the above IAEA safety documents.

OBJECTIVE

103. The purpose of this guide is to provide safety guidance for the design and operation of radioactive waste incineration facilities. The guide emphasizes the design objectives and system requirements to be met and provides recommendations for the procedure of process selection and equipment design and operation. It is recognized that some incinerators may handle only very low or 'insignificant' levels of radioactivity, and in such cases some requirements or recommendations of this guide may not fully apply. Nevertheless, it is expected that any non-compliance with the guide will be addressed and justified in the licensing process. It is also recognized that the regulatory body may place a limit on the level of the radioactivity of the waste to be incinerated at a specific installation.

For the purpose of this guide an insignificant level of release of radioactivity may typically be defined as either the continuous or single event release of the design basis radionuclide inventory that represents a negligible risk to the population, the operating personnel, and/or the environment. The guidance on what constitutes a negligible risk and how to translate negligible risk or dose into level of activity can be found in Ref. [5].

SCOPE

104. This guide defines the principal requirements for the design and for the operation of systems and facilities for the incineration of radioactive waste. It concentrates

on the incineration process and its associated effluent control equipment. Included are requirements and recommendations for safety provisions to cover the broadest range of potential risk associated with the operation of radioactive waste incineration facilities. This guide does not cover the detailed radiological safety considerations nor the additional non-radiological hazards that may result from the chemical or physical properties of the waste and may require additional safety provisions.

STRUCTURE

105. After stating the principal design and operational objectives for the radioactive waste incineration facilities the guide first addresses the basic safety aspects and issues in Section 3, such as potential accident conditions, radioactivity containment principles, environmental consequences and preventive measures. Specific safety related requirements from a system viewpoint are addressed in Section 4. Section 5 contains requirements as well as recommendations for the conceptual design and the process selection. The remaining sections present more detailed safety related requirements and recommendations at the subsystem and the component levels, specific requirements and recommendations concerning instrumentation and controls, the building and physical arrangement, system commissioning and operation, and other information.

2. DESIGN AND OPERATIONAL OBJECTIVES

SAFETY OBJECTIVES

201. The radioactive waste incineration facilities shall be constructed and operated in compliance with the authorization for plant discharges to the environment as determined by the competent authority, and also to minimize industrial hazards.

202. Radiation exposure to the public and the operating personnel shall be ensured in the design and operation to be as low as reasonably achievable (ALARA), social and economic factors being taken into account. This requirement implies that the hazardous consequences from the practice of radioactive waste incineration should be reduced by suitable protective measures to a value such that further reductions become less justified in relation to the additional expenditure required. The dose equivalent to individuals shall not exceed the applicable dose limits set by the competent authority. Further guidance on radiation protection principles may be found in Ref. [6].

203. Radioactive and non-radioactive wastes should be managed separately. However, under certain circumstances, co-incineration of these different materials in a radioactive waste system could be acceptable provided the applicable regulatory requirements are met.

204. A well defined safety evaluation procedure should be an integral aspect of the design of a radioactive waste incineration facility.

PERFORMANCE OBJECTIVES

205. The waste acceptance capability of the radioactive waste incineration facility shall enable the facility to process the waste volumes generated during normal operation and the anticipated operational occurrences of the nuclear power plant or facility.

206. The reliability of components, ease of operation, system maintenance and future decommissioning should be considered in the design and specification of radioactive waste incineration facilities.

207. The selected waste incineration process and subsequent treatment steps shall ensure that the final waste form meets the requirements as set by the competent authority for transport, storage and/or disposal.

OPERATIONAL OBJECTIVES

208. The incineration facilities for processing nuclear power plant wastes should be designed to meet the operational objectives identified in Ref. [4]. The design of facilities for processing other radioactive wastes may assume that the operational objectives identified in Ref. [4] are still valid.

3. BASIC SAFETY ASPECTS

SYSTEM SAFETY ANALYSIS

301. A system safety analysis shall be performed to analyse the consequences under normal operating conditions, and to investigate the potential causes of accidents and their associated risks. The analysis shall investigate all important safety parameters which include but are not limited to the following:

(a) The required conditions for normal operation;
(b) The nature of possible accidents and their probabilities;

(c) The combination of circumstances needed for an accident to occur;
(d) Fault detection and preventive measures;
(e) The technical measures necessary for minimizing the risks and the consequences of these;
(f) Possible consequences in relation to:
   — the public,
   — the operating personnel,
   — the environment,
   — the process equipment;
(g) The definition and consequences of the worst credible accident;
(h) The possible impact of the incineration facility on the plan for the site in the event of an emergency.

ACCIDENT CONDITIONS

302. The origins of potential accidents include but are not limited to the following:

(a) Design deficiencies that render the incineration system unable to overcome the difficulties caused by thermal, mechanical, chemical or radiological failures;
(b) Introduction of materials into the waste feed that lead to excessive temperatures, overpressurization and/or explosive conditions within the incineration system;
(c) Loss of critical utility supply (e.g. electric power, air, fuel and water);
(d) Human error;
(e) Natural phenomena (e.g. earthquake, wind and flood);
(f) Other external events.

FIRES AND EXPLOSIONS

303. Serious and damaging consequences may result from accidents caused by fires and explosions. Therefore, the incineration system and its off-gas treatment system should be designed to withstand the effects of the overpressure caused by an explosion, and provided with a suitably located pressure relief mechanism. Furthermore, the following measures shall be instituted to minimize the potential for explosions or fires:

(a) Explosive mixtures shall be avoided.
(b) Potential ignition sources both inside and outside the incineration system shall be minimized.
(c) Systems and components shall be purged to ensure that they do not contain explosive mixtures prior to startup, restart, inspection and maintenance.

(d) Anomalies that could cause a fire with or without the hazard of explosion shall be averted as far as practical; examples of these anomalies are:
- leakage from gas or liquid fuel pipes feeding the burners,
- insufficient oxygen levels producing explosive gas mixtures,
- sudden extinction of burner(s),
- leaks in solvent piping systems,
- complete failure of incineration off-gas extraction,
- discharge of hot ash containing unburned materials,
- fly ash with a high carbon content in filter equipment,
- inadvertent introduction of dangerous material into the incinerator (e.g. a solvent with a low flashpoint or aerosol bottles),
- suspension of fine combustible particles in the air, which could form an explosive mixture (e.g. dust in the shredding area),
- off-gas system blockage.

CONTAINMENT OF RADIOACTIVITY

304. Prevention of the spread of contamination into the incinerator building shall be achieved by ensuring the leaktightness of the incineration system boundaries, and by operating the incineration system under a negative pressure with respect to the building. Prevention of the spread of contamination to the outside environment in the event of accidental radioactive contamination inside the building shall be ensured by operating the incinerator building at a negative pressure with respect to the outside environment. Further guidance is contained in paras 411 to 416.

305. Incineration systems burning alpha bearing wastes shall be located in an additional leaktight enclosure within the incinerator building.

PREVENTIVE MEASURES

306. To minimize the probability of an accident, analyses should identify suitable preventive and mitigating measures. These measures should include but not be limited to the following:

(a) Waste inspection with determination of the characteristics of the waste to permit removal of materials having an accident causing potential.
(b) Minimization of the potential for leaks of flammable gases and liquids.
(c) Control of the average (bulk) thermal properties of the waste feed to ensure operation within the thermal capacity of the incinerator.
(d) Detailed operator training involving all phases of the operation and the system design.

(e) Use of automatic controls to the fullest extent practical.
(f) Documentation of operating procedures, safety requirements and maintenance requirements for the incinerator and its peripherals. This documentation should be maintained in a separate, updated instruction file comprising:
— description of the system,
— general operating rules,
— operating instructions,
— safety instructions,
— health physics instructions,
— maintenance instructions.
(g) Recognition of system independent risks and the formulation of countermeasures to mitigate the consequences of these.

OPERATING CONDITIONS

307. Maintaining normal operating conditions is an essential requirement for the operation of an incineration system. Therefore, the design shall provide either intrinsic compliance with such a requirement, or effective means for monitoring the process and preventing unfavourable conditions from arising. The latter includes control of the waste feed quantity and quality, and demands careful monitoring of the system pressures and temperatures, off-gas composition, and other parameters.

SAFETY CONTROL FUNCTION

308. The system shall be provided with sufficient controls for a system shutdown, and for returning the system to a stable condition from all situations that can occur with any significant probability. Further information about controls and instrumentation may be found in Section 8.

CRITICALITY

General

309. An accumulation of a given quantity of fissile material may cause a criticality accident. The design and operation of an incineration system for wastes containing fissile radionuclides shall be such that criticality cannot occur. The following aspects are important:

(a) Type, quantity, concentration and chemical form of fissile nuclides;
(b) Presence of moderating materials;

(c) Geometrical shape of the unit;
(d) Presence or absence of nuclear poisons;
(e) Distance between stacks of fissile materials;
(f) Type of structural materials that may act as reflectors.

Criticality considerations

310. In the design and operation of an incineration facility for wastes containing more than trace quantities of fissile materials, a criticality safety analysis shall be carried out and appropriate operational limits shall be established. Inventory control of the fissile nuclides should be the key element in the criticality safety. The following provisions shall be taken into consideration:

(a) Inventory control of fissile nuclides entering and leaving the installation,
(b) Minimization of the presence of the moderating (e.g. hydrogenous) materials,
(c) Safe geometry at specific locations of concern (e.g. ash collecting equipment),
(d) Suitable distances between waste containers,
(e) Use of neutron absorbers,
(f) Neutron counting,
(g) Surveillance of fissile material accumulation throughout the installation,
(h) Limitation of masses,
(i) Periodic inspection and cleaning of the installation.

INDUSTRIAL SAFETY

311. In addition to meeting the radiation protection requirements for plant operations and keeping the radiation doses ALARA, the design shall also meet the applicable regulatory requirements for non-nuclear industrial safety.

EFFLUENT DISCHARGES

312. The operating organization shall ensure that the incineration system complies with the national radioactive and non-radioactive effluent control criteria established by the competent authority. The principles detailed in Refs [6, 7] shall also be taken into account. The design shall ensure that the above criteria and requirements are satisfied under all anticipated operating conditions. Additional guidance on effluent monitoring is given in Ref. [4].

OVERPRESSURE PROTECTION

313. Pressure surges within the incineration system could be detrimental to the integrity of the system and to the safety of operating personnel. Materials that can cause overpressurization should be excluded from the waste feed, using strict administrative control and waste feed inspection. The incineration system should be designed to withstand overpressurization as a result of a postulated accident, and should also be equipped with pressure relief mechanisms. The discharge from the pressure relief mechanism should be routed to radiological control equipment.

4. SYSTEM REQUIREMENTS

REGULATORY REQUIREMENTS

401. The design of the radioactive waste incineration system shall meet the applicable regulatory standards and safety requirements. Basic guidance for the design of radioactive waste management systems at nuclear power plants is given in Ref. [2]. Additional guidance may be found in Refs [3–6]. Furthermore, the design and operation of the incineration system shall meet the applicable national and local regulations for effluent discharges. Incineration systems installed at facilities other than nuclear power plants may be governed by different regulations. However, it is recommended that all facilities adopt the intent of this Safety Guide.

PROCESS REQUIREMENTS

General

402. The incineration process and equipment shall be designed such that both the primary radioactive wastes being incinerated and the secondary wastes produced by this treatment are managed in a systematic way that takes into consideration safety and regulatory requirements, economic considerations, as well as the relevant aspects of storage, transport and disposal. The incineration system design (including its off-gas system) should take into account the characteristics of the waste feed, the desired form of the ash, waste volume reduction and throughput requirements, the operational limitations, and the physical dimensions and location of the equipment. Implementation of the ALARA principle shall be achieved by a comparative assessment of alternative incineration techniques.

Waste classification and characterization

403. Incinerable radioactive wastes may have different physical forms and chemical compositions, and their radionuclide and activity contents may vary over a wide range. The criteria and method for identification and classification of these wastes should be prepared during the system design stage in order to allow selection of a process flow with appropriate system components, and to establish the effect of their incineration on the materials used in the construction. Additionally, such information will permit planning of the appropriate segregation of waste according to the selected process. Examples of waste classification schemes may be found in Ref. [8]. Information on waste feed categories may be found in para. 505 and in Annex I.

404. The presence and the relative amounts of non-combustibles, water, detergents, halogenated plastics, corrosive materials, and substances that may present a biological hazard in the waste may all affect the choice of incineration process and off-gas treatment, the overall process flow, and the materials used in the construction. Special attention shall be paid to the presence of spent ion exchange resins and organic liquids in the waste.

Waste feed preparation

405. Radioactive wastes should be segregated into incinerable and non-incinerable categories consistent with the feed requirements of the adopted incineration scheme. This segregation should be carried out as close as possible to the place of the waste generation. All pyrophoric and corrosive waste materials shall be eliminated from the waste feed unless the system is specifically designed to accept them. Other materials or objects such as halogenated plastics, metal, glass, other non-combustibles, and items with a radioactivity exceeding a set limit may have to be eliminated from or controlled in the waste feed depending on the process design, the materials selected for the construction and the provisions for radiation control.

406. While some incineration processes can accept waste feed in the form that the waste is generated, other processes require pretreatment such as size reduction, homogenization, reduction of moisture content and absorption of combustible liquids on sorbent materials. Further information may be found in para. 506.

Process flow

407. It is recognized that there are many combinations of components that would meet the objectives of this Safety Guide. An example of a generic flow diagram is given in Fig. 1 and examples of component combinations are given in Ref. [9].

OPERATIONAL RELIABILITY AND MAINTAINABILITY

408. The operational reliability of an incineration facility can be improved during the design stage by the selection of equipment and components that are properly designed to give a long serviceable lifetime under expected operating conditions.

409. Adequate space should be allowed for the maintenance of the incineration system, especially around components that may become contaminated and require frequent replacement. Proper shielding, either permanent or portable, should be available to protect workers during operation and maintenance. Provisions for remotely controlled maintenance of the system should be considered.

410. The design of the system should include provisions to facilitate component replacement, adjustment and proper servicing. Many components may not need to have the full lifetime planned for the entire incineration system. Items such as refractory components, fan bearings and seals, pump bearings and seals, and instrumentation will require the determination of a replacement schedule.

RADIOACTIVITY CONTAINMENT

411. Containment of radioactivity in the incineration system shall be ensured by equipment boundaries (static barrier) and by maintaining negative pressure in the equipment (dynamic barrier). Negative pressure in the incinerator building shall provide an additional (secondary) dynamic barrier against the spread of contamination from the facility proper to the environment.

Static barrier

412. The static barrier shall be constituted by: the boundaries of the process equipment, which have been designed to be leaktight (e.g. welded and leak tested); the boundaries of glove boxes, having similar provisions to those specified above, that enclose non-leaktight equipment; and connection pipes and unions having metallic and plastic bellows provided for tightness and expansion clearance. Every effort should be made to avoid compromising the integrity of the static barrier.

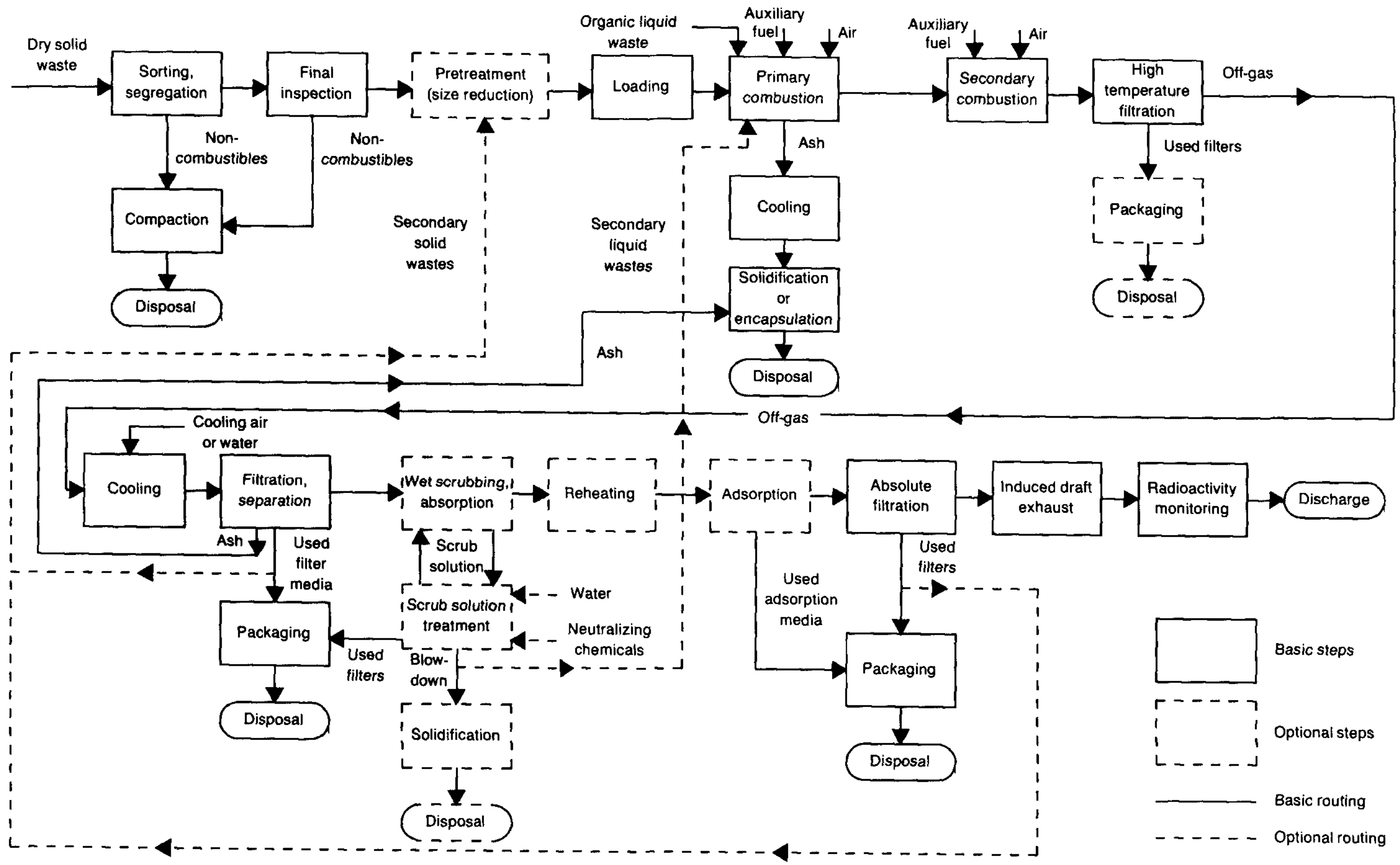

FIG. 1. Generic block diagram of an incineration system for radioactive wastes.

Dynamic barrier

413. The total system shall be maintained under negative pressure at all times with respect to the building, to enhance the effectiveness of the static barrier for preventing the dispersion of radioactive materials into the incinerator building in the event of an accidental leak in the equipment. This dynamic barrier is provided by the incineration system's exhaust or induced draught fan. When a positive pressure is essential as a process requirement in a part of the incineration system, special precautions shall be taken to ensure that leakage beyond the static barrier cannot occur.

Secondary dynamic barrier

414. The pressure in the incinerator building shall also be kept negative with respect to the environment, to prevent the spread of contamination into the environment in the event of a failure of any of the primary (static or dynamic) barriers. The building should be exhausted into the ventilation system of the building, which incorporates radioactivity control equipment.

Special provisions

415. In the event of equipment maintenance or remedial work, it may be deemed impractical to maintain negative pressure reliably within the whole or within part of the incineration system. These events shall be taken into account in the design of the facility to permit an application of special (temporary) provisions for radioactivity containment.

Processing of alpha bearing wastes

416. Because of the concern felt about dispersion associated with the processing of waste containing alpha emitting particles, a leaktight (secondary static) barrier shall enclose the incineration system within the incinerator building. The area within this barrier shall be kept under negative pressure with respect to the non-radioactive areas of the building.

CONSTRUCTION REQUIREMENTS

417. Consideration shall be given to the selection of an appropriate method of construction consistent with the selected materials and the design of the incineration system. All construction methods and procedures used shall be documented as outlined in Section 12.

418. In order to minimize the potential for leakage from the incinerator and the off-gas system, welded construction should be used to the fullest practical extent. However, due consideration should be given to maintenance requirements. The following aspects should be considered where welding has been used in construction:

(a) Any welding of the parts constituting the pressure boundary of pressure retaining components and piping shall be performed by qualified welders.
(b) Piping carrying fluids with high concentrations of particulate matter or ion exchange resins should have welds that are smooth on the inside, to minimize radioactive buildup at the weld joints.

MATERIALS CONSIDERATIONS

419. The selection of the materials used in the incineration systems shall give due consideration to the components that are subject to substantial mechanical and thermal loads, erosion, corrosion and wear. The following aspects should be considered:

(a) Components that are subject to thermal loads shall be designed and constructed to withstand the effects of high temperatures, temperature variations, and the resulting material expansions and contractions. Materials of adequate strength and suitable properties shall be used, especially when high temperatures are expected.
(b) The effects of direct contact and/or vapour condensation corrosives shall be considered.
(c) Seal and gasket materials shall be selected for compatibility with the chemical and physical conditions that are present.
(d) Component connections and material surfaces shall be designed to facilitate decontamination.

QUALITY ASSURANCE

420. A quality assurance (QA) programme shall be established and documented for the radioactive waste incineration system to ensure that the applicable requirements are followed during the design, construction and operation stages of the facility. Further guidance may be found in Ref. [10] and the related Safety Guides.

SYSTEMS FOR ALPHA BEARING WASTE PROCESSING

421. The following essential principles shall be observed during the design of systems for processing alpha bearing wastes:

(a) Accurate accountability of the plutonium entering and leaving the facility,
(b) Assessment of the plutonium hold-up on the inside of the incineration system,

(c) Determination of the plutonium quantity in each drum by radiation counting methods,
(d) Plutonium accountability at the ash collection points.

OTHER CONSIDERATIONS

422. The design of the incineration facility should include a provision, to the extent deemed necessary by the regulatory body, to limit the effects of the significant risks identified in the system safety analysis. These risks may include both natural events (e.g. earthquakes, tornadoes, floods) and man-made events (e.g. nearby explosions, impact of aircraft).

5. CONCEPTUAL DESIGN

GENERAL REQUIREMENTS AND CONSIDERATIONS

Objectives and basic requirements

501. The objectives of incineration may be the reduction of waste volume and weight, the conversion of the initial waste form into a form having different properties and characteristics (e.g. more suitable for immobilization), the facilitation of selective radionuclide recovery, or any combination of the above. The type of the incineration system should be carefully selected to meet the operational objectives fully, as well as the safety objectives given in Section 2. Usually, several types of incinerator can offer a feasible solution in a given application. However, the designers should not base their choice of system on this single criterion, but should compare the qualities of the different systems (e.g. fundamental features, process characteristics, simplicity, safety, reliability, performance, flexibility, operating labour requirements and experience acquired in the field). The fundamental aspects of an incineration system should be as follows:

(a) Maximized combustion efficiency through the maintenance of appropriately high temperatures, adequate air (oxygen) supply and its distribution, adequate residence time of solid combustible matter and gaseous fractions in the system, and an adequately turbulent flow of gases.
(b) Cleanup of the off-gas by means of a suitable treatment system that offers the required decontamination factors.
(c) Simplicity and reliability of equipment and components, and their suitability for automation and maintenance.

(d) Operation with a negative pressure against the ambient during all operating conditions to minimize the hazard of contamination outside.
(e) Acceptance of a wide range of waste feed.[1]
(f) Instrumentation and controls that guarantee the meeting of functional and safety requirements under all normal and abnormal system conditions.

Radiological considerations

502. The low and intermediate level wastes that may be processed in an incineration facility are produced in different forms and are of different origins (e.g. from the operation, maintenance, modification and decommissioning of nuclear reactor facilities, from spent fuel reprocessing plants, from nuclear research laboratories, from hospital laboratories). Additional information on waste sources and characteristics is provided in Annex I. The radiological characteristics of the incinerator waste feed may vary considerably, and the wastes may be divided into three main categories:

(a) beta-gamma waste with no or an insignificant level of alpha emitters,
(b) waste with alpha emitters,
(c) mixed wastes (radioactive and chemically hazardous).

503. The radiological hazard of the waste feed category under consideration shall be considered in the design from the viewpoint of protection of personnel, the public and the environment. If the radiation levels exceed the design values at any stage of waste handling and processing, suitable precautions shall be taken. The presence of long lived alpha emitters shall entail stringent safety procedures. The release of alpha emitting radionuclides to the environment shall be prevented by transporting the waste in leaktight containers (prior to incineration), by providing adequate off-gas cleaning, and by providing suitable ash conditioning. When processing other hazardous wastes (e.g. mixed wastes), the appropriate design and operational safety requirements of the competent authority shall be met.

FUNCTIONAL REQUIREMENTS

504. It is necessary to ensure in the conceptual design that the basic functional requirements of the incineration facility will be met. These requirements may typically include the following:

(a) Maintaining a positive flow of off-gas through the incineration system and its individual treatment components, taking into account the variable pressure losses in these components;

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[1] This recommendation does not apply when the incineration system is designed for the processing of a specific waste feed (e.g. ion exchange resin, rubber, halogenated plastics).

(b) Maintaining adequate and suitable process temperatures in the combustion chambers and in the key components of the off-gas treatment system;
(c) Maintaining the appropriate amount of air (oxygen), adequate residence time and gas turbulence in the combustion chambers during all the operating conditions that can be planned for;
(d) Maintaining accountability of waste feed weight and approximate heat value in order to operate within the thermal capacity of the incinerator;
(e) Preventing the entry into the incinerator of waste feed that does not meet the specified make-up;
(f) Maintaining the incineration system at a certain negative pressure with respect to the building (including shutdown mode).

WASTE FEED

Waste feed categories

505. During the conceptual design it is necessary to establish what constitutes waste feed. The waste feed characteristics and the relative volumes of the different waste categories to be incinerated will probably affect the selection of the combustion technique and also the basic concept of the off-gas treatment system. The distinct categories of wastes that may affect the design or selection of the incineration system are as follows:

— ion exchange resins,
— organic liquid wastes,
— filter sludges,
— inorganic (aqueous) liquid wastes,
— alpha bearing wastes,
— wastes containing a significant amount of non-combustible materials,
— wastes containing a significant amount of plastics,
— tritiated wastes,
— biological wastes,
— activated charcoal,
— graphite,
— waste with a high level of gamma radiation,
— waste containing corrosive material.

Waste pretreatment

506. The amount and type of pretreatment, if any, shall be established in the conceptual design of the incineration system. The waste preparation or pretreatment

may consist of: inspection; segregation of waste types or items that are considered incompatible with the given system; sorting and packaging of combustible wastes into the desired form, mass or volume, and geometrical size for feeding into the combustion chamber; shredding of dry waste feed; and others. Any or none of these pretreatment procedures may be required depending on the waste category, waste feed mechanism, combustion technique, off-gas treatment and ash removal method.

Undesirable waste materials

507. Depending on the particular design of the overall incineration system (including the off-gas treatment system), some of the items or batches of waste having any of the following characteristics may have to be excluded from or minimized in the waste feed:

- metal and glass contents,
- high radioactivity content,
- excessive heat value,
- insufficient heat value,
- undesirable chemical characteristics (e.g. high sulphur content, high halogen content),
- high content of non-combustible materials,
- large physical dimensions.

Halogenated and sulphur compounds

508. It is necessary to establish early in the conceptual design whether acid gas forming materials (e.g. halogenated or sulphur compounds) should be included or eliminated from the waste feed. If included, the system must be capable of processing these materials and the resulting combustion products.

Waste sorting

509. Waste sorting should be done to the extent possible at the place of waste generation. If this is not possible the incineration facility shall have a sorting area where material not suitable for incineration can be removed. Depending on the radioactivity level of the wastes and the potential for airborne contamination, the wastes may or may not be sorted by hand. Alpha bearing wastes shall be sorted in a sealed glove box.

Exclusions

510. Excluded from incineration are those materials that pose an explosion hazard, typically such items as aerosol spray cans, propane torch canisters and oxygen containers. Explosives shall be excluded by means of administrative controls and waste segregation. Pyrophoric materials shall be restricted in all cases to avoid damage to the system.

DESIRED ASH CHARACTERISTICS

511. The ash product formed by the combustion of dry active waste contains radionuclides in a mixture of alumina, silica, unburned carbon and various metal oxides. The physical form of generated ash ranges from a free flowing homogeneous powder to a mixture of powder, small metallic items, and char or slag. Ideally, the ash should be homogeneous, with a low carbon content, chemically and biologically inert, and free of organic materials. When the ash is to be subsequently immobilized, it shall be compatible with the immobilization agent and process. Additional specific ash characteristics may be required when the objective of incineration is the recovery of radionuclides such as uranium or plutonium.

WASTE VOLUME REDUCTION EFFECTIVENESS

512. Incineration can result in a substantial volume reduction of incinerable wastes when the volume of primary waste feed is compared with the sum of the resultant volume of the ash and the other secondary wastes. The overall volume reduction factor achieved may range from (approximately) 10 to 100 depending on the density, composition and homogeneity of the waste feed, method of combustion, method of off-gas cleanup, method of ash conditioning, and method of the secondary waste treatment. The volume reduction factor will increase when non-incinerable and other (incompatible) materials have been segregated from the waste feed. On the other hand, the volume reduction factor may be reduced considerably when acid forming materials are present in substantial quantities in the waste feed, owing to the generation of additional secondary wastes from the use of neutralization chemicals.

OPERATIONAL REQUIREMENTS

513. A list of operational requirements shall be prepared before or during the conceptual design phase. The requirements should be considered in the design of

the facility to the extent practical. The following are a few examples of possible operational requirements:

- local and remote controls for important components,
- visual contact between control room and main working area(s),
- access to rooms and work levels without unnecessary detours.

ARRANGEMENT AND LOCATION

514. The incineration system shall be located, arranged and shielded in such a manner as to minimize the radiation exposure to site personnel during the system operation and maintenance. Further information about the building layout and equipment arrangement can be found in Section 9.

515. The selection of a site for an incineration facility should take into account the method of waste transport, the distance from the waste source to the incinerator site, and the distance from the incinerator site to the disposal site. All environmental aspects shall be taken into consideration.

SYSTEM CAPACITY

516. The determination of the required capacity of the incineration system shall take into consideration the annual waste quantities in the individual categories, the maximum waste generation rates (e.g. in kilograms per day), the waste categories and their characteristics, the required reliability and availability factors, and the required annual operating time. The calculation of the volumetric rates of waste to be fed into the incinerator shall be based on the average heating values of the individual waste categories and their bulk densities. The design volumetric rate and the waste heat value will dictate the required thermal capacity of the incineration system.

INTERFACE WITH IN-PLANT SYSTEMS

517. The incineration facility may be designed as a self-supporting facility that may be attached to a waste storage or disposal site, or may form a part of a nuclear generation plant, research institute or other nuclear facility. While all or most of the necessary services and subsystems may need to be specially provided for the former, the latter may benefit from the availability of similar in-station systems (e.g. liquid radioactive waste treatment, waste immobilization, environmental monitoring, demineralized water, instrument air, the backup electrical supply and controlled building ventilation including absolute filtration).

ECONOMIC CONSIDERATIONS

518. Before deciding whether the waste should be processed by incineration, consideration shall be given to the following factors:

(a) The difference in the overall costs of conditioning, transport, storage and disposal of the wastes with and without incineration;
(b) The benefit of having a substantially lower volume (e.g. 2 to 5% of initial volume) of ash rather than untreated waste (or waste treated by another method) to store and dispose of;
(c) The benefit of having stable ash rather than untreated burnable waste to store and dispose of;
(d) The difference in costs in terms of radiation doses to the workers and to the general public arising from the conditioning, transport, storage, and disposal of the wastes with and without incineration.

519. In the conceptual design of an incineration facility, care must be taken in the selection of both the combustion technique and the design of the off-gas cleanup system. Since there are 'high technology' as well as 'economy' systems available that differ significantly in cost, a comprehensive survey of the available incineration systems should be carried out in the conceptual design phase. However, the safety of the system shall not be compromised because of costs. The cost savings resulting from a simpler design should be compared with the economic penalty caused by the potential loss in overall volume reduction efficiency, by the reduced system availability, and by the higher operating/maintenance cost.

SYSTEM DESIGN

520. The development of an incineration system process flow diagram is one of the most important aspects of the conceptual design. This activity includes the determination of individual process steps and subsystems, and their relative sequence. A generic block diagram of a radioactive waste incineration system is shown in Fig. 1.

System integration

521. An overall incineration system consists of a number of subsystems, such as waste feed, combustion chamber, off-gas treatment, and ash handling systems. Each of these subsystems consists of several components or process steps. In the overall system design, as represented by the process flow diagram, the suitability of each subsystem and its components needs to be carefully established from the viewpoint of mutual compatibility, equipment layout and system controls. Often, the interfacing requirements will dictate the final selection of components. Further direction on subsystem and component selection can be found in Sections 6 and 7.

Approvals

522. The design of systems and components important to safety shall be prepared, reviewed and documented in accordance with the applicable design codes and QA requirements and shall be submitted to the regulatory body for approval before construction begins. Modifications of the above systems and components shall follow a similar procedure.

Process flow modifications

523. The process flow diagram shall be revised to reflect the revised configuration of the installed equipment following any modification of the system.

COMBUSTION TECHNIQUE

524. The combustion technique should be selected according to the waste feed characteristics, with the objective of achieving complete combustion and of meeting the primary goal of selecting incineration as a treatment method. An off-gas treatment system can subsequently be chosen on the basis of the particular combustion technique selected and the specific environmental and occupational requirements.

Design considerations

525. The aspect of complete combustion of the waste feed must be addressed in the design considerations; complete combustion can be enhanced by a properly designed combustion chamber. Considerations must include proper waste preparation and feed, the proper mixture of waste with air, adequate residence time in the combustion chamber, sufficiently high temperatures above the ignition temperatures, sufficiently long retention time, and an adequate degree of turbulence in the gaseous fraction. Methods that can be utilized to enhance combustion further include feed homogenization and the use of a two step combustion technique.

Incineration techniques

526. The basic requirement for complete combustion of the waste is that the waste and the air meet in the correct proportions and under such conditions that prompt ignition and combustion or controlled pyrolysis occur. This basic requirement can be relatively easily met with liquid and pulverized homogeneous solid waste feeds. The requirement is more difficult to meet with bulky non-homogeneous materials such as dry active waste, owing to the variability in the physical and chemical properties of the waste materials. Because of this difficulty a number of different types of incinerators have been developed. Examples of basic incineration techniques are included in Annex II of this guide and also in Ref. [9].

OFF-GAS TREATMENT

527. Thermal decomposition of wastes during the combustion process generates gaseous effluents that contain the following:

— carbon dioxide
— nitrous oxides
— nitrogen
— oxygen
— carbon monoxide
— steam
— halogenated compounds
— sulphurous compounds
— hydrocarbons
— organic or mineral particles.

Radioactivity may be present in the off-gas in the form of solid aerosols (dusts bearing radioactive emitters such as ^{60}Co), in chemical gases (e.g. CO_2 containing ^{14}C) and in liquid aerosols (such as H_2O condensed in cold sections of the system containing ^{3}H).

528. The primary objective of off-gas treatment is to ensure that radiological and chemical releases to the environment are minimal and in compliance with the regulatory standards for the specific pollutants. Analysis of waste feed characteristics and the combustion conditions should determine the expected presence of objectionable materials in the off-gas, and therefore the type of treatment necessary. The off-gas treatment systems may consist of 'dry' (non-aqueous) or 'wet' (aqueous) components or process steps. Further information on the treatment concepts may be found in Annex III of this guide and in Ref. [9].

6. SUBSYSTEM REQUIREMENTS

WASTE FEED INSPECTION AND PRETREATMENT

Waste inspection

601. Dry solid wastes may typically be received in metal drums, wood or cardboard boxes, or plastic bags, depending on the source and characteristics of the waste. The following factors should be taken into consideration:

(a) Provisions shall be available for monitoring the radioactivity of the waste prior to its pretreatment or incineration.

(b) When processing unsorted dry solid wastes inspection systems may include visual X ray equipment or an equivalent for scanning the waste packages.
(c) Non-conforming packages shall be identified for more detailed inspection.
(d) In some instances waste may have to be assayed for radionuclide content.

Waste pretreatment

602. When pretreatment of dry active waste is required, the following factors should be taken into consideration:

(a) Drum or container emptying may be carried out either by hand or by a remotely controlled system, depending on the characteristics and packaging of the waste feed. Empty containers should be monitored for radioactivity before returning to the source. If the containers themselves are combustible, the whole package could be loaded into the pretreatment subsystem.
(b) Shredding (or size reduction) may typically be carried out in shredders furnished with twin rotor shears fitted with knives. Motion of the rotors should reverse automatically in the event of waste jamming in the shredder. Depending on the type of incinerator it may be necessary to have provisions in place for screening the shredded waste to ensure that only the required size of particle enters the incinerator.
(c) Removal of metal and glass objects prior to the entry of the waste into the shredder may be necessary unless the incinerator and/or the shredder are designed to process these objects.
(d) Light precompaction of voluminous waste for batch feeding may be helpful with some incineration systems, but undesirable with others.

Alpha bearing wastes

603. If the incinerator is to be used for processing alpha bearing wastes, an inhalation/ingestion hazard may exist during waste inspection and pretreatment. In this application all subsystems shall be designed with sufficient barriers to protect the operators from radiological contamination.

Other requirements

604. Other requirements may include:

(a) Containment of radioactivity during inspection and pretreatment, which may be achieved by the use of glove boxes, enclosures and other provisions.
(b) Effective provisions to prevent fires and explosions, for example keeping essential equipment such as the shredder and/or the feed system under an inert atmosphere.

WASTE FEEDING

Solid waste

605. The factors to be considered here are:

(a) Waste may be charged into the incinerator in batches by means of an enclosure that is under negative pressure with respect to the building, and/or by means of physical containment, which prevents the spread of contamination. For further information and guidance see paras 709 and 711.

(b) Feeding of shredded waste may be carried out in a continuous manner by means of a suitable system such as an Archimedean screw, or a pneumatic transfer system. For further information and guidance see para. 710.

Liquid waste

606. The factors to be considered here are:

(a) Special precautions may be required for incineration systems designed for burning organic liquid wastes. Depending on the degree of volatility of the liquids it may be appropriate to keep the liquid waste under an inert atmosphere. Provisions should be included for the containment of spills. The electric supply within the liquid waste area shall be explosion-proof. The design of systems for liquid waste storage should take the ambient temperature conditions into consideration.

(b) Use of emulsifying and suspension agents may be necessary to avoid phase separation or precipitation of solids within the feed system.

(c) Consideration should be given to pretreatment sampling and mixing of the liquids prior to incineration. The following chemical and physical parameters should be determined prior to incineration:

— net heat values
— water content
— viscosity
— density
— flash point
— halogen and sulphur content
— solids content.

(d) High efficiency burners should be used to achieve adequate combustion of the liquids. Special burners for underfiring may be considered when burning liquid wastes with low heat values.

ASH REMOVAL

607. The following factors should be taken into account:

(a) Ash removal should preferably be done by gravity, either by batch or continuously. Care must be taken to prevent blockages arising from slag formation or the hygroscopic properties of the ash.

(b) Since incineration results in the concentration of radioactivity in the ash product, the ash shall be retained inside a pressure retaining enclosure (during its cooling and removal from the combustion chamber) to prevent dispersion into the air.

(c) If separate ash containers are used, they should either be fastened to the incinerator with airtight seals or located inside a pressure retaining enclosure. Depending on the level of radioactivity the enclosure should have remote manual capabilities, shielding, double lid closure systems and other containment provisions as appropriate.

(d) A glove box may be provided to facilitate ash removal after the ash has cooled.

(e) Negative pressure with respect to the ambient pressure should be maintained reliably in the ash container or the enclosure during ash removal and cooldown.

ASH TRANSFER AND IMMOBILIZATION

608. The following factors should be taken into account:

(a) If transfer of incinerator ash is necessary as a part of the process or for immobilization purposes the design shall ensure that the ash product is maintained inside sealed metal components at all times.

(b) When a mechanical or a pneumatic type of transport system is used, it shall be designed to prevent any air leakage or a spread of loose contamination. High quality components should be used to minimize maintenance requirements.

(c) Comminution (or breaking up) of agglomerated ash may be required prior to transfer or to additional processing steps.

(d) Incinerator ash may require additional conditioning (e.g. immobilization or encapsulation) depending on its specific radioactivity and applicable national transportation and disposal regulations. The ash immobilization requirements involve interfacing the incinerator with a waste immobilization subsystem.

(e) Ash sampling capabilities should be incorporated into the incinerator system design.

(f) Special precautions shall be taken when ash is immobilized with cement, owing to the potential generation of combustible gases.

FLY ASH REMOVAL

609. Fly ash may be entrained throughout the incineration system (e.g. in expansion chambers, cyclones or filters). Removal methods for trapped fly ash may differ depending on the cleaning method used with each individual device.

Dry method

610. Collection and storage hoppers should be provided at the bottom of each affected device for removal of batches of the fly ash. The hoppers may be equipped with: sliding doors, mechanical trap doors, rotary partitioned devices, Archimedean screws, conveyor vibrators, belt conveyors and other devices.

Wet method

611. A wet method may be used especially when secondary liquid waste treatment facilities are available. Drains should be provided for washing solutions at the bottom of the equipment involved. These drains should be connected to the radioactive liquid waste collection system, or to its equivalent.

SPENT FILTER REMOVAL

Filter replacement

612. Filters that have lost their efficiency, or have been completely or partially destroyed or clogged, shall be replaced without delay. Control of contamination during filter replacement may require that a temporary leaktight enclosure or tent be constructed. Depending on the contamination level, the enclosure may require negative pressure with respect to the ambient pressure. Suitable provisions for replacing the filters shall be incorporated in the system design. Further guidance on filters may be found in para. 731.

High radioactivity filters

613. Filters that have a high radiation level shall be dismounted, removed remotely and placed into a mobile shielded cask. Care should be taken to avoid radiation exposure to personnel; this should be taken into account in the design of the facility. Sufficient access and space allowance for filter servicing are required.

Low radioactivity filters

614. Provisions should be included in the design for the replacement of low radioactivity filters without spread of contamination.

Filter disposal

615. Discharged used filters should be packaged for storage and disposal, with or without volume reduction. Some of the filters, or their parts, may also be incinerated. Some filtering media, such as those removed from regenerable filters, may require coating or immobilization prior to off-site transportation or disposal as required by the competent authority.

SCRUB SOLUTION TREATMENT

616. Scrub solutions used for off-gas cooling or cleanup, together with all condensates and purge streams, should be collected, treated and returned to the scrubbing process. There shall be no direct pathway for active liquids to the environment. The scrub solution system blowdown should be treated by a radioactive liquid waste treatment system. In some instances the blowdown may be processed (e.g. dried) in the incineration system.

617. The scrub solution treatment system may consist of: a neutralizing solution tank, a metering pump, a scrub solution recirculation pump, a scrub solution filter, a cooler, a sump, etc. The liquor in the scrub solution treatment system should be monitored periodically for liquid level, density, pH value, radioactivity and suspended solids. To maintain the content of dissolved salts safely below the saturation point, blowdown of the scrub solution shall be carried out periodically or continuously, depending upon the design of the system. It should be ensured that the scrub solution does not crystallize in the piping and in the discharge line owing to the high concentration of dissolved solids or suspended matter.

7. COMPONENT REQUIREMENTS

GENERAL REQUIREMENTS

701. It is recognized that there may be more than one design or concept of an individual component that would meet the performance objectives of this Safety Guide. This section contains recommendations for typical components and also

addresses the potential alternatives where appropriate. Selection of the material for the construction of a component is very important and shall be considered such that the component can operate safely and reliably within the process parameters. Every effort should be made to keep the components as simple as possible, preferably using established and proven technologies, to ensure a high degree of reliability and maintainability.

REDUNDANT AND BACKUP COMPONENTS

702. Redundant or backup components shall be provided for those parts of the system that are necessary for safe system shutdown and for returning the system to a stable condition from all the hypothetical situations considered in the safety analysis. Examples of components that should be redundant or have backups are exhaust fans, high efficiency particulate air (HEPA) filters, and thermocouples in the combustion chamber.

703. Redundant components or systems shall be tested during startup, and put into operation periodically for test purposes. However, redundant components should not be used alternately, in order to prevent both from wearing out at the same time. The quality of redundant systems shall be equivalent.

704. There are other parts of the system where component redundancy is not required for safe shutdown of the system, but rather for sustaining the incineration process. In particular, these are the system components that directly affect the flow of process streams. Redundant or backup components may be considered for these parts. If redundant or backup components are not provided the failure of a component in these parts shall automatically switch the system to a stand-by mode.

WASTE TRANSPORT CONTAINERS

705. Waste transport shall comply with the national regulations for the transport of radioactive material. Such national regulations are often based on Ref. [11]. Further information can be found in Ref. [2].

Packaging and containers

706. Packaging and containerization of the waste and the ash shall minimize the possibility of the spread of radioactive contamination. The shape and size of the waste and ash containers shall be defined during the design phase of the incineration system. Consideration shall be given to the suitability of the ash container for on-site storage and direct disposal, dependent on the competent authority regulations. Off-site transportation containers shall meet all the applicable regulatory requirements.

Depending on the design of the system and the regulatory requirements, incinerable waste containers (e.g. plastic bags or cardboard boxes) may be used for waste feed packaging. A double lid system (or equivalent) shall be considered when alpha bearing waste is handled, to prevent the spread of radioactive contamination.

On-site transport systems

707. Transportation and handling of the packaged waste at the incineration facility shall be done with suitable equipment, for example cranes, fork lifts and roller conveyors. On-site transportation containers shall meet all the conditions necessary to prevent radioactive contamination of the area and the operating personnel.

WASTE FEED SYSTEMS

708. The waste feed systems shall ensure that waste is charged into the incinerator without the spread of contamination. The waste feed components should be designed so as to minimize uncontrolled ingress of air, and to limit the heat transfer from the combustion chamber to the environment. Uncontrolled leakage of incineration gases during the waste feeding shall be prevented.

Charging boxes

709. Waste charging boxes may be desirable for the gravity feed of waste into the incinerator. To prevent the spread of contamination, the charging box pressure should be negative compared with the building pressure, but positive compared with the incinerator. An airlock should be located between the charging box and the incinerator. The airlock may be equipped with a rupture disc or other pressure relief device. The waste charging box should be constructed of welded steel and equipped with fire extinguishing equipment. For more information see para. 926.

Screw feeders

710. Screw feeders may be used to feed shredded waste into the incinerator through a connecting chute or a pipe. The screw spindle may be provided with a cooling jacket to prevent ignition of waste feed prior to entering the incinerator, and to protect the material of construction. The screw spindle and the pipe should be made of steel with a high wear resistance. To minimize fire hazards during waste shredding and storage, and to prevent the spread of fire from the combustion chamber, the area near the screw feeder equipment should use an inert atmosphere.

Ram feeders

711. Ram feeders are designed to push the waste into the incinerator by using a horizontal piston shaped ram. The charging box for the ram feeder should be isolated from the incinerator by an airlock. The ram feeders may be provided with cooling jackets and use an inert atmosphere. The ram feeder should be made of steel with a high wear resistance.

Feeding of liquid wastes and sludges

712. The incinerator may be designed to process organic liquid wastes or sludges (e.g. waste oil or ion exchange resin). Organic liquid waste characteristics vary widely and each waste stream may require special pretreatment and safety precautions. Fire protection for the storage and feed system for liquids and sludges shall meet the national fire protection regulations and practices. Further information is given in para. 927.

713. Organic liquid waste is often stored in storage tanks and fed into the incinerator by a pump or by other suitable means. Storage tanks should preferably be located outside the incineration facility in order to minimize the fire hazard. The contents of the storage tanks may require heating, mixing, making inert, venting and sampling. The materials used in the construction shall take into account the potential corrosiveness of some of the waste feed materials. Incineration of liquid wastes may require the use of special burners.

COMBUSTION CHAMBERS

714. The following criteria should be considered during the design and evaluation of the combustion chambers:

— Type and nature of the incineration process,
— Chemical influences from the combustion process,
— Furnace heat load,
— Temperature fluctuations during the combustion process,
— Mechanical influences during waste loading and ash removal,
— Waste feed rates,
— Gas velocities and turbulence,
— Residence time for solid and gaseous fractions,
— Waste feed form,
— Method of ash removal,
— Supply and distribution of combustion air,

— Withdrawal of the off-gas,
— Geometry of the combustion chamber interior.

715. The combustion chamber shall be designed to be operable at maximum temperature and pressure conditions during normal operation as well as during anticipated operational occurrences. The effect of thermal cycling shall be taken into consideration.

716. The steel shell of the combustion chamber shall be designed for sufficient strength and rigidity at the temperatures expected. It may be required to design the chamber for overpressures as well as for static or dynamic loads.

717. In the design of the refractory lining, the following factors shall be considered:

— Temperature limitation of the steel shell,
— Refractory thickness (e.g. several layers may be appropriate for wear),
— Refractory smoothness to mitigate contamination buildup (e.g. ash, tar),
— Compatibility of the refractory with the expected waste feed materials,
— Design life of the refractory (e.g. longer refractory life may minimize the maintenance needs).

718. To protect the shell against the effect of condensed acid vapours, the internal surfaces of the steel shell may be provided with an anticorrosion coating. When no refractory lining is used the surfaces shall be corrosion and wear resistant.

719. The internal structure and refractory lining of the combustion chamber are subject to wear and corrosion, which limits their service life. Consequently, appropriate apertures for repair or replacement of the contaminated refractories shall be provided.

720. Burners shall be provided for startup as well as for combustion of waste materials having low heating values.

721. The combustion chamber should be provided with sight glasses, connections for pressure and temperature measurements, and other instruments as appropriate.

AFTERBURNER CHAMBERS

722. Afterburner chambers are intended to ensure complete burnout of the off-gas. The design of an afterburner chamber shall ensure sufficient temperature, turbulence, residence time and excess of oxygen to accomplish complete off-gas burning.

Proper introduction of the off-gas into the afterburner shall ensure good mixing with the secondary air. In order to obtain sufficiently high temperatures the afterburner chamber should be provided with an auxiliary burner.

723. Afterburner chambers should be of welded steel construction with an internal refractory lining, or constructed of steel that can withstand the conditions of operating temperatures and the corrosiveness of the off-gas.

724. Afterburner chambers should be equipped with sight glasses, inspection hatches, connections for measurement devices and a fly ash discharge.

BURNERS

725. Burners are intended either for warming up the system and waste ignition in the startup phase, or for auxiliary firing during operation to maintain the desired operating temperatures. The burners and their control system shall meet the applicable regulations of the competent authority. Special burners for contaminated oils, solvents or aqueous mixtures may also be required.

726. The burners should meet the following requirements:

(a) One or more burners shall be installed in each combustion chamber (e.g. primary chamber or afterburner). The burners shall be designed for the appropriate temperatures at their locations.
(b) Burners may be installed in a high temperature filter, to promote burnout of trapped unburnt particulate matter on the surface of the filter elements.
(c) Burners should be designed with airflow for cooling and to minimize any plugging and fouling by fly ash.
(d) Burners shall use preliminary air scavenging for a predetermined period of time prior to burner ignition.
(e) Burners shall be controlled by automatic control units, and shall include a flame detector in accordance with the regulations set by the competent authorities.
(f) Burners should be designed for servicing and maintenance from outside the incinerator.
(g) Burners may be designed for gas or oil firing, or other fuel as appropriate for each incinerator design.

HEAT EXCHANGERS

727. Heat exchangers may be installed to cool the off-gas to temperatures suitable for off-gas cleaning. The heat exchangers may be of the radiative or convective type.

The design of the heat exchangers shall take into account easy cleaning of their heat transfer surfaces. Provisions should be made for the removal of ash or deposits. The materials used in the construction shall be compatible with the process fluid used for cooling, and with the off-gas stream, taking into account the off-gas composition at operating temperatures.

AIR INJECTORS

728. The off-gas may be mixed with fresh dilution air in air injectors or static mixers in order to reduce its temperature. Air injectors should preferably be of a cylindrical design and provided with baffles to intensify the mixing of the streams. Depending on the design temperature, the air injectors should be of welded steel construction, either refractory lined or of steel that is resistant to high temperatures. The dilution air may be filtered to prevent an extra load on the off-gas HEPA filters.

EVAPORATIVE COOLERS

729. The off-gas may be cooled by the evaporation of water. Evaporative coolers are generally of a vertical cylindrical design. The material of construction should be a high quality corrosion and temperature resistant alloy or steel with a refractory lining. The water or scrub solution should be injected by one or more spray nozzles. In the absence of a refractory lining the tube walls may be protected by a water film. The cooler should be equipped with a coolant supply and drainage system. Owing to the increased water vapour content, the off-gas should be kept at temperatures higher than the dewpoint to prevent vapour condensation.

CYCLONE SEPARATORS

730. Concentration of fly ash in the off-gas may be reduced by cyclone separators. The cyclone separators may also be used as spark arrestors. Depending on the design temperature, the cyclone separators may be made of carbon steel, a steel that is resistant to high temperatures, or be provided with a refractory lining.

FILTERS

731. Filters may be used for the removal of fly ash from the off-gas. Filters shall have instrumentation for measuring the differential pressure across the filter media to determine the actual operating status of the filter. A rise in the differential pressure

across the filter media may indicate that the filter is plugged or that it requires cleaning. If the filter cannot be cleaned it shall be replaced. A drop in the differential pressure may be an indication that the filter is damaged or broken, and due for replacement. The spent filters and collected particulate matter (fly ash) shall be treated as secondary waste.

High temperature (hot gas) filters

732. High temperature (hot gas) filters allow the filtration of the off-gas at temperatures of up to approximately 900°C. The off-gas is filtered through temperature resistant filter elements arranged as tubular candles, or mats, for example. The filter elements should be tightly held in a filter suspension plate. Filter elements may also be precoated by suitable filter media. High temperature filters operate continuously. The filter elements may be backflushed periodically by pressurized air or air pulses, during either operation or shutdown.

733. The following factors should be taken into consideration:

(a) The filter shall be provided with ash discharge equipment, such as an attached hopper with a double door airlock. The temperature of the fly ash shall be taken into consideration in the design of the ash discharge equipment. The ash discharge equipment may either be cooled, or the ash may be discharged only when the high temperature filter has cooled down.

(b) The parts of the high temperature filter that are in contact with the hot gases should be made of steel coated with a refractory lining or of a steel that is resistant to high temperatures.

(c) The filter elements may be made of ceramic materials, sintered steel, or micro-expanded metal with a precoated filtration material, as specified by the manufacturer.

(d) High temperature filtration may be achieved in a single filter. However, primary and secondary filtration may be desired with two filters working in series.

(e) High temperature filters may be equipped with burner(s), inspection hatches and sight glass(es).

Baghouse filters

734. Baghouse filters are intended to separate and retain the fly ash particles contained in the off-gas at relatively low temperatures. The off-gas expands in a filter chamber and passes through the fabric filter bags. The fly ash is collected on the surface of the filter bags. To prevent failures of the filter material, the temperatures and the gas flows should be limited to the values specified by the filter manufacturer.

735. The following factors should be taken into consideration:

(a) Cleaning of the filter bags may be achieved by mechanical shaking or preferably by blowing a pulse of compressed air through a nozzle into the clean side of the filter bag; this separates the filter cake, which falls into a collection chamber. The filter bags should be cleaned in sections. The pulse jet type of baghouse permits an on-line filter bag cleaning operation of the incineration system.
(b) The baghouse filter housing should be of welded steel construction, and withstand the design pressure. The housing should be equipped with inspection hatches or ports.
(c) The filter bags may be made of natural or synthetic fibre, depending on the design temperature.
(d) The bag filter should operate at temperatures above 120°C or at least 20°C above the dewpoint, whichever is greater, in order to avoid moisture condensation.
(e) If it is planned to incinerate spent filters, the selection of filter material should take into consideration the off-gas generated from the material itself.
(f) The baghouse shall be equipped with a fire detection and suppression system.

HEPA filters

736. An HEPA filter consists of a filter frame with a fibre filter mat. In the off-gas cleanup system, the HEPA filters are usually arranged so that they form the last filtration step, to retain the very fine particulate matter. To prevent fast clogging of the HEPA filter it may be preceded by a prefilter.

737. The following factors are important:

(a) The filter frame shall provide a seal against the filter casing. It shall be possible to check for leakage with leakage test equipment.
(b) Two absolute filters may be installed in series to increase the reliability and safety of the system. To provide an element of redundancy two filter banks may be arranged in parallel. In the case of two parallel 100% capacity filter banks the spent filters in one bank may be replaced during operation.
(c) The end of the working life of an HEPA filter is characterized by the maximum allowable differential pressure across the filter at a constant gas flow rate. When this differential pressure is reached the HEPA filter shall be changed.
(d) A predetermined maximum allowable surface dose rate measured on the filter casing may be considered as another criterion for changing the filters.
(e) There is usually a high percentage of water vapour in the off-gas that is released from the incineration process, and this may increase substantially if wet scrubbing is used. The HEPA filter should operate at temperatures above

120°C or at least 20°C above the dewpoint, whichever is greater, in order to avoid moisture condensation within the filter. An auxiliary heater may be used to increase the off-gas temperature; however, the maximum allowable filter temperature specified by the manufacturer for permanent operation must be taken into consideration if an auxiliary heater is used.

CHARCOAL ADSORBERS

738. Charcoal adsorption may be used to remove volatile or semivolatile radioactive products from the off-gas. The adsorption material is usually a specially coated activated carbon.

739. The following factors need to be taken into consideration:

(a) If activated carbon is used as a layer it shall be arranged between two HEPA filters to protect the carbon from being loaded by particulate matter, and to prevent the carry-over of activated carbon loaded with radionuclides.
(b) Adsorption should be carried out at temperatures as low as possible, but above the dewpoint, to prevent adsorption of water from the off-gas.
(c) Replacement activated carbon filters shall be tested after installation and then at regular intervals. During operation, their effectiveness may be measured by monitoring the off-gas radioactivity before and after the filter.

SCRUBBERS

740. The type of scrubber selected depends on the application.

(a) Wet scrubbers may be used for the removal of acidic gases such as HCl, HF, SO_2, etc., from the off-gas. Particles are also removed by wet scrubbers. There are a variety of possible scrubber types, including venturi, rotary and jet types. To obtain the appropriate off-gas inlet temperature, wet scrubbers are usually preceded by quenchers.
(b) Dry scrubbers that are used for acid gas removal in non-active incinerators may also be used for radioactive service. However, there is less operating experience in radioactive service with dry scrubbers than with wet scrubbers.
(c) When selecting the scrubber type, careful consideration shall be given to its location in the off-gas cleanup system. For example, if the scrubber system is located downstream of HEPA filters, the scrubber solution blowdown may have negligible radioactivity levels that are below regulatory concern, such that it may be disposed of as non-radioactive.

OFF-GAS FANS

741. Induced draught fans shall be used to maintain a negative pressure in the total system. Radial fans are the preferred type of off-gas fan. Control of the off-gas fans may be ensured by throttle dampers or by frequency control of the electric motor. The casing and frame of the off-gas fans shall be made of steel or special alloys if necessary. The fan casing should be provided with a condensate drain at its lowest point. Vibration monitors should be provided on the induced draught fans.

742. Since the off-gas fans are of major importance to the safety of the system redundant fans should be provided. As an alternative to a fully redundant design, the use of two 50% capacity fans or a smaller 'backup' fan, which is sufficient to ensure a safe plant shutdown and to maintain negative pressure in the system, may be considered.

STACKS

743. A stack shall be used to provide an elevated release of the off-gas with a sufficient velocity (e.g. $v > 12$ m/s) for dispersing the off-gas. If a plant ventilation stack is available the off-gas discharge piping may be connected to the plant stack to provide a common release and monitoring point. The applicable air pollution control laws and regulations shall be observed for the stack design.

744. The design of the stack shall consider the possibility that moisture containing acidic constituents may condense in the stack. Corrosion resistant stainless steel or carbon steel with an internal lining should be considered for stack construction. Insulation may be required to prevent condensation. Stacks made of reinforced concrete should be provided with an inner coating of acid-proof paint or another suitable liner. Condensate that may collect at the foot of the stack shall be drained into a collection tank since it may contain radioactive material. Stacks may be equipped with manholes, gas sampling probes, ladders and platforms.

8. CONTROLS AND INSTRUMENTATION

SYSTEM CONTROL AND MONITORING

801. The controls and instrumentation discussed in this section include sensors, control switches and position indicators for components and valves, as well as other

process instrumentation and automatic control equipment necessary to ensure safe and reliable operation. Building radiation monitoring is addressed in para. 930.

802. The following factors should be taken into consideration:

(a) The instrumentation shall provide for reading or recording of parameters necessary for safe monitoring and control of the total system and its equipment.
(b) Critical parameters shall automatically signal the need for operator or automatically initiated corrective action.
(c) Malfunctions or off-limit parameter levels that constitute short term health and safety hazards or threaten the integrity of equipment shall indicate the need for or automatically initiate system shutdown. The causes for the shutdown should be annunciated and the control system should require that the deficiency is corrected before incineration is restarted.
(d) The measuring range of the instrumentation should cover the system variables under normal conditions and anticipated abnormal conditions.

Safety systems

803. In general, the controls and instrumentation of the waste management systems are not required to be redundant. However, if the controls and instrumentation are for systems important to safety, redundancy should be provided. If the control function that would initiate a shutdown is not redundant, it shall be designed for an automatic fail-safe followed by a shutdown.

Process control and instrumentation

804. The system consists of the following components:

(a) *Instrumentation.* The incineration system shall have sufficient instrumentation and adequate alarms to ensure safe operation. The list of parameters to be monitored may vary, depending on the type of the incineration system and the requirements of the competent authority. The following parameters are considered essential to safe operation of the system and therefore shall be measured:
— temperature in the combustion chamber;
— pressure in the combustion chamber;
— CO and O_2 concentrations at the outlet from the combustion chamber;
— differential pressure across the filter.
In addition, the following typical parameters may be desirable or necessary to measure depending on the system design:
— temperatures at different points within the off-gas treatment system;
— flows of combustion air, off-gas and cooling air;
— levels in scrub solution tanks and caustic tanks;

— flow rates of liquid feed to the incinerator;
— gas or liquid flows to burners;
— mechanical positions of valves, slide gates and other important mechanical devices;
— pH of scrub solution;
— hydrocarbons at the off-gas outlet from the combustion chamber;
— off-gas particulate matter concentration;
— HEPA filter inlet temperature.

(b) *Remote controls.* In order to minimize personnel exposure and to allow a better display of the system's operating status, remote control switches should be provided for frequently actuated valves and components.

(c) *Interlocks.* To ensure proper system operation and component protection, and to minimize operator errors, the control system shall be provided with interlocks that prevent the possibility of undesirable and/or unsafe operating conditions.

(d) *Manual overrides.* A manual override capability of the automatic controls for individual equipment and components should be provided to maintain system operability during an abnormal occurrence. However, it shall not be possible to override automatic shutdown actions.

(e) *Control rooms and panels.* Controls and instrumentation should be provided to allow operation of the incinerator system from the radioactive waste management or incinerator control room. Local control panels should be provided where necessary for specific process requirements (e.g. for the incinerator charging box, and for ash discharge airlocks and burners). Control room ventilation requirements are discussed in para. 913.

(f) *Communications.* Communications should be possible between operating locations and the incinerator control room.

RADIOACTIVE EFFLUENT MONITORING

Gaseous effluents

805. The requirements for gaseous effluents are as follows:

(a) Suitable instrumentation and sampling shall be provided to monitor (and record) the radioactive gases and particulates that may be released from the incineration facility, to confirm compliance with the regulatory requirements and authorized limits.

(b) Instruments having instant readout shall initiate alarms when releases exceed predetermined values.

(c) Effluent monitoring readout and alarm displays shall be located in the incinerator control room.

(d) Discharges shall be monitored to provide instant or composite values as appropriate, and recorded in such a manner as to enable the actual radioactive releases to be assessed. In order to facilitate this monitoring and recording, the gaseous effluent discharge points should be as limited in number as practical.
(e) Consideration should be given to the requirements pertaining to isokinetic flow conditions, types of materials and equipment to be used, positions of sampling probes in the stack, and instrument calibration.

Liquid effluent monitoring

806. The requirements for liquid effluent monitoring are as follows:

(a) Liquid wastes should be monitored and processed within the radioactive liquid waste treatment system of the nuclear facility. If the incineration facility is not a part of a nuclear facility that has a treatment capability, the incineration facility shall have provisions for the sampling and analysis of liquid wastes prior to their storage, treatment or discharge.
(b) A positive action by the operator shall be required to initiate any discharge of liquid effluents (after monitoring) to the environment.

9. BUILDING AND PHYSICAL ARRANGEMENT

GENERAL REQUIREMENTS

901. In accordance with the objectives discussed in Section 2, equipment and components within the low and intermediate level radioactive waste incineration facilities shall be located, arranged and shielded to minimize radiation exposure to site personnel during system operation and maintenance. The system design and arrangement shall limit the need for personnel to enter radiation areas to perform maintenance, inspection and testing. It should also facilitate the installation and replacement of major process components. The operating organization may establish radiation and contamination reference levels for various areas within the plant to ensure that ALARA objectives are met. Further information on radiation protection may be found in Ref. [12]. The facility design shall meet the regulatory requirements for non-nuclear industrial safety where applicable.

Building and general layout

902. The building structure and general system layout shall be arranged such that gross leakage from any piping, duct system, tanks or equipment will be confined to

the local area. The layout should give consideration to segregating equipment containing high radioactivity materials from other equipment.

Access

903. Piping, tubing, conduit and valve extension handles from components or equipment should not hinder the access of personnel and the ordinary movement of materials. Emergency exits shall be indicated and clearly marked.

Component, services and instrument location

904. Non-radioactive components or services such as cooling water or purge air services should be located away from process equipment containing radioactive materials or outside of the shielded areas, to minimize radiation exposure to operators or maintenance personnel.

905. Instrumentation, controls, valves and chemical addition points should be located, as much as practicable, outside the process equipment enclosures unless the anticipated radiation level within the enclosure is not significant.

Pipe runs

906. Process subsystem piping such as wet scrubber solution piping should be arranged to minimize T junctions, elbows, dead legs and the length of piping runs, thus minimizing the number of points in the piping where radioactive sediment can collect. The piping should include connections for flushing if the risk of plugging exists.

907. Attention should be paid to the following features:

(a) If the piping is insulated the outer cover of the insulation should be sealed to minimize contamination of the insulation.
(b) It is recommended that gravity and a minimum slope of piping be used as much as possible to ensure proper flow and drainage. Formation of unintended siphons should be prevented.
(c) The use of double containment, utility trenches and concentric double piping should be considered for all pipes transporting radioactively contaminated material to avoid subsoil contamination and to facilitate the detection and repair of potential leaks.

Electrical equipment

908. Electrical switchgear and controls shall be located in areas that would prevent damage resulting from component failures and shall conform to the applicable

environmental qualification requirements and industrial safety codes. Wherever possible, electrical equipment should not be located in potentially contaminated areas. Electrical penetrations through walls that contain the combustion chambers shall be evaluated to determine if they need fire barrier seals. Electrical equipment should be watertight or installed in dry areas.

Eyewash and showers

909. Appropriate safeguards shall be provided to protect operating personnel from chemical hazards in areas where hazardous chemicals are handled or stored. This will usually be in the form of emergency eyewash stations and showers.

SHIELDING

910. The following factors need to be taken into consideration:

(a) Shielding calculations shall be based upon the design basis activity levels (including contamination build-up) and the waste quantities.
(b) The shielding and the component arrangements shall be functions of the degree of access required for operation, inspection, testing and maintenance.
(c) Consideration should be given to the possibility that systems containing non-radioactive fluids during normal operation may carry radioactive fluids under anticipated abnormal operation.
(d) Component separation by distance and/or shielding should be utilized to minimize radioactive exposure to operating personnel.
(e) Penetrations of shielding walls by pipes and ducts shall be designed to minimize personnel exposures apart from other design considerations such as fire barriers, ventilation airflow, etc.
(f) Shielding and insulation around radioactive process equipment that must be periodically inspected or serviced should be designed to permit a rapid simple removal and reassembly so as to minimize radiation exposure to operating personnel.

CONTAMINATION CONTROL

911. Process subsystems and equipment, such as waste pretreatment, ash handling, filters and scrubbers, should be arranged in such a way as to minimize the spread of contamination and to facilitate their decontamination. Typical measures may include adequate ventilation, drainage, curbing and surface finishes that facilitate decontamination.

MATERIAL HANDLING

912. The building design should include provisions for the intermediate storage of the waste feed and ash. The building housing the material handling subsystem (e.g. the incinerator feed system) should have sufficient space to allow for inspection, sorting and/or pretreatment of the active solid waste feed. The material handling design should consider the interfaces between the individual operations. Controlled ventilation and fire protection shall be provided for this area. Additional information is available in Refs [2, 13].

VENTILATION

Control area

913. The incinerator operation control room or control area should have a ventilation system that is separate from the equipment ventilation system or is kept at a higher pressure than the surrounding equipment areas. This is required to keep any airborne radioactive contaminants out of a normally occupied area. The control room may also be air conditioned.

Equipment areas

914. The ventilation airflow should proceed from areas of low contamination to areas of higher contamination in order to minimize the risk associated with the spread of airborne contamination.

Material handling area

915. The area designated for dry active waste inspection, sorting and pretreatment shall have sufficient clean air intake and exhaust conditions to prevent or minimize the probability of internal contamination of operating personnel by inhalation. A ventilation hood or a glove box should be considered appropriate for work spaces where the operator opens containers or plastic bags of waste. Glove boxes shall be used when handling alpha contaminated material.

Ash handling area

916. The design of the waste handling subsystem should contain provisions to prevent or minimize any release of airborne ash within the waste incineration facility. The ventilation system should be designed to remove or mitigate the results of abnormal conditions resulting from an ash spill or exhaust leak. The ash drum filling

system may be connected to a special ventilation system that is provided with appropriate filtering equipment.

Liquid waste storage area

917. Storage tanks for organic liquid waste should be located outside the incineration building. When located inside the building for any reason, adequate ventilation shall be provided to avoid fugitive emission problems from both chemical exposure and fire or potential explosion. The ventilation system should be separate from that serving the incineration area. Vents from the liquid tanks should not be connected with the ventilation system.

REQUIREMENTS FOR OPERATION

Equipment location

918. Subsystems and components (e.g. combustion chambers, scrubbers, ash handling) that may contain more radioactivity than other subsystems should be separated from equipment and components requiring periodic maintenance, calibration and/or inspection. The amount of shielding required between the pieces of equipment will depend on the expected radiation levels.

Valves

919. All manual valves and valve operators shall be located in areas readily accessible to operating personnel. If valves are installed in areas of high radiation or other hazards they should be provided with extended stems or equivalent devices allowing actuation from a lower radiation area. Handwheels and chain or extension handle operators should be located at a reasonable height above either the floor or a permanently installed platform to allow easy operation. Piping ducts and valves should be located and marked such that the operators can easily identify the flow paths. Pipes or ducts that cross the normal and safety pathways should be at least 2 m above the floor.

REQUIREMENTS FOR MAINTENANCE

Equipment removal

920. Equipment and components shall be arranged such that adequate clearances are provided to perform removal and maintenance activities, including the removal and replacement of internal parts. Piping, tubing, conduit runs, ventilation ducts, etc., should be arranged to facilitate access and maintenance. These items should not

be attached to or mounted on the equipment in a manner that interferes with the maintenance or removal of equipment or components. Where necessary, ladders and platforms should be provided to permit access and minimize the time spent in radiation zones. Further guidance may be found in Ref. [3].

Local shielding

921. Depending on the design of the incineration system and the arrangement of the equipment, components with high maintenance or servicing requirements may require shielding from other components. Whenever local shielding is provided (e.g. around radiation monitors), it should be structurally supported, independently of the equipment or components, and arranged for easy removal and replacement.

Lifting and transfer provisions

922. Lifting and transfer facilities should be provided for the removal and transfer of heavy equipment or parts from the area in which they are installed to permit maintenance activities in other areas.

Emergency lighting

923. Adequate emergency lighting and the indication of escape routes shall be provided in all equipment areas.

Maintenance of equipment with accumulated activity

924. Design consideration shall be given to the removal of components containing a significant quantity of radioactivity. The various means of accomplishing or facilitating maintenance include:

(a) Semiremote methods using long handled tools that utilize distance and equipment shielding to reduce personnel exposure.
(b) Temporary shielding of local radiation sources that minimizes the exposure of maintenance personnel. Sufficient space should be provided in the design for the installation of such shielding.
(c) In-place decontamination that may be accomplished by water flushing or chemical cleaning. The relevant facilities to support decontamination should be provided. Care shall be exercised when selecting a method of decontamination to ensure that: there is no adverse effect on equipment; the secondary waste can be conditioned for disposal; and the decontamination agents do not contribute to potential accidents. Detailed guidance may be found in Refs [3, 14].
(d) Use of robotic devices to accomplish repetitive tasks.

FIRE PROTECTION

925. Protection against fire shall be provided for the waste incineration facility. The actual amount and type of protection will vary from facility to facility, depending on the characteristics of the wastes, the incinerator design, and the national fire protection regulations. The design of the fire protection system should consider secondary effects such as flooding of the building from the water systems and uninhabitability resulting from use of the gaseous fire fighting system. Radiation levels and accessibility shall be taken into consideration when locating fire fighting equipment. As a minimum a fire alarm shall be located in the main control room for a nuclear plant or in the central waste processing centre control room, where site personnel are always on duty. Further guidance may be found in Ref. [15]. Paragraphs 926 to 929 give examples of areas requiring fire protection.

Waste feed and segregation area

926. A fire protection system shall be provided for areas used for combustible dry waste storage, inspection, or segregation prior to processing. Fire protection equipment such as automatic sprinkler systems with automatic detection, manual actuation and/or automatically closing fire doors may be used in addition to the conventional fire fighting systems (e.g. hoses, fire extinguishers). The choice of a fire protection system depends on the physical and chemical properties of the materials in storage as well as on national fire protection regulations and practices.

Liquid waste storage

927. Special consideration for fire protection shall be given to areas in which volatile organic liquids are stored and handled. A fire suppression system using halon gas (or an equivalent substitute) as the fire suppression agent shall be installed. An inert gas purging system may be considered for the liquid tanks.

Combustion chamber area

928. The space or room containing the incinerator combustion chambers and their accompanying burners should have a fire detection and alarm system. Fire protection may be provided by automatic extinguishing means such as a water sprinkler system or a fire hose station. In particular applications, foam or powder may be more appropriate. Depending on the radiation level expected for some of the components, an automatic or remotely actuated suppression system may be required.

Other areas

929. Other factors that need to be considered include:

(a) *Filters.* HEPA and combustible filters shall be provided with an appropriate fire detection system.
(b) *Ash conditioning.* The room used for ash conditioning may require a fire detection, alarm and suppression system depending on the conditioning process.
(c) *Ventilation ducts.* Fire or smoke detectors may be located in ventilation exhaust ducts from storage or processing areas. Provisions for isolating fires within the ducts shall be included.
(d) *Fuel.* The fuel storage and supply area shall be provided with an appropriate fire protection system.

RADIATION MONITORING

930. Radiation protection and aerosol sampling monitors shall be used within the waste incineration facility in areas that could become restricted because of radiation contamination. To ensure that there is no buildup of airborne contamination, periodic spot checks for the accumulation of deposits on the surfaces of equipment shall be performed. The range of the area monitoring instrumentation shall be such as to give a clear reading during normal operation as well as during any of the conditions considered in the safety analysis. Extended scale instrumentation for accident conditions beyond the design basis values should also be available. The preset alarm levels shall be commensurate with the expected radiation levels during operation, the anticipated activities in the areas, and the general requirement of keeping radiation doses within established limits and consistent with the ALARA principle. Radioactive effluent monitoring is discussed in paras 805 and 806.

EXPLOSIVE GAS MONITORING

931. Because of the possibility of explosive gas formation and accumulation within some sections of the incinerator building, explosive gas monitoring shall be located near the fuel feed system, the combustion chambers, and in the area where organic liquids are stored prior to their incineration. To minimize the potential for explosive gas formation, an automatic purge system should be considered along with periodic checks for the buildup of combustible gas mixtures.

10. SYSTEM TESTING AND COMMISSIONING

GENERAL REQUIREMENTS

1001. System testing and commissioning consists of a number of individual steps. Their sequence shall be stipulated in the commissioning procedure. In this context, the tests and inspections required by the manufacturer and licensing authorities and those recommended in Ref. [16] shall be taken into account.

1002. The future plant owner/operator as well as the licensing authorities should be consulted and should participate in the required activities early in the testing and commissioning planning stage. A report shall be prepared for each individual test and inspection, and together with the startup and commissioning programme, these reports shall form an integral part of the documentation of the system.

STRUCTURAL INTEGRITY

1003. The first test to be carried out after the construction of the facility is a structural integrity test. This test should consist of the following steps:

(a) All components should be completely installed.
(b) Components and pipelines should be flushed down to remove any foreign matter.
(c) The individual components and subsystems should be tested with the applicable test media (liquid or gas).
(d) Electrical installation, instrumentation and control systems shall be tested.

THERMAL COMMISSIONING

Thermal commissioning with burners

1004. Commissioning with burners should not commence until the operating manual is available. Approval may be required by the regulatory body in accordance with national practices. The incinerator should be heated slowly with burners at a rate specified by the manufacturer of the refractory lining. Parameters such as pressure differentials, tightness, off-gas flow rate and temperature should be monitored during this process.

Thermal commissioning with simulated waste

1005. The thermal commissioning test has to demonstrate that the equipment is capable of operating in a safe and reliable manner and that provisions are available to cope with anticipated operational occurrences. The characteristics of the simulated waste used for thermal commissioning should be similar to those specified for operating waste, excepting the radioactive content. The thermal commissioning programme shall continue until all the deficiencies are eliminated, covering all operational phases including:

— startup
— normal operation
— temperature control
— shutdown
— abnormal operational modes.

Thermal commissioning with radioactive waste

1006. This test shall demonstrate that the incinerator can be operated safely in accordance with the design assumptions and intent, and the operating limits and conditions, as well as with the requirements of the regulatory body. Thermal commissioning with radioactive waste shall be continued until all the required tests are carried out and satisfactory functioning of the entire system is verified.

11. SYSTEM OPERATION

GENERAL REQUIREMENTS

1101. As a minimum requirement, the incineration system shall be operated according to the manufacturer's instructions and recommendations, provided that they are within the authorized operating limits and conditions.

STARTUP

1102. The startup of an incineration system shall begin with no waste in the combustion chamber. In order to produce a negative draught and to ventilate the system the off-gas fans shall be started first. Once this has been achieved the burners may be ignited. During the startup operation, the waste feed equipment shall not be operated. When the required temperature is reached the feed equipment may commence operation and waste can be fed into the incinerator. This sequence, however, may not apply to some incineration systems, for example batch loading, in which the waste is fed into the combustion chamber prior to igniting the burners.

NORMAL OPERATION

1103. In normal operation safety related parameters such as negative draught, oxygen and dust concentration, and temperature should be controlled automatically without action from the operators. Process control and instrumentation parameters are listed in para. 804.

1104. Temperature controls shall automatically increase or decrease the thermal output of the burner to reach and maintain the required temperature.

ABNORMAL OPERATION

1105. Abnormal conditions as described in this section should result in automatic corrective actions.

Loss of services

1106. The following types of losses can all occur.

(a) *Loss of instrument air.* When compressed air for the instrument and valve operator or other pneumatic systems is lost, all affected components shall go to a safe condition. For example, waste feed to the incinerator shall be automatically discontinued.

(b) *Loss of water.* Water may be necessary for quenching or cooling. When no water is available, off-gas and equipment temperatures may rise unacceptably. An adequate reserve water supply shall therefore be provided for a safe shutdown of the equipment.

(c) *Loss of electric power.* The incinerator shall return to a safe condition. The facility may be provided with an emergency electric power source for instrumentation and monitoring equipment, and for the induced draught fan.

(d) *Loss of flame.* Loss of flame in the support burner is a critical event in the operation of an incinerator and shall be monitored. In the event of a loss of flame, the system shall be shut down as described in the operating manual.

Failure of components

1107. Functions important to the safe operation of the facility should have redundant components. For incinerators burning alpha bearing wastes a secondary enclosure shall be provided as protection against failure of the safety components.

Pressure transients

1108. A pressure transient, which may occur from an explosion in the incinerator, could be the result of abnormal conditions. An example of such conditions may be a high amount of solvents in the waste or an improper mixture of oxygen and combustible gases. The incinerator design should include provisions to mitigate the consequences of a pressure transient, and may include rupture discs or other pressure relief devices discharging (typically) into gaseous expansion chambers.

Temperature transients

1109. Temperature transients may be caused by a high proportion of material with a high heat value in the waste. To avoid such temperature transients, the operating procedures should ensure that waste materials with high heat values are segregated and fed into the incinerator in smaller proportions together with waste with a low heat value.

SHUTDOWN

1110. When a shutdown of the incinerator is planned, the waste feed shall be discontinued. The waste contained in the combustion chamber should be burned out under normal operating conditions (e.g. under a negative pressure and at an inadequate temperature). The temperature in the combustion chamber should be reduced slowly to mitigate thermal shock on the refractory. The exhaust fan should be operated during the cooldown period to meet the system material requirements. After the burners are shut off the airflow through the burner nozzle should be maintained during the cooldown period. A controlled cold airflow into the combustion chamber should be provided for progressive cooling of both the combustion chamber and the off-gas system to remove condensation and cool the system. The ash should be removed after the system is cooled and prior to the next startup.

ORGANIZATIONAL AND ADMINISTRATIVE ASPECTS

Organizational structure and auxiliary services

1111. The operating organization shall provide an adequate organizational structure to operate the incineration facility. Competent management and skilled personnel, all fully aware of the safety aspects of operation, shall be employed. The organizational structure shall be documented with clear identification of lines of authority and communication. The functions, duties and qualifications for each individual position in the structure shall be described. Guidance on this subject may be found in Refs [17–19].

1112. The operating organization should satisfy the following requirements.

(a) The operating organization shall ensure that all support services (other than operation and routine maintenance) necessary for the operation of an incineration facility are available in accordance with the operating requirements and programmes. These support services include:
   — radiation protection for site personnel and the general public;
   — medical services for injured persons;
   — chemical and radiochemical laboratory services;
   — fire protection;
   — procurement of materials and spare parts;
   — engineering and technical support services (e.g. to review plant operation, investigate abnormal occurrences, interface with the regulatory body);
   — administrative services such as stores, files, personnel administration, plant security, etc.

(b) Whether all, or only some, of these services need to be provided directly by the organization operating the incineration facility may depend on local conditions such as:
   — whether the incineration facility is located at a site where other facilities are operated;
   — whether the incineration facility is a part of a large system, having adequate headquarters capabilities.

(c) The operating organization shall identify applicable procedures for the use of the above services, whether they are provided within the organizational structure for operating the incineration facility, or outside of it.

Training

1113. Adequate training is essential to proper operation of a radioactive waste incineration facility. Plant personnel shall be made aware of the operations, safety and performance objectives of the waste management programme. The potential for human error will be reduced by proper training and implementation of effective procedures.

1114. Operating personnel shall be instructed in the functioning and proper operation of each subsystem and component of the incineration system, and the effects of malfunctions. The operating personnel shall be aware of the design bases of the system, the consequences of operational error, and the corrective measures to be taken in the event of a malfunction or error. Operators shall receive periodic refresher training on the operation of the incineration system. They shall be made fully aware of modifications to the systems and procedures, together with the reasons for these modifications. They shall be trained in appropriate responses to abnormal events that may be encountered during the operation of the systems, with particular attention being paid to emergency preparedness procedures [20].

Procedures

1115. The facility shall be operated and maintained in accordance with written procedures. These procedures shall also cover the necessary actions to be performed during abnormal operating conditions. The procedures shall be drafted, reviewed, approved, circulated and modified when necessary in accordance with the QA requirements [10, 17, 19], and, if required, submitted to the regulatory body. Only the latest version of the document shall be available to the personnel. Copies of outdated versions shall be kept on file, but only for reference purposes.

12. DOCUMENTATION

CONTROL OF DOCUMENTS

1201. Documents shall be produced in accordance with the applicable QA requirements [10]. The documents shall be produced in a form that is retainable, retrievable and modifiable throughout the life of the incineration facility or any other length of time as may be required by the regulatory body.

DESIGN CRITERIA

1202. Design criteria, along with their intents and assumptions, shall be clearly written to document the basis for the overall design of the incineration system. The design codes and standards used for the systems and components shall be clearly documented and shall include addenda as applicable.

BASELINE DOCUMENTS

1203. Baseline documents shall include information about the operation and maintenance of the waste incineration system and components, the discharge of effluents, and the monitoring and assessment of radiological impact.

Design documents

1204. All technical design documents for the system, such as the design criteria, specifications, equipment descriptions, process flow diagrams, piping drawings, component drawings, equipment operating and maintenance manuals, etc., shall be made available to the operating organization in updated, as-built versions.

Commissioning and test documents

1205. Baseline information derived during the commissioning programme, including documents such as test specifications, test procedures and test reports, shall be kept at the incineration facility or plant administrative office. Additional guidance may be found in Ref. [16].

Safety analysis documents

1206. A complete safety analysis report, including the effects of postulated failures, shall be prepared. Further guidance on the safety analysis may be found in para. 301 of this guide. Copies of the current safety analysis report and the related operational safety requirements shall be made available to all members of the operating staff.

Waste management documents

1207. The waste management documents shall include:

(a) Accounts of all releases of radioactive effluents from the site, including estimates of any unmonitored releases;
(b) Reports on any investigations into abnormal conditions or deficiencies associated with the waste management programme such as unplanned releases or spills;
(c) Details of the wastes collected, processed and stored on site;
(d) Information about each off-site shipment of waste, including the type and quantity of waste, the type of packaging and the destination;
(e) Information needed for a periodic assessment of the doses received by the public as a consequence of incineration facility operations;
(f) Information on non-radioactive hazardous effluents.

Training documents

1208. Documents concerning personnel training on the incineration system shall be maintained within the operating organization.

Annex I

WASTE SOURCES AND CHARACTERISTICS

This annex lists typical waste sources and materials and provides examples of the information required to facilitate the proper design of an incineration system.

Origin of waste

The typical composition of the waste largely depends on where the waste was produced. Combustible radioactive waste may be produced in the following facilities:

- nuclear power plants
- research centres and laboratories
- hospitals
- universities
- radioisotope production facilities
- reprocessing plants
- fuel fabrication plants or laboratories
- industrial plants.

Typical waste materials

(a) Plastic objects in the form of bags, foils, boots, gloves, overalls, laboratory equipment, containers and bottles. Plastic objects may typically be made of polyethylene (PE), polypropylene (PP), polymethylmethacrylate (PMMA), polyvinylchloride (PVC), polytetrafluoroethylene (PTFE), nylon (PA) and ethylvinylacetate (EVA).

(b) Rubber in the form of gloves, boots and hoses.

(c) Polyester fibres in the form of rags, clothes and overalls.

(d) Paper in the form of bags, sheets, wrappings, cartons and overalls.

(e) Activated charcoal.

(f) Wood in the form of wooden HEPA filter frames, packing, plywood and lumber.

(g) Cotton and other cellulosic fabrics.

(h) Glass in the form of ampoules, bottles, sheets and laboratory equipment.

(i) Asbestos, glass fibre and other thermal isolation materials.

(j) Metals in the form of small components, laboratory equipment, tools, wires, sheets, pipes and screws. The objects may be made of carbon steel, stainless steel, copper, aluminium and other metals or alloys.

(k) Aqueous sludges containing miscellaneous organic or inorganic suspended matter.
(l) Ion exchange resins in the form of slurries, contained in filter cartridges or in a dried form.
(m) Biological material.
(n) Organic liquids such as waste oils, solvents and scintillation liquids.
(o) Water and aqueous solutions of chemicals as well as their residues in containers and bottles.

The average waste composition should be verified and specified in weight per cent.

Physical waste data

— heat value (kJ/kg)
— average density (kg/m^3)
— average moisture content (wt%)

Waste flow rate

— mass flow (kg/h)
— mass flow (kg/a)

Identity and concentration (Bq/m^3) of radionuclides

^{3}H	$^{95}Zr/^{95}Nb$	$^{144,141}Ce$
^{14}C	$^{106,103}Ru$	^{226}Ra
^{35}S	^{125}I	^{235}U
^{54}Mn	^{129}I	^{238}U
^{59}Fe	^{131}I	$^{239,241}Pu$
^{60}Co	^{134}Cs	^{241}Am
^{65}Zn	^{137}Cs	

Annex II

BASIC INCINERATION CONCEPTS

Combustion is a process of rapid exothermic chemical reaction between a combustible substance and oxygen. In principle, the end products of combustion are oxides of the elements in the substance (e.g. waste feed). Combustion is generally a gas phase phenomenon, with the exception of combustion of solid carbon which, in forms such as soot and char, reacts heterogeneously. Incineration of solid wastes primarily involves the combustion of vapours and gases resulting from the thermal decomposition of the waste feed, and the combustion of the residual char.

Incinerators, developed for the processing of radioactive wastes, use a variety of diverse combustion techniques. This fact alone suggests that the design of a good system for radioactive waste incineration is not straightforward and simple. It has been acknowledged that the degree of 'success' of the total incineration system depends significantly on the extent to which the basic combustion process requirements are successfully met in its engineered realization (i.e. what can be achieved in actual practice against what can be achieved in theory). In principle these requirements are as follows:

(a) Capability to process a variety of non-homogeneous wastes of differing chemical compositions, physical dimensions, densities, moisture contents and heat values, while displaying a low sensitivity to items incompatible with the process-system design;

(b) Complete oxidation of the waste feed, including the combustible products of the waste thermal decomposition, within the boundary of the combustion part of the system;

(c) Minimal carry-over of particulate matter into the off-gas;

(d) Consistent process parameters and consistent composition of the off-gas at the exit from the combustion part of the system;

(e) Consistent quality of ash having desirable physical characteristics from the viewpoint of its ease of removal, transfer and immobilization.

Although complying with all of the above process requirements remains the ultimate objective in the design of the combustion system, it is recognized that no combustion technique by itself can meet all the requirements to an absolute, or even a satisfactory, degree. In practice, those requirements that are not satisfactorily met by the design of the combustion system need to be compensated for in the design of the associated subsystems such as the feed preparation, the ash removal and particularly the off-gas treatment. Otherwise, the requirements that are not satisfied may lead to operational difficulties and/or represent permanent limitations of the system.

To achieve a high degree of combustion of the waste feed in a combustion system it is necessary to ensure an adequate combustion temperature, a sufficient excess supply of air, an ample mixing of the air and the thermal decomposition gas, and an adequate reaction time. In a successful incinerator design, careful consideration is given to the provision of adequate excess air and the appropriate location of the air supplies; the combustion temperature is carefully controlled; the gas flow velocities through the combustion chamber are adequately low; and the gas and solid waste residence times in the combustion chamber are of sufficient duration.

Some incinerator designs attempt to accomplish combustion of both the gaseous and solid phases in one combustion chamber. It appears much more preferable, however, to employ two combustion chambers connected in series. In these designs the waste feed is loaded into the primary chamber where it undergoes thermal decomposition and where the carbon residue burnout is also (later) completed. This is followed by a secondary combustion chamber (afterburner) for oxidizing the remaining gases and volatiles, including the particulate matter carried over from the primary chamber, under conditions where there is excess air. A support burner and additional air injection equipment are usually required in the secondary chamber to maintain a sufficiently high and consistent temperature.

The principal combustion techniques and their typical process temperatures as they have been used for incineration of radioactive wastes can be categorized as follows:

— excess air incineration at 800–1100°C,
— controlled air incineration at 800–1000°C (primary process),
— pyrolysis at 500–600°C (primary process),
— high temperature slagging incineration at 1400–1600°C,
— fluidized bed incineration at 800°C.

The excess air incinerators allow an excess of oxygen during the primary combustion process so that both the gaseous and solid fractions can burn directly in one combustion chamber. Incineration in excess air is the simplest combustion technique utilized.

The controlled air incinerators limit the air supply in the primary combustion step (e.g. to near or below the stoichiometric ratio), and a secondary combustion step is needed for the completion of the combustion of the gaseous fraction in an oxygen rich atmosphere.

The pyrolysis (or thermal decomposition) process requires a reducing atmosphere, usually maintained by restricting the air supply to much less than stoichiometric levels. The pyrolysis of organic materials causes their thermal degradation and a distillation of the volatile fraction, forming combustible liquids and vapours. The vapours are composed primarily of methane, hydrogen, carbon monoxide, carbon dioxide, water and the more complex hydrocarbons such as ethane, propane, oils and tars. The material remaining after pyrolysis is char, a charcoal-like substance consisting primarily of fixed carbon residue. Pyrolysis is an endothermic process and a continuous source of heat is required to maintain it. The source of heat may be hot air or gas, but the process can also be sustained by the heat generated in local burning of the surrounding wastes. The pyrolysing incinerators employ secondary chambers where the ash and the gaseous products of pyrolysis are fully oxidized in an oxygen rich atmosphere.

The incinerators employed to produce the slag use relatively high process temperatures to burn the carbonaceous residue by receiving heat, typically from burning fuel, thus releasing an amount of heat energy sufficient to convert all non-combustibles contained in the waste feed to molten slag.

The fluidized bed incinerators use a distinctly different combustion technique. The incinerator vessel contains an inert bed of particles that are kept in suspension by fluidizing air flowing through the bed at a rate that is just rapid enough to sustain that condition. The shredded waste ignites instantly upon introduction into the fluidized bed incinerator. The combustion of both the solid and gaseous fractions of the waste is accomplished in one chamber and the fly ash resulting from the process leaves the chamber with the off-gas.

The end product of the incineration of radioactive waste materials generated by using the techniques described is radioactive ash. The composition and character of the ash vary with the combustion technique used and with the composition of the waste feed. The pyrolysis process yields char containing some fixed carbon. The excess air and the controlled air incineration leave a similar end product but contain less carbon. A high temperature slagging process produces a glass-like aggregate containing very little or no fixed carbon, the main constituent being SiO_2. Fluidized bed incinerators produce solid residues in the form of fly ash.

In addition to the combustion techniques described, there have been other non-conventional methods developed and demonstrated for the oxidation of radioactive wastes. These, however, have not led to a significant commercial utilization to date. They typically include pyrohydrolysis, acid digestion, molten salt and molten glass oxidation, and other methods that are further described in the technical literature.

Annex III

BASIC OFF-GAS TREATMENT CONCEPTS

Incineration of the radioactive waste produces combustion gases that leave the combustion part of the system at temperatures generally up to 1100°C. The bulk of the radionuclides from the initial waste feed remains in the incineration solid residue collected from the primary combustion chamber: the remaining radionuclides will be present in the incinerator off-gas. Some radionuclides will be contained in the carry-over particulates while others may volatilize during the combustion process and be present in the off-gas in the form of a vapour. Typically, iodine and ruthenium are the most common volatile elements observed at moderate incineration temperatures, and caesium will become a volatile constituent at temperatures above 1000°C. Finally, there will be permanent radioactive gases in the off-gas such as $^{14}CO_2$, $^{3}H_2O$, $^{35}SO_2$ and other gases. The off-gas can also contain noxious and/or corrosive gaseous constituents such as NO_x, CO, HCl, HF and SO_2, depending on the chemical composition of the incinerated waste and on the combustion temperatures. For all, or most, of these objectionable constituents, an off-gas treatment system has to be incorporated into the incineration system to protect the environment against the radiological as well as the conventional chemical hazards.

There are a variety of components and process steps and combinations thereof that may be used for off-gas treatment. The process design, its complexity, and the characteristics of a particular off-gas treatment system depend on the choice of combustion technique and its engineered realization, on the characteristics of the waste including its level and type of radioactivity, and on the regulatory requirements. In simple terms, filtration, separation and wet scrubbing are used for the removal of particulate matter, wet scrubbing and absorption for the removal of corrosive acid gases (e.g. HCl, HF and SO_2), and adsorption is used for the removal of radioactive iodine. Dry scrubbing could also be used for the removal of corrosive acid gases, but so far there has been little experience in applications to problems involving radioactivity. Since most of these treatment processes and components require relatively low operating temperatures (in some instances close to ambient), the off-gas has to be cooled. On the other hand, the off-gas needs to be reheated following a wet scrubbing step and prior to the final filtration on HEPA filters, to increase the temperature of the off-gas above its dewpoint so that the vapour will not condense on the filter.

The off-gas treatment systems using 'dry' (non-aqueous) cooling and treatment steps are commonly referred to as 'dry' systems, as compared with 'wet' systems that incorporate any of the 'wet' (aqueous) steps. Systems using water or steam injection for partial temperature reduction without the scrubbing function, but otherwise containing dry process steps, are considered as dry systems. The wet systems containing wet scrubbing need to employ scrub solution recirculation and conditioning subsystems that contain filters, coolers, chemical adjustment and radioactivity monitoring components. These subsystems generate a blowdown, which should be treated as a liquid radioactive waste.

Cooling of the off-gas may be achieved by injection of water or steam, dilution by air, or heat exchange. The cooling can be achieved either in one step or in several steps combining any of these methods. Cooling by water injection may be combined with a wet treatment (scrubbing) function. Dilution with air leads to increased off-gas volumes, and consequently requires adjustment in the sizing of treatment components downstream of the injection point. However, the net usage rate of filter elements will not be affected, provided that the dilution air is relatively dust free, because the specific particulate loading in the off-gas will be reduced. Air-to-air heat exchangers are used, preferably as a second cooling step, in lower temperature ranges, to avoid or minimize the high temperature corrosion and the potential for scale buildups due to deposition of particulate and volatile materials.

The wet off-gas treatment systems containing wet scrubbers have the capability to remove corrosive gases, and exhibit the highest decontamination factors for the total radionuclides. In particular, such a system would be used for processing wastes containing substantial amounts of corrosive acid gas forming materials.

The dry off-gas treatment systems are simpler and more economical to operate. These systems may preferably be used if there are no specific reasons for the incorporation of wet scrubbers. The dry systems keep the off-gas temperature well above the dewpoint so that corrosion by acid gas condensation can be minimized. A dry system may be selected when processing tritiated wastes (subject to regulatory conditions and to tritium concentrations) since it will release tritium, together with the dry-filtered off-gas, into the environment. This practice may present a lesser radiological hazard when compared with the aqueous scrubbing of tritium and the consequent need for the handling and conditioning of the tritiated scrub solutions.

The operation of both the dry and wet off-gas treatment systems generates secondary radioactive wastes. These typically include filters and filtration materials, adsorption materials, and in the case of wet scrubbers, liquid scrub solutions and blowdowns. Dry scrubbers would produce secondary wastes in the form of solid neutralizing agents and their residues, probably mixed with fly ash. Some of these secondary wastes (both solid and liquid) may be processed by incineration or drying in the same incineration system. Others need to be handled by a separate volume reduction system or disposed of with or without immobilization. The ash removed from the various collection points in the off-gas treatment system also needs to be treated and disposed of with the bulk of the ash collected from the combustion system.

Typical incinerator designs are described in Ref. [9].

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CONTRIBUTORS TO DRAFTING AND REVIEW

Bertini, A.	Ente Nazionale per l'Energia Elettrica, Italy
Borduin, L.C.	Los Alamos National Laboratory, United States of America
Carpentier, S.	Société générale pour les techniques nouvelles, France
Chalupa, G.	Österreichisches Forschungszentrum, Austria
Chevalier, G.	Centre d'études nucléaires de Fontenay-aux-Roses, France
Christensen, H.	ABB Atom AB, Sweden
Efremenkov, V.M.	International Atomic Energy Agency
Faurholdt, B.	ENVIKRAFT, Denmark
Gritti, R.	Commission of the European Communities
Hladky, E.	Nuclear Power Plant Research Institute, Czechoslovakia
Kohout, R.	Ontario Hydro, Canada
Kuribayashi, H.	JGC Corporation, Japan
Lindbom, G.	National Institute of Radiation Protection, Sweden
Matteman, J.L.	Keuring van Electrotechnische Materialen NV, Netherlands
Moreno, A.	Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative, Italy
Oyen, L.C.	Sargent & Lundy Engineers, United States of America
Renard, C.	Organisme national des déchets radioactifs et des matières fissiles, Belgium

Tocci, M.	Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative, Italy
Tsarenko, A.F.	International Atomic Energy Agency
Underhill, M.	Central Electricity Generating Board, United Kingdom
van Brabant, E.	CEN/SCK, Belgium
van de Voorde, N.	CEN/SCK, Belgium
Wurster, W.	Kraftanlagen AG, Germany

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