

8 Decontamination

The first part of this Chapter describes decontamination techniques of large volume systems, segmented parts and walls and floors. Advantages and disadvantages of the different methods are discussed and examples of decontamination procedures and their results in laboratory- and large scale are demonstrated. Considerations are focussed on nuclear facilities and power plants during operation and decommissioning.

The second part deals with decontamination of the human skin. In case of contamination of the human skin by radionuclides suitable measures have to be initiated to keep the dose to the skin below the limits recommended by the ICRP. For purposes of dose estimates numerical values of the equivalent dose rate in Sv/s at an activity per area of 1 Bq/cm² are given for 128 radionuclides. In addition first aid and specific decontamination procedures are described as simple decontamination appliances immediately after contaminations or for decontamination of specific body regions and organs below reference values for residual contamination.

8.1 Decontamination of materials

List of Abbreviations

AGR	Advanced Gas Cooled Reactor
ALARA	As Low As Reasonable Achievable
AMDA	Automated Mobile Decontamination Application
AP	Alkaline Permanganate
APAC	Alkaline Permanganate Ammonium Citrate
APACE	Alkaline Permanganate Ammonium Citrate EDTA
BWR	Boiling Water Reactor
CAN-DECON	CANdu DECONtamination
CANDU	CANada Deuterium Uranium Pressurized Heavy Water Reactor
CEA	Commissariat à l'Energie Atomique (France)
CEC	Community of European Countries
CEGB	Central Electricity Generating Board
CITROX	CITric Acid OXalic Acid
CORD	Cyclic Oxidation Reduction Decontamination
DF	Decontamination Factor
EDTA	Ethylene-Diamine-Tetraacetic Acid
EPRI	Electric Power Research Institute (USA)
Framatome	Company's Name
HX	Heat Exchanger
LOMI	Low Oxidation-state Metal Ions

MOPAC	Modified Permanganat Ammonium Citrate
NP	Nitric Acid Permanganate
NPP	Nuclear Power Plant
OZOX	OZone OXalic Acid
PWR	Pressurized Water Reactor
SGHWR	Steam Generating Heavy Water Reactor
WAGR	Windscale Advanced Gas Cooled Reactor

8.1.1 General approaches to decontamination

8.1.1.1 Contamination

Contamination is the deposition of the radioactive elements or compounds from a contaminant media or gas, by chemical, physical or other ways, on the surfaces of components, systems, and structures in nuclear facilities. The characteristics of the contamination are strongly correlated with the nature and features of the surface and of the contaminant media. In metallic surfaces there often exists a chemical similarity with the contaminant element (as for example for metallic cations in the water) that can cause its diffusion into the metallic sub-layer, hence becoming very difficult to remove.

Contamination can be classified into three types:

- free contamination; i.e. can be removed by simple blowing, vacuum or similar methods;
- loose contamination; i.e. can be removed by common cleaning techniques;
- fixed contamination; i.e. cannot be removed without removal of surface layers.

The following presents typical contamination patterns encountered in nuclear facilities [88Int]. In reactor systems, the radioactive contamination on the internal surfaces is caused by deposition from the reactor coolant of neutron activated particles and dissolved elements, and of fission products and transuranics released following a failure of the fuel cladding. These deposits become part of the oxide layer, which forms on the inside of the piping. This layer has a complex structure, which depends on a variety of parameters such as coolant chemistry, temperature of formation, system materials, operating time, etc. Over long periods of time, the radionuclides in the layer can diffuse slightly into the base metal or penetrate the pipes along grain boundaries. In general for water cooled reactors, two types of oxides form on the internal surface of reactor piping: an adherent inner layer which is formed by in-situ corrosion of the base metal, and a relatively loose outer layer which is formed by deposition or precipitation of crud from the coolant.

8.1.1.2 Characteristics of oxide layer in BWRs and PWRs

Occupational dose in BWRs and PWRs is mostly caused by corrosion-originated nuclides: ^{60}Co , ^{58}Co , ^{54}Mn , ^{51}Cr and ^{59}Fe . Depending on fuel failure rate, the other fission species would contribute to plant dose rates. Most part of these species is included in oxide layer inside pipes and equipment. Decontamination usually dissolves or removes the radioactive species together with the oxide layer.

Characteristics of the oxide layers are quite different between BWRs and PWRs. Iron occupies 80-90 % of metal elements in the BWRs oxide layer. BWRs use stainless steels and carbon steel for the reactor cooling and the feedwater systems. PWRs use great amount of nickel-base alloys for steam generators. Metal fraction of Ni and Cr is 60-70 % in PWRs oxide layer.

BWRs oxide layer grows in oxidising water chemistry and consists of $\alpha\text{-Fe}_2\text{O}_3$, Fe_3O_4 , and NiFe_2O_4 . Reducing environment of PWRs forms $(\text{Ni}_x\text{Fe}_{3-x-y}\text{Cr}_y\text{O}_4)$ -type Cr-rich oxide layers. Table 8.1 compares the oxide characteristics of Japanese BWRs and PWRs. Usually oxide forms indistinct double layer. The inner layer grows from base metal and deposits tightly on the base metal surface. The outer layer contains fuel surface crud released with shear stress by primary coolant flow. In some specific cases, the outer layer crud is easily removed with ultrasonic vibration or high-pressure water jet.

Table 8.1 Crud characteristics of Japanese BWRs and PWRs [00Hir1]

Characteristics of primary system	Primary coolant chemistry		BWRs	PWRs
	Surface area percentage of materials		Oxidising	Reducing
Crud analysis	Form	Outer layer	SS: 38-42 %	SS: 4-6 %
			Carbon steel: 16-20 %	Zircaloy: 25-28 %
			Zircaloy: 40-44 %	Ni-base alloy: 65-70 %
			Ni-base alloy: <1 %	Other alloys: <1 %
Crud analysis	Metal fraction	Inner layer	Fe ₃ O ₄ , NiFe ₂ O ₄ (dominant)	Fe ₃ O ₄ (dominant), NiFe ₂ O ₄ , FeCr ₂ O ₄
			Fe ₃ O ₄ (dominant), α-Fe ₂ O ₃ , NiFe ₂ O ₄ , FeCr ₂ O ₄	FeCr ₂ O ₄ , Fe ₂ CrO ₄
			Fe: 80-90 %	Fe: 20-40 %
			Ni: 7-10 %	Ni: 25-60 %
Crud analysis	Metal fraction		Cr: 1-10 %	Cr: 15-45 %

8.1.1.3 Other types of contamination

In fuel reprocessing facilities, the acid process stream in the dissolution and separation steps of the process, tends to inhibit the formation of an internal oxide layer and deposition of radionuclides is thus limited. Nevertheless, after separation, the phase, which carries the uranium and plutonium, can form pasty and heavy deposits in the pipes and tanks. These deposits are often very difficult to remove.

In other types of nuclear facilities such as hot cells and mixed oxide fuel fabrication plants, low levels of contamination can exist in process vessels, cells, etc. as a result of normal operation. In UO₂ fuel fabrication plants low levels of activity are present from the processing of UO₂.

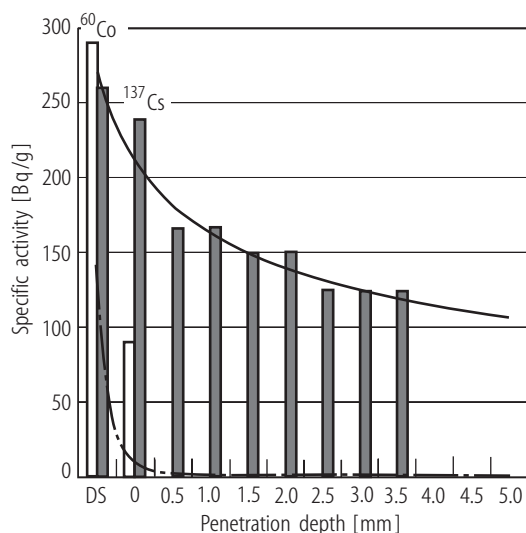


Fig. 8.1 Penetration in concrete of ¹³⁷Cs and ⁶⁰Co in samples of Gundremmingen KRB A Reactor (concrete samples of floors were taken from the decommissioned nuclear power plant). DS = decontamination seal; filled columns and solid line: Cs-137; open columns and dashed-dotted line Co-60.

In most nuclear facilities, many external surfaces become contaminated as a result of leakage and spillages from process systems and from demolition, maintenance and waste management activities. Airborne or waterborne activity can deposit out forming contamination layers on floors, equipment, instrumentation, etc. Thus surfaces can become contaminated by physical or chemical mechanisms.

Of particular concern is the potential contamination of concrete surfaces by waterborne contamination. Unless the surface of the concrete is sealed, water-soluble radionuclides, such as ¹³⁷Cs, can penetrate deeply into concrete. The only method for removing such contamination would be to cut or

chip away the surface layer of concrete containing the radioactivity. To measure the penetration of the contamination in Gundremmingen KRB-A, concrete surfaces were drilled and analysed by gamma spectroscopy in the radiation protection laboratory to determine the nature and depth of the contamination. ^{137}Cs and ^{60}Co , and traces of ^{134}Cs , were found to be present. The isotope ^{137}Cs accounted for about 90 % of the radioactivity. As shown in Fig. 8.1, most of the activity is embedded in the decontamination seal, but some contamination with a high proportion of ^{137}Cs penetrates to a greater depth than contamination in which ^{60}Co is predominant [84Ebe].

For ventilation systems, the surface contamination is usually loose, although adherence is aided by oil films often found on the inside of ducts particularly downstream of fans. Since the exhaust systems operate at negative pressures they tend to draw in dusts and aerosols, which may contain activity. Deposition tends to be heavier in sections of the ducting where the direction or velocity of the fluid changes or at edges of joints or flanges.

For motors, instrumentation and walls etc., loose airborne contamination is usually the major problem. This contamination can generally be removed if it is accessible. If motors and other delicate equipment need to be reused, ultrasonic and freon decontamination processes are sometimes used.

8.1.1.4 Decontamination

Decontamination is the removal by chemical, physical or other methods, of surface radioactive material from both internal and external surfaces of components, systems and structures in nuclear facilities. Usually decontamination and cleaning are considered as separate processes even though they can often be the same physical process; the difference is the degree of cleaning and the emphasis on species removed. Decontamination is the removal of radioactive dirt and oxides from surfaces, whilst cleaning usually refers to the removal of non-radioactive materials. Decontamination should be considered to be a part of cleaning because, in general, only a small part of the material removed during decontamination is radioactive. It is important to note that decontamination is not the elimination of the radioactivity, just the removal to a different location. The term decontamination is widely used in reference to surfaces commonly in contact with contaminated agents (such as reactor coolant, off gases, etc.) whereas the term cleaning refers to surfaces only lightly contaminated by aerosols or by purge liquids, etc.

The concept of decontamination was introduced at the birth of the nuclear industry and was used to describe the reduction of radiation levels on the surfaces of components, systems and structures in order to allow their maintenance, repair, and control works. The importance of decontamination, and the consequent development of new decontamination processes varied as the problems of reduction of radiation levels and man-sievert expenditures (including costs) affected the exploitation of nuclear stations and facilities.

In the early 1960s, decontamination was already a common practice in the nuclear industry. In the mid 1970s, with the support of regulatory agencies and industries, decontamination processes became more sophisticated and a complete evaluation including environmental concerns, costs, legal and public requirements became a common feature of decontamination practices. In the late 1970s, a new emphasis was placed on the decommissioning of nuclear facilities and this introduced a new concept in decontamination, not only to reduce radiation levels, which is normally the major objective of decontamination, but also to facilitate waste management and, if possible, to permit reuse of the material or components.

8.1.1.5 The use of decontamination in decommissioning

The techniques used in decontamination for decommissioning purposes have two main differences in comparison with common in-service decontamination techniques. The techniques can be allowed to affect the integrity of the base materials. This is because, in principle, the component or system will not be reused. The techniques should generate the minimum quantity of secondary wastes.

The basic approach to decommissioning work must be to answer the question: whether, when and how decontamination is to be carried out. Hence, the decision to carry out decontamination is based on a compromise between the advantages and disadvantages of separating the radioactivity or dealing with the fully active installation or component. Decontamination processes could be carried out merely to ease the handling of materials or to bring the radioactivity down to a level where unrestricted release is possible. The latter objective presupposes the existence of such a level, agreed upon with the relevant authorities.

Some examples are presented below of the above argument [90Ber]:

- a) A system or a component is to be worked on for inspection, maintenance or modification, and it is so contaminated that the radiation levels in the work areas are above acceptable values with reference to the established regulations or to the ALARA principle;
- b) A facility, system or component is to be re-used for other purposes, which require it to be “free” from contamination;
- c) A facility, system or component is to be dismantled and the wastes arising from such proceedings are to be collected, conditioned, and disposed of in a safe and economical way according to national practices and regulations, and consistent with an operational national waste management system.

In case (a), the objective is only to obtain a reduction in the level of the contamination without damaging the components. Here the problem is to weight the overall decontamination costs, including management of the necessary provisions for safe work in radiation areas, such as reduced individual working hours, shields, remote operation, telemanipulation.

In case (b), complete decontamination is the main goal and the problem is a question of feasibility i.e. is it “possible” to obtain the required level of decontamination, and of cost i.e. is it less expensive as a whole, to decontaminate, or to dismantle everything and use new components?

Case (c) is common to all decommissioning strategies for nuclear facilities, although in some instances cases such as (a) and (b) may arise. In this case, it may be necessary to consider in more detail, factors that can influence the decision on whether to carry out decontamination in the first place. If decontamination is the preferred option, then there is also a wide range of processes available to choose from.

8.1.1.6 Identification of decontaminable components

From the above, it can be concluded that decontamination is a useful tool in decommissioning work but it is not possible to generalise which parts should be decontaminated and, if so, how the decontamination should be carried out. In reality a priority list of components and systems required for decontamination needs to be drawn up [85Lör].

Components for decontamination should be identified as early as possible in order to avoid wasting time and money on unnecessary decontamination work. Simple decontamination to remove weakly adhesive contamination is still useful because it reduces radiation exposure and facilitates subsequent handling.

One must first compare the two approaches, namely, decontamination for unrestricted release, or direct transfer to some type of repository for radioactive materials. The exposure of personnel and the respective costs of each approach must be considered. In addition to the main criteria above other factors should be taken into consideration, these are:

- The type and degree of contamination;
- The geometry of the components;
- The mass of the components to be decontaminated.

It is possible to determine the type and degree of contamination but careful consideration must be given to whether components exposed for long periods to high pressures and temperatures (e.g. primary circuit) can in fact be decontaminated, whereas components contaminated only by contact with air, whether through moisture or other factors, clearly are decontaminable. In between lies a grey area, which needs further investigation, based on operating data and/or tests, before a proper decision can be taken.

The geometry of the components plays a major role. Decontamination processes are mostly not able to ensure even removal or cope with particular corners and cavities and these are the precise points at which substantially higher contamination can occur. With complicated geometries, the measurements required to produce evidence that the limits have been observed may not be possible or may only be carried out with great difficulty.

The mass of components of the same type to be decontaminated, i.e. components that will be subjected to the same decontamination process, is important in two ways. Firstly, there is little likelihood that very large masses will be transported to a final repository, simply because they contain a few grams or kilograms of radioactive material. Secondly, the decontamination process used must be suitable for such large masses.

When selecting the process, one must ensure that the time needed for decontamination remains within acceptable limits, since personnel costs, which are an important factor, increase in proportion to that time. Where the amounts received from the sale of decontaminated material are significant the process need not in principle spare the material; on the contrary it can be quite aggressive, since it is not planned to re-use the material in its original form.

An estimate of the mass of material that might need to be decontaminated was made for two German nuclear power stations, one with a pressurised water reactor and one with a boiling water reactor. An effort was made to make a distinction on the basis of the above-mentioned criteria. The material was divided into three categories: nondecontaminable material, decontaminable material and material on which no decision can yet be taken. Components, which today are still very difficult to decontaminate, or where decontamination is not viable can naturally be reclassified at a later date on the basis of experience and in the light of progress in decontamination techniques.

8.1.1.7 Effectiveness of decontamination, decontamination factor

The efficiency of different decontamination processes has to be evaluated. The common parameter is called the “decontamination factor”. This is “a numerical representation of the effectiveness of a decontamination process” and it is calculated as ratio between predecontamination and post-decontamination measurements, i.e.:

$$DF = Mb / Ma \quad (8.1.1)$$

Where DF = decontamination factor (generally greater than 1)

Mb = measurement “before” decontamination (at a reference point) and Ma = measurement “after” decontamination (at the same reference point as Mb).

In terms of a percentage, the decontamination factor can be expressed as:

$$DF(\%) = \frac{Mb - Ma}{Mb} \quad (8.1.2)$$

In the following, only the definition (8.1.1) will be considered.

With regard to the kind of measurements, which can be considered, the decontamination factor can be defined (or calculated) by two different methods [85Duc].

The first method is to use radiation measurements. This is called the “*radiation DF*” and is defined as:

$$radiationDF = \frac{Ib}{Ia} \quad (8.1.3)$$

Where I_b = dose (radiation) rate “before” decontamination (at a reference point) and I_a = dose (radiation) rate “after” decontamination (at the same reference point as I_b).

This definition is widely used in decontamination for operating plant, where the radiation measurements referred to are dose rate area measurements; for this case the term “man-sievert DF ” is also used. In many cases the radiation measurements can be taken from monitor counters located near or over the surface to be measured.

The second methods is to use activity measurements. This is called the “*decon DF*” and is defined as:

$$deconDF = \frac{Ab}{Aa} \quad (8.1.4)$$

where Ab = activity “before” decontamination (at a reference point) and Aa = activity “after” decontamination (at the same reference point as Ab)

This definition is widely used for off-line decontamination where the surface activity can be properly measured. In laboratory studies and research, the *decon DF* is more widely used than the *radiation DF*. As mentioned before, each numerical value of DF must be referred to a single measurement before decontamination and a single measurement after decontamination. This means that the decontamination factor can be of relevance only for single points or for very small surfaces or components (which can be measured with a single operation). In any other case, where many measurements have been carried out it is necessary to calculate an “*average DF*”.

The activity of the background is a parameter which is strongly dependent on the procedures and instrumental techniques used for the activity measurements. For evaluation of Decontamination Factors according to (8.1.3) shielding measurement devices are necessary to provide correct data.

8.1.1.8 Decontamination techniques (processes)

Decontamination techniques may be classified in several different ways depending on the purpose of decontamination e.g. to save man-sieverts, for restoring the component/system, for decommissioning, the kind of decontamination media e.g. chemical, mechanical, electrochemical, etc., and on the nature of the surface required for decontamination (e.g. metal, concrete, painted surfaces, etc.).

The most widely used criterion refers to the kind of decontamination media. Nevertheless different classifications have been proposed since in many cases it is not easy to clearly define the “decontamination media”. Some processes may combine several different decontamination media e.g. electropolishing, which combines chemical and electrical actions, or water jets used with detergents, which combine mechanical and chemical actions. In the following paragraphs some of the classifications of decontamination techniques proposed by different studies are presented:

The US-Department of Energy (DOE) “Decommissioning Handbook” [80Man], in 1980, classified decontamination techniques into four categories: (i) chemical decontamination, (ii) manual and non-chemical decontamination, (iii) electropolishing, and (iv) ultrasonic/chemical decontamination

- Chemical decontamination:
Alkaline Permanganate (AP), Ammonium Citrate (AC), EDTA, Oxalic Acid (OX), Citrox, Sulphamic Acid, Hydrochloric Acid, Nitric Acid, Sulphuric Acid, Phosphoric Acid, Oxalic Peroxide (OP), Sulphox, Can - Decon, NS - 1
- High-pressure water lance
- Electropolishing: in-tank and in-situ
- Ultrasonic decontamination

Further Classifications were given by:

The Electric Power Research Institute (EPRI) [82Gar], in 1982,

The US-Nuclear Regulatory Commission (NRC) [81Nel], in 1981,

The Commissariat A l'Energie Atomique-France (CEA) [82Com] in 1982,

and the International Atomic Energy Agency (IAEA) [83Int], Vienna, in 1983.

8.1.1.9 Decontamination and secondary waste generation

The problem of secondary waste arising from decontamination works is of major concern in terms of quantities and characteristics. This problem is of particular relevance for chemical decontamination processes for decommissioning. In this context it became one of the leading factors for the real acceptance of the process.

On-line chemical processes like Can-Decon, Cam-Derem, LOMI, CORD/OZOX and EMMA include phases of solution cleaning in the process itself and generate relatively low volumes of ion-exchange resins as secondary waste. With electropolishing decontamination using standard electropolishing solutions, such as concentrated phosphoric acid, the treatment of the spent solution by reprocessing and recycling the solutions in order to reduce the final volume of wastes for storage has to be considered.

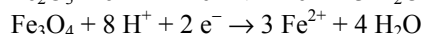
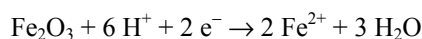
8.1.2 Decontamination techniques for large volume closed systems

8.1.2.1 Reactor decontamination in BWRs and PWRs

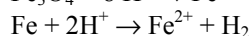
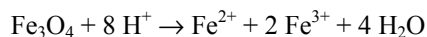
8.1.2.1.1 Chemical decontamination principle

Chemical decontamination reagent work to dissolve spinel oxide involving Fe^{3+} , Ni^{2+} and Cr^{3+} on the inner surfaces of pipes and equipment. The three-valent ions have low solubility. The oxide can be dissolved as follows:

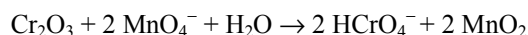
Reducing dissolution: Fe-containing oxide is effectively dissolved with reducing reagent and acid following the reducing dissolution scheme:



Acid dissolution: Acid can dissolve the spinel oxide. But acid alone also attacks the base metal:



Oxidising dissolution: Cr-containing oxide is dissolved following the oxidising dissolution scheme with permanganate ion:



A pH-potential diagram is illustrated in Fig. 8.2. Chemical decontamination is an oxide-dissolving technique used not in the passive state area, but in the metal corrosive area (indicated with hatched line in the Fig. 8.2).

Nearly all decontamination processes like Can-Decon, NS-1, LOMI and CORD reduce Fe^{3+} to Fe^{2+} .

Fig. 8.1 shows the Redox-potential as a function of pH-value of nitric-acid-permanganate (NP) and alkaline permanganate (AP). HP (permanganic acid) is in the same potential range of NP. All three oxidation methods (HP, NP and AP) oxidize Cr^{3+} to Cr^{6+} but have no ability to dissolve Fe_2O_3 and Fe_3O_4 . NP solution is advantageous in the field of Fe/Cr/Ni - austenitic materials, AP in the field of Ni-alloys.

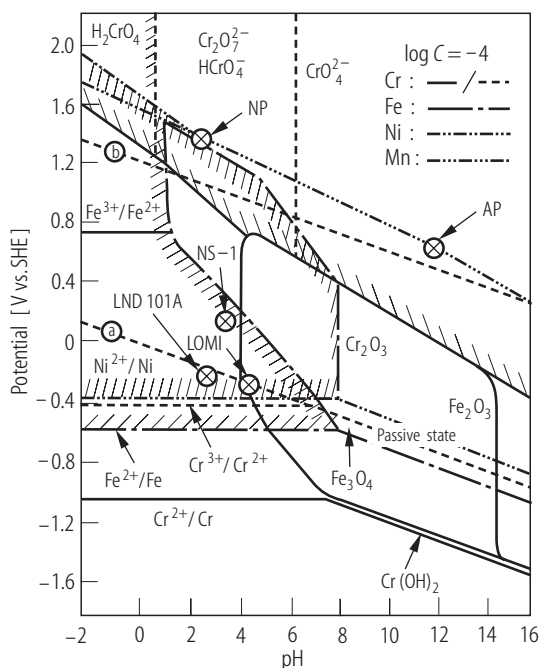


Fig. 8.2 pH-potential diagram of chemical decontamination; [00Hir]

Application of oxidation decontamination

Metal fraction of Cr in the oxide layer strictly affects decontamination performance. In the case of lower chromium content than 7 %, reducing reagent achieves successful result. But in the cases of Cr content higher than 7 %, very few reducing reagent works well without the steps of oxidising decontamination. The oxidising reagent dissolves Cr and breaks spinel structure before the reducing step.

8.1.2.1.2 Testing material compatibility during and after decontamination

Before application of any decontamination process it has to be qualified in laboratory tests.

Table 8.2 lists evaluation issues to confirm materials compatibility during laboratory test. This basis qualification covers the influence of the solvent during decontamination and the post operation behaviour in the NPP systems. In addition during application on site test coupons can be inserted to the decontamination circuit to monitor the corrosion and IGSCC. Occasionally, actual pipes are taken from the plant and used for own compatibility evaluation.

Materials compatibility during decontamination

General corrosion is evaluated with weight loss measurement and surface/cut surface observation of test coupons. General corrosion is a key issue of carbon steel and low alloy steels rather than stainless steels and nickel base alloys. Flowrate of decontamination liquid, temperature and inhibitor effect should be taken into account.

No galvanic corrosion effect is reported on the present existing decontamination methods for BWRs and PWRs.

To evaluate pitting or inter-granular corrosion, new test coupons might be inappropriate. Probes from actual tube materials that experienced plant operation history should be tested. Corrosion in crevices caused by residual decontamination reagents should be evaluated.

Table 8.2 Material testing for decontamination reagent evaluation [00Kat]

	Evaluation issues	Materials
During decontamination	General corrosion	Carbon steel
	Pitting, crevice corrosion	Carbon steel Low alloy steel
	Inter-granular corrosion	Stainless steel Ni base alloy
After decontamination	Long term compatibility against IGSCC	Stainless steel
	Crack growth rate of SCC	Ni-base alloy
		Stainless steel
	Corrosion with residual decontamination reagent	Ni-base alloy
	Effect of decontamination repetition	All reactor materials
	Recontamination	All reactor materials

Material behaviour after decontamination is one of the most concerning issues. Results of a systematic survey conducted in western countries are described below.

United States

In 1980s, London Nuclear Ltd., GE and other organisations tested material compatibility to apply reactor decontamination mainly for BWRs and Candu reactors. The tests were mainly on IGSCC susceptibility of type 304 stainless steel (SS) and nickel base alloys (Inc 600). Can-Decon, PNS-Citrox, and LOMI were tested as listed in Table 8.3 [00Kat1].

Can-Decon slightly increased SCC susceptibility of type 304 stainless steel, therefore the process was modified to a process called “CANDEREM”.

8.1.2.1.3 LOMI, Can-Decon/CANDEREM and CORD / CORD UV

LOMI, Can-Decon/CANDEREM and CORD / CORD UV were the most important processes for the last 10 years, LOMI mainly in the US, CANDEREM in Canada and US, CORD UV in Western Europe and Japan. In recent years in the US a revival of the CITROX process could be observed instead of applying LOMI and CANDEREM.

LOMI was developed by CEGB with the target to dissolve only iron oxide (hematite) located on fuel elements within the core of the SGHWR. By adding an AP and NP oxidation step the application range of the process was extended mainly to BWR.

Until 1990s, Can-Decon was applied to BWR recirculation systems and other actual plants at least 34 times. After the evaluation regarding IGSCC, CANDEREM was developed. The CANDEREM uses EDTA and citrate but no oxalate, which was the main chemical of Can-Decon. Both processes were developed by AECL. The CANDEREM is used at a temperature higher than 100 °C.

In 1991, the CORD method developed by Siemens/KWU was applied to NPP Isar, a BWR in Germany. The CORD process strictly controls pH-value and corrosion potential using oxalic acid as reducing reagent. As a preoxidation step permanganic acid (HP) is applied. Many plants including Japanese BWRs have applied CORD since 1991 to the present. Since 1994 the CORD process was improved to the CORD UV process, in which the decontamination chemicals are destroyed during the process to carbon dioxide and water. There has been no negative information regarding IGSCC with the CORD/CORD UV process. Many plants have used this process. There is a lot of experience available on this decontamination technique. Questions how circulate and to heat the solutions are well experienced. As example Fig. 8.3 shows the Fukushima Daiichi, Unit 2 Flow Diagram for decontamination [00Wil]. In total, more than 400 full system decontaminations have been performed with the Cord process.

Table 8.3 Material-testing results for decontamination reagent evaluation in the US [00Kat1]

Decon reagent	Test method	Materials	Water chemistry	Results	Corrosion	Reporting organisation
Can-Decon (Nutek L-106, LND-101)	Tube test	304 SS	BWR (DO: 8ppm)	No acceleration on propagation rate of existing crack	50µm IGA was observed on sensitised 304 SS.	London Nuclear Ltd. [85EPR]
Can-Decon (LND-101A)	SSRT	304 SS	BWR (DO: 0.2ppm)	No effect on SCC susceptibility in 100 h decon, but 500 h decon. Increased on sensitised 304 SS.	No description	Ontario Hydro [85EPR1]
Can-Decon (LND-104, LND-101A)	Double U-bend 4-point-supporting bend test	304SS, Inconel 600	PWR (DH: >3ppm)	No susceptibility increase to SCC	Pitting on 304 SS and 1.5µm IGA symptom on Inconel 600	London Nuclear Ltd. [85EPR2]
Can-Decon (LND-104)	SSRT	304SS, Inconel 600	PWR (DH: >3ppm)	No susceptibility increase to SCC	No IGA	London Nuclear Ltd. [85EPR3]
Can-Decon, LOMI	SSRT Stress beam Test	304SS, Low alloy steel, (SA533B) Inconel 600	BWR (DO: 0.2ppm)	Can-Decon increased 304SS SCC susceptibility. No effect with LOMI	Can-Decon caused 200µm IGA on 304SS and 100µm IGA on Inconel 600. No IGA with LOMI.	G.E. [86EPR]
PNS-Citrox	SSRT	304SS, Low alloy steel, (SA533B) Inconel 600	BWR (DO: 0.2ppm)	Sensitized 304SS increased susceptibility to SCC in some cases.	80µm IGA on 304SS and 60µm IGA on Inconel 600	G.E. [86EPR1]
LOMI, Can-Decon PNS-Citrox	SSRT Stress beam Test	304SS, Inconel 600	BWR (DO: 0.2ppm)	Can-Decon and PNS-Citrox increased susceptibility of sensitised 304SS to SCC	IGA were observed as the same extent as the above two columns	G.E. [86Man]
LOMI	Tube test Crack growth rate measurement	304 SS 316 NG SS	BWR (DO: 0.2ppm)	No susceptibility increase to SCC	No description	G.E. [86Man]
Can-Decon (LND-101A)	SSRT	304SS	BWR (DO: 0.2ppm)	No susceptibility increase to SCC	Slight IGA symptom was detected in some cases	G.E. [86Man]

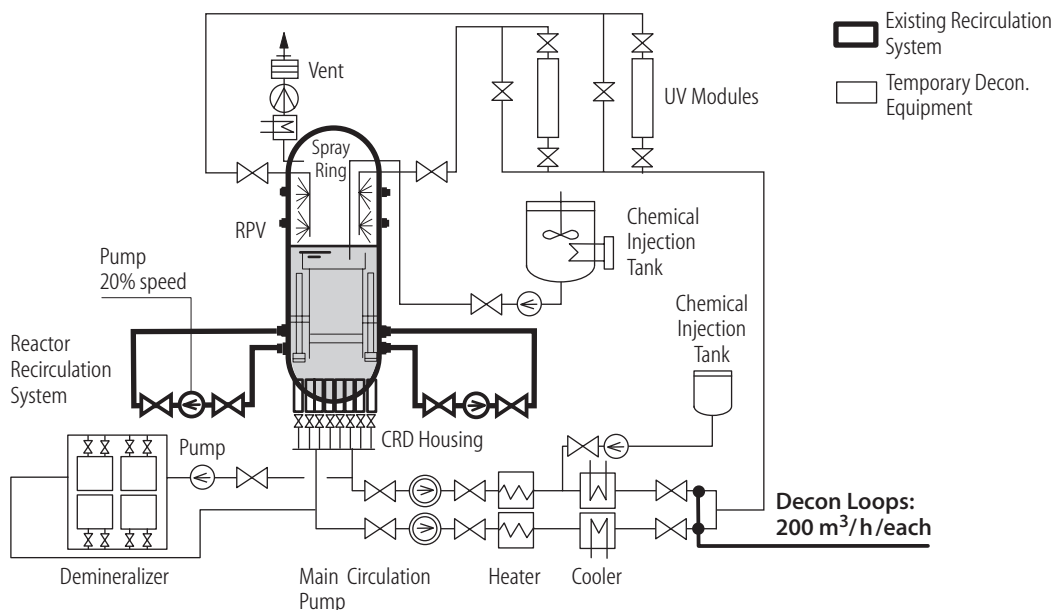


Fig. 8.3 Fukushima 1 Unit 2 Flow diagram; [00Wil]

8.1.2.2 Fuel assemblies and decontamination

Fuel surface crud usually contains a 100 to 1000 times higher inventory of radioactivity than recirculation system oxide layers. A decontamination reagent is easily decomposed by gamma rays and neutrons from the fuel even in reactor lay down periods. In spite of these difficult conditions fuel elements may have to be decontaminated for two reasons. In case the crud deposits cause too high pressure drops to achieve a homogeneous reactor coolant water flow cleaning is required. In addition, the treatment of spent fuel elements depends on a certain degree of cleanliness.

The SGHWR (100 MWe, closed in 1991, UK) and Candu reactors often performed the decontamination of fuel assemblies in situ. The LOMI developed for this purpose has self-regenerating ability in the presence of radiolysis. Pressure-tube-type reactors are usually designed for on-power refueling. This requires more time than required for BWRs and PWRs to discharge all fuel from the core. In spite of that, Fugen (165 MW, Japan) a pressure tube type reactor, was decontaminated after discharging the fuel to obtain a higher decontamination factor and to reduce radioactive waste.

NPP Paks found a thermal-hydraulic anomaly in the reactor core caused by corrosion product deposits. Consequently, the coolant flow through the fuel assemblies was insufficient resulting in a temperature asymmetry in the reactor core. The fuel assemblies were removed from the core and successfully cleaned applying the CORD UV process.

8.1.2.3 Decontamination of sodium cooled systems

These systems may be decontaminated effectively by acid solutions. Within the research and development programme of the CEC an inorganic acid-based process has been evaluated and tested by CEA for the RAPSODIE reactor in France [89Cos]. Decommissioning operations began in 1987. Preliminary cleaning and water rinsing after isolation of the main vessel eliminated all traces of residual sodium. Main contamination nuclides were ^{137}Cs , ^{63}Ni and ^{54}Mn .

After steam-cleaning to remove the residual sodium, the specimens were highly rusted. One of the first reagents to provide satisfactory results was a mixture of nitric acid and sulphuric acid at 85 °C. In order to improve the effectiveness of the decontamination, the aggressiveness of the reagent was

enhanced by adding cerium (IV) in sulphate form. This reagent is sufficiently oxidising (Redox potential $E_h = 1.610$ V) iron, chromium and nickel in austenitic steels. Together with an alkaline washing excellent decontamination results were obtained: The estimated initial contamination level of 5500 Bq cm^{-2} was reduced to less than 10 Bq cm^{-2} . The low residual contamination values allowed to estimate the pipes to be melted down for reutilization and release and an authorisation has been applied for. The dose rates were uniform throughout the facility, ranging from 1 to $15 \mu\text{Gy h}^{-1}$

8.1.2.3 Gas cooled reactors (WAGR)

An important feature of the Windscale AGR dismantling programme was the removal and disposal of the four heat exchangers [89Cro]. Each heat exchanger contains tube banks (or superheater banks), with plain Cr/Mo low alloy steel tubes and evaporator and economiser banks with finned mild steel tubes.

Contamination was found to be incorporated in this oxide layer and to consist predominantly of ^{137}Cs with some ^{134}Cs and ^{60}Co . Average values of $1.6 \times 10^3 \text{ Bq cm}^{-2}$ for Cs and $0.2 \times 10^3 \text{ Bq cm}^{-2}$ for Co were measured, giving a total for the superheater of about $2 \times 10^{11} \text{ Bq}$. To remove the activity it was necessary to remove the oxide layer from the tubes.

The decontamination was performed by spraying with a 3000-litre mixture of 0.5 molar (3.15 % by weight) nitric acid and 0.0025 molar citric acid at ambient temperature. In total the radiation level was removed by 70 %, activity were removed, the manSv-uptake was reduced remarkably and the targets reached.

8.1.3 Decontamination techniques for segmented parts

8.1.3.1 Chemical decontamination

The chemical decontamination of an item removed from a nuclear plant or facility is generally carried out by immersion in a tank containing the chemical reagent [92Com]. The size of the tank depends on the dimensions of the item to be decontaminated. A common size is one, which is 1-2 m square with a depth of 0.5-1 m. Tanks for water rinsing are always installed. In sequential multistep processes the availability of several tanks can be useful in order to reduce the time needed.

Chemical decontamination is characterised by the following parameters:

- Type and nature of the chemical reagent;
- Temperature of the process;
- Duration of the process.

The effectiveness of decontamination can be improved by increasing the duration of the treatment and the temperature. Optimum results are usually obtained with the solvents at elevated temperatures (up to 120°C). During the decontamination process, as the concentration of the contaminants in the solution increases, the item being cleaned may become re-contaminated. This problem can be minimised by cleaning the least contaminated items first and by cleaning or replacing the solution if the concentration of contaminants exceeds certain levels.

It should be noted that strong corrosive attack of the base metal may not result in high decontamination factors. These can however be achieved without significant corrosion of the base metal. Strong solutions of nitric and phosphoric acid used in the USA Bonus programme resulted in the removal of up to 0.2 mm of the inner wall of pipes, but only an average decontamination factor of approximately 100 was achieved. Results to date with non-aggressive processes indicate that decontamination factors as high as 2000 can be achieved without significant corrosion of the base metal [81Nel].

Some multistep processes are commonly used for removing highly adhesive contamination layers. In many cases chemical decontamination can be used as a single step in complex processes e.g., before electropolishing, items covered with thick oxide layers are submitted to chemical decontamination in order to soften the oxide.

8.1.3.1.1 Chemical reagents

Since the 1950s several chemical reagents have been commonly used for cleaning contaminated items. Lists with more than 100 chemical products can be read in dedicated decontamination handbooks [88Int, 81Nel, 82Com]. Some examples of chemical reagents used are given in Table 8.4.

Table 8.4 Some reagents typically used in chemical decontamination of reactor components depending on type of material to be decontaminated.

Materials	Reagents
Aluminium	HNO ₃ , Na-EDTA + 2 % detergent, 10 % citric acid, sulphamic acid
Brass	HNO ₃ , 5 % AC
Carbon steel	Inhibited HCl, inhibited sulphamic acid, EDTA, citric + oxalic acids, APAC, CITROX,
Copper	Phosphorous, nitric and acetic acids
Nickel & Alloys	AP, 25 % HNO ₃ + 25 % HF, AP + AC, AP + CITROX, EDTA
Monel	25 % sulphamic acid
Stainless steel	AP- CITROX, EDTA-CITROX, 30 % HF + 20 % HNO ₃ , 70-80 % H ₃ PO ₄ , 0.4 M Cr SO ₄ + 0.5 M H ₂ SO ₄ , AP-HNO ₃ , AP-AC, AP-OX, APACE
Zircalloy	OX + H ₂ O ₂ + glucosic acid, EDTA, 8 M HNO ₃ , ...

AP: alkaline permanganate, AC: ammonium citrate, OX: oxalic acid, CITROX: citric + oxalic acid, APACE: AP + AC + EDTA.

There is a wider range of solvents to choose from for decommissioning programmes since corrosion of the base metal is of little concern. Certain solvents exhibit a time dependency in the mixing, heating, recirculation and draining cycle that affects both the chemical solution stability and the solubility of contained contamination. Each process under consideration would have to be evaluated for the effect of a loss-of-flow accident and associated cooling of the solvent. Factors considered would include toxic or explosive gas generation, excessive plate-out and excessive corrosion. The selected process must include appropriate emergency procedures, e.g. emergency draining, gas detection, and emergency ventilation.

8.1.3.1.2 Spent decontaminant solutions

The selection of the chemical reagent directly affects the features of the secondary wastes arising from the process. It is obvious that continuously renewing the solution increases the decontamination effectiveness [85Pas] but the quantity of spent solution to treat and to dispose of also increase dramatically. In latter years the regeneration of chemicals have become a fundamental step in all chemical decontamination processes.

Several conventional chemical processes can be used for regenerating the spent solutions either on their own or in combination and they include: ion exchange, evaporation/distillation or electro-dialysis.

The problem of limiting the secondary wastes arising from the decontamination process, sometimes leads to the selection of other similar processes like electropolishing or ultrasound with chemicals rather than chemical decontamination. As stated previously, only a detailed cost/benefit analysis can provide the actual criteria for selecting the best option for decontamination.

8.1.3.2 Electrochemical decontamination

8.1.3.2.1 In-Tank

Electrochemical decontamination can be considered in principle to be a chemical decontamination assisted by an electrical field. Nevertheless the best electropolishing is a process widely used in non-nuclear industrial applications to produce a smooth polished surface on a variety of metals and alloys. It can be considered the opposite of electroplating as metal layers are removed from a surface rather than added as a coating. Usually the object to be electropolished is immersed in a tank of electrolyte and is used as the anode in the electrolytic cell. The passage of electric current results in the anodic dissolution of surface material and, for normal operating conditions, a progressive smoothing of the surface.

A progressive dissolution of the surface material occurs within a certain range of voltage and current density [83Int]. If the voltage and current densities are too low, the surface is attacked non-uniformly, causing etching rather than polishing. Similarly voltages that are too high cause severe pitting of the surface [87Pav].

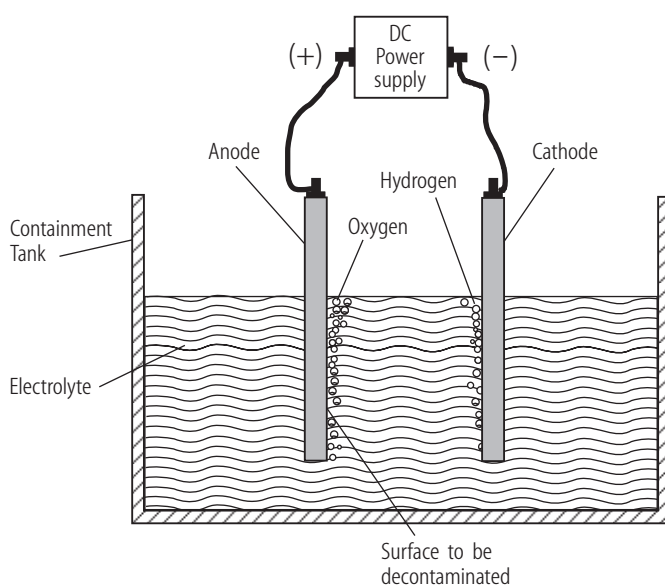


Fig. 8.4 Electropolishing device

If the anode is a contaminated material such as metal or alloy, all radioactive contamination on the surface (or entrapped within surface imperfections) can be removed and released into the electrolyte by this surface dissolution process [85Pas]. The process produces a very smooth (0.02-0.03 mm), non-reactive and non-adsorbing surface resistant to recontamination during further operations. Experience has shown that electropolishing is an effective technique for removing both fixed and smearable radionuclide contamination. Moreover it is fast and easily controlled.

In general, there are two methods of application for electropolishing. The most common method is immersing the item to be decontaminated in a tank filled with a suitable electrolyte. The second method involves the use of “in-situ” mobile devices that are able to electropolish part of the surface of the item, which, because of size or installation, cannot be electropolished in a tank.

Phosphoric acid is normally used as the electrolyte in electropolishing because of its stability, safety and applicability to a variety of alloy systems. Moreover, the non drying nature of phosphoric acid helps minimise airborne contamination, and the good complexing characteristics of phosphoric acid for metal ions is a significant factor in minimising recontamination from the electrolyte.

Representative operating conditions for decontamination using phosphoric acid electrolytes are: solution temperatures of 5 to 25 °C, phosphoric acid concentrations of 40 to 85 %, electrode potentials of 8 to 12 V and current densities of 5 to 25 A cm⁻².

The direct current power supply converts alternating current into direct current which generates the current flow between anode and cathode required for the electrochemical reaction. Voltage requirements range from 0 to 24 V with sufficient amperage to provide the required current densities.

From experience gained in non-nuclear industrial applications, electropolishing normally uses phosphoric acid as the electrolyte (sulphuric acid is an alternative). However, during the last decade a variety of different electrolytes have been tested and developed with particular reference to the problem of reducing the secondary wastes arising from the process. As a consequence new processes usually called electrodecontamination or electropickling decontamination have been proposed. These consider the use of basic solutions as well as organic acid mixtures. Finally, among the electrodecontamination processes for "in situ" applications, electrobrushing using an electrobrush continuously fed by an electrolyte should be mentioned.

Electrolytic decontamination can be used to remove fixed or imbedded contamination on iron-based alloys, including stainless steel, as well as on copper, aluminium, lead, and molybdenum. However the effectiveness of the decontamination can be limited by the presence of foreign materials on the surface of the items to be decontaminated. Materials such as oil, grease, oxide (rust), and paint or other coatings should be removed before decontamination.

In decontaminating (mainly for decommissioning purposes) reactor coolant systems, the systems are usually covered by oxide layers that in principle work as a barrier for electropolishing. This problem can be overcome by increasing the electropolishing time. Nevertheless some new processes consider the periodic switching of polarity between cathode and anode, as well as changing voltage and current in order to increase the removal of the surface materials [86Gau]. Generally, at least two (stainless steel) tanks are required for performing electropolishing. One tank contains the electrolyte, electrodes, and parts to be decontaminated (as anode). The other tank holds the water used for rinsing the parts after decontamination. Power supply amperage capacities up to 2700 A are common.

The cathode is normally a piece of copper, or stainless steel, positioned in the electrolyte within 30-100 mm from the item to be decontaminated. In addition for special items, the walls of the tank for immersion electropolishing can also serve as the cathode.

To control vapours released from the electrolyte during the electropolishing process an extraction hood is located alongside the electropolishing tank. Provision for heating and agitating the electrolyte and rinse tank is also required.

Studies on "in-tank" electropolishing became of relevance in the early 1970s in the USA where they were used to decontaminate hot-cells, glove-boxes, and tools contaminated by alpha emitters. Decontamination carried out in conjunction with Rockwell Hanford Operations and United Nuclear Industries in the USA, show that components heavily contaminated with PuO were decontaminated from 1 million dpm per 100 cm² to background in less than 10 minutes [78All].

Typical decontamination times range from 5 to 30 min, corresponding to the removal of 10 to 50 mm of surface material at a current density of 2-15 A/dm². It is usually necessary to remove the anode contacts at least once during a cycle in order to decontaminate the area under the contacts.

Since the early 1980s commercial use of electropolishing in decontamination of reactor coolant water systems and components for decommissioning purposes was made at the KRB power station (reactor A) in Germany [83Eic, 01Eic].

Electrochemical decontamination by electropolishing causes a steady increase of dissolved iron in the phosphoric acid. If the content of iron exceeds 100 g dm⁻³, a precipitation of iron phosphate occurs and this stops the efficiency of the decontamination process. Therefore the acid has to be exchanged or regenerated periodically. The regeneration of phosphoric acid is based upon the reaction of Fe²⁺ with oxalic acid (see Fig. 8.5). Electrochemical decontamination of steel, however, generates a high percentage of Fe in the phosphoric acid, which cannot be precipitated to iron oxalate. The high content of Fe³⁺ is reduced to Fe²⁺ by subsequent pickling. When a high portion of Fe²⁺ is obtained, the phosphoric acid has to be mixed with an aqueous solution of oxalic acid. The activity (mainly ⁶⁰Co) is mostly separated from the solution by precipitation together with the iron. The iron oxalate is dried and stored for subsequent processing. The initial concentration of the phosphoric acid can be achieved by an evaporation process [89Sta].

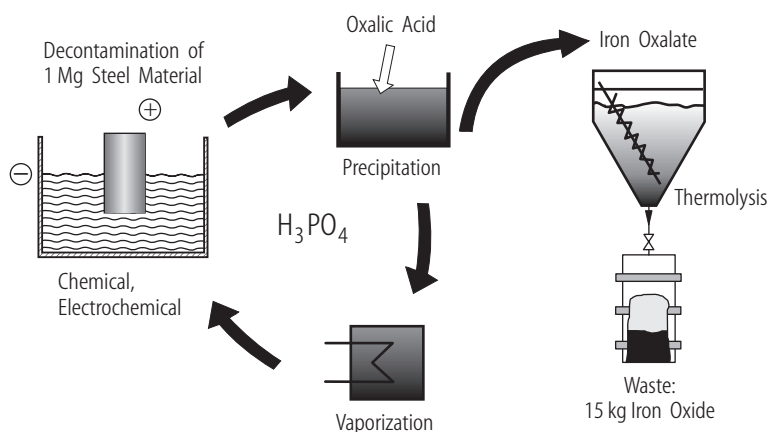


Fig. 8.5 Flow chart of the phosphoric acid regeneration

Several electrolytes were investigated and proposed as alternatives to phosphoric and sulphuric acid. The need for new electrolytes was initially motivated by the incompatibility of phosphoric and sulphuric acids with the existing treatment facilities and by the possibility of generating secondary liquid wastes which are more easier to process.

This regeneration process was extensively proved at KRB Gundremmingen in Germany where more than 200 m³ of phosphoric acid (concentration 20-40 %) have been regenerated. The iron oxalate can be converted to iron oxide by pyrolytic decomposition.

With this method, KRB-A-Reactor materials like pipes, pumps, and housings were decontaminated. Decontamination Factors of more than 100000 were reached.

8.1.3.2.2 “In-situ”

In the case of “in-situ” electrochemical decontamination, the surface of the item to be decontaminated is flooded with electrolyte through a gap between the cathode of the device and the item's surface. The inside of tanks, housings and other relatively open vessels, without internal components, can be decontaminated without removal using an expandable “bladder” with a conductive surface that serves both as the cathode and as a displacement device to minimise the electrolyte volume. Several devices have been developed in the USA for application of “in-situ” electropolishing [82Gar1]:

The internal cathode device consists of a perforated, tubular, copper or stainless steel cathode section with insulator-spacers at each end and has the provision for pumping the electrolyte and feeding power through the insulator at one end. The perforated tubular section permits flow of the electrolyte to the pipe surface being decontaminated, thus accomplishing the electropolishing action. An improved device with four module heads was designed and used in Germany for the Obrigheim power plant [84KWU]. The pump stream device consists of a perforated, disc-shaped, copper or stainless steel cathode facing the surface to be decontaminated, with an insulated handle for flow of electrolyte and supply of power. The electrolyte flows out of the end of the device in a stream and impinges on the surface being decontaminated.

8.1.3.2.3 Electrobrushing

Electrobrushing is an electrodecontamination process for selected areas. The item to be decontaminated is used as the anode, while an electrobrush serves as the cathode. The brush itself is a cellulose sponge wetted by a continuous feed of an electrolyte, such as 5 % sulphuric acid solution inhibited with 1 g dm⁻³ ethyl quinolinium. Decontamination is carried out by scrubbing at a current of 15 to 40 A at 15 to 20 V, and decontamination factors of around 30 are reported at a rate of 0.6 m²h⁻¹ [81Nel].

The disadvantages of this process include the production of large volumes of aqueous radioactive waste and excessive attack of the surface by the electrolyte. In addition, if the decontamination is performed manually rather than remotely, the radiation exposure to operators may be high.

Single electropolishing and brushing processes can be combined. Subsequently, in decontaminating cast steel components at the KRB Gundremmingen power station in Germany, it was found that brushing prior to electropolishing resulted in a 35 % reduction of the time required for the galvanic decontamination process and the reduction of dissolved iron in the electrolyte was also found to be a benefit of prebrushing [89Sta].

8.1.3.3 Jetting decontamination techniques

The impingement of either a liquid or a solid media (or a liquid solid mixture called slurry) can be successfully used for decontamination. Extensive use of jetting methods to clean surfaces and items has been made in many industries and for varied applications. As a result of this several decontamination methods have been studied, developed and as a result of this several contaminated materials.

Generally, jetting decontamination processes have a high flexibility and can therefore be applied to both large surfaces e.g. floors and walls, and relatively small-contaminated items and systems. Contaminated glove-box internals and several types of tools have also been cleaned using jetting processes.

The problem of amount and characteristic of secondary wastes is one of the main concerns for jetting processes. The amount of waste can be strongly reduced by recirculating, treating and rinsing the impinging jetting media. Particular care must be applied to processes using abrasives.

A variety of nozzles and lance configurations can be used for high-pressure water cleaning depending on the configuration of the item to be decontaminated. A straight jet can be used on the end of a long handled lance to reduce worker exposures for decontamination of accessible tank interiors, walls or floors. Self-propelling mole nozzles on a flexible high-pressure lance or hose can be used to decontaminate the inside of tubing or pipes.

Because high pressure water cleaning is very effective for the removal of smearable surface contamination, water lances have been successfully used to decontaminate pump internals, valves, cavity walls, spent fuel pool racks, reactor vessel walls and heads, fuel handling equipment, feedwater spargers, floor drains, sumps, interior surfaces of pipes and storage tanks.

Although decontamination factors of up to several hundred are commonly achieved, the normal factor for most applications is up to 50. Decontamination factors of 2 to 50 with water as the agent and of 40 with the addition of a proper cleaning agent were achieved at a particular site [79Rem].

8.1.3.3.1 Abrasive jetting

Abrasive jetting is a very effective decontamination method in which an abrasive medium is propelled by a jet of air (dry blasting) or water (wet blasting) against the surface to be cleaned [82Gar, 81Rem]. Typical abrasives are sand, alumina and metals, metal oxides and sawdust. Sand is the most common abrasive because it is inexpensive and a good scouring agent.

Abrasive cleaning can be wet or dry. Abrasive particles are impelled at high velocity against the surface to be cleaned by air, water or a mixture of the two, as in the following air abrasive blasting, water abrasive blasting, air slurry blasting. Alternatively the particles may be carried in a viscous matrix and rubbed against the surface (liquid honing or abrasive slurry cleaning) or the abrasive may be in the form of stones, which can be used to grind or hone the surface to be cleaned. For effective cleaning either high-pressure air at about 1 MPa or water at pressures similar to those used in hydrolaser systems are used, depending on the application. The abrasive can also be attached to a flexible backing to form a type of sandpaper or emery cloth or it can be forced against the surface by centrifugal action.

The different types of abrasive can be grouped into three general classifications depending on hardness:

Hard abrasive materials: For decontamination, hard abrasive materials (harder than the material to be removed) are commonly used [64Ame]. In addition, there are three special sub-classifications: Cleanable abrasives, soluble abrasives and system compatible abrasives. The last one being important only for the decontamination of items required for reuse.

A cleanable abrasive simplifies the problem of secondary wastes by markedly reducing the quantity of contaminated material to be disposed of after decontamination. One type of cleanable abrasive that can be used on non-stainless steel surfaces is steel shot. To facilitate cleaning the particles should be smooth; unfortunately smooth particles also reduce the abrasive action.

A soluble abrasive is a material, which can be used in solid form in an air or water jet and can later be removed from the system by dissolving it in a liquid and flushing it out of the system. Boron oxide, which dissolves in water to form boric acid, is such a material.

There are a number of methods of application of abrasive jetting, which depend on the carrier fluid, flow velocity and kind of abrasive used. Abrasive blasting is often carried out in special cabinets [91Bru].

A specific case of abrasive blasting is dry ice blasting which uses ice pellets (2-3 mm in diameter) produced by CO₂ flashing at 40 °C. The use of dry ice pellets as an abrasive media strongly reduces the volume of secondary wastes produced [70Ayr].

The vacuum blasting method is a modification of air abrasive blasting for “in-situ” use where the discharge nozzle is surrounded by a concentric hood. An air exhaust line is attached to the hood and the blast air, debris and spent abrasive are drawn out through the exhaust line. The debris and abrasive are separated and the abrasive is reused. Smaller, hand-held units are also available.

Water abrasive blasting has been used successfully to decontaminate a wide variety of contaminated components. Methods of remote application have been developed for “in-situ” cleaning to supplement the more common manual application methods. Decontamination factors of 200 to 300 are commonly achieved.

8.1.3.3.2 Freon jetting

Systems have been developed to remove loose contamination from surfaces and equipment using commercial freon (trichlorotrifluoroethane) cleaning solvents [88Int]. Freon has a low viscosity and surface tension, which allows it to penetrate into cracks and crevices and remove contamination, including that associated with grease, oil, etc. Freon is non-flammable and chemically inert and can therefore be used to clean many types, of equipment without damaging delicate components. Most radioactive contaminants are insoluble in freon and can be removed by filtration or distillation, allowing recycling of the freon. Freon decontamination is carried out by directing a high pressure (15 MPa) jet of the liquid onto the surface to be cleaned. The decontamination is usually carried out inside a glove box [81McV], but experimental units have been developed for “in-situ” cleaning.

The freon liquid and particles of contaminant are collected in a sump; the liquid is then filtered to remove the contaminants, cleaned and recycled. The freon is distilled as required to remove any radioactive material, which has dissolved in the liquid. The use of this decontamination technique is often limited due to legislative and regulatory restrictions in the industrial use of freon and freon-compounds due to their potential effect on the environment.

8.1.3.4 Ultrasonic decontamination

Ultrasound consists of longitudinal mechanical waves and has been used over a long period of time for cleaning dirty surfaces in non-nuclear industry. In particular, ultrasonic cleaning has been used with good success for removing oil, grease, dirt and scale from a variety of items of various sizes and configurations. As a result of this ultrasound was used as one of the first methods for surface decontamination purposes in the nuclear industry [81McV].

The process is particularly appropriate for decontaminating items with complex surfaces where other decontamination techniques are not suitable. It has been successfully used to clean dirt from holes, cracks and crevices in parts made of metal, glass, and a variety of plastics. Its most common application is for decontamination of tools and items that are evenly contaminated and it is carried out by immersion in an ultrasonic tank containing water (or water with chemical additives) [82Gar]. New applications have been developed replacing water with more aggressive chemicals in order to combine the cleaning effect of both the chemical and ultrasound.

8.1.3.4.1 Ultrasonic technique

The two main components of ultrasonic cleaning systems are the ultrasonic generator and the transducer (or vibrator). The ultrasonic generator converts normal 50-60 Hz power to a high frequency supply usually in the range of 18 to 25 kHz. The high frequency alternating current is then fed to a transducer to produce vibration in the liquid. The transducer is generally made of piezoelectric material (i.e. material that will elongate or contract depending upon the polarity). As a consequence of the vibration, compressive and rarefacted phases are present in the solution. In the rarefaction phase, cavities are generated (mainly originating from nucleation points) and during the compressive phase these collapse causing a phenomenon called "cavitation". When an item is immersed in the solution, the collapse of cavities causes scrubbing on its surface and hence produces a cleaning action. It is important to note that the presence of many nucleation points causes cavitation mainly on the surface of the items. The cavitation occurs even if the surfaces are inhomogeneous and complicated or located in inaccessible zones. Calculations indicate that during cavitation localised peak pressures as high as 70 MPa can be reached. These conditions produce a strong cleaning action on any surface upon which they act [82Gar].

Two factors play a fundamental role in the action of ultrasound: the cavitation threshold and the scrubbing factor. The cavitation threshold is the pressure difference inside the fluid, which allows the cavitation phenomenon to take place, and is directly correlated with the ultrasonic power applied to the solution.

8.1.3.4.2 Ultrasound in conjunction with chemicals

It is well known that in order to increase the effectiveness of the process in terms of scrubbing effects, or decontamination factors, an appropriate liquid should be selected. In ultrasonic cleaning, specific chemical agents are commonly added and the ultrasonic cleaning combines the effect of cavitation of a liquid at the surface to be cleaned with the chemical action of the liquid.

The physical and chemical properties of the liquid are important. Decontamination factors as low as 2 have been obtained by using pure water at room temperature. The addition of a cleaning or wetting agent in the amount of 2 to 5 % by weight, with an increase in temperature to about 80 °C, can greatly increase the cleaning ability of water. The addition of small amounts of citric acid, or other chemicals, can also enhance the cleaning ability.

Reports on the effectiveness of ultrasonic decontamination from the 40 or more nuclear plants where it has been used are mixed. Some plants use it on a regular basis with good success, obtaining decontamination factors in the range of 5 to 100 [80Man]. Other plants report little success, and some have stopped using ultrasonic cleaning entirely [82Gar].

KWU-Service used ultrasonic decontamination to clean primary recirc pumps at several power plants (Biblis A-B, Neckarwestheim, Unterweser, Borselle and Atucha). This equipment has also been used in more recent power plants. At the KWU Centre in Karlstein, Germany, a large amount of scaffolding and small tools were decontaminated up to the release limit [84KWU].

8.1.3.4.3 Decontamination by mobile ultrasonic tools

A specially designed ultrasonic hand-held wall cleaner and floor cleaner has been designed at the Argonne National Laboratory in the USA for decontamination of flame-sprayed zinc on hot cell liners [70Ayr].

8.1.3.5 Decontamination by foams

Foam decontamination uses liquid foam generated from an acid or acid mixture, using air, nitrogen or an inert gas. The foam also contains various chemical additives such as inhibitors, foam stabilisers and surfactants [82Com]. Typical acids used are hydrochloric, nitric, hydrofluoric, sulphuric, and phosphoric and organic acids can also be considered. The foam is produced in a foam generator and the density can vary considerably – typically 1 litre of acid solution is used to produce 20 dm³ of foam. Foams have been successfully used in decontamination. The use of foams started more than 40 years ago [60Ayr] and at that time, inhibited hydrochloric acid, together with special surfactants, was used. Decontamination factors in the range of 5 to 50 are obtained with a single foam application using 7-10 % phosphoric acid [82Gar].

8.1.3.6 Decontamination by gels

A gel medium is defined as a semisolid system obtained by flocculating and immobilising particles in a continuous medium. The problem in utilising this method of decontamination is the generation and *maintenance of* adequate gel systems in combination with decontaminating chemicals. For example, it has been found difficult to develop an adequate gel system using alkaline permanganate solutions [82Gar].

Gels can be made from either organic based or inorganic based systems and contain in the gel formulation decontaminating chemicals which are normally acids such as phosphoric, sulphuric, or nitric [80Des]. High decontamination factors (in excess of 50) have been obtained in the laboratory for mild steel, stainless steel, aluminium, copper and Plexiglas. Large decontamination tests by gel spraying decontamination have been performed at CEA-CEN-Cadarache, France, on 17 Mg of steel from the German ISAR-BWR (consisting of 11 Mg of frame and 6 Mg of pipes) [89Brun]. The chemicals used were sulphuric acid (2 mol dm⁻³) and hydrofluoric acid (1.6 mol dm⁻³) and during the decontamination 100 litres of gels were used.

8.1.3.7 Decontamination by pastes

Cleaning pastes are widely used for treating metal surfaces, particularly for stainless steel, and can be extremely effective for decontamination. They consist of a filler, carrier and use an acid or mixture of acids as the active agent. The concept of decontamination pastes follows the method used for the older paste systems, however new acid systems particularly effective in removing radioactive contaminants have been developed. These pastes, when applied in a thin layer on contaminated surfaces, can provide effective decontamination, together with generating relatively small quantities of waste.

8.1.3.8 Mechanical decontamination techniques

Mechanical techniques include many decontamination methods based on the use of mechanical tools or devices to remove the surface contamination [56USS]. Mechanical devices are commonly used for cleaning industrial tubing and piping and can be adapted for the decontamination of similar items in a nuclear installation.

8.1.3.9 Decontamination by strippable coatings

Decontamination by strippable coatings consists of the application of a coating over the surface to be decontaminated. This coating is then left on the surface for a set period (from few hours to a few days) and then removed/stripped resulting in removal of the contamination. Strippable coating formulations usually consist of high molecular weight, film forming, synthetic polymers such as polyethylene, polyvinylacetate, polyvinylchloride, acrylics, etc., dispersed as an emulsion in an aqueous base. These coatings usually contain an active agent e.g., an acid or mixture of acids, which attack the contaminants on the surface to which the coatings are applied. The coatings may be applied with a brush, spray system, roller or other similar method. In some cases, it may be necessary to apply two or more coats to ensure that the coating has sufficient strength to be readily removed from the surface without tearing. The coatings are applied in varying thicknesses from 0.5 to 2 mm [79TMI]. Usually the coating is then manually stripped off the surface in sheets, compacted and placed in waste containers.

8.1.3.10 Melting

Melting is considered as a decontamination process since it can be used to reduce the specific contamination. The method completely destroys components and is effective only for contaminants that are volatile or more soluble (e.g. plutonium) in the slag than the molten metal. The decontamination efficiency varies widely depending on the radioisotope present. The radionuclides remaining in the molten material are distributed homogeneously and effectively immobilised, thus reducing the possibility of the spread of contamination. The melting should take place in a suitable refinery, which has filters on the gas exhaust system to protect the environment [85Pfl].

Melting is extensively used in Germany. From 1984 to 1989 more than 2000 Mg of low-level contaminated scrap ($<74 \text{ Bqg}^{-1}$) have been melted and recycled [90Sap].

8.1.4 Decontamination techniques for building surfaces

Decontamination processes to be used for contaminated concrete depend greatly on the characteristics of the concrete surface to be cleaned. They can vary from very simple hand based processes, to jackhammers or drilling removal techniques. The former is normally used for cleaning painted or smooth surfaces covered by loose contamination and the latter for decontaminating concrete in which the contamination has penetrated deeply. The following techniques are in use:

Brushing, washing and scrubbing: These are widely and frequently used at nuclear facilities to clean smooth surfaces, because they are simple and inexpensive. They are generally considered together, because they are related and in many decontamination works are used jointly or sequentially.

Smearable contamination can be removed by wiping with a dry or damp cloth if the surface is smooth or impervious. To increase the effectiveness of decontamination detergents and solvents are added to the solutions especially if the loose contamination is associated with grease or oil. Abrasive powders or pads can be used if the contamination is associated with rust if it is embedded near the surface.

Vacuum cleaning: Vacuum cleaning is one of the most widely and frequently used decontamination processes to clean smooth concrete surfaces. It is also used to collect dust resulting from brushing decontamination processes such as scarifying, spalling, etc. The process is very simple and can be efficiently used for loose particles on both wet and dry surfaces.

Scarifying and grinding techniques: Scarifying and grinding processes [80Bar] have been widely used for a long time for the decontamination of concrete walls and floors of different nuclear facilities. They are particularly appropriate for the removal of thin concrete contamination layers (typically less than 10 mm).

Thermal scarifying: Thermal scarifying processes are based on the removal of concrete layer by thermal energy introduced by flame (or plasma) impingement on the surface to be decontaminated. In principle two different thermal scarifying phenomena may take part in the process: spattering and melting [85Ebe].

Both spattering and melting use almost all the thermal energy of the flame, so that no heat penetrates the material. The energy remains in the spattered and molten material, which becomes separated from the concrete. After flame scarifying, the loose particles and remnants of combustion must be removed from the treated surface. Circular brushes or cleaning machines, which can be fitted with steel wire brush rollers or beater rollers, are recommended for this task. Flame scarifying has long been used to treat surfaces in order to produce a clean, dry base for paint and other surface coatings.

Spalling: When a floor or wall is deeply contaminated, a thick concrete layer must be removed in order to decontaminate it completely. Removal of the surface radioactivity in this manner, in comparison with demolishing the entire structure, eliminates the need to dispose of large quantities of non-radioactive concrete, which may arise with other volume removal techniques. To remove these thick concrete layers hard mechanical processes should be used. Surface breakers, pneumatically or hydraulic operated drilled bits, and water cannons are typically used in spalling processes.

8.2 Decontamination of skin

8.2.1 Introduction

Radiation protection rules in national legislation generally include action levels or limits for protection measures in case of surface contamination at the workplace and of objects (see Section 8.1). Frequently limits for decontamination measures of skin are not included. However, radiation protection in practice requires at least reference values to avoid unsuitable or detrimental decontamination measures which may lead to skin lesions or increased incorporations. Based on new calculations of equivalent dose rates for the skin [85Hen], recommendations of reference values have been developed, among others, by the German Commission on Radiological Protection [92SSK] which serve as a basis for the following specifications.

The described measures in case of skin contamination are generally based on the following principle: In the event of contamination, the resulting radiation dose must be kept as low as reasonably achievable, economic and social factors being taken into account, and considering individual situations also below the dose limits for the skin, in accordance with the recommendations of the International Commission on Radiological Protection ICRP [91ICRP] (see also Sect. 4.8).

Adherence to this principle requires in working areas, where contamination cannot be excluded, suitable measures to keep the skin dose after contamination as low as possible. The following specifications serve this purpose. They are no recommendations for measures in emergency and disaster situations and do not include medical treatment of contaminated wounds. They are rather addressed to technical, medical and scientific installations where sealed and unsealed radioactive sources are handled, in accordance with the respective radiation protection rules of their national legislation.

The following areas are mainly involved:

- Nuclear power plants
- Nuclear fuel cycle installations
- Scientific and industrial laboratories
- Hospitals, medical laboratories and practices of doctors in nuclear medicine.

8.2.2 Transport of radioactive substances via the skin

8.2.2.1 Anatomy of the skin

The skin (cutis) consists of epidermis and subcutis. The epidermis is the avascular external skin layer. The subcutis consists of a tissue layer with connective tissue septa in which fat cell clusters and nerves are located.

In case of skin contamination the epidermis is primarily concerned. Due to permeation of radioactive substances, radioactivity may enter the transfer compartment (see Chapter 7) via the subcutis and thus lead to internal contamination of the organism.

The epidermis consists of multi-layer corneal squamous-cell epithelium of a thickness between 30 μm and 2 mm, depending on the body region:

The external layer of the body skin, i.e. the upper layer of the epidermis, is the stratum corneum, on the surface of which flat, denucleated corneal cells peel off in fine scales. It is followed by the stratum lucidum consisting of denucleated cells which is only produced at thick parts of the epidermis - palm and sole. It is followed by the stratum granulosum, the so-called granular cell layer. Then follows the stratum spinosum, the so-called prickle cell layer and the stratum basale, the basal-cell layer. Stratum spinosum and stratum basale are also called stratum germinativum (germ cell layer), because here the corneal cells scaled off at the surface of the epidermis are substituted by cell division. Therefore, the cells of the stratum germinativum are the radiation-sensitive cells of the epidermis. Their radiation dose (equivalent dose) has to be determined in case of skin contamination, their dose level determines the introduction and conclusion of decontamination measures.

8.2.2.2 Transport procedure

The detriment to health due to skin contamination from radioactive substances depends mainly on

- Type of the radionuclide and its chemical compound
- Activity per area and/or specific activity
- Solubility of radioactive substance
- Situation and size of possibly affected part of skin.

In principle the healthy skin is protected best against percutaneous incorporation of radioactive substances. Therefore, all persons handling unsealed radioactive sources should give special care to their skin, particularly at their hands, and keep it in a good and healthy condition, because fissured skin surface may become openings for entry of radioactive substances and consequently for incorporations of radionuclides.

The intact skin is an effective but not completely dense barrier against radioactive substances. Whereas solid particles, preferred by rubbing, may enter the skin mechanically, liquids are subject to capillary forces and diffusion processes. As long as a liquid wets the skin surface, a transport of material occurs from the surface into the skin and through the skin. This leads to both a transient deposit of radioactivity in the corneal layer and transport into deeper skin layers (subcutis) together with uptake into blood and subsequent internal radiation exposure (see Chapter 7).

The capacity of the corneal skin layer to take up radioactive liquid is exhausted within several minutes. This layer takes up about one micro litre liquid per square centimeter wet surface [92Pra]. Activity from this procedure taken up into the corneal layer is therefore proportional to the specific activity of the liquid and to the size of the affected skin surface. However, the corneal layer may have a special affinity to some substances. In case of a permanent contamination this may lead to radioactive enrichment in the corneal layer.

The transport through the skin (permeation) from a liquid on the surface is proportional to the specific activity in the liquid and to the size of the affected skin surface and additionally to the time period during which the contaminated liquid remains on the skin. In case of inorganic substances dissolved in water, organic acids, salts, or lipophilic compounds, the substance transported through the skin per square centimeter and hour is equal to the amount contained in 0.001 to 0.1 µl [92SSK]. The permeation rate is significantly higher with gases dissolved in water or easy volatile substances.

8.2.3 Skin dose at contamination

8.2.3.1 Calculation of the equivalent dose to the skin

The equivalent dose of the contaminated skin can be calculated as follows [85Hen]:

$$H_S = A_F \cdot T_{1/2} \cdot \frac{86400}{\ln 2} \cdot \left(1 - e^{-\frac{\ln 2}{T_{1/2}} t}\right) \cdot \dot{h}_s =$$

$$H_S = 1.25 \cdot 10^5 \cdot A_F \cdot T_{1/2} \cdot \left(1 - e^{-\frac{\ln 2}{T_{1/2}} t}\right) \cdot \dot{h}_s$$
(8.2.1)

with H_S equivalent dose of contaminated skin in Sv

A_F activity per area at the surface in Bq/cm²

$T_{1/2}$ physical half-life in days (d)

t time of contamination in days (d)

\dot{h}_s equivalent dose rate conversion coefficient in Sv/s per Bq/cm² (see Section 8.2.3.2)

If a dwell time of one week is assumed for contamination, equation (8.2.1) simplifies for long-lived radionuclides, i.e. for radionuclides with significantly longer half-life than 7 days, as follows:

$$H_S = 604800 \cdot A_F \cdot \dot{h}_S \quad (8.2.2)$$

8.2.3.2 Equivalent dose rate conversion coefficients

The equivalent dose rate conversion coefficient for skin contamination is defined as follows (see equation 8.2.1):

The numerical value of the equivalent dose rate conversion coefficient corresponds to the equivalent dose rate in Sv/s in the contaminated skin at an activity per area of 1 Bq/cm². For determining these values [85Hen] the mean skin dose was calculated by integration over a skin depth between 50 and 100 µm, and the contribution of gamma-, beta-, electron radiation (Auger electrons) and alpha-particles was considered. Contamination of the whole skin surface was assumed to calculate the contribution of gamma radiation to skin dose. The assumption that the radiation-sensitive layer (stratum germinativum, Sect. 8.2.2.1) is situated mainly in a skin depth of 50 to 100 µm leads to somewhat higher equivalent dose rate conversion coefficients than those obtained for the reference skin depth of 70 µm [91ICR].

Radioactive substances may enter the corneal layer, however, the activity concentration decreases significantly with depth of the corneal layer (exponentially with a half-value thickness of about 2 µm). As a consequence this permeation has only little influence to dose in the radiation-sensitive skin layer (stratum germinativum). Therefore the ambient activity distribution in the corneal layer was not considered in the calculation of the equivalent dose rate conversion coefficients.

The equivalent dose rate conversion coefficient values for 128 radionuclides are summarised in Table 8.5.

Table 8.5 Equivalent dose rate conversion coefficients (Sv/s/(Bq/cm²)) for contaminated skin (averaged over a depth of 50-100 µm) [85Hen]

Radionuclide	Radiation		
	Electrons/Beta-Particles	Gamma-Radiation	Alpha-Particles
Na-24	4.3E-10	6.6E-11	-
Cr-51	7.1E-12	1.4E-12	-
Mn-54	2.1E-12	1.6E-11	-
Mn-56	4.2E-10	3.0E-11	-
Fe-55	-	1.2E-12	-
Fe-59	2.7E-10	2.2E-11	-
Co-56	8.8E-11	6.2E-11	-
Co-58	7.0E-11	1.9E-11	-
Co-60	2.4E-10	4.5E-11	-
Ni-59	-	1.6E-12	-
Ni-65	4.1E-10	9.7E-12	-

Radionuclide	Radiation		
	Electrons/Beta-Particles	Gamma-Radiation	Alpha-Particles
Zn-65	7.5E-12	1.3E-11	-
Zn-69	4.3E-10	1.1E-16	-
Zn-69m	2.4E-11	7.7E-12	-
Se-75	3.0E-11	9.3E-12	-
Rb-86	4.2E-10	1.8E-12	-
Rb-88	1.7E-10	1.1E-11	-
Rb-89	3.9E-10	3.6E-11	-
Sr-89	4.2E-10	1.6E-15	-
Sr-90	3.9E-10	-	-
Sr-91	4.2E-10	1.3E-11	-
Sr-92	3.7E-10	2.4E-11	-
Y-90	4.2E-10	4.3E-16	-
Y-90m	5.9E-11	1.1E-11	-
Y-91	4.2E-10	6.6E-14	-
Y-91m	2.4E-11	1.0E-11	-
Y-92	3.8E-10	4.6E-12	-
Y-93	4.1E-10	1.5E-12	-
Zr-93	1.8E-13	-	-
Zr-95	2.8E-10	1.4E-11	-
Zr-97	4.2E-10	3.3E-12	-
Nb-93m	-	4.7E-13	-
Nb-95	4.0E-09	1.4E-11	-
Nb-95m	4.5E-10	2.8E-12	-
Nb-97	4.2E-10	1.2E-10	-
Mo-93	-	2.5E-12	-
Mo-99	4.1E-10	2.9E-11	-
Mo-101	4.6E-10	2.4E-11	-
Tc-99	2.6E-10	-	-
Tc-99m	5.1E-11	2.2E-12	-
Tc-101	4.3E-10	5.8E-12	-
Ru-103	1.5E-10	8.8E-12	-
Ru-105	4.2E-10	1.5E-11	-
Ru-106	-	-	-
Rh-103m	-	3.2E-13	-
Rh-105	3.2E-10	1.4E-12	-
Rh-106	3.9E-10	3.8E-12	-

Radionuclide	Radiation		
	Electrons/Beta-Particles	Gamma-Radiation	Alpha-Particles
Ag-110m	1.2E-10	5.1E-11	-
Ag-111	4.2E-10	4.6E-13	-
Sb-124	3.7E-10	3.2E-11	-
Sb-125	1.8E-10	8.8E-12	-
Sb-126	3.5E-10	5.3E-11	-
Sb-127	4.1E-10	1.3E-11	-
Sb-129	3.9E-10	2.6E-11	-
Sb-130	4.9E-10	6.0E-11	-
Sb-131	4.1E-10	3.4E-11	-
Te-125m	2.8E-10	3.1E-12	-
Te-127	3.9 E-10	8.9E-14	-
Te-127m	1.5E-10	1.0E-12	-
Te-129	4.4E-10	1.5E-12	-
Te-129m	3.1E-10	1.3E-12	-
Te-131	4.9E-10	7.6E-12	-
Te-131m	3.9E-10	2.6E-11	-
Te-132	2.1E-10	5.0E-12	-
Te-133	4.1E-10	1.7E-11	-
Te-133m	4.4E-10	4.2E-11	-
Te-134	4.6E-10	1.7E-11	-
I-129	9.2E-11	1.7E-12	-
I-130	4.1E-10	4.0E-11	-
I-131	3.7E-10	6.9E-12	-
I-132	4.2E-10	4.2E-11	-
I-133	4.2E-10	1.1E-11	-
I-134	4.2E-10	4.8E-11	-
I-135	4.0E-10	2.8E-11	-
Cs-134	2.8E-10	2.9E-11	-
Cs-134m	3.3E-10	1.4E-12	-
Cs-135	1.5E-10	-	-
Cs-136	3.3E-10	4.0E-11	-
Cs-137	3.7E-10	-	-
Cs-138	4.1E-10	4.0E-11	-
Ba-137m	4.5E-11	1.1E-11	-
Ba-139	4.4E-10	7.4E-13	-
Ba-140	4.1E-10	3.9E-12	-
La-140	4.3E-10	4.0E-11	-
La-141	4.2E-10	7.5E-13	-
La-142	4.1E-10	4.4E-11	-

Radionuclide	Radiation		
	Electrons/Beta-Particles	Gamma-Radiation	Alpha-Particles
Ce-141	4.1E-10	1.4E-12	-
Ce-143	4.3E-10	5.7E-11	-
Ce-144	2.1E-10	5.1E-13	-
Pr-143	6.6E-13	6.7E-12	-
Pr-144m	1.1E-11	9.2E-13	-
Pr-145	4.2E-10	2.5E-13	-
Nd-147	4.0E-10	3.2E-12	-
Pm-147	1.3E-10	1.0E-16	-
Pm-148	4.2E-10	1.0E-11	-
Pm-148m	3.3E-10	3.7E-11	-
Pm-149	4.2E-10	1.9E-13	-
Pm-151	4.1E-10	5.7E-12	-
Eu-152	2.0E-10	2.1E-11	-
Eu-152m	3.3E-10	5.7E-12	-
Eu-154	4.5E-10	2.3E-11	-
Eu-155	8.4E-11	1.4E-12	-
Eu-156	3.7E-10	2.3E-11	-
At-211	1.4E-11	1.6E-12	-
Ra-226	1.1E-11	1.4E-13	-
U-234	8.7E-12	4.6E-13	-
U-235	6.1E-11	3.5E-12	-
U-238	-	3.8E-13	-
Np-237	6.2E-11	3.1E-12	-
Np-238	2.9E-10	1.2E-11	-
Np-239	6.2E-10	4.8E-12	-
Pu-236	1.0E-11	5.3E-13	6.9E-20
Pu-238	8.0E-12	4.6E-13	5.5E-20
Pu-239	1.9E-13	2.5E-13	1.2E-20
Pu-240	8.4E-12	4.4E-13	1.3E-20
Pu-241	1.0E-09	2.8E-16	-
Pu-242	7.0E-12	3.7E-13	-
Am-241	4.7E-11	3.1E-12	5.7E-20
Am-242	3.1E-10	1.4E-12	-
Am-242m	2.6E-13	1.0E-12	8.1E-20
Am-243	2.1E-11	1.7E-12	2.1E-20

Radionuclide	Radiation		
	Electrons/Beta-Particles	Gamma-Radiation	Alpha-Particles
Cm-242	4.7E-12	4.3E-13	7.7E-15
Cm-243	3.3E-10	4.2E-12	3.0E-16
Cm-244	-	4.0E-13	8.6E-20
Cm-245	1.2E-10	3.7E-12	3.0E-20
Cm-246	-	3.5E-13	3.0E-20
Cm-247	3.5E-11	6.0E-12	4.0E-21
Cm-248	-	2.7E-13	5.4E-21

8.2.4 Decontamination measures

8.2.4.1 Organisational and preliminary measures

When handling radioactive substances contamination should always be anticipated. Therefore, organisational measures and practical procedures for personal decontamination have to be provided. There is need for developing special instructions of decontamination for the respective operation and also for individual workplaces.

These measures include, among others, to take off contaminated clothing before decontamination measures are started. Care shall be taken that no additional parts of skin will be polluted and no contaminated dust will be emitted into the air. The emergency staff should wear protective gloves or protective clothing.

8.2.4.2 First aid measures of skin decontamination

Simple decontamination appliances which can be used immediately after contamination and at any place should be available for decontamination. If need be, immediate decontamination measures will be given priority over assessing the value of skin contamination by activity measurement. Based on the experience that both specific activity concentration of a contaminated liquid and the time of influence or action may be the decisive parameters for skin permeation, skin decontamination should be started immediately after contamination, if possible.

However, it should always be considered that incorporation of radionuclides due to permeation might be effectively reduced by simple and quickly performed washing measures.

In general washing with lukewarm water, special soaps or wash lotions using soft hand-brushes, if required, are first and rapid decontamination methods. Also secondary contamination of the surrounding skin from washing procedures with lukewarm water is widely negligible in practice, because if enough water is immediately used, the radionuclide concentration is significantly decreased and the time of influence is short.

Minor contaminations can usually be removed already in a first washing course. During this stage only the contaminated skin parts should possibly be cleaned with lukewarm water, e.g. only the palm of the hand. Washing should be finished after 2 minutes and the skin should be dried with absorbent material. In case of remaining contamination the procedure according to Section 8.2.5 should be applied.

8.2.4.3 Specific decontamination procedures

Decontamination by removing contaminated corneal cells

Small-surface contamination can be removed by taking off corneal cells with adhesive film: after 5 strippings 97 % of the radioactive substance was removed from the skin at the forearm [58Bor]. However, this stripping method is only suitable with dry skin and fails at the palms of the hand.

Cleaning by sorption agents

To remove substances penetrated deeper into the corneal layer, cleaning methods are required where the procedure of penetration shall be inverse, i.e. from internal to external penetration. In order to avoid transfer of radioactive substances into the corneal layer from capillary forces, it is suitable to apply for the decontamination sucking sorption agents, e.g. silicon dioxide, titanium dioxide or silica gel.

Cleaning by detergents

Although cleaning with customary detergents is a natural decontamination method, it should be considered that without penetration of a decontamination agent into the corneal layer, the substance deposited there cannot be reached. Therefore when cleaning a substance situated in the corneal layer it shall be dissolved by the detergent and rinsed to the skin surface. Therefore the corneal layer must not be decontaminated by alkaline or strong acidic cleaning agents, because the bond capacity of keratin to ions increases with each deviation from the pH value 4.2, as it has been proved by experimental results with ^{22}Na and ^{131}I ions in corneocytes [71EI, 84Pra].

Specific decontamination

Specific decontamination methods have been described by Wijker [66Wij]. However, they should only be performed by specially trained experts. Warning is particularly issued about chemicals for nuclide-specific decontamination, if there is no knowledge about the chemical composition of radionuclides involved.

Decontamination agents for skin and hair

For the decontamination of skin and hair the following decontamination solutions are normally used:

Decontamination lotions for skin and hair

- Titanium oxide paste (general skin decontamination procedure)
- Wiping paste (general skin decontamination procedure)
- Citric acid 3 % (e.g. decontamination of hair and external auditory canal)
- Complexing solutions (e.g. in case of contamination of the eyes, general skin decontamination procedure) [97Ger]
- Potassium permanganate solution (general skin decontamination procedure), removing brown skin colouring with sodium disulfite solution
- Physiological sodium chloride solution (decontamination measure also in case of contamination of the eyes).

8.2.4.4 Decontamination of specific body regions and organs

Hair

Contaminated hair should be washed with a wash lotion (see Section 8.2.4.3), assisted by a helper wearing protective gloves, in an adequate hair washbasin with the head bent backwards. Then the hair should be rinsed with plenty of water. Special care must be taken that no contaminated water runs into the face, eyes or ears. Before hair drying, control measurement by contamination monitor is required.

Eyes

In case of contamination of the eyes, these should be properly rinsed with plenty of water; cleaning lotions (physiological sodium chloride solutions and integration solutions (see Section 8.2.4.3) should be used, if necessary. This method of eye decontamination must be performed under medical supervision.

Mouth, nose, ears

If mouth, nasopharynx and auditory canal are contaminated, a physician must always be contacted.

The mouth should be rinsed with plenty of water for decontamination.

Contamination of the nasal cavities can be decreased by blowing the nose.

Rinsing (wash bottle) with physiological sodium chloride solution or citric acid must only be done on the instructions or assistance of a physician, if possible, because there is hazard of radionuclide incorporation. In any case secondary contamination has to be avoided.

Skinfolds, groove of the nail bed, and fingernails

If contamination is detected in skinfolds, in the groove of the nail bed or under the fingernails, this should be specifically removed. Simple instruments can be used such as nail cleaner, soft brush or adhesive strips.

8.2.5 Procedure at residual contamination and fixing a reference value

8.2.5.1 Frequency of decontamination steps

If the first decontamination procedure (see Sections 8.2.4.2, 8.2.4.3 and 8.2.4.4) is not successful, the decontamination method can be repeated up to two times while measuring each individual decontamination effect. If the decontamination effect is lower than 10 %, and the surface-related residual activity is lower than the reference value of 10 Bq/cm² – averaged over 100 cm² with contamination predominantly dispersed over the whole surface (see Section 8.2.5.2) – the additional decontamination step can be waived. As far as the decontamination effect is higher than 10 % and the skin condition is good, further wash procedures may be reasonable.

8.2.5.2 Derivation of the reference value for residual contamination

The reference value of 10 Bq/cm² of a remaining skin contamination after several decontamination steps leads to the fact that for more than 90 % of the radionuclides listed in Table 8.5 which are essential for practical radiological protection purposes the remainder equivalent dose is significantly less than 1 % of

the annual dose limit to skin of 500 mSv [91ICR] in a 1-week-dwell time. All dose values lie below 5 % of this limit, except for ^{254}Cf . This stipulation ensures that even in case of several contamination events in the calendar year which were not successfully removed, the distance to the limit value is sufficient.

When fixing a reference value to decide on further decontamination measures, it can also be assumed that activity concentration decreases exponentially with depth in the corneal layer. The complete scaling off of this layer within two weeks leads to a very quick exponential decrease with time of the residual activity in the skin. Consequently the 1-week-dwell time taken as a basis for dose calculations (see equation 8.2.1 in Sect. 8.2.3.1) overestimates significantly the actual equivalent dose.

Table 8.6 gives an example of the activity per area values in some radionuclides relevant for radiological protection purposes. Considering the physical half-life at 1-week-dwell time they lead to a dose of about 1 % of the annual dose limit to skin of ICRP of 500 mSv [91ICR].

Table 8.6 Activity per area of some radionuclides leading after 1-week-dwell time to a skin equivalent dose of about 5 mSv (1 % of the annual dose limit for skin of 500 mSv [91ICR]).

Radionuclide	Activity per area [Bq/cm ²]
^{14}C	170
^{60}Co	35
^{90}Sr	20
^{90}Y	40
^{131}I	35
^{137}Cs	20
^{141}Ce	20

The reference value of 10 Bq/cm² is adequately conservative and can also be used for radionuclides which, due to the short range of radiation emitted (mainly Auger electrons), provide a main contribution to dose in the skin layer sensitive to radiation (stratum germinativum). Consequently, precaution against the hazard of transmitting radioactive substances from the restricted access area is ensured, whereby it should be taken into account that remaining residual contamination is a very rare event and that remaining activity clings tightly to the skin.

Apart from exposure to skin, radionuclides situated in the corneal layer may principally lead to exposure in other body regions:

- Radiation – mainly gamma radiation – may expose other body organs or tissues
- Radioactive substances may reach body liquids by permeation and thus disperse in the body with final irradiation of organs or tissues.

Usually, external exposure to other body regions by gamma radiation resulting from the corneal layer compared to skin exposure is negligible. In case of very high surface contaminations, however, very large affected body surfaces and long contamination periods, the permeation of radionuclides through the skin and hence internal dose to body organs and tissues can play a role that should not be underestimated.

8.3 References

- 56USS Fabrication of USS Stainless Steels, 2nd ed., p 88, Bulletin published by United States Steel Corporation, Pittsburgh, Pa, 1956.
- 58Bor W. Born: Beseitigung radioaktiver Verunreinigungen von der Haut des Menschen; Strahlentherapie 106, 435 (1958)
- 60Ayr Ayres, J. A., Demmitt, T.F., Larrick, A.P., Neubow, G.E., Richman, R.B., Perrigo, L.D., Weed, R.D.: Decontamination studies for HAPO water-cooled reactor systems; USAEC HW-67937. Dec. 27, 1960.
- 64Ame American Society for Metals: Abrasive blast cleaning. Metals Handbook, 8 ed. Vol. 2, 1964.
- 66Wij Skin Contamination; Euratombericht 41-67 (1966)
- 70Ayr Ayres, J.A. (ed.): Decontamination of nuclear reactors and equipment New York: . The Ronald Press Co., 1970.
- 71El R. El-Julani: Zur Adsorption von Na⁺ und I an Keratinzellen der menschlichen Haut; Med. Dissertation, Ludwig-Maximilians-Universität München (1971)
- 78All Allen, R.P., Arrowsmith, H.W, Charlot, L.A., Hooper, J.L.: Electropolishing as a decontamination process: Progress and applications; PNL-SA-6858, April, 1978.
- 78Rie Riess, R., Bertholdt, H.: Chemische Dekontamination von Reaktoranlagen, Reaktortagung 1978, 4.-7. April in Hannover, Tagungsbericht, S. 963-966.
- 79Rem Remark, J.F., Miller, A.D.: Review of plant decontamination methods, Sun Valley (ID), USA: American Nuclear Society, September 17-19, 1979.
- 79TMI TMI Reports: Evaluation of strippable decon coatings; TMI Reports No.'s 1-22 (1979).
- 80Bar Barbier, M.M., Chester, C.V.: Decontamination of large horizontal concrete surfaces outdoors; CONF-800542-2, ORNL, TN (USA), 1980.
- 80Des Desryoches, J., Koenig, J., Lebrun, J.C.: La décontamination en milieu gélif ou colloidal; Workshop on waste washing; Organised by Radioactive Waste Management Committee and OCED Nuclear Energy Agency at Centre d'Etudes Nucléaires de Cadarache, France. November 19-21, 1980.
- 80Man Manion, W.J., Laguardia, T.S.: Decommissioning Handbook; DOE/EV/10128-1, November 1980.
- 81McV McVey, J.T., et al.: Tools and equipment: From nuclear waste to reusable items, Nucl. Chem. Waste Manag. **2-3** (1981).
- 81Nel Nelson, J.L., Divine, J.R.: Decontamination processes for restorative operations and as a precursor to decommissioning: A literature review. PNL-3706, Battelle-Pacific Northwest Laboratory, May 1981.
- 81Rem Remark, J.F.: Plant decontamination methods review; EPRI NP-1168; May 1981.
- 82Com Commissariat à l'Energie Atomique, Institut de Protection et de Sécurité Nucléaire: Décontamination radioactive du matériel', Publication PMDS, Mars 1982.
- 82Gar Gardner, H.R., Allen, R.P., Polenz, L.M., Skiens, W.E., Wolf, G. A.: Evaluation of nonchemical decontamination techniques for use on reactor coolant systems; EPRI NP-2690, October 1982.
- 82Garl Gardner, H.R., et al.: Comparison of decontamination techniques for reactor coolant system applications; EPRI NP-2777, December 1982.
- 83Eic Eickelpasch, N., Lasch, M.: Electrochemical decontamination experience at Gundremmingen power plant; Water chemistry of nuclear reactor, Systems 3, Bournemouth (UK), 17-21 October, 1983.
- 83Int International Atomic Energy Agency: Decommissioning of nuclear facilities: Decontamination, disassembly and waste management; Vienna: Technical Report Series No. 230, 1983.
- 84Ebe Ebeling, W., Boedeker, B., Rose, K.: Dekontamination von Betonoberflächen durch Flammstrahlen; EUR 8969, 1984.
- 84KWU KWU Service Report, No. 1, April 1984.

- 84Pra H. G. Pratzel, K. Dirnagel, H. Drexel: Kontamination der menschlichen Haut durch Radionuklide; *Nuklearmedizin* 23, 197-200 (1984)
- 85Duc Duce, S.W., Simpson, F.B., Mandler, J.W.: Observations of plant decons; EPRI Seminar on Chemical Decontamination of BWRs, Charlotte (USA), February 26-28, 1985.
- 85Ebe Ebeling, W., Boedeker, B., Rose, K., Schaller, R.H.: Decontamination of concrete, with particular reference to flame scarifying; Decommissioning of nuclear power plants; Luxembourg 22-24 May 1984; EUR 9474, 1985.
- 85EPR EPRI: EPRI NP-4222, Vol.2, 1985.
- 85EPR1 EPRI: EPRI NP-4222, Vol.3, 1985.
- 85EPR2 EPRI: EPRI NP-4222, Vol.4, 1985.
- 85EPR3 EPRI: EPRI NP-4222, Vol.5, 1985.
- 85Hen K. Henrichs, C. Eiberweiser, H.G. Paretzke: Dosisfaktoren für die Kontamination der Haut und der Kleidung; GSF-Bericht 7/85, 5-1285 (1985)
- 85Lör Lörcher, G., Chapuis, A.M., Essmann, J.: Factors to be considered in deciding whether to decontaminate for unrestricted release; Decommissioning of nuclear power plants, Luxembourg, 22-24 May 1984, EUR 9474, 1985.
- 85Pas Pascali, R., Bregani, F., Ahlfänger, W., Lasch, M., Gauchon, J.P.: Chemical and electrochemical decontamination; Decommissioning of nuclear power plants; Luxembourg, 22-24 May 1984, EUR 9474, 1985.
- 85Pfl Pflugrad, K., et al.: Treatment of steel waste arising from decommissioning of nuclear installations by melting; Bethesda, (MD) USA: Nuclear Reactor Decommissioning Planning, 1985.
- 86EPR EPRI: EPRI NP-4687, 1986.
- 86EPR1 EPRI: EPRI NP-468, 1986.
- 86Gau Gauchon, J.P., Mordenti, P., Bezia, C., Fuentes, P., Kervegant, Y., Munoz, C., Pierlas, C.: Decontamination par des methodes chimiques, electrochimiques et au jet d'eau; EUR 10043, 1986.
- 86Man Mang, M.: Issue of the second seminar on chemical decontamination, BWRs-Section 3, Corrosion Issues, 1986.
- 87Pav Pavlik, O., Sipos, T., Vicsevne, M., Miko', M.: Decontamination of Nuclear Facilities by Electrochemical methods; 1987 International Decommissioning Symposium, Pittsburgh, (PA) USA, October 4-8, 1987.
- 88Int International Atomic Energy Agency: Decontamination and demolition of concrete in the decommissioning of nuclear facilities; Vienna: Technical Reports Series No. 286, 1988.
- 89Brun Brunel, G.: Decontamination using chemical gels, electrolytical SWAB, abrasives; Decommissioning of Nuclear Installations, Bruxelles (B), October 24-27, 1989, EUR 12690, 1990.
- 89Cos Costes, J.R., Antoine, P., Gauchon, J.P.: Decontamination before dismantling a fast breeder reactor primary cooling system; Decommissioning of Nuclear Installations. Elsevier Science Publishers Ltd, EUR 12690, 1989, ISBN 1-85166-523-4, p. 554
- 89Cro Crossley, H., Wakefield, J.R.: Development of techniques to decontaminate the WAGR Heat Exchangers, UK, Windscale, Decommissioning of Nuclear Installations. Elsevier Science Publishers Ltd, EUR 12690, 1989, ISBN 1-85166-523-4, p.567.
- 89Sta Stang, W., Fischer, A., Rubischung, P.: Large-scale application of segmenting and decontamination techniques, Decommissioning of Nuclear Installations, Bruxelles (B), October 24-27, 1989, EUR 12690, 1990.
- 89Wil Wille, H., Bertholdt, H.O.: Recent developments in component and system decontamination, conference on water chemistry of nuclear reactor systems 5. London: BNES, 1989, p. 163.
- 90Ber Bertini, A.: Some remarks about decontamination; Decommissioning of Nuclear Installations, Bruxelles (B), October 24-27, 1989; EUR 12690, 1990.
- 90Sap Sappok, M., Lukacs, G., Ettemeyer, A., Stang, W.: Melting of radioactive metal scrap from nuclear installations, Decommissioning of Nuclear Installations, Bruxelles, October 24-27, 1989, EUR 12690, 1990.

-
- 91Bru Brunel, G., Gauchon, J.-P., Kervegant, Y., Josso, F.: Nouvelles techniques de décontamination: Gels chimiques, électrolyse au tampon et abrasifs; EUR 13497 FR, 1991.
- 91ICR 1990 Recommendations of the International Commission on Radiological Protection ICRP Publ. 60; Annals of the ICRP, 1991, Vol. 21 No. 1-3; Pergamon Press Oxford, New York, Frankfurt, Seoul, Sydney, Tokyo (1991)
- 92Com Commission of the European Communities: Ispra, Joint Research Centre, Institute for Safety Technology, Private Communication, 1992.
- 92Pra H.G. Pratzel: Dekontamination der Haut aus der Sicht experimenteller Ergebnisse; in SSK Veröffentlichungen Band 18; Gustav Fischer Verlag Stuttgart, Jena, New York, 71-95 (1992)
- 92SSK Strahlenschutzkommission SSK: Massnahmen nach Kontamination der Haut mit radioaktiven Stoffen; Empfehlung der SSK vom 22. September 1989; in SSK Veröffentlichungen Band 18; Gustav Fischer Verlag Stuttgart, Jena, New York, 1-30 (1992)
- 97Ger P. Gerasimo, D. Jourdain, A. Cazoulat, D. Schoulz, P. Laroche, R. Ducousso: Modeling of cutaneous radio-contamination: effects of washings by soap and by solutions of DTPA (in French); Ann Pharm. Fr. 55 (3), 116-124 (1997)
- 00Hir Hirabayashi, T., Ishigure, K., et. al.: Handbook of reactor water chemistry, Corona Pub. Co., 2000, p. 276.
- 00Hir1 Hirabayashi, T., Ishigure, K., et. al.: Handbook of reactor water chemistry, Corona Pub. Co., 2000, p. 275.
- 00Kat Kato, S., Ishigure, K., et. al.: Handbook of reactor water chemistry, Corona Pub. Co., 2000, p. 284.
- 00Kat1 Kato, S., Ishigure, K., et. al.: Handbook of reactor water chemistry, Corona Pub. Co., 2000, p. 284.
- 00Wil Wille, H., Bertholdt, H., Lessons, H.O.: Learned in full system decontamination by application of the CORD family concept, BNES, VIII Int. Conference on Water Chemistry of Nuclear Reactor Systems, Bournemouth, UK -26.10.2000.
- 01Eic Eickelpasch, N., Steiner, H.: Stilllegung von Kernkraftwerken, VGB Power Tech. 6, 2001, p. 142.