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Protection strategies in case of nuclear detonation

Recommendation by the
German Commission on Radiological Protection

Adopted at the 334th meeting of the German Commission on Radiological Protection on 10 October 2024

1 Preface

After the Cold War and the reunification of Germany, there was widespread confidence that the threat of weapons of mass destruction (whether from terrorism or military conflict) was unlikely to affect citizens. Therefore, the preparedness of state actors and private households for such threats has been greatly reduced. Even after military conflicts in Europe (e.g. the war in the Balkans and the annexation of Crimea by Russia), Germany saw no reason to change course. The Cold War was over, and even demonstrations against nuclear weapons hardly took place any more.

Since 2022 at the latest, nuclear threats from Russia (and other nuclear powers) have once again become part of everyday life for German citizens. However, the threat does not come solely from states with nuclear weapons. Also terrorist groups could come into possession of a nuclear weapon and use it. Although we all hope these threats never materialise, the SSK firmly believes in the necessity of emergency preparedness. In the event of a nuclear weapon being used in Germany, appropriate and optimised preparation can make an important contribution to saving and preserving the health of tens of thousands of people.

The document makes suggestions for preparing appropriately and responsibly for the possible occurrence of such scenarios to strengthen the resilience of the country and learn the right lessons from the use of nuclear weapons. Dealing with the issue of nuclear weapons is by no means a pleasant experience because it makes us realise the destructive power of these weapons, which would have massive consequences for the well-being of the people affected if they were to be used. The reflections on the devastating use of nuclear weapons against the inhabitants of Hiroshima and Nagasaki underscored this.

We respectfully remember the victims of the atomic bombs dropped on Hiroshima and Nagasaki.

To develop this recommendation, the SSK set up a working group in 2022 with the following members:

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1 Introduction

After the Cold War and the fall of the Iron Curtain in the early 1990s, awareness of the nuclear threat decreased in politics, society, and science in Western Europe, especially in Germany. As a result, a great deal of knowledge about nuclear weapons and possible protective measures has since been lost among both the general population and public authorities. In addition, safety precautions have been considerably scaled back over the decades. Following the Russian invasion of Ukraine on 24 February 2022 and the shortcomings of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) of 1970[1], the threat of nuclear weapons has once again become a major concern in Germany. In March 2022, the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) took the need to review and, if necessary, adapt its own risk assessment as an opportunity to commission the German Commission on Radiological Protection (SSK) to assess appropriate protective measures in the event of nuclear explosions. The aim of the protective measures is to enable as many citizens as possible to survive and maintain their health in the event of a nuclear weapon explosion and to minimise exposure to ionising radiation. The recommendation aims at improving the current preparation in Germany and avoiding unrealistic maximum demands in the sense of optimisation.

In the scientific justification section of this SSK recommendation, the status of national and international preparations is presented in extracts. This is followed by a detailed chapter on the characteristics and types of nuclear weapons as well as their effects depending on the type of weapon and distance from the explosion site. The findings to date on the radiation doses associated with nuclear weapon explosions and the resulting dangers to life and limb were obtained from the atomic bombs dropped on Hiroshima and Nagasaki as well as from nuclear weapon tests and are summarised here.

For the scientific basis of the present recommendation, sources from the atmospheric nuclear weapons tests in the 1950s and early 1970s were analysed in part. Also, more recent sources were used. In the US, in particular, protection of the population from nuclear weapons explosions became even more important after the terrorist attacks of 11 September 2001.

This SSK recommendation includes a systematic description of acute and chronic radiation injuries caused by nuclear weapons (also in combination with mechanical injuries or burns) as well as measures to prevent or reduce them. Preparation for nuclear weapon explosions involves distinguishing between general protective measures for the public and specific measures for the healthcare of affected individuals and emergency personnel.

In 2023, the SSK published recommendations on the “Medical management of radiation emergencies – Requirements and organisational matters” (SSK 2023a), and in the previous year it published the “Radiation emergency medicine handbook for medical care and education” (SSK 2022a). Although nuclear weapon explosions are not explicitly dealt with in this report, the scenario “Terrorist or otherwise motivated release of radioactive substances or exposure to ionising radiation” addresses aspects that can be transferred to nuclear weapon explosions. However, the number of people exposed to nuclear weapons is expected to be orders of magnitude higher. In addition to the damage to physical health, psychosocial effects and adequate risk and crisis communication also play a central role, according to current findings from the Chornobyl and Fukushima reactor accidents.

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[1] https://www.iaea.org/publications/documents/treaties/npt, last accessed on 16 September 2024

The principle of disaster control is that good planning and preparation can save many lives and minimise adverse health effects in the event of an incident. With regard to the recommendations of the SSK, there is a certain tension in Germany due to the distribution of responsibilities.

2 Consultancy engagement

On 7 March 2022, the BMUV tasked the SSK with evaluating whether protective measures for radiological emergencies would be effective and appropriate in the event of a nuclear weapon being used in Germany or a neighbouring country, as well as identifying any special requirements for implementation. Furthermore, the SSK was asked to prioritise the question of the benefits of iodine blockage (SSK 2022b) and the use of respiratory masks (SSK 2023b) as protective measures.

3 Recommendations

With regard to a possible nuclear weapon attack, the SSK believes that there is a clear need to optimise the protective measures to be applied. The scenario considered within the scope of the commission is one or a few non-strategic nuclear weapon explosions in Germany or in neighbouring countries with immediate radiological consequences for the civilian population. The existing regulations for major incidents are designed primarily for nuclear power plant accidents and are therefore not sufficient for attacks with nuclear weapons. In some cases, there would also be different consequences and measures. In addition, the SSK considers the preparation for an incident and the implementation of its recommendations to be a task for society as a whole within the framework of civil defence (see also Rahmenrichtlinien für die Gesamtverteidigung - Gesamtverteidigungsrichtlinien (RRGV) [Comprehensive Defence Framework Guidelines][2].

In anticipation of this recommendation, the SSK has already issued a statement on iodine blockage (SSK 2022b) and a recommendation on the use of respiratory masks (SSK 2023b). The SSK does not consider the ingestion of iodine tablets (iodine blockage) to be a relevant protective measure in the event of nuclide releases from nuclear weapons because of the low risk from inhaled and incorporated radioactive iodine isotopes in relation to the total amount of activity released and the high external exposure. However, all citizens should hold FFP2/FFP3 masks available as part of a self-protection concept.

The emergency planning requirements for nuclear explosions in the regulations are considered insufficient. Existing regulations, particularly from other departments, should be evaluated and optimised.

The SSK recommends prioritising the implementation of the following measures:

1) the prompt development of a risk communication concept and the creation of an information platform covering all aspects of a nuclear attack with varying means of access and tailored information for ministries, authorities, emergency and rescue services, hospitals, medical and psychosocial care personnel, and citizens

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[2] https://www.bmi.bund.de/SharedDocs/downloads/DE/veroeffentlichungen/themen/sicherheit/RRGV.pdf?__blob=publicationFile&v=1, last accessed on 16 September 2024

2) the creation of all prerequisites for medical emergency management as set out in the corresponding recommendation of the SSK (SSK 2023a) (e.g. staff training, logistics, upgrading of hospitals)
3) a better networking of all institutions involved. The SSK sees the need to analyse the responsibilities, communication, and cooperation of all agencies involved, to check for structural weaknesses, and, if necessary, to optimise them. In the opinion of the SSK, close interaction at the federal and state level, stringent planning, and regular exercises are essential to be adequately prepared in the event of the use of nuclear weapons.
4) an evaluation and, if necessary, upgrading of protective measures for the general population with special consideration of "protective spaces[3]" in public areas.
5) the development of protection concepts for particularly vulnerable groups in hospitals, schools, and nurseries.

The SSK recognises the absolute necessity of providing sufficient financial resources for implementing the recommendations (e.g. for training, equipment, infrastructure, and research) as part of the tasks of society as a whole.

The SSK also makes the following recommendations:

I. Planning principles:

I-1) In an international comparison of preparations for nuclear explosions, the "Planning Guidance for Response to a Nuclear Detonation" of the US Federal Emergency Management Agency (FEMA) (2023) should also be used as a sound basis for planning in Germany.

I-2) German radiation protection legislation does not systematically include nuclear weapon explosions in its system of reference levels for the population and emergency personnel because the Radiation Protection Act is not applicable to civil defence cases. For the emergency personnel, the SSK recommends a system based on the recommendations of FEMA (2023) with the initiation of first aid measures only below a dose rate of 100 mSv h^{-1}. The optimisation principle of radiation protection should be observed.

I-3 Initial evacuations will be feasible only with considerable difficulty and, if carried out incorrectly, could lead to avoidable life-threatening health damage to tens of thousands of evacuees from fallout. It may, therefore, be necessary to refrain from an initial evacuation of affected persons – despite exceeding the reference levels of 1 mSv h^{-1} or 100 mSv cumulative dose over seven days (ANoPl-Bund 2023) for radiation exposure.

I-4) The relevant authorities must be equipped to provide behavioural guidance to the public following a nuclear weapon explosion, even under challenging technical conditions. This information should be easily accessible in different languages via various communication channels (e.g. radio, television, mobile phones, social media, and loudspeakers).

I-5) When planning medical care, it must be taken into account that, depending on the population density, tens of thousands of deaths and injuries can initially be expected in the event of nuclear weapon explosions – often with combined injuries caused by

[3] Protective spaces include conventional rooms such as cellars, underground car parks, and underground stations as well as bunkers and shelters.

mechanical trauma, burns, and radiation. After exposure to fallout, the number of people requiring care can be many times higher.

I-6) Emergency stations designed for nuclear power plant accidents should be upgraded, optimised, and adapted for use in responding to nuclear weapon explosions. These facilities can, among other things, help to intercept the expected rush of worried people and direct them to psychosocial care. Furthermore, a two-tier system of hospital facilities for the comprehensive and extended care of radiation emergency patients must be established and upgraded (SSK 2023a).

I-7) The importance of “protective spaces” should be given appropriate consideration in housing construction (e.g. inclusion and upgrading of basements and underground car parks).

I-8) In the event of a nuclear weapon explosion, the fallout can also contaminate food and feed grown outdoors in distant areas. Immediately after the explosion, a large-scale temporary ban on harvesting should be imposed, and the population should be warned against eating home-grown fruit and vegetables. In the following, a large-scale and intensive control of feed and food is recommended (i.e. the IMIS intensive operation for the affected areas in Germany should be activated, and food monitoring should be intensified).

II. Preparatory measures:

II-1) A suitable redundant emergency response system should be maintained to assess radiation exposure as quickly as possible in the event of a nuclear weapon explosion. For this purpose, the existing RODOS system should be extended with regard to dispersion modelling in order to take into account the explosion strength (also for weapons > 30 kT) as well as the height of the explosion above ground, the atmospheric dispersion at altitudes of up to 15 km, the release of short-lived radionuclides, and the dispersion of different particle sizes.

II-2) The existing IMIS system for measuring the local dose rate (Ortsdosisleistung; ODL) should be tested for its resilience to electromagnetic pulses (EMP) and hardened if necessary.

II-3) Resilient and redundant reporting channels for critical information in the event of a nuclear weapon explosion should be established. This information on the type of explosion, height of the explosion above ground, explosion strength, and characteristics of the cloud should be made available to the Federal Radiological Situation Centre as quickly as possible. Despite uncertainties, early automated communication to affected individuals must be ensured, as do tailored and optimised radiation protection recommendations for evacuation or sheltering in “protective spaces” within minutes to a few hours after the detonation of a nuclear weapon.

II-4) A structured knowledge platform should be established. This should also serve to identify and network specialists from the relevant authorities and other experts (e.g. from universities, research institutions, expert organisations, aid organisations, and business) and contain bundled information, advice, and offers of help.

II-5) In 2023, the SSK recommended establishing and maintaining a two-tier network of specialised hospitals and mobile teams for the medical care of radiation emergency patients. At the centre of this network, a central coordination office will enable the Germany-wide distribution of radiation emergency patients based on daily updated data on the treatment capacities, equipment, and personnel available (SSK 2023a).

These capacities will not be sufficient in the event of nuclear weapons explosions. Therefore, basic medical care facilities must also be enabled to provide support.

II-6) Radiation emergencies should be a subject in medical studies and the training of rescue personnel, caregivers, medical technologists, and crisis intervention personnel.

II-7) The training of specialised doctors and specialists for the medical care of radiation emergency patients should be intensified. The “Radiation emergency doctor” and “Radiation emergency management” qualifications proposed by the SSK 2023a are to be established.

II-8) Medication for the treatment of patients suffering from acute radiation syndrome should be kept in depots that are quickly accessible in an emergency and rapid distribution should be feasible.

II-9) All emergency personnel should be equipped with appropriate measurement technology and Personal Protective Equipment (PPE) to be able to provide on-site assistance as quickly as possible.

II-10) After the initial recommendation (i.e. in the first 24 to 48 h) to seek shelter or stay indoors, the remaining dose rate from the fallout in large areas can still be so high that the population may receive a considerable and potentially harmful dose in the following days and weeks. Therefore, a (subsequent) population evacuation should be considered for such areas.

II-11) A concept for collecting initial clinical and radiological data of all patients should be developed. For after-care, concepts should be developed, and designated and upgraded facilities should be established for conducting regular physical and mental health check-ups for those exposed. These should also support the scientific analysis of the data collected.

II-12) Proactive, continuous, and multilingual risk communication is necessary and should be established. The responsible federal and state authorities should standardize this because the population's resilience in hazardous situations depends on how well sufficient information enabled their preparedness for the potential threat and readiness to take self-protection measures.

II-13) Protection against nuclear weapons explosions should be the subject of large-scale multilingual publicity campaigns that prepare the population for easy-to-implement protective measures and provide rules of behaviour in the event of nuclear weapons explosions. Schools and similar institutions should be made particularly aware of the need for protective measures and appropriate preparations. This includes recommendations for easy-to-use, inexpensive measuring devices or special apps for mobile phones.

III. Recommended measures for the population in the event of an emergency:

III-1) During the explosion, you can effectively protect yourself from flying debris and heat radiation by taking suitable cover. Therefore, ducking – preferably behind walls or mounds of earth as protective barriers – and shielding exposed body parts are the most important initial protective measures.

III-2) In the first 24 h to 48 h after the explosion, the best protection in the vicinity of the explosion and in areas potentially affected by fallout is to take shelter in protective spaces (e.g. cellars, underground car parks). Stocking up on drinking water and food is recommended as a precaution. Facilities for decontamination (water, wipes) and spare clothing should be available.

III-3) Self-evacuations are strongly discouraged because they can lead to avoidable, life-threatening radiation doses from fallout. Vehicles do not provide adequate radiation protection.

III-4) In the event of a nuclear attack, it is not advisable to take stable potassium iodide (i.e. iodine blockage (tablets)).

III-5) FFP 2/FFP 3 respiratory masks should be kept available and worn if protective spaces have to be left (e.g. when obtaining vital medication or in the event of an imminent evacuation).

III-6) All citizens should inform themselves about the danger of nuclear weapons explosions and, in particular, about protective measures/rules of conduct at home and at work and discuss this with colleagues, family members, and neighbours.

III-7) The fallout that is deposited within a short time after a nuclear weapon explosion can lead to high radiation exposure. This, in turn, can cause damage to health. It is, therefore, important to seek protection from fallout or to decontaminate as quickly as possible. Simple self-decontamination by removing clothing, washing exposed body surfaces and hair, and subsequent showering is therefore strongly recommended for the population in the areas affected by the fallout.

IV. For emergency personnel in the event of an emergency:

IV-1) First responders and emergency personnel should first shelter in protected spaces and await instructions from the authorities, especially within the first 24 h.

IV-2) Of particular importance is a dose determination for first responders and emergency personnel during the operation (if possible, using an alarm dosimeter) and avoiding the incorporation of radioactive substances.

IV-3) Before entering a hazardous radiation zone, first responders and emergency personnel must receive thorough preparation, and rotations must be based on defined dose levels.

Scientific justification

4 Findings on national and international preparation for recommended measures in the event of nuclear weapons explosions

4.1 National measures

4.1.1 Responsibilities in civil protection

According to Section 1 of the Federal Civil Protection and Disaster Relief Act (ZSKG), amended in 1997 (ZSKG 1997), "the task of civil defence is to provide non-military measures to protect the public, their homes and workplaces, as well as civilian offices, businesses, facilities and infrastructure that are vital or important for defense, and cultural assets from the effects of war and to mitigate their consequences. Official measures complement the self-help of the population". Civil defence includes self-protection, residence regulations, and measures to protect the public health.

Section 4, para. 2 ZSKG assigns administrative responsibilities under this Act to the Federal Office of Civil Protection and Disaster Assistance (BBK), which is part of the Federal Ministry of the Interior and Community (BMI). The federal government develops standards and framework concepts for civil defence according to Section 18, para. 3 ZSKG, and provides supplementary equipment (e.g. for NBC protection; now CBRN protection) according to Section 13 ZSKG. The supplementary equipment for CBRN protection includes equipment for monitoring, decontamination, and contamination analyses, as well as PPE for emergency personnel[4]. The BBK is also responsible for coordinating the CBRN Analytical Task Force (ATF) as well as for promoting, intensifying, and coordinating civil-military cooperation with the Territorial Tasks Command of the German Armed Forces (Bundeswehr). For police situations, the Federal Police heads the German CBRN response capabilities on the federal level (UVB-CBRN), which also includes the Federal Criminal Police Office, the CBRN Defence Command of the German Armed Forces, the Robert Koch-Institute (RKI), the Bundeswehr Institute of Military Science, and the Federal Office for Radiation Protection (BfS).

Responsibility for operational crisis management lies with the federal states and municipalities. This involves the planning and provisioning of hospitals by the health ministries of the federal states. According to Section 21, par. 1 ZSKG, the authorities responsible under state law must plan supplementary measures for providing healthcare to the population in the event of defence; they should work closely with the health and medical services of the Bundeswehr.

According to Section 98 of the Radiation Protection Act of 2017, the BMUV assesses possible emergency exposure situations. In 2023, the BMUV issued a "General Federal Emergency Plan" (ANoPl-Bund); the reference scenarios defined there include various types of nuclear power plant accidents and other accidents involving radioactive material, under item S14 it covers a nuclear weapon explosion (although not in connection with cases of tension or defence). In particular, the ANoPl-Bund includes strategies for protecting the public and emergency personnel that are optimally tailored to the respective reference scenario and take into account particularly vulnerable people (optimised protection strategies). The Federal

[4] https://www.bbk.bund.de/DE/Themen/Ergaenzende-Ausstattung/Zivilschutzfahrzeuge/CBRN/cbrn_node.html https://www.bbk.bund.de/DE/Themen/CBRN-Schutz/CBRN-Faehigkeiten/cbrn-faehigkeiten_node.html, last accessed on 16 September 2024

Radiological Situation Centre (RLZ-Bund), which is part of the BMUV, is responsible for coordinating national and international radiation protection assistance measures. In accordance with Section 106 StrlSchG, the BMUV has set up the RLZ-Bund, which fulfils the tasks under Section 106, para. 2 StrlSchG. The RLZ-Bund is organised as a network of the BMUV, the BfS, and the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS).

The BfS oversees the Integrated Measuring and Information System (IMIS), which monitors environmental radioactivity through a network of over 1,500 measuring stations across Germany. In the event of a radiological emergency, the BfS plays a key role in drawing up the radiological situation report at the RLZ-Bund (based on the IMIS measurement data, among other things). Furthermore, the BfS advises the authorities involved in the UVB-CBRN on the radiological aspects of a police situation and provides personnel and technical support in dealing with radiological hazards. The BfS fulfils the following tasks, among others:

- Assessment of the radiological situation (based, among others, on IMIS measurement data),
- Advising the incident commander on radiation protection issues and possible hazards posed by radioactive substances
- Ensuring radiation protection for emergency personnel
- Search for, detection with measuring devices and identification of radioactive substances and quantity estimation
- Estimation of the dispersal of radioactive substances (e.g. in a scenario involving a dirty bomb)
- Dose estimation
- Advising on the transport of radioactive substances
- Advising on the implementation of decontamination measures
- Planning and organisation of training courses and exercises.

Tab. 4-1: Interlinking of tasks and responsibilities for dealing with the explosion of nuclear weapons at the federal and state level.

Tasks	Federal department	Federal authority	State departments
Civil protection	BMI: Civil defence concept. Civil protection planning.	BBK: Civil protection planning. ATF coordination Federal Police: manages UVB-CBRN	Interior Departments: Organisation of disaster control together with the police, fire brigades, rescue services, and Federal Agency for Technical Relief (THW)
Health protection	Federal Ministry of Health (BMG): Health legislation	RKI: involved in UVB-CBRN	Health departments: Hospital planning, provision of the necessary infrastructure
Special emergency response for RN situations in peacetime	BMUV: StrlSchG, federal emergency plans, RLZ-Bund	BfS: Operation of the IMIS, involved in RLZ-Bund and UVB-CBRN. RLZ-Bund: Preparation of the radiological situation report, involvement of the coordination centres of the higher federal authorities	Partly environmental departments, partly interior departments or others: Emergency plans of the federal states, coordination of the radiation protection head offices of the federal states with the RLZ-Bund
Civil-military co-operation	BMVG: has a well-developed infrastructure	Command Territorial Tasks. CBRN defence command, the Bundeswehr Research Institute for Protective Technologies (involved in UVB-CBRN)	

Tab. 4-1 provides only limited information on the tasks and responsibilities for dealing with the consequences of nuclear weapons explosions. In particular, the distribution of tasks within the Bundeswehr is not addressed; only civil-military cooperation is mentioned here. The table is intended primarily to illustrate the complex interdependencies of responsibilities.

According to Section 19 ZSKG, a protection commission should advise the Federal Minister of the Interior on scientific and technical issues relating to civil defence and disaster relief. This protection commission, which was set up in 1951 in connection with the impending Cold War and comprised voluntary experts from the natural sciences, technology, medicine, and social sciences, was tasked with drawing up hazard reports at regular intervals. In these, the Protection Commission has repeatedly emphasised the need to develop a cross-departmental and cross-state concept for care and after-care in the medical, pharmaceutical, and psychosocial areas of disaster relief. However, the protection commission was dissolved without replacement in 2015.

4.1.2 Status of preparations

The ANoPl-Bund came into force on 24 November 2023, according to Section 98 StrlSchG. The regulations of this ANoPl-Bund and the forthcoming Special Federal Emergency Plans (BNoPl-Bund) do not apply to emergencies arising from situations of tension or defence. Planning for such radiological emergencies is carried out in the "Civil Defence Concept" (KZV) published by the BMI in 2016, and the reference documents that specify and supplement the KZV (e.g. the "Framework Concept for CBRN Protection" (BBK 2014, printed 2016)).

According to the ANoPl-Bund of 2023, insofar as the KZV and the CBRN protection framework concept do not contain any special regulations for radiological emergencies (e.g. nuclear weapon explosions), the regulations of the emergency plans under the StrlSchG may be applicable in whole or in part to such radiological emergencies. The CBRN protection framework concept (BBK 2014) states that the responsibility for ensuring CBRN protection capability lies with the federal, state, and local authorities responsible for emergency response.

According to the KZV, the entire population should have basic knowledge or basic skills in the following areas: Staying safe in hazardous situations, proper behaviour in the event of CBRN incidents, self-sufficiency, first aid, and fire-fighting. Basic knowledge, particularly with regard to CBRN scenarios, was certainly communicated to the population during the Cold War. For example, with the then much-discussed educational publication "Jeder hat eine Chance" [Everyone has a chance] (published by the then Federal Office of Civil Protection in 1962). With the dissolution of the Soviet Union in 1991, the confrontational situation associated with the Cold War was considered to be over. Information campaigns to prepare the general population for nuclear explosions were discontinued. In contrast to other countries (see Section 4.2), the responsible authorities in Germany have not yet resumed activities to inform the public about nuclear weapons explosions.

The KZV (BMI 2016) stipulates "that existing buildings be used as physical protection (cover) and as safeguards against contamination by CBRN substances to ensure public safety through self-protection measures. Measures to strengthen residential and commercial structures are recommended, subsidised, or mandated by the federal government. However, the comprehensive provision of public shelters is unfeasible and, given the likelihood of short or no warning times, offers limited protection in such scenarios.

Accordingly, the Federal Ministry of the Interior decided as early as 2007 to abandon the bunkers and shelters in the West German federal states. 1,400 out of 2,000 shelters had been "decommissioned"; around 600 shelters, including large ones in underground stations or car parks, are still available and could be reactivated. However, no such reactivation is currently planned. Any shelters that may still exist in Eastern Germany were not even included in the protection concept of the federal government. (Süddeutsche Zeitung, 6 March 2022).

Large-scale evacuations are planned and prepared using the example of an incident at a nuclear power plan, according to the KZV (BMI 2016), based on the "Framework recommendation for the planning and implementation of evacuation measures including evacuation for an extended region" that was agreed by the federal states.

The KZV (BMI 2016) specifies that the following sub-capabilities, among others, must be ensured to cope with chemical (C), biological (B), radiological (R), and nuclear (N) incidents:

- CBRN detection
- CBRN decontamination
- Personal protection
- Collective protection
- CBRN hardening
- CBRN health protection
- Radiological emergency response (including nuclear emergency response).

In its recommendation, "Medical management of radiation emergencies – requirements and organisation" (SSK 2023a), the SSK commented in detail on the care of radiation emergency patients in RN situations, highlighted deficits in care, and made suggestions to eliminate them.

In this recommendation, the SSK considers the preparations for preclinical, more technical measures such as CBRN detection, decontamination, and PPE to be generally sufficient for small and medium-sized radiological emergencies, but probably not sufficient in scope for the response to a nuclear weapon deployment. However, the SSK has no existing data on actual stockpiling and local distributions. The transport of radiation emergency patients by ambulance is regulated in principle and, according to the SSK, is excercised occasionally – as are the measures listed above. In contrast, there are some considerable deficits at the interface between preclinical and clinical care in hospitals ready to accept patients. To overcome these deficits, the SSK (SSK 2023a) recommends, among other things, establishing and maintaining a two-tier network of hospitals specialising in radiation emergencies and of mobile teams for the care of radiation emergency patients, which must be kept available. At the centre of this network, a central coordination office shall enable the Germany-wide distribution of radiation emergency patients based on daily updated data on the treatment capacities, equipment, and personnel available. In its recommendation, the SSK also proposes content for a curriculum for the planned qualification level "radiation emergency management" and "radiation emergency doctor".

4.2 International measures

Current measures recommended in other countries to protect in case of nuclear detonation and recommendations from other organisations

4.2.1 US: Planning Guidance for Response to a Nuclear Detonation of the Federal Emergency Management Agency (FEMA) (2023)

The Federal Emergency Management Agency (FEMA) is an agency of the US Department of Homeland Security (DHS). The DHS was founded after the terrorist attacks on the World Trade Centre on 11 September 2001. It is responsible for preparing for and dealing with all kinds of disasters.

The Guide for Planning State Responses and Actions, which was developed in collaboration with the Department of Energy, the Department of Health and Human Services, the Department of Defence, and the Environmental Protection Agency, was expanded in its third edition in 2022 compared with earlier editions from 2009 and 2010 (FEMA 2023). It no longer considers only smaller nuclear explosions in the context of terrorist attacks but also mentions explicitly larger nuclear explosions on ground level and in the air, including threats from other states. These guides are described in detail here because the SSK considers them to be a useful basis for planning in other countries, including Germany. Its clear and non-technical language and public availability also make it accessible to potential disseminators such as teachers, media professionals, and interested citizens. It also contains helpful references to further documents for the individual subject areas.

Chapter 1 of the guide provides a clear and easily understandable overview of the relevant hazardous events in the event of a nuclear weapon explosion (flash of light, initial radiation, electromagnetic pulse, heat wave, pressure wave, residual radiation[5] from activation, and fallout), their temporal sequence, and the expected spatial extent of the events as a function of explosion yield and height. Five scenarios are considered: Near-surface explosions with explosion yields of 0.1 kT 1 kT, 10 kT, and 100 kT as well as explosions with 100 kT yield at

[5] In the case of a nuclear weapon explosion, residual radiation is the ionising radiation that occurs as a nuclear weapon effect from one minute after the explosion. This is generated by the resulting fission and activation products as well as the unreacted fission material.

heights of approx. 1,000 ft (300 m) and 5,000 ft (1,500 m) above ground. A comparable compilation that is also accessible to non-experts is lacking in the German-speaking world.

Chapter 1 also introduces a zoning system that serves as a basis for the emergency measures to be taken and their prioritisation. This categorisation was based on visible building damage: The Severel Damage Zone (SDZ) comprises a region in which only a few buildings have remained structurally intact and in which very few people can survive in appropriate protective structures. The Moderate Damage Zone (MDZ) is also characterised by substantially damaged buildings; however, more stable buildings (e.g. made of reinforced concrete) can withstand the blast wave. A considerable number of survivors can be expected in this zone; in the event of a near-surface 10 kT nuclear weapon explosion, it covers distances of approx. 0.4 km – 1.5 km from Ground Zero (the point on the Earth's surface lying vertically below the explosion site, also known as hypocentre). In the Light Damage Zone (LDZ), most of the building shells are intact. However, injuries are likely to occur because of glass splinters and other flying objects. The LDZ ranges from approx. 1.5 km to 5 km for a 10 kT nuclear weapon explosion near the surface. In addition, the recommendation in this chapter introduces zones based on the expected dose rate: In the Dangerous Radiation Zone (DRZ), the dose rate is over 100 mGy h^{-1}, whereas the dose rate values in the Hot Zone (HZ) are between 0.1 mGy h^{-1} and 100 mGy h^{-1}. These zones cannot be assessed on the basis of the degree of destruction of buildings but instead must be determined by dose rate measurements, especially in the areas affected only by fallout. Because of the distance-dependent deposition lasting up to several hours and the initially rapid decay of the radioactive components in the fallout, the extent of these dose rate zones changes relatively quickly and in a complex manner shortly after a nuclear weapon explosion (Fig. 9.1). This chapter highlights minimising external exposure to fallout, particularly ground shine (external irradiation from radionuclides on surfaces), as the most urgent measure to save lives and protect health outside the SDZ: By entering and remaining in buildings for at least 12 h to 24 h (unless acute other hazards such as fire, collapsing buildings or medical emergencies require evacuation), external exposure to fallout can typically be reduced to less than one ten.

Chapter 2 provides a more detailed description of the necessary measures for the general population and emergency personnel in the various zones. Reference is made to the dose guidelines for emergency personnel and the various options available to reduce the exposure of emergency personnel. It also describes the non-nuclear dangers for emergency personnel in the destroyed zones. Because of the various relatively high risks for the emergency personnel and the low number of survivors in the SDZ, rescue operations in this zone are not considered a priority. On the other hand, it is expected that many survivors in the MDZ can benefit from rapid rescue operations. In addition, an organised evacuation in this zone can prevent many more casualties (e.g. because of fires and collapsing buildings). The guide, therefore, considers this zone a priority for rescue operations, whereby the potential hazards to emergency personnel are still considerable, especially in DRZ areas (cf Section 9.1). Chapter 2 also deals with the need to plan and prioritise the decontamination of vital infrastructure facilities as well as to develop concepts for handling waste contaminated with radioactive and other hazardous substances.

Chapter 3 goes into more detail on the topic of sheltering in buildings as an urgent early measure, especially if no further information is available. Successful preventive sheltering can be life-saving for many affected people by protecting them from damage caused by the blast wave, the heat wave, and the initial radiation. However, a nuclear weapon could also be used without warning. Here, seeking shelter outdoors by "duck and cover" can reduce health damage caused by the early effects (pressure and heat wave, initial radiation). For sheltering after a nuclear weapon explosion, there is a time window of a few minutes – even at close range – before the fallout hits the ground; in the long-distance area, the time window extends up to several hours. This time should be used to find a building that provides adequate protection. In the fallout area, sheltering plays the predominant role in preventing external exposure to fallout as well as inhalation of dust and smoke. Overall, for the topics of acute protection (including sheltering) it is necessary to publicise criteria for suitable building sections in advance , to develop corresponding key messages (in the US: “Get inside, stay inside, and stay tuned”), and to identify suitable mass shelters. Because sheltering is a temporary measure (for the first 12 h to 24 h), the subsequent steps, such as evacuation and lifting of the sheltering recommendation, must also be planned.

Chapter 4 describes the expected mass casualty incident and the resulting challenges for acute medical care with a simultaneously impaired infrastructure. Injured patients with mechanical trauma, burns, and acute radiation syndrome, as well as combinations thereof, are expected. The overall prognosis for combinations of these health effects is worse than expected if the individual prognoses were combined. Chapter 4 also provides an introduction to the various dose-dependent symptoms of acute radiation syndrome and their treatment, as well as the delayed effects of acute radiation exposure (DEARE). Preparatory planning is also necessary for psychosocial care and necessary triage measures, as well as the national stockpiling of medicines and materials, the involvement of medical facilities, and the respectful treatment of the deceased.

Chapter 5 addresses the need for the prompt monitoring of all potentially affected individuals, focusing on required medical treatment, contamination of clothing and body (including internal contamination, if necessary), and decontamination measures. For subsequent dose and risk assessments, it is also recommended to collect all relevant data, where available. In addition, instructions for the self-reliant implementation of contamination-reducing measures by those affected should be clearly communicated.

Chapter 6 deals with questions of communication and preparing the general public for a nuclear weapon explosion. Preparatory communication prior to such an event is a decisive factor that can save many lives because many communication channels will no longer function in the event of a nuclear weapon explosion, instinctive (escape) behaviour can lead to (avoidable) high radiation exposure, and a great deal of scepticism or fatalism must be expected in the population on this topic. All of these further complicate the dissemination of information. In the US, the strategy is, therefore, to combine preparatory communication for a nuclear explosion with other preparatory actions (e.g. for tornadoes and other natural disasters or for the intrusion of armed persons into school buildings) and to use a national “Preparedness Month” for this purpose. In the event of an emergency, the guidelines recommend distributing a standardised, ready-made message through all available communication channels. In the US, this is “Get inside, stay inside, and stay tuned” until further information is available. Preparation is also necessary to harden the communications infrastructure against the expected outages.

Finally, Chapter 7 deals with alarm and warning systems and is relatively specific to the situation in the US. However, it highlights the complexity of the interlinked reporting channels and the necessary preparation.

4.2.2 National emergency plan for Austria in the event of the use of nuclear weapons at a greater distance from Austria (2022)

The national emergency plan of Austria was drawn up in accordance with the Austrian Radiation Protection Act (StrSchG 2020) by the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology with the involvement of all federal ministries concerned. It forms the working basis for official emergency management at the federal level and ensures a coordinated emergency response by all organisations involved. Only nuclear weapon explosions at a greater distance are considered where Austria is not affected by the direct effects (primary effect: blast wave, heat radiation, nuclear electromagnetic pulse), direct radiation) but rather by a possible atmospheric transport of radioactive air masses to Austria. Two scenarios are explicitly described as possible affected areas: Deployment of tactical nuclear weapons in Ukraine or at a NATO base in Europe (including indicated German sites) where nuclear weapons are stored. A near range is defined (distances from several tens of kilometres to about 100 km downwind of the explosion site, initial dose rate above 100 mSv h^{-1}) and a far range (distances from about 100 km to several thousands of kilometres downwind). Based on possible scenarios, the document is limited to events that occurred several hundred kilometres away from Austria; because of the lower radioactive inventory, these events are considered to have a less serious effect on Austria than severe nuclear power plant accidents at a similar distance. Based on these basic assumptions, procedures planned at the federal level for the use of nuclear weapons at a greater distance from Austria should be analogous to the procedures for other large-scale radiological incidents.

Following a description of scenarios, the emergency plan provides an overview of the organisations involved in emergency management, their responsibilities, and operational readiness. Information and reporting channels are then described as are the structure and function of the situation centre to be set up. It also describes the methods for determining soil contamination and passing on data. The emergency plan assumes that in the event of a near-ground explosion of a tactical nuclear weapon at a greater distance (several hundred kilometres) from Austria, the protective measures “preparation and intake of potassium iodide tablets” and “staying inside” will not be necessary in Austria. However, depending on the situation, protective measures in the agricultural and food sector may be necessary.

At one point, the document also mentions protective measures at close range. Because of the lack of or very short warning phase in the event of a nuclear weapon being used, it is strongly recommended to stay inside (usually for at least 24 h) as far away as possible from windows and, if possible, on the lower floors or in the basement. The population should inform themselves via radio and television as far as possible. To avoid unnecessary exposure, immediate evacuation is not recommended. Even at close range, the need to take potassium iodide tablets is considered to be quite low.

4.2.3 Report by the Swedish Radiation Protection Authority (SSM) on the radiological consequences of fallout from nuclear weapon explosions (2023)

Swedish radiation protection legislation also applies in the event of an international event of tension unless otherwise stipulated by specific regulations. Sweden's government, armed forces, and radiation protection authorities are authorised to draw up regulations that deviate from the current legislation for employees in the Swedish total defence[6]. The Swedish Armed Forces are currently developing regulations for their own personnel. However, no such work is under way

[6] Compulsory military service applies in Sweden. This means that anyone who lives there and is between 16 and 70 years old can be called upon to help in various ways in the event of war. There are three types of general defence obligation: a) compulsory military service in the armed forces, b) civilian service in activities decided by the government (e.g. in the emergency services, childcare, and healthcare), and c) general service obligation (i.e. serving in organisations that must function even in the event of war and the threat of war). This may mean continuing to carry out the regular job, serving under a special arrangement that may arise from membership of a voluntary defence organisation, or being assigned work that is particularly important to the overall defence by the employment service.

to develop regulations for persons working in the Swedish total defence who are not employed by the Swedish Armed Forces.

It is also unclear whether, based on the current legislation, in the event of tension the Swedish government or another state agency may issue regulations that deviate from the applicable radiation protection regulations for the general public or employees who are not involved in the total defence.

The reference levels for emergency exposure situations are regulated in the Swedish Radiation Protection Ordinance. The reference level for exposure of the population in an emergency exposure situation is 100 mSv annual effective dose for events in a nuclear power plant and 20 mSv annual effective dose for all other events, including fallout from nuclear explosions. However, the SSM notes that a reference value of 20 mSv effective dose is not suitable as a starting point for optimising radiation protection after fallout from nuclear weapon explosions. In their comments, they therefore consider assumed reference values of 100 mSv, 500 mSv, and 1000 mSv effective dose in the first year.

The SSM report provides an analysis of the possible radiological effects of fallout at a distance of about 10 km to several hundreds of kilometres from the explosion site. It is intended as a collection of available knowledge – and not as a ready-made basis for planning activities. Assuming a 100 kT weapon with 50 % fusion content that detonates close to the ground and taking into account various weather conditions (coverage of 70 %, 80 %, and 90 % of the weather conditions actually occurring in Sweden), effective doses for unprotected persons are estimated as a function of the distance from the explosion site. The assessment shows that in the first two days without protection (i.e. without remaining in buildings) potentially lethal effective doses are possible at a distance of several tens of kilometres, and effective doses above 1,000 mSv at a distance of 50 km – 75 km from the explosion site. Effective doses above 100 mSv are possible up to 250 km from the explosion site in the fallout area. These doses are almost entirely dominated by external doses from deposited radionuclides whilst external irradiation from the cloud or inhalation contributes at most only a few percent to the effective dose These data emphasise the importance of seeking out rooms with a good protective effect (sheltering) in the first two days. However, even without exposure in the first two days, the remaining activity must be considered. This can lead to the effective doses of people in their regular residential buildings exceeding an annual dose of 1,000 mSv or 100 mSv (at a distance of approx. 10 km – 20 km or 100 km – 150 km from the explosion site, respectively). This highlights the importance of planning evacuation and resettlement measures.

It is also stated that thyroid doses above 500 mSv are considered unlikely for survivors without sheltering. Iodine blockage is not recommended.

The authors emphasise that the relative importance of the different exposure routes for an unprotected person from fallout after a nuclear weapon explosion and fallout from a reactor accident is different. For fallout after nuclear weapon explosions, external exposure through deposited radionuclides dominates; in severe nuclear power plant accidents, inhalation doses, especially through the incorporation of radioiodine, dominate. This difference has important implications for the effectiveness of protective measures.

The authors’ most important conclusions for preparatory planning are as follows:

- Finding a well-protected space before the fallout arrives is crucial. Depending on the distance and weather conditions, the time available can range from a few minutes to several hours (i.e. appropriate warnings and behavioural prompts are possible for at least some of those affected). However, evacuations are not advisable because of the limited time available.

- Unprotected persons can still be exposed to doses that lead to deterministic effects at distances of up to 75 km away from the explosion site. The possible occurrence of deterministic effects, especially skin effects, must be considered in the planning.
- Even if the initial phase was spent in a protective space, effective doses exceeding 100 mSv can be reached by staying at the place of residence during the first year – even at distances greater than 100 km from the explosion site. Resettlement or other restrictions due to soil contamination may be necessary to keep the effective dose below 100 mSv. At shorter distances, relocations may have to take place within the first week.

4.2.4 Recommendations of the International Commission on Radiological Protection (ICRP)

In 2022, the ICRP published advice for the public on protection in the event of a nuclear weapon explosion on its website[7] in 13 languages (including German). The key protective measures (get inside, stay inside, stay tuned) are illustrated with drawings and embedded videos, and their backgrounds are clearly explained. In addition, further behavioural measures for various periods of time after the explosion are described as are possible preparations for such an explosion. These recommendations are based on the US Planning Guidance for Response to a Nuclear Detonation (cf Section 4.2.1). In addition, the ICRP has made Publication 146 (2020a), “Radiation protection for the public in the event of a severe nuclear accident”, freely accessible on the Internet. However, this does not cover the military or terrorist use of nuclear weapons. The mandate of Task Group 120 was therefore expanded to include the task of drawing up protection recommendations for authorities and the public for malicious events and nuclear explosions based on comprehensive literature analyses.

5 Characteristics, types, and effects of nuclear weapons

5.1 Properties of nuclear explosions

An explosion is basically caused by the rapid release of a large amount of energy in an initially confined space. This applies to both conventional explosives (e.g. TNT) and nuclear explosions. However, in both cases, the release of energy is based on different physical principles. The sudden release of high energy in an explosion causes a huge increase in temperature and pressure, essentially turning the surrounding matter into a hot and compressed gas. At the prevailing high temperatures and pressure, the gas expands immediately and generates a pressure shock wave (referred to here in simplified terms as a pressure wave) in the surrounding medium (usually air, earth/rock or water). The wavefront of this pressure wave moves predominantly at a speed that is considerably greater than the speed of sound.

Nuclear explosions are similar to explosions from conventional explosives in that the pressure wave usually causes the main effect. However, there are also fundamental differences between explosions of nuclear explosive devices and those of conventional explosives:

- The explosive yield of nuclear weapons is usually in the range of a few kilotonnes (kT) to several megatonnes (MT) of TNT equivalent. It is, therefore orders of magnitude more powerful than conventional explosions.

[7] https://www.icrp.org/page.asp?id=613, last accessed on 16 September 2024

- For a given explosion yield (amount of energy released), the actual mass of nuclear material converted is orders of magnitude less than the mass of conventional explosives (theoretically) required.
- The temperatures reached in a nuclear explosion are many times higher than in conventional explosions. As a result, a considerably higher proportion of the energy released in nuclear explosions (explosion energy) is released in the form of thermal radiation. This is also known as *heat flash*.
- A nuclear explosion is accompanied by far-reaching ionising radiation. This radiation consists mainly of gamma and neutron radiation and is known as *initial radiation*.
- The fission products produced during nuclear fission are predominantly radioactive for a longer period of time and emit ionising radiation. The neutron radiation that is also produced during nuclear fission and nuclear fusion activates surrounding matter, which then also becomes radioactive and emits ionising radiation for a longer period of time. This ionising radiation, which lasts beyond the explosion process, is referred to as *residual radiation*.
- A nuclear explosion also generates pulsed electromagnetic radiation that can either temporarily disrupt or permanently destroy electronic devices. This is known as a *nuclear electromagnetic pulse (NEMP)*, which has a broad frequency distribution of up to several hundred megahertz. Because of its long range, the EMP is of great military and civilian importance, especially in the case of the exo-atmospheric explosion of a nuclear weapon.

Nuclear explosions in the air and exo-atmospheric explosions lead to the ionisation of local or larger areas of the atmosphere. This leads to a change in the electromagnetic properties of the atmosphere. This, in turn, can have a negative effect on the propagation of electromagnetic waves (e.g. in radio transmission or radar applications).

5.2 Initial and residual nuclear weapon effects

The effects of a nuclear weapon depend fundamentally on its individual design, the explosion yield, the operational environment, and the time considered after the explosion. In the first microsecond after the time of explosion, the processes are fairly similar for all nuclear weapon explosions in terms of the effect. The entire explosion energy is released within this first microsecond, and the entire prompt nuclear radiation is emitted during this time interval. What remains are the vaporised reaction products of the nuclear reactions and the vaporised weapon parts. The resulting fission products are predominantly highly radioactive and emit gamma, beta, and alpha radiation. This radiation component is regarded as secondary radiation. The high temperatures lead to immense internal pressure, which causes the vaporised weapon material to expand radially at high speeds. The vaporised material cools down quickly because of the expansion. During the first microsecond, around 80 % of the explosion energy of most nuclear weapons is emitted as thermal energy, the largest proportion of which is (soft) X-rays (Glasstone and Dolan 1977). At the end of this first microsecond, the remaining explosion energy consists essentially of kinetic energy. After the first microsecond, the vaporised weapon material interacts with the environment. The further effects of the nuclear weapon explosion depend strongly on the density, composition, aggregate state, and pressure of the surrounding material. In a ground-level nuclear weapon explosion, the initial effects of the nuclear weapon are the initial radiation pulse described above, followed by the thermal radiation pulse (heat flash), and finally, the pressure wave.

A few minutes after the explosion, the remaining effects are primarily those resulting from residual radiation from fallout and ionisation of the atmosphere. Therefore, the period from the nuclear weapon explosion to one minute[8] afterwards is defined as the time of initial effects. All effects that occur after the first minute of the explosion are therefore residual effects of a nuclear weapon explosion.

5.3 Functionality and types of nuclear weapons

All nuclear weapons are based on the physical principle of nuclear fission in a chain reaction and, depending on the type of nuclear weapon, on the principle of nuclear fusion reactions.

5.3.1 Nuclear fission

When neutrons split uranium or plutonium nuclei, further neutrons are emitted in addition to the fission energy released. This is the basic prerequisite for a chain reaction that can theoretically be triggered by a single neutron and leads to a huge release of energy in a relatively short time. In practice, the fissile nuclides ^{235}U and ^{239}Pu are relevant for nuclear weapons. Nuclear fission produces around 60 primary nuclides in 35 chemical elements (Hoffmann 1987). A total energy of around 200 MeV is released per fission event; of this, around 180 MeV is released as explosion energy. The kinetic energy of the fission fragments has by far the highest proportion of the fission energy. In a nuclear explosion with an explosion yield of 1 kT, only 57 g of ^{235}U or 58 g of ^{239}Pu are split by nuclear fission. However, with a simple fission assembly, only a maximum of 20 % of the fissile material present is fissioned in the explosion because the chain reaction collapses as a result of the enormous release of energy and thus the rapid expansion of the fissile material (Hoffmann 1987).

5.3.2 Nuclear fusion

Like the energy generation in the sun and other stars, energy production in thermonuclear weapons occurs via nuclear fusion (i.e. via the fusion of hydrogen nuclei to form heavier nuclei). The chemical element hydrogen exists in the form of the isotopes hydrogen (^{1}H) and deuterium (^{2}H or D), as well as the radioactive tritium (^{3}H or T). All three isotopes have one proton but differ in the number of neutrons. An extremely high temperature and high pressure are required for fusion to take place. These processes are, therefore, also known as thermonuclear fusion reactions.

At temperatures of several tens of millions of Kelvin, essentially two different DD and one DT fusion reaction occur. These three fusion reactions release an energy of around 24.8 MeV during the fusion of five deuterium nuclei. With 2.48 MeV, each nuclear particle (nucleon) in thermonuclear fusion releases around three times as much energy as in nuclear fission, which releases 0.85 MeV.

The prerequisite for these fusion reactions to take place at the necessary reaction speed is a temperature of several tens of millions of Kelvin. In weapons technology, this temperature can be achieved only by exploding a fission assembly. A thermonuclear fusion reaction can be achieved by combining a fission assembly (primary) with a specific assembly of fusion material (secondary) in a warhead.

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[8] After this time, the explosion cloud, which still contains most of the fission products, has already reached such heights that the gamma radiation emitted by the fission products is practically irrelevant for an immission point on the Earth’s surface compared with the radiation dose of the first minute.

5.3.3 Nuclear fission weapons

Nuclear fission weapons can be manufactured according to the gun design or implosion principles, whereby boosted implosion arrangements are also possible.

Usually, highly enriched uranium (HEU) with a ^{235}U content of at least 80 % is used for a nuclear weapon based on the gun design. In this design, a sub-critical mass of the fissile material used is shot into a second sub-critical mass located at the other end of the tube in an arrangement similar to a gun barrel. The first mass is accelerated using conventional explosives. Therefore, the supercriticality of the fissile material required to start a nuclear chain reaction is achieved by quickly combining two sub-critical masses to form a supercritical mass.

In the implosion method, on the other hand, the supercriticality of the fissile material is achieved by compressing a single mass of fissile material that is sub-critical at normal ambient pressure. Compression is achieved by surrounding an approximately spherical mass of fissile material with conventional explosive lenses, which are ignited in such a way that they compress the fissile material symmetrically to the centre. In practice, weapons-grade plutonium with an enrichment level (^{239}Pu) of around 90 % is used for this purpose.

In the meantime, boosted implosion assemblies are likely to be increasingly used (Gsponer 2006). Weapons-grade plutonium is designed as a hollow sphere with a small amount of the fusion fuels deuterium and tritium in its cavity. When sufficient pressure and temperature have been created by the advancing chain reaction, the fusion process ignites and releases fast neutrons. Also, these fusion neutrons split a considerable proportion of the plutonium. This uses the available fissile material more efficiently and increases the explosion yield.

5.3.4 Thermonuclear weapons

Modern nuclear warheads are likely to be predominantly of the thermonuclear type (Gsponer 2006). To ignite the fusion fuel, thermonuclear weapons require extremely high temperatures and pressures, which are generated by the explosion of a nuclear fission device (primary). Nowadays, the use of a boosted implosion detonator (cf Section 5.3.3) is probably common. The primary explosion energy is released mainly as (soft) X-rays and generates an extremely hot plasma locally and thus pressure. Under these conditions, the fusion assembly (secondary) can ignite the fusion process in the fusion material. Technically, this process can be implemented in different ways. The best-known is probably the Teller–Ulam design. The primary fission assembly and the fusion assembly (secondary) are located in close proximity to each other in a bomb or warhead casing. The remaining cavity is filled with foam (e.g. polystyrene).

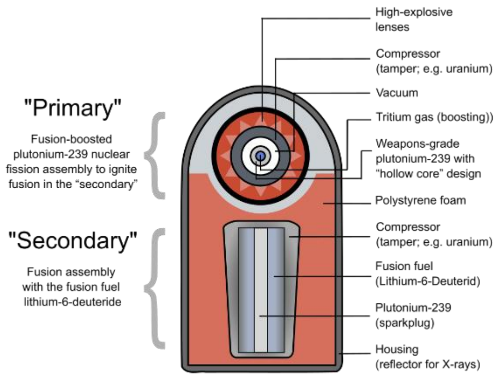

Fig. 5-1: Schematic diagram of the structure of a thermonuclear warhead according to the Teller–Ulam design consisting of a primary (boosted fission assembly) and a secondary (fusion fuel) located directly next to each other. (Source: Rambousky according to Wikimedia Commons)

There are also two special versions of a thermonuclear warhead, which are mentioned briefly here. On the one hand, the fusion device can be provided with a casing of natural or depleted uranium (^{235}U content of 0.7 % or less). This is referred to as a three-phase weapon[9]. The fission of uranium by the fast fusion neutrons present can greatly increase the explosion yield. However, the disadvantage is that a large amount of fission products – and thus also fallout – is produced and such a bomb is therefore considered very *dirty*[10]. However, another clever design can be used to minimise the amount of fission products whilst maximising the emission of the initial neutron radiation. The result is the "*neutron bomb*". If anything, both the three-phase weapon and the neutron bomb are probably only of secondary importance today.

5.4 Nuclear arsenals

Information on the arsenals and design details of nuclear weapons of the established nuclear weapon states is generally kept secret and, therefore, not freely accessible. Nevertheless, the open literature[11] contains data and facts that allow a reasonably realistic classification and estimation of the arsenals (Kristensen and Korda 2022a,b).

In the case of arsenals, a distinction is made primarily between strategic and non-strategic nuclear weapons. The main criterion for this categorisation is not the explosion yield (kT value) of a nuclear warhead but rather its intended use. Strategic nuclear weapons are designed to target locations deep within the enemy's territory and function primarily as a nuclear deterrent. Non-strategic (tactical) nuclear weapons are designed for use in a combat zone and are therefore often referred to as "battlefield weapons".

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[9] This is referred to as a three-phase weapon because the energy release takes place in the 1st fission (primary), 2nd fusion (secondary), and 3rd fission (secondary, ^{238}U) phases.

[10] This has nothing to do with a "dirty bomb". In a (conventional) dirty bomb, an attempt is made to disperse the radioactive substances contained in the explosive device by detonating conventional explosives in the surrounding area.

[11] This section looks mainly at the arsenals of the nuclear weapons states US and Russia.

5.4.1 Strategic nuclear weapons

The strategic deterrence of a nuclear weapons state is generally based on three pillars. The first pillar consists of sea-based strategic nuclear weapons. This pillar is considered the pillar with the highest “second strike capability” (ability to retaliate against the attacker after a nuclear strike with the aim of “assured destruction”). The second pillar consists of land-based weapons. This pillar enables the greatest responsiveness. Finally, the third pillar consists of air-based strategic nuclear weapons. This pillar is considered to be the most flexible and the most visible. Although there is no strict classification according to explosion yield, strategic nuclear warheads tend to be in the upper kT range (usually three-digit). In relation to the three pillars, the following kT ranges can be roughly specified for each nuclear warhead:

- “Sea-based” pillar: 100 kT–500 kT
- “Land-based” pillar: 300 kT–800 kT
- “Air-based” pillar: 5 kT–1,200 kT

Sea- and land-based intercontinental ballistic missiles in particular can carry several nuclear warheads (multiple independently targetable re-entry vehicles, MIRV) at the same time. These can be aimed at different targets independently on the final approach. Because of the MIRV technology and the increased accuracy of (intercontinental) ballistic missiles in recent decades, nuclear warheads with explosion yields of several megatons are likely to play only a minor role, if any, in the arsenals of nuclear weapons states.

Strategic nuclear weapons are kept ready for nuclear deterrence and are intended to guarantee a first or second strike capability in the event of a military emergency. The potential strategic targets are usually located in the territory of the nuclear adversary, which may be far away.

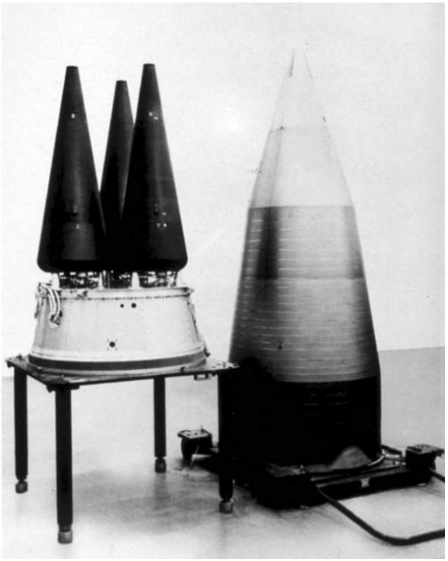

Fig. 5-2: Three nuclear warheads of type W78 as MIRV MK12-A for a ballistic missile LGM-30G Minuteman III, (Hansen 1945).

5.4.2 Non-strategic nuclear weapons

The potential use of non-strategic nuclear weapons is considered in military areas of operation or on battlefields. Non-strategic nuclear weapons tend to have an explosion yield in the lower kT range (one or two digits). Also nuclear explosive devices in the sub-kT range are technically possible (keyword: nuclear backpack bomb). However, it is likely that their relevance in current arsenals is minimal. However, it cannot be ruled out that also nuclear weapons with higher explosive yields will be used as non-strategic weapons. A realistic range of explosion yields for non-strategic nuclear weapons can be roughly estimated at 0.03 kT–50 kT.

5.5 Effects of nuclear weapons

A distinction is made between the direct and indirect effects of nuclear weapons. Direct effects include effects caused by (in chronological order)

- the initial radiation from neutron and gamma radiation
- the thermal radiation (heat flash)
- the pressure wave (pressure pulse)

The indirect effects include

- effects of radioactive fallout from the explosion cloud and the associated ionising radiation emitted by the fission products (residual radiation)
- effects caused by a NEMP, which arises because of the interaction of the initial gamma radiation in a nuclear explosion both outside the Earth's atmosphere and – with a considerably smaller effective range – inside the Earth's atmosphere
- Transient Radiation Effects on Electronics (TREE) as the effect of neutrons and photons from the initial radiation on electronic components, in particular semiconductor components
- the temporary change in the electromagnetic properties of the atmosphere, which can have a negative effect on the propagation of electromagnetic radiation in radio transmission or radar applications

Every nuclear explosion[12] within the Earth's atmosphere leads to the formation of a fireball. This is not usually explicitly assigned to the effects but is nevertheless essential for the development of the heat flash and the pressure wave. In the event of nuclear explosions, it is impossible for people and materials in the area of the fireball to survive.

5.5.1 Creation and properties of the fireball

Because of the very high energy density and the fact that most of the explosion energy is released as radiation, the nuclear weapon vaporises almost instantaneously during the explosion, and the gaseous explosion products initially barely exceed the original volume of the weapon. As a result, the gaseous explosion products as a whole become an intense source of X-ray radiation. The relatively soft X-rays emitted by this source are quickly absorbed in the case of explosions in denser layers of the atmosphere, thereby playing a considerable role in the formation of a fireball. In high-altitude explosions under the *de facto* conditions of a vacuum, X-rays appear as an independent nuclear weapon effect. In the case of ground and underground explosions, the fireball also contains large quantities of vaporised and molten earth and rock (see also Chapter 6).

The fireball of a nuclear weapon explosion is a brightly glowing, more or less spherical structure in which all substances are in a plasma state. Because of the high energy density in the initial phase of its development, the fireball is the cause of the formation of a pressure wave as well as the source of intense thermal radiation throughout its existence.

[12] For explanations of the different types of explosion, see Section 5.5.5

Initially, the fireball represents an isothermal sphere (i.e. a sphere in which the temperature is the same everywhere). The expansion speed of the fireball and the speed of the pressure wave are the same. This causes the surfaces of the fireball and the pressure wave to align. As the size of the fireball increases, the temperature of the isothermal sphere decreases. Beginning at the time after the explosion, when the temperature has decreased to about 300,000 K, the pressure wave front moves faster than the front of the isothermal sphere. The pressure wavefront then detaches from the fireball. Because of the large pressure gradient and the resulting high speed of the pressure wavefront, the air in this front is compressed to such an extent that it is heated to extraordinarily high temperatures due to the friction that occurs, thereby causing it to glow. The fireball now consists of two separate concentric areas: the inner isothermal sphere and the glowing outer pressure wave front, which is impermeable to the thermal radiation generated by the inner isothermal sphere. The pressure wavefront therefore appears as the radiating surface of the fireball. As the pressure wave continues to propagate, the overpressure in the wavefront decreases rapidly – as does the temperature. This causes the pressure wavefront to once again become transparent, thereby allowing the hotter thermal radiation from the inner isothermal sphere to act as the radiating surface. As a result, the temperature rises to the second temperature maximum. The further course of the fireball is characterised by a drop in surface temperature, which finally extinguishes the fireball because of further expansion and energy radiation.

5.5.2 Pressure wave of a nuclear explosion

The destructive effect of a blast wave is caused mainly by the static overpressure inside it. Further properties of the pressure wave are the dynamic pressure, the duration of the pressure effect, and the arrival time. The different static pressure on various surfaces of a mechanical structure causes destructive mechanical forces that act on the object. The maximum static overpressure at the shock wave front is referred to as *peak overpressure*. The extremely hot and highly pressurised gases in the fireball cause a pressure wave, the front of which moves radially outwards at high speed. The main characteristic of this pressure wave is the sharp rise in overpressure at the wavefront, which decreases much more gradually behind it (i.e., towards the explosion site).

In particular for buildings or similar infrastructure, *dynamic pressure* is another relevant factor for destructive effects. The dynamic pressure results from the high wind speeds behind the wavefront; these have a destructive effect on the objects for a certain period of time. The dynamic pressure is proportional to the square of the wind speed and the air density behind the shock front. These variables both depend on the peak overpressure. In the early phase, the speed of the wavefront is a multiple of the speed of sound in the air. At greater distances from the explosion site, when the overpressure has fallen to less than about 10 kPa, the pressure wave approaches the speed of sound. When the shock front arrives at the observation point, the static overpressure rises abruptly from zero to the peak overpressure and then falls again much more slowly. The positive phase (compression phase) ends when the overpressure once again reaches zero. The duration of the compression phase increases with greater explosion yield and greater distance from the explosion site. At sufficiently large distances from the explosion site, the overpressure drops to negative values and leads to the “negative phase” (suction phase). The suction phase generally lasts longer than the compression phase but has a considerably lower amplitude. The changes in the overpressure cause corresponding changes in the dynamic pressure and, thus, in the wind conditions at the observation site. The compression phase is associated with a strong but decreasing wind from the direction of the explosion site. During the initial part of the suction phase, a weaker wind blows towards the explosion site.

When a nuclear weapon explodes in the air (near the ground), the portion of the blast wave travelling downwards is reflected from the Earth's surface. For a flat and smooth earth surface[13] in an area close to Ground Zero[14], the total static overpressure will be twice as high as the peak overpressure of the incoming pressure wave. However, the reflected wave always moves in areas already compressed and heated by the incoming pressure wave. As a result, the reflected pressure wave soon moves at a higher speed than the incident wave and catches up with it so that a common wavefront can form. This behaviour is referred to as *Mach reflection*. The area in which the two pressure waves are combined is referred to as the *Mach region*.

5.5.3 Thermal radiation from a nuclear explosion

The thermal radiation of a nuclear explosion (within the atmosphere) originates from the formation of the fireball. This emits electromagnetic radiation similar to sunlight. The wavelengths occurring are predominantly in the ultraviolet, visible, and infrared radiation range. In the context of the effects of nuclear weapons, the term 'thermal radiation' refers to the radiation emitted from the surface of the fireball. This is also referred to synonymously as light, thermal, or heat radiation. Because this is a pulsed emission, the term *heat flash* is also widely used.

The proportion of the explosion energy that radiates as a heat flash within the atmosphere during a nuclear explosion is referred to as the *thermal component*. In an air explosion, the thermal component is around 35 %. The thermal component of near-ground explosions is considerably smaller than that of air explosions. This is due to the lower permeability (transmittance) of the layers of air close to the ground because of the higher dust and water vapour content caused by the explosion. For contact explosions with an height of burst of zero, the thermal component is around 18 %.

As it passes through the atmosphere, thermal radiation is attenuated by absorption and scattering. Absorption is caused by the nitrogen and oxygen molecules in the air as well as by impurities and additives such as dust and water vapour. The term scattering refers to the deflection of radiation from its original direction of propagation. The scattering cross-section depends on the wavelength of the radiation. Scattering occurs on gas molecules as well as on dust and smoke particles and small water droplets. The scattering on aerosols in the air is particularly important for weakening the heat flash in the atmosphere. If the wavelength of the radiation is of the same order of magnitude as the aerosol diameter, the scattering cross-section is particularly large. With the inclusion of attenuation coefficients or transmission factors, the thermal fluence of the heat flash on the ground can be estimated for a certain distance to Ground Zero if the weather conditions are known. Visibility in kilometres is usually used to estimate the weather situation. Compared with high visibility (exceptionally clear air, approx. 100 km), the thermal fluence of the heat flash is considerably lower at low visibility (light fog, approx. 2 km).

The heat flash can cause burns to the skin of people outdoors as well as large-scale fires in infrastructure and the environment.

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[13] An ideal surface acts as a perfect reflector for the pressure wave.

[14] Ground Zero (GZ) or the hypocentre refers to the vertical projection of the explosion site onto the Earth's surface.

5.5.4 Initial radiation of a nuclear explosion

In a nuclear explosion, the processes of nuclear fission and nuclear fusion lead to the emission of ionising radiation. This basically consists of neutron, gamma, beta, and alpha radiation, whereby only the neutron and gamma radiation are dose-relevant when considering the initial radiation.

Even at low explosion yields, the (radioactive) explosion cloud reaches within one minute such heights that the ionising radiation it emits is no longer significantly effective on the ground. The initial radiation of a nuclear weapon explosion in a dense atmosphere consists mainly of gamma and neutron radiation. The duration of the initial radiation is defined as the period up to one minute after the explosion. In practice, however, their effective duration is less than 10 s in most cases. Ionising radiation released after one minute following the explosion is, by definition, residual radiation.

The effect of the initial radiation produced by nuclear explosions can vary considerably depending on the situation. In addition to the explosion yield, the type of explosion, and the height of the explosion, the type of energy release (the respective proportion of nuclear fission and nuclear fusion in the explosion energy) as well as the construction and design of the nuclear detonator, play a decisive role. (Glasstone and Dolan 1977)

5.5.4.1 Neutron component of the initial radiation

The type of energy release and the design of the nuclear weapon have an even greater effect on the properties of the neutron radiation emitted than on those of the gamma radiation. The neutron component of the initial radiation is produced as *prompt neutron radiation* directly in the processes of nuclear fission and nuclear fusion. Neutron radiation is also produced during the disintegration of radioactive fission products; however, its proportion remains of secondary importance (Glasstone and Dolan 1977).

The neutrons produced in the nuclear fission process are known as prompt neutrons because they are emitted within less than one microsecond. Most of these prompt neutrons with an average energy of around 1 MeV to 2 MeV are strongly weakened by the casing of the nuclear weapon. This shifts the primary fission spectrum of the neutrons towards lower energies.

Nuclear fusion is the most important neutron source for thermonuclear explosive devices. Each kilotonne (kT) of nuclear fusion yield releases around $1.5 \cdot 10^{24}$ neutrons, with an initial energy of around 14 MeV. As in the case of fission neutrons, the exit spectrum is also determined by the interaction processes of the fusion neutrons with the (vaporising) weapon material.

5.5.4.2 Gamma radiation component of the initial radiation

The gamma radiation component of the initial radiation is generated first as prompt gamma radiation directly during the nuclear fission process, second as gamma radiation released during radioactive transformations of the resulting fission products, and finally as gamma radiation generated as a result of the interaction of the neutrons with the material of the weapon casing and the environment (air, ground, shielding). The gamma radiation field is characterised by the number of photons present at the respective distance from the explosion centre as well as their energy spectrum and angular distribution.

The proportion of the gamma radiation dose that nuclear fission delivers as *prompt gamma radiation* is small – even with pure nuclear fission weapons. This prompt gamma radiation is emitted during a period when the nuclear weapon has not yet decomposed and is, therefore strongly attenuated by the casing. The energy spectrum of the prompt gamma radiation emitted from the explosion centre is, thus, not identical to the original fission spectrum. The duration of prompt gamma radiation is approximately a fraction of a microsecond (Glasstone and Dolan 1977).

The fission products as source of *gamma radiation* are located in the fireball or the explosion cloud and rise with it. The gamma radiation spectrum is determined by the composition of the fission product mixture, which changes over time. The proportion of gamma radiation from the fission products becomes effective in the final stage of the explosion (i.e. when the original nuclear weapon has already been vaporised). Therefore, the energy spectrum of the gamma radiation emitted by the radioactive cloud is virtually identical to the initial spectrum of the fission products. In the first 20 s after the explosion, around 50 % of the total gamma radiation from the fission products is effective. For the time interval of the initial radiation, the energy spectrum of the gamma radiation caused by the fission products can be assumed to be virtually constant with an average energy of around 2 MeV (Hoffmann 1987).

In addition to the fission products, *interactions between fission and fusion neutrons* and atomic nuclei of the surrounding atmosphere provide the second major contribution to the gamma radiation of the initial radiation. The duration of this gamma radiation depends on the action time of the prompt neutrons. Neutron capture, in particular, releases high-energy gamma radiation, the energy of which increases with the atomic mass. For thermal neutrons, neutron capture by nitrogen nuclei plays the most important role in air and results in the emission of gamma radiation with an average energy of around 4 MeV. The energy spectrum of the neutron-induced or secondary gamma radiation is therefore much harder than that of the fission products.

5.5.5 Influence of the type of explosion

Whether a certain initial nuclear weapon effect poses an acute threat to people, material, and infrastructure at certain distances from Ground Zero depends not only on the explosion yield but also on the type of explosion. In the event of a nuclear weapon explosion outside the Earth's atmosphere, there are no direct effects[15] on the Earth's surface (pressure wave, thermal and ionising radiation). Depending on the height of the explosion or the surrounding medium, the following types of explosions can occur: underground explosion, ground explosion (on or near the Earth's surface), air explosion, and exo-atmospheric explosion. With air explosions, a distinction is made between near-ground explosions and explosions in higher altitude. For water, explosions can occur on or near the surface (water explosion) or underwater (underwater explosion).

In the following, only the near-ground explosion and the higher altitude air explosion are considered. The most relevant nuclear weapons effect in military terms is the pressure wave and the associated destruction. Because of the aforementioned formation of a Mach front above the ground, there is a certain height of burst for each explosion yield where a maximum effective range is achieved for a given peak overpressure. Fig. 5-3 illustrates how the effective range depends on the height of burst of a 1 kT nuclear weapon for given values of peak overpressure (near-ground). For a peak overpressure of 7 kPa, the determined height of burst is around 500 m, with an effective range of around 2,100 m. At an height of burst of 200 m, the effective range for a peak overpressure of 7 kPa is reduced to around 1,700 m.

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15 However, an exo-atmospheric nuclear weapon explosion generates a nuclear electromagnetic pulse (NEMP) that can reach large areas on the Earth's surface.

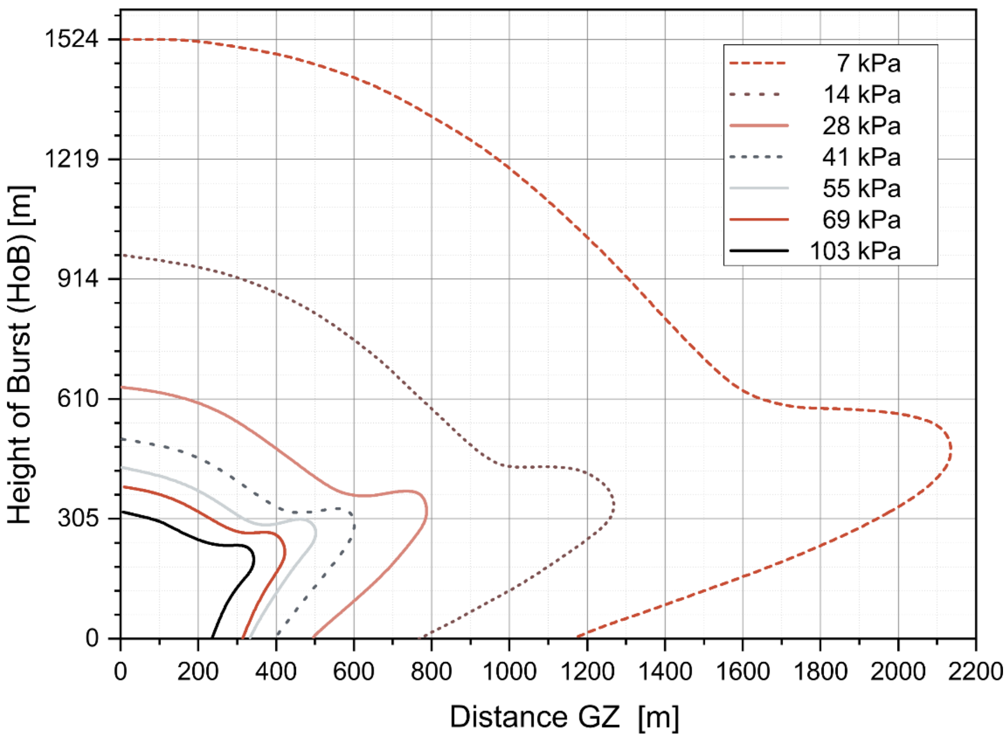


Fig. 5-3: Dependence of the effective range of selected peak overpressures on the height of burst for an explosion yield of 1 kT (source: Rambousky, data according to (Glasstone and Dolan 1977))

The height of burst determines whether a nuclear explosion produces a large amount of localised fallout or small amounts of fallout with predominantly fine particles that is strongly diluted and dispersed in higher atmospheric layers. If the height of burst is so low that the fireball reaches the ground, a considerable amount of dust and earth material is swept upwards with the explosion cloud. The vaporised fission products combine with the earth and dust particles and are subsequently released as fallout. In this case, a relatively large amount of localised fallout is produced. This settles locally because of the predominantly large particle sizes of the fallout particles and usually leads to relevant radiation exposure in the fallout area. Considerable localised fallout can occur up to a distance of a few hundred kilometres from the explosion site, depending on the explosion yield and the operational and weather conditions.

5.6 Hazard assessment for initial nuclear weapon effects

5.6.1 Ionising radiation, thermal radiation, and pressure waves

As said before, nuclear weapon's initial effects depend on several technical circumstances and operational conditions. The following ranges for hazards are based on a certain anticipated variation in technical circumstances and operational conditions. Explosion yields from 0.01 kT (10 t of TNT) to 1,000 kT (1 Mt of TNT) are considered. Furthermore, it is conservatively assumed that at explosion yields below 10 kT, only nuclear fission takes place, whereas above 10 kT, a thermonuclear reaction (i.e. a combination of nuclear fission and nuclear fusion) occurs.

In the vicinity of the initial nuclear weapon effects of a nuclear weapon use, the most important thing is to survive the explosion itself. Therefore, the range of an acute risk to life and limb is considered here; potential long-term health effects are not considered in this context (Pennington et al. 2022). The study examines individuals who stay outdoors in urban environments. The following hazard parameters were defined for the three initial nuclear weapon effects (pressure wave, heat flash, and initial radiation).

- A value of 35 kPa is used for the peak overpressure. With this peak overpressure, urban areas are severely damaged and, in some cases, destroyed. Weak buildings collapse, and life-threatening injuries to the population are widespread. The main danger to people in urban areas is posed by flying objects and collapsing infrastructure. A peak overpressure of 35 kPa is not in itself life-threatening for a person.
- For the thermal hazard it is assumed that 50 % of individuals outdoors would suffer third-degree burns on parts of their skin. It is not possible to specify a fixed value for the radiation fluence (J cm^{-2}) here because this depends on the duration of the thermal radiation pulse, which depends on the explosion yield. Good weather conditions and clear visibility are assumed.
- As the initial radiation dose (period up to one minute after the explosion) 1 Gy[16]is selected· at a dose of 1 Gy the first signs of radiation sickness appear; however, the acute symptoms are usually reversible.

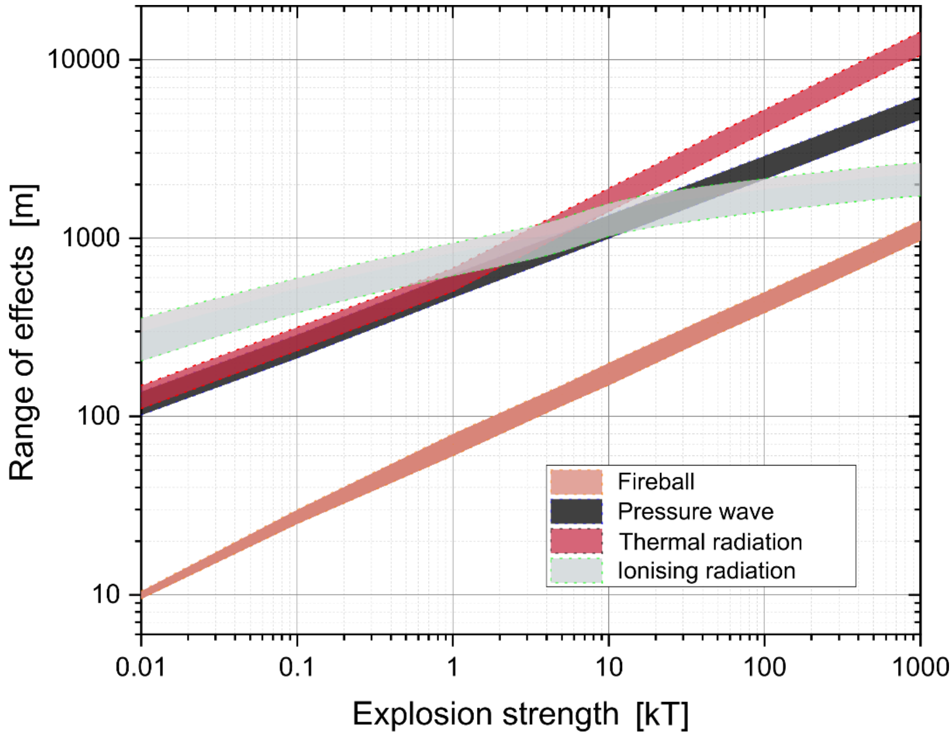


Fig. 5-4: Range of effects for an acute hazard to individuals in the open air, as caused by the initial effects of nuclear weapons as a function of the explosion yield (source: Rambousky, data according to (Dolan 1972), (Wellerstein 2024))

From Fig. 5-4, it can be seen that the range of effects for initial radiation (occurrence of a radiation dose of 1 Gy) dominates for explosion yields of less than about 2 kT. For explosion yields greater than about 2 kT, the range of effects of thermal radiation dominates when people are outdoors (50 % of those affected receive 3rd degree burns on parts of the skin surface).

For individuals who in the event of a nuclear explosion are behind suitable cover, a protective wall, or in a shelter, thermal radiation is generally irrelevant. In this case, the range of effects

[16] The absorbed dose for soft tissue (free in air) is used here as dose.

due to initial radiation would dominate up to an explosion yield of about 20 kT. At higher yields, the range of effects due to a peak overpressure of 35 kPa determines the acute hazard.

For people in a reasonably stable structure (e.g., solid residential or industrial building), the effect ranges for an acute hazard caused by the blast wave or thermal radiation are considerably smaller. Because the initial radiation consists primarily of neutrons and gamma radiation, and neutrons, in particular, have a high penetration ability for most materials, the shielding effect of the existing infrastructure is generally minimal. In such cases, the initial radiation (dose of 1 Gy) becomes the dominant effective range for the entire kT range under consideration.

The ranges of effects depend on the operational parameters of the nuclear weapon and the prevailing environmental conditions. The bandwidth display reflects this aspect. The prediction of the actual damaging outcome to people at a specific physical nuclear weapon effect is subject to even greater uncertainty, depending on the behaviour of the persons (e.g. lying down on the ground) or the use of immediately available protection options (e.g. cover). The physical ranges of effects differ only moderately between the "acute hazard" shown in Fig. 5-4 and a high probability of an actual fatal outcome. This is illustrated in Fig. 5-5 using the dose of initial radiation. The bandwidths are shown for radiation doses of 1 Gy (onset of radiation sickness), 4.5 Gy (about 50 % of irradiated persons die without intensive medical treatment), and 10 Gy (survival is almost impossible). The dashed lines show the progression for a selected set of parameter values, so the differences for the radiation doses under consideration can be better compared.

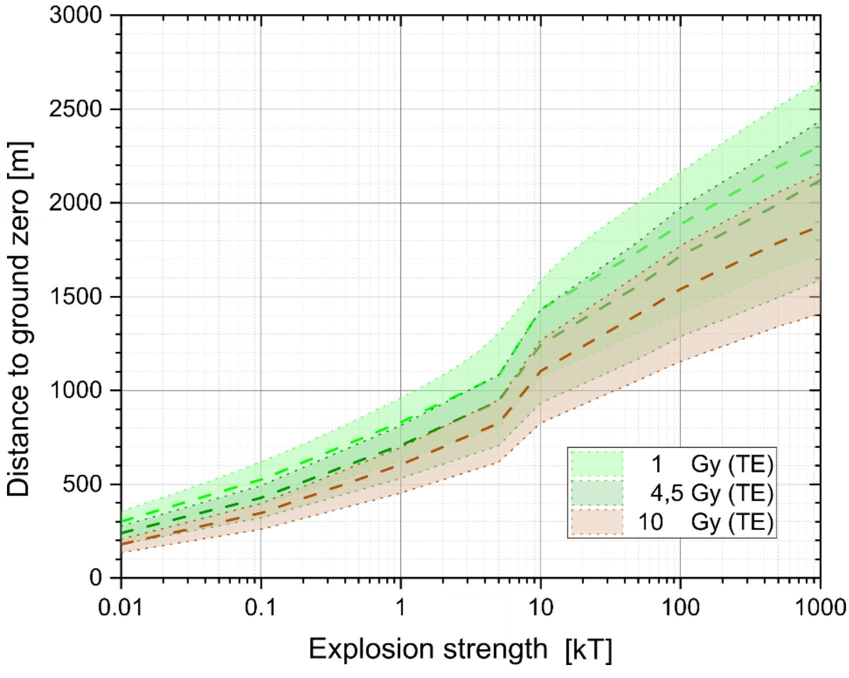


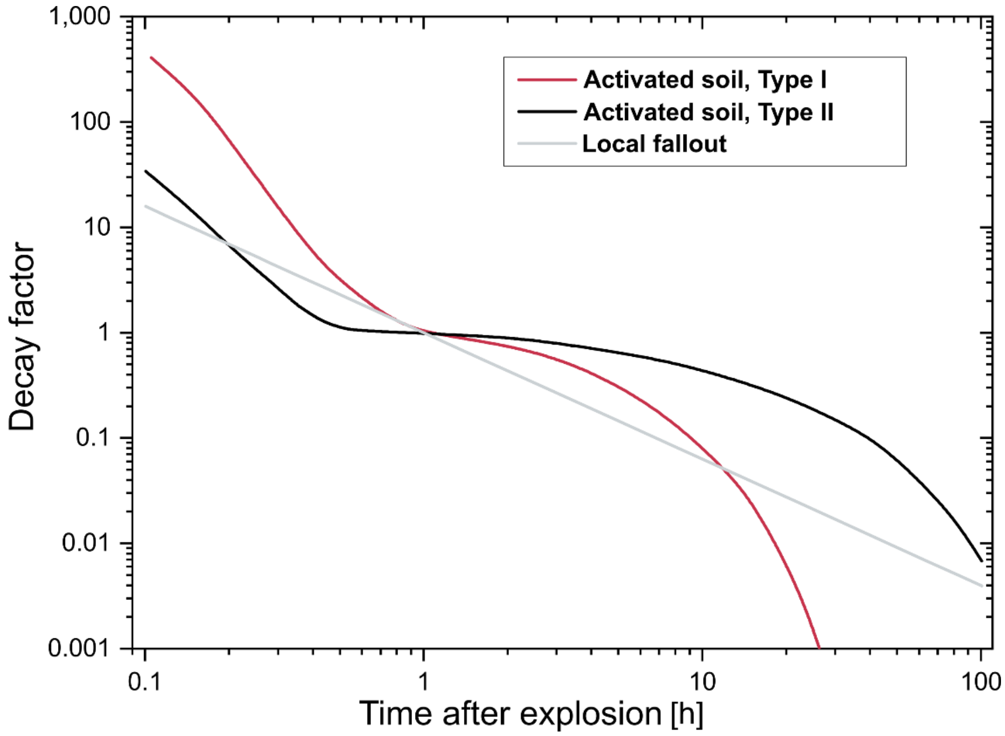
Fig. 5-5: Bandwidths of the effective range for the doses from initial radiation of 1 Gy, 4.5 Gy, and 10 Gy as a function of the explosion strength of a nuclear weapon (source: Rambousky, data according to (Dolan 1972))

For a 1 kT nuclear weapon, the effect ranges are reduced by about 15 % each between 1 Gy and 4.5 Gy and between 4.5 Gy and 10 Gy. In the case of a nuclear weapon with an explosion yield of 100 kT, the percentage values are lower, with each around 10 %.

From the above estimates of the effect ranges for potentially lethal consequences, it can be concluded that they are comparable for the three initial effects of the nuclear weapon explosion (thermal effects, pressure, and radiation exposure). Even with an explosion yield of 1 MT, the maximum ranges of effects are in the region of approx. 10 km.

5.6.2 Activation of the ground in the vicinity of a nuclear weapon explosion

Neutron radiation can activate non-radioactive matter by capturing neutrons in the atomic nuclei. These atomic nuclei are then radioactive and, in turn, emit ionising radiation. This is particularly relevant when neutrons penetrate the ground during nuclear explosions. The elements sodium, manganese, and aluminium have a particularly high effective cross-section for such neutron capture reactions. The gamma radiation it emits is of practical relevance here. The activation of the soil depends heavily on the soil composition. However, compared with the dose rate from localised fallout, the dose rate from soil activation is lower. The hazard from radiation from soil activation, therefore, relevant only for heights of burst that are high enough for hardly any localised fallout to occur, yet low enough for sufficient neutron fluence to reach the ground and activate it. A nuclear weapon with an explosion yield of 10 kT generates a fireball with a radius of around 200 m. A height of burst of around 400 m is high enough that no considerable localised fallout is generated and that the dominant hazard in the vicinity of Ground Zero is soil activation after the explosion is. One hour after the explosion, a gamma dose rate of about 100 mGy h^{-1}prevails at Ground Zero (i.e. directly below the explosion site) and of about 2 mGy h^{-1} (Dolan 1972) at a distance of 1,000 m from Ground Zero. Because of the diversity of the nuclear weapon designs and the existing soil compositions, the actual dose rate can deviate by a factor of two to three from the values given above. After two days, these dose rates would decrease about seven-fold to the values of 14 mGy h^{-1} and 0.14 mGy h^{-1} = 140 µGy $h^{-1,}$ respectively. At a lower height of burst (e.g. 100 m), relevant local fallout occurs. The gamma dose rate of the local fallout (fission products) at a distance of 1,000 m from Ground Zero in the downwind direction is approx. 10,000 mGy h^{-1} (Wellerstein 2024) at 1 h after the explosion and thus 100-fold higher than the gamma dose rate for the maximum soil activation



at a height of burst of 400 m.

Fig. 5-6: Illustration of the decay behaviour of soil activated by neutron radiation (for two different soil compositions) and the approximated $t^{-1.2}$ decay of local fallout (source: Rambousky, data according to (Dolan 1972))

Fig. 5-6 shows the decay of soil activated by neutron radiation from a nuclear explosion normalised to 1 h after the explosion. The decay factor for 1 h is therefore 1. The data (Dolan 1972) refer to two soil compositions. Type I describes typical sandy soil in the African desert and Type II typical soil at the Nevada Test Site.

For the first weeks after a nuclear explosion, the decay of the local fallout can be approximated with a $t^{-1.2}$ curve where t is the time after the explosion in hours. For comparison, the progression of decay factors for localised fallout is also shown in Fig. 5-6. This is again standardised to the time 1 h after the explosion. Considerable differences in the decay rate over time for various material compositions can be observed.

6 Source term, fallout, and radiological consequences

6.1 Source term: Quantity and composition of radionuclides released

In a nuclear weapon explosion, a number of radionuclides are released into the environment through nuclear fission or fusion. For nuclear weapons, the fission products of the fissile material constitute the largest proportion of total activity. ^{235}U and ^{239}Pu are suitable for nuclear weapons because they have a high fission probability in addition to their high mass. Furthermore, the neutrons released during nuclear fission and especially during nuclear fusion can activate surrounding material, such as the casing of the weapon. Nuclear weapons often also contain ^{238}U (e.g. as a neutron reflector). This can also be fissioned by fast neutrons and thus contributes to the generation of fission products. Because of ground activation, near-ground explosions are expected to produce significantly more activation products than high-altitude explosions, where the fireball and fission products do not reach the ground, and the neutron component near the ground is much weaker. However, the proportion of activation products is small compared with the total amount of radionuclides produced (Dolan 1972). Depending on the efficiency of the nuclear weapon, a certain proportion of the fissile material is not fissioned and is, therefore, also part of the nuclide vector. Transuranium elements such as ^{239}Np, ^{240}Pu, or ^{241}Am, which are produced by the capture of released neutrons by the fissile material, account for a further, albeit small, proportion of the radionuclides produced.

The quantity and composition of the radionuclides released is known as the source term, which consists of several hundred individual radionuclides. The source term for nuclear weapon explosions depends on many factors, whereby the total activity released scales primarily linearly with the explosion yield. The explosion yield is, therefore, a decisive factor in estimating the radiological consequences of a nuclear weapon explosion as well as the associated dose rates and radiation doses. The source term is also determined by the fissile material used (^{235}U or ^{239}Pu), the height of burst (near or far from the ground; also referred to as height of burst or HOB), and the background (water or soil, according to the composition) as well as the type (nuclear fission or fusion) and structure of the weapon (design).

The radionuclides produced by a nuclear weapon explosion that settle on the ground are known as fallout and can cause contamination tens to hundreds of kilometres away. The complexity of the source term complicates the radiological evaluation of fallout. Software tools are generally used to estimate the source term. For example, the Lawrence Livermore Weapons Activation Code (Spriggs and Egbert 2020, Kraus and Foster 2013). Extensive data on fission yields, nuclear structure, and decay properties are used. These come, e.g., from the ENDF-B database (Brown et al. 2018) or the JENDL database (Shibata et al. 2011) and are based on experimental results and supplemented with theoretical models.

Extensive information on the source term for a uranium-based weapon with an explosive yield of 10 kT was published by the Lawrence Livermore National Laboratory (Kraus and Foster

2013). The radionuclides that make the greatest dose contribution at distances of more than 10 km from ground zero were identified. It was assumed that all nuclides with a half-life of less than 2.5 minutes were converted into their daughter nuclides. This assumption is justified because the development and thermal stabilisation of the initial cloud takes about ten minutes, and the atmospheric transport modelling starts only after this period. At this point in time, these parent nuclides have already largely decayed and, therefore, make only a small contribution to the dose. Forty-four radionuclides were identified which together account for more than 92 % of the effective dose from the entire source term that would be received 10 km downwind.

In principle, radionuclides with short half-lives dominate in nuclear weapon explosions; this leads to a rapid decrease in activity and, thus, the dose rate. For example, the dose rate of the fission products about 7 h after the explosion is only one tenth of the value that would result after 1 h. After about two days, it is only approx. 1 %. It is stated that the dose rate of the fallout typically decreases in proportion to a power function of time with an exponent between −1.2 and −1.35 (Glasstone and Dolan 1977, Kraus and Foster 2013) (see also Fig. 6-6).

Another study discussed 10 radionuclides in fallout and their relative proportions of the total activity after 100 days, 1 year, and 10 years (Buddemeier 2018). This showed that 100 days after a nuclear explosion, the activity is dominated by the nuclides ^{91}Y, ^{95}Zr, and ^{103}Ru. After 1 year, the nuclides ^{106}Ru and ^{144}Ce dominate the remaining activity. In the late phase, 10 years after the explosion, ^{90}Sr and ^{137}Cs, along with their daughter nuclides, account for approx. 82 % of the remaining activity. Detailed information on the time periods in which various radionuclides and their daughter nuclides are dose-relevant can be found in Kraus and Foster (2013) and Izrael (2002), among others.

6.2 Differences between explosion types

6.2.1 Influence of the type of fissile material

The type of explosion directly influences the source term. In the previous analyses, in particular in Kraus and Foster (2013) and Spriggs and Egbert (2020), a uranium-based explosion was assumed. Plutonium-based explosions show a tendency towards nuclides with larger mass numbers, especially for the lighter fission fragment.

For the radionuclides specified in Buddemeier (2018) and Kraus and Foster (2013), on average there are, however, only slight deviations with regard to the fission yield. A uranium-based fission weapon can thus be used as a good approximation to assess the radiological effects of a ^{239}Pu-based fission weapon. The difference in the ambient gamma dose rate from ground radiation in the periods in the first year after the explosion is about 10 %. A comparison of the normalised ambient gamma dose rate of ground radiation from the fallout of a ^{239}Pu nuclear weapon (red) and a ^{235}U nuclear weapon (black) is shown (Fig. 6-5); this was calculated using nuclide-specific fission cross-sections and dose rate factors (Brown et al. 2018, ICRP 2020b).

6.2.2 Influence of the fusion component of thermonuclear weapons

A thermonuclear weapon uses both nuclear fusion and nuclear fission to release energy. Nuclear fusion requires higher temperatures and a greater density than can be achieved with chemical explosives. This is why a nuclear fission explosive is used as the primary “igniter”.

As a rule, deuterium and tritium are used as fusion materials, which fuse to form a helium nucleus by emitting a neutron. Compared with nuclear fission, nuclear fusion produces far fewer and shorter-lived radionuclides. After the explosion of a thermonuclear weapon, helium, unreacted deuterium, and neutrons remain. Tritium is almost completely converted.

In a typical configuration of a thermonuclear weapon, nuclear fission and nuclear fusion each contribute about half of the total energy yield. However, only the radionuclides released from the fission process of the thermonuclear weapon are radiologically relevant. Therefore, about half the activity of the source term of a pure nuclear fission weapon of the same explosion yield is expected.

With the same explosion yield, a thermonuclear weapon produces more and higher-energy neutrons than fission. This is expected to result in more activation products.

6.3 Activity particle size distribution

Of relevance for atmospheric dispersion and for assessing the radiological effects of fallout are, in addition to the nuclide vector of the cloud, also the distribution of radioactivity among particles of different sizes (the activity particle size distribution, hereinafter referred to as particle size distribution), the spatial extent of the cloud, and the local distribution of radioactive particles in the cloud itself. . The heat generated by the explosion causes the radionuclides produced to be transported to high atmospheric layers and subsequently dispersed over a large area. Some of the resulting particles sediment, whereby the settling rate does not correlate linearly with the particle size. The particle size depends on the height of burst, the nature of the ground, and the physico-chemical properties during the initial condensation of the vaporised material after the explosion. Considerably larger particles are expected in a ground-level explosion than in a high air burst.

For the dispersion calculations described below, the cloud is divided into six layers based on the procedure in Rolph et al. (2014), in which the radioactivity is distributed (Fig. 6-1). The height of the stem and the cap, as well as the diameter of the stem, are parametrised with regard to the explosion yield as described in Rolph et al. (2014) and Nato (2020).

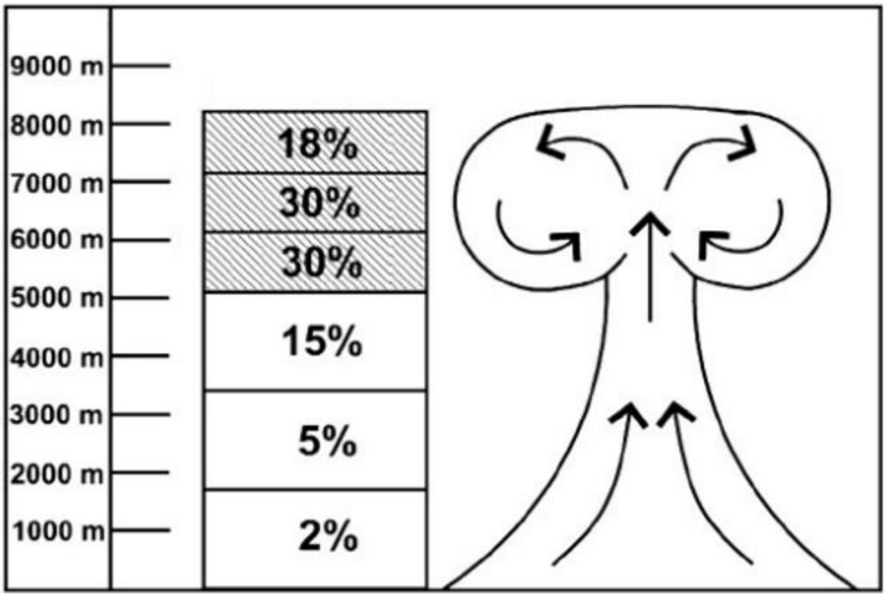


Fig. 6-1: Model representation of the cloud with activity components for a near-ground explosion of 10 kT (Rolph et al. 2014)

In Glasstone and Dolan (1977), particle size distributions within these six layers were estimated for an explosion near the ground, and the particles were divided into 13 size categories in the 20 µm–500 µm range. Most of the total activity for near-ground explosions (80 %) is in the upper three layers (i.e. the cap of the mushroom cloud).

From the information on radionuclide composition, particle size distribution and cloud geometry, a source geometry can be defined, with which further dispersion and dose calculations were carried out as shown in Section 6.4.

The particle size distribution greatly influences the atmospheric dispersion of the fallout, and there are complex relationships between predicted fallout areas, the uncertainties of the activityparticle size vs height distribution, and the uncertainties of meteorological data. An example is the influence of possible wind shear with altitude and uncertainties in height distribution. The particle size distribution that actually occurs depends largely on the height of burst (Spriggs et al. 2020). When the fireball does not touch the ground, the particle size distribution is relatively uniform and consists mainly of small, spherical particles a few micrometres in diameter; these are formed through the condensation of initially liquid or gaseous fission and activation products. Because these particles settle only very slowly, the radioactivity of the fallout decays for a long time before it reaches the ground, and in addition it is subject to a stronger dilution effect. In such cases, local exposure to fallout, therefore, plays a comparatively minor role.

If, on the other hand, the explosion occurs close to the earth's surface, depending on the explosive force of the weapon thousands of tonnes of soil or debris are stirred up and sucked into the resulting cloud. This material mixes with the radioactive fission and activation products in the cloud. As a result, a considerable proportion of the radioactivity adheres to relatively large particles with an average diameter of 50 µm–150 µm. Such particles sediment quickly. This means that a considerable proportion of the radioactivity released reaches the ground locally (i.e. up to several hundred kilometres away from Ground Zero). In addition, precipitation events, which often occur locally and can vary greatly in intensity, lead to the scavenging of large quantities of airborne radioactivity. This results in "hot spots" where considerably increased dose rates can be observed locally. Such precipitation events can also lead to radiologically relevant depositions in the case of detonations in which the fireball does not touch the ground. Under certain meteorological conditions, this can be the case even at a considerable distance from the explosion site; for example, in connection with the above-ground nuclear weapons test "*Simon*" (43 kT, approx. 90 m above ground) during the operation "*Upshot Knothole*, local dose rates of over 10 µSv h^{-1} were measured 36 h after the explosion more than 3,500 km away, in New York State. These were caused by heavy rainfall and the associated wet deposition.

In reality, mixed forms of the two extremes mentioned, a detonation on the ground and a detonation without ground contact of the fireball, can often be observed, as explained in more detail in Spriggs et al. (2020). The various regimes of possible cloud and particle size constellations are shown in Fig. 6-2. These occur when the fireball touches the ground, but the explosion still takes place at a height of several hundred metres (depending on the explosion yield) above ground. In these cases, an "air-gap" can occur between the stem and the cap (column b in Fig. 6-2). Dust, soil or debris is then sucked into the trunk. However, this material is not mixed with the radioactive fission products from the nuclear weapon; these are located mainly in the cap. In these cases, locally occurring, strong fallout is not expected. Even without an "air gap", different particle size distributions can develop in the stem and in the cap. The difference is that in these cases, some localised fallout of the fission products can occur (columns c and d in Fig. 6-2).

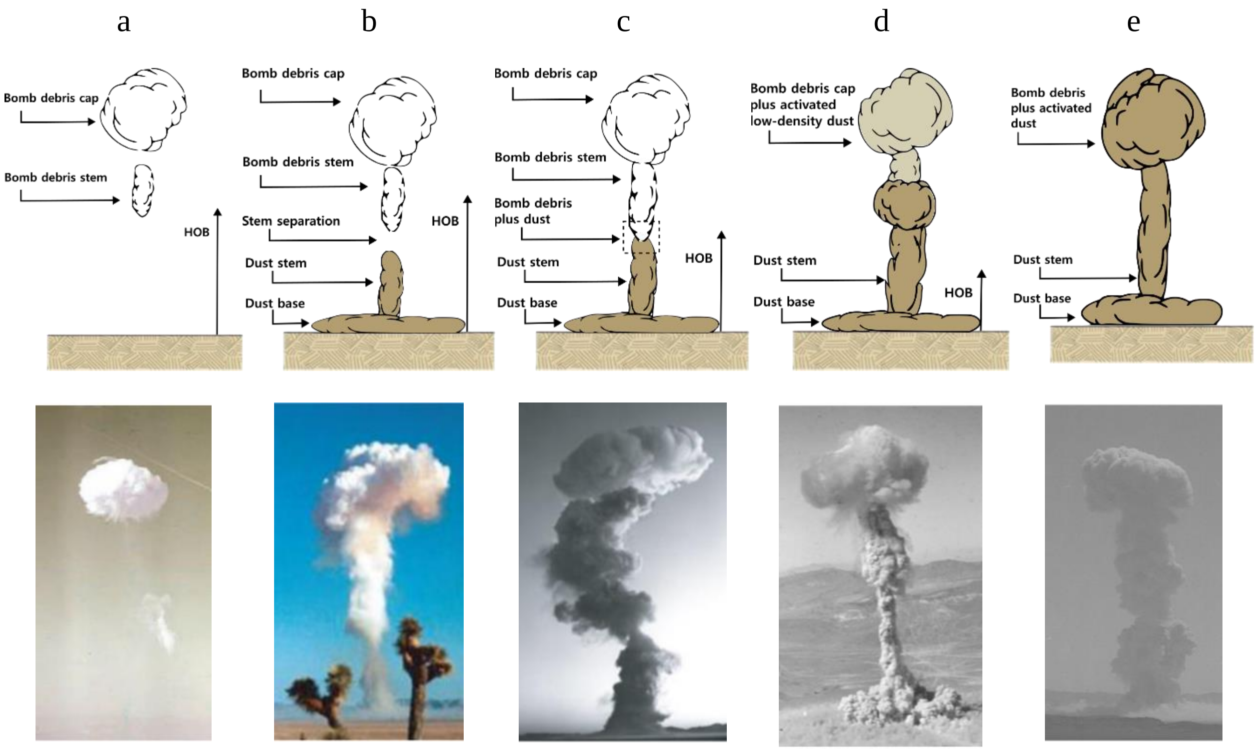


Fig. 6-2: *Illustration of different regimes of stabilised mushroom clouds as a function of the height above ground (HOB) (above), with example images from the nuclear weapons tests in Nevada for the respective regimes (below). From left to right, the HOB decreases and the radiological importance of locally occurring fallout increases. Reproduced from (Spriggs et al. 2020). The predominant particle sizes are described by the colours, whereby a darker colour indicates larger average particle sizes.*

In addition, an effect known as fractionation occurs under real-world conditions. This means that the particle size distribution depends on the chemical element or even the respective isotope. Shortly after the explosion, all fission products are in gaseous form. As the fireball cools down, the different elements condense at different times, depending on their individual melting or boiling temperatures as well as on the particles that are available at that time. This tends to result in larger particles containing more refractory elements and smaller particles containing disproportionately more volatile elements – similar to the relationship between particle volume or surface area and particle diameter. The particles are particularly small for isotopes resulting from the decay of (short-lived) noble gases, such as the decay of ^{138}Xe into the dose-relevant ^{138}Cs.

Various publications contain different parametrisations with regard to particle size distributions. These parametrisations are based on both theoretical modelling and comparison with measurement data from above-ground nuclear weapons tests. For near-ground explosions, a log-normal distribution with a median diameter of 80 µm–150 µm is typically assumed. Fig. 6-3 shows a comparison of various such activity particle size distributions from Glasstone and Dolan (1977), Izrael (2002), and Jodoin (1994). The particle size distribution according to Magee (Magee 1953, Freiling 1961) shown in this diagram describes a deviating distribution that would be expected in an explosion without ground contact and which is not log-normal.

Various authors mention that in such cases, practically no activity is to be expected on particles larger than 20 µm–30 µm (Izrael 2002, Magee 1953, Freiling 1961)

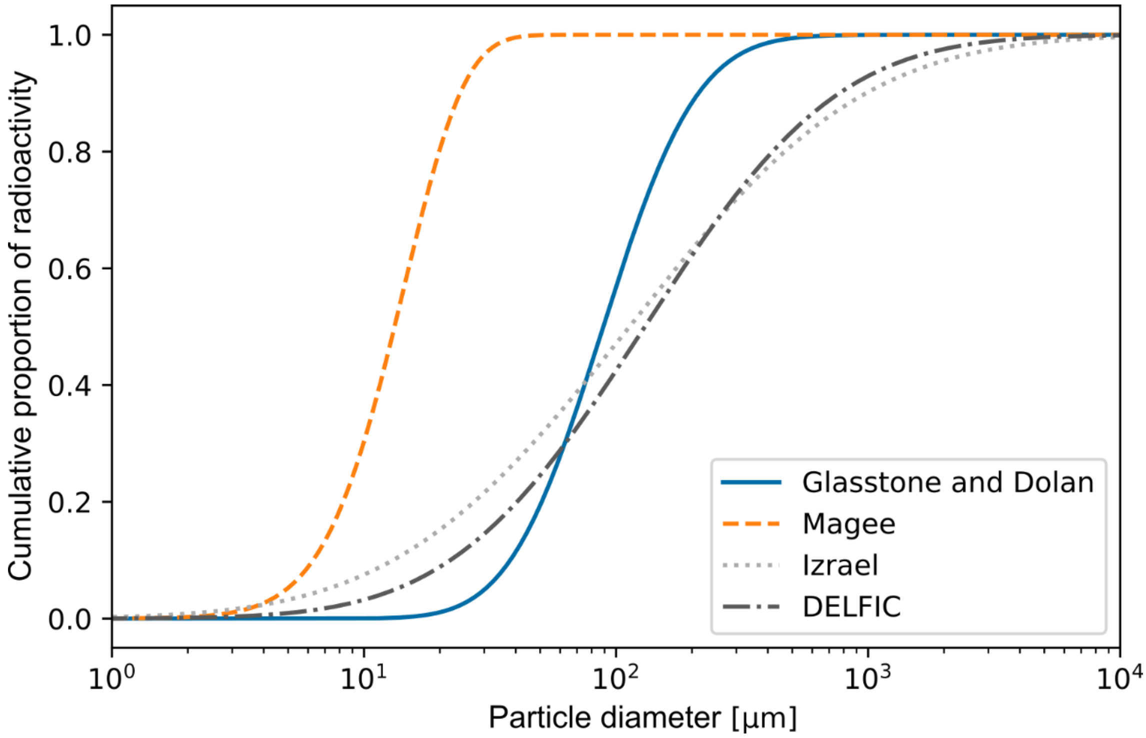


Fig. 6-3: Cumulative activity particle size distributions from the scientific literature. The "Glasstone and Dolan" (1977), "Izrael" (2002), and "DELFIC" (Jodoin 1994) distributions refer to near-ground explosions and are log-normal. The "Magee" distribution describes an explosion in air with free condensation of weapons material (Magee 1953, Freiling 1961). The frequency distribution in "Magee" behaves exponentially with the particle radius. For the "Magee" distribution, it is assumed that the radioactivity ingrained in the particles is proportional to the particle volume.

6.4 Dispersion modelling

Based on the previous illustrations, dispersion calculations were carried out with the Lagrange particle model "LASAT", which is integrated in the decision support system RODOS. These calculations were carried out by the Federal Office for Radiation Protection.

The explosion of a 10 kT nuclear weapon near the ground was assumed. A ground-level detonation for a given explosion yield results in the strongest radiological effects from the fallout. With regard to the detonation yield, the case of a 10 kT detonation is selected as the reference scenario for the present analyses. This is because the current modelling capacities are limited to cases below 30 kT (see below). Furthermore, it can be assumed that a range around 10 kT can still be achieved by "improvised nuclear devices" (i.e. in the context of non-military use) and is, therefore, within the scope of the ANoPl-Bund as explained in Section 4.1.2. A ground-level detonation with a yield of 10 kT (as referenced in the FEMA Guide) serves as a basis for comparison of the available analyses.

In the simulation, the particle size distribution was assumed to be constant and independent of height. The height distribution of the activity is parametrised with respect to the explosion yield and is shown for the assumed case of a 10 kT explosion in Fig. 6-1.

The particle size distribution given in Glasstone and Dolan (1977) ("Glasstone and Dolan" in Fig. 6-3) was approximately divided into five sections, as shown in Tab. 6-1. With regard to the particle size distribution, no distinction is made within the dispersion model according to chemical element or isotope; the same particle size distribution is assumed for each radionuclide considered.

Tab. 6-1: Discretised particle size distribution and respective activity fraction after a near-ground explosion

mean particle diameter [μm]	Proportion of activity [%]
10	12
50	28
100	30
150	18
250	12

In addition, calculations were carried out with a particle size distribution similar to the "Magee" distribution (Fig. 6-3) to investigate the consequences of a non-near-ground explosion.

Tab. 6-2: Discretised particle size distribution and respective activity fraction after a non-near-ground explosion

mean particle diameter [μm]	Proportion of activity [%]
10	65
18	15
22	10
26	5
33	5

For the dispersion calculations, an arbitrary, unspecified location in Eastern Europe – hereinafter referred to as the example location – was assumed as the event location. In total, 365 calculations were performed for a near-ground explosion, each at a randomly selected time evenly distributed across the days of 2021 with a forecast period of 100 h. In addition, 36 calculations (with three randomly distributed to each month of 2021) were carried out for a location in Frankfurt, Germany, in order to largely rule out location dependence. In addition 36 such calculations were carried out using the "non-near-ground" particle size distribution. Numerical weather forecast data from the ICON-EU model of the German Weather Service was used in the 0 m – 2,000 m altitude layers. Wind speeds and directions in overlying height layers were estimated by continuous extrapolation. The computational grid of the dispersion model in RODOS covers a height of up to approx. 10 km above ground; this cannot be changed by user input. Radioactivity above this level is not taken into account in the dispersion calculation and therefore also not in subsequent dose calculations. This is why the model can be used only for nuclear weapons with an explosion yield of up to approx. 30 kT. All decay series of the radionuclides under consideration were taken into account during the dispersion calculation with the LASAT model.

Subsequent calculations of dose and the contamination of the environment and agricultural products are carried out using the “Food and Dose Model terrestric” (FDMT) integrated in RODOS (see Section 6.5.1). Fig. 6-4 shows examples of such dispersion calculations with regard to the (temporal) maximum of the predicted total beta surface contamination in the event of an explosion in Frankfurt am Main.

Distance-dependent radiological effects can be determined from the results of the dispersion calculations. To do this, the distance to the event location is determined for each cell of the computational grid. For each dispersion calculation, the respective maximum of the effects under consideration (e.g. of a dose value) is determined in this distance interval. This results in an ensemble of the respective maximum values for each distance interval (e.g. an ensemble of maximum values for the ambient gamma dose rate at a distance of 9 km – 10 km from the detonation site). The median, 10th percentile, and 90th percentile are determined for each ensembles (i.e. for each distance interval). This allows the corresponding sizes to be plotted against the distance, as shown in the following subsections and their figures.

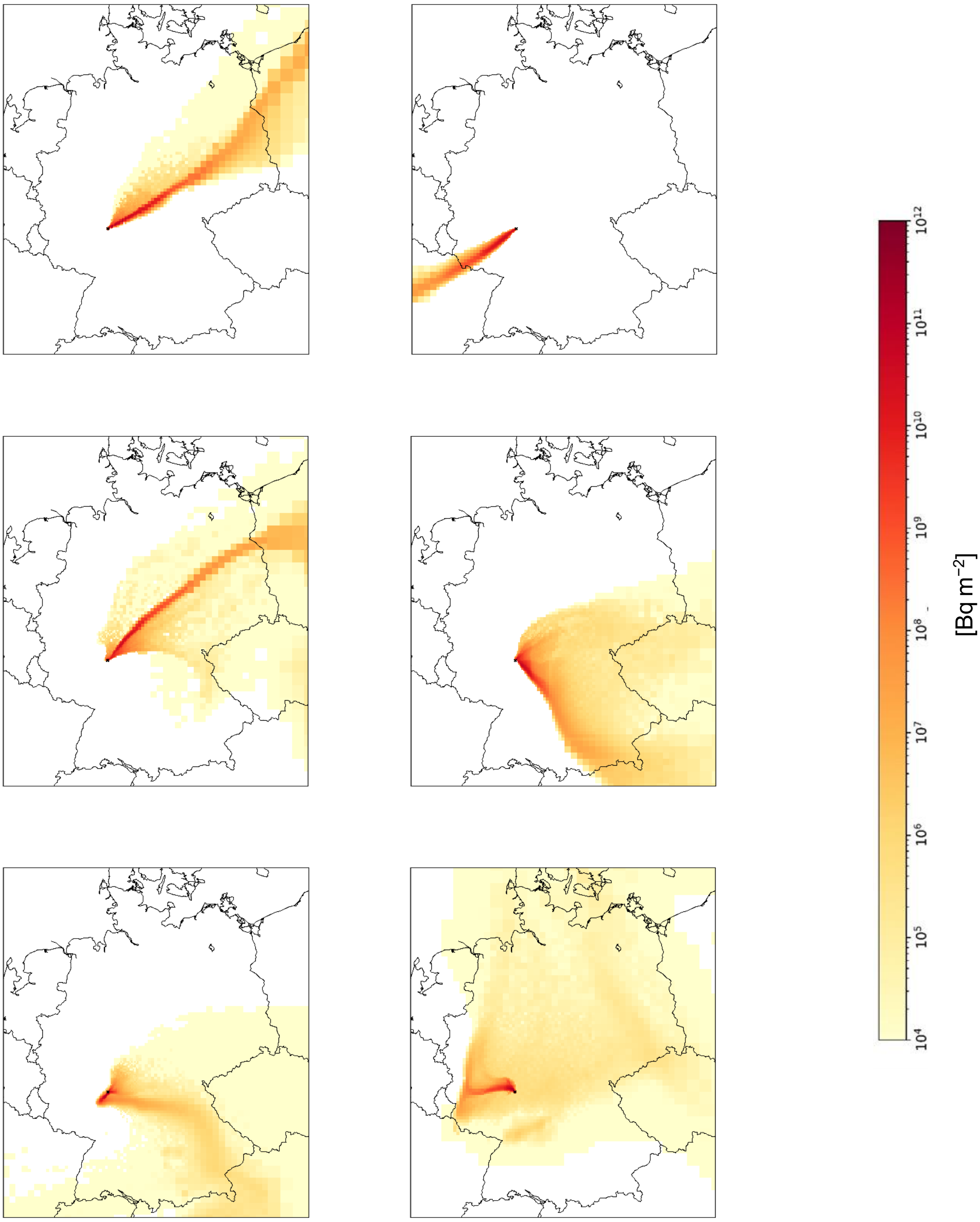


Fig. 6-4: *Examples of dispersion scenarios with different weather data for a 10 kT near-ground explosion. The temporal maximum of the total beta surface contamination is shown in logarithmic colour scaling. Increasing complexity of the prevailing weather and wind situation from top to bottom.*

6.5 Radiological consequences

6.5.1 Exposure pathways and dose calculation

Based on the dispersion modelling results, the various exposure pathways can be evaluated regarding the resulting doses. In scenarios involving atmospheric dispersion of radioactivity, typically both external radiation exposure and incorporation pathways play a role. The external exposure pathway can be further subdivided into exposure from a passing radioactive cloud (cloud radiation) and exposure from external radiation from ground-deposited radioactive material (ground radiation). The exposure pathway of incorporation essentially consists of the inhalation of radioactive substances from the passing radioactive cloud and the ingestion of contaminated products. In addition, there are other secondary effects or pathways in both categories (e.g. contamination of skin and clothing or resuspension and subsequent inhalation of soil-deposited material).

The following is an overview of the most relevant exposure pathways in the event of a nuclear weapon explosion and the calculation methods used to assess the radiological effects.

6.5.1.1 Cloud radiation

The cloud radiation results mainly from gamma quanta emitted during the radioactive decay of a fallout cloud that reach the ground and can lead to the exposure of an individual. For a person on the ground, the cloud radiation results from all contributions from a complex cloud geometry that passes over this individual. Complex algorithms are available for the calculation, such as shown in SSK (1992); however, these are not discussed in detail here. For these calculations, the LOPGAM sub-program of the LASAT dispersion model is used. It performs the necessary integration via the three-dimensional concentration distribution for each grid cell of the computational grid on the ground. This calculates the flux density of gamma quanta resulting from the passing radioactive cloud at each point or cell of a computational grid on the ground as a function of time. The input parameters for this are the time-dependent concentration of radioactive substances in three-dimensional space as obtained from the dispersion calculation and factors for the absorption of the radiation as it passes through the atmosphere. By multiplying this location- and time-dependent flux density (unit $Bq\,m^{-2}$ or $s^{-1}\,m^{-2}$) with the dose rate coefficients from Supplements 160a and b to the Federal Gazette (BMU 2001) and other correction factors (e.g. for reflection of radiation on the ground), the organ-specific equivalent dose rate or the effective dose rate is calculated for each age group and then integrated over certain time intervals (e.g. over seven days).

The contribution of cloud radiation to the effective dose is around 2.6 % in the first 24 h (Kraus and Foster 2013). The low contribution is partly due to the dispersion of radioactivity to extreme altitudes. A person on the ground is thus at an enormous distance from much of the radioactivity released. The inverse square law applies.

6.5.1.2 Ground radiation

Radioactive material deposited on the ground decays and emits radiation that causes exposure to people in the vicinity. Using the dose rate coefficients for ground radiation from ICRP 144 (2020b), the resulting ambient dose rate (H*(10)) can be calculated directly on a nuclide-specific basis by multiplying it by the surface contamination on the ground ($Bq\,m^{-2}$).

However, for calculating integrated doses (e.g. over seven days), time-integrated versions of the dose rate coefficients from ICRP (2020b) are used within the FDMT model in RODOS. These consider the build-up (ingrowth of daughter nuclides) or the decrease (radioactive decay, vertical migration in the soil) of the dose rate over time. Additionally, radionuclides in decay series not directly included in the source term but derived from their parent nuclides are considered.

This dose rate is caused mainly by gamma radiation but also by bremsstrahlung and characteristic X-rays due to beta decay.

The contribution of ground radiation to the effective dose is by far the dominant exposure pathway for near-ground nuclear weapon explosions. The contribution of ground radiation to the external dose is approx. 96 % in the first 24 h (Kraus and Foster, 2013).

Based on the data from Kraus and Foster (2013) and Spriggs and Egbert (2020), as well as tabulated data on decay data from Brown et al. (2018), both the most dose-relevant radionuclides and their initial quantities were determined as mentioned in Section 6.1.

For this, the initial nuclide quantities were calculated to match their projected activity after 10 minutes as closely as possible to the temporal activity projection of a complete initial nuclide vector derived, as from data in Spriggs and Egbert (2020) and Brown et al. (2018). Fig. 6-5 shows the time course of the potential gamma radiation dose rate from ground radiation (calculated with data from ICRP (2020b)) of a complete activity vector based on the fission cross-sections from Brown et al. (2018) for ^{235}U (black) and ^{239}Pu (red). Also shown is the time course of the dose rate calculated from the activity vector with respect to those 44 radionuclides that were taken into account for the dispersion calculations (blue).

The dose rate can be mapped well for periods of more than 1 h after the explosion, whereas the dose rate may be underestimated at close range. However, the calculation in Fig. 6-5 assumes complete deposition of the fallout at all times; this is not the case for the short time periods. In addition, it is assumed that the effective dose via the external exposure path shortly after the detonation (e.g. after 10 min) is dominated by the prompt effects (immediate radiation). Therefore, taking into account the 44 selected radionuclides is considered sufficient, especially for determining areas where effective doses of a few 100 mSv are obtained (as opposed to those where several Gy[17] are obtained).

When evaluating the following graph with regard to resulting doses or distances, it should nevertheless be taken into account that the dose within a radius of approx. 10 km is potentially underestimated, especially with regard to immediate radiation. This particularly influences the calculated dose rates in the first 1 h – 2 h after the explosion. The dose rate of soil-deposited material is calculated in RODOS, based on the selected radionuclides, by multiplying the predicted surface contamination by the dose rate factors (ICRP 2020b). No further conversions of parent and daughter nuclides are taken into account. This and the selection of the 44 radionuclides mentioned above results in a considerable underestimation of the ambient gamma dose rate by RODOS within the first approx. 2 h. However, this does not affect the calculation of the integrated doses, such as the effective dose or dose equivalent with regard to the unconsidered parent–daughter relationships but rather only the prediction of the ambient gamma dose rate. For this reason, in contrast to RODOS, the dose rate was calculated by multiplying the ratio of the location- and time-dependent calculated surface contamination of a nuclide and its initial release by a time-dependent dose rate factor summed over a complete nuclide vector. This corresponds to a non-normalised version of the black curve shown in Fig.

[17] Stochastic effects are given in Sv and deterministic effects in Gy

6-5. However, the blue curve in this graph shows the dose rate as it would be calculated with the help of the 44 nuclides described above.

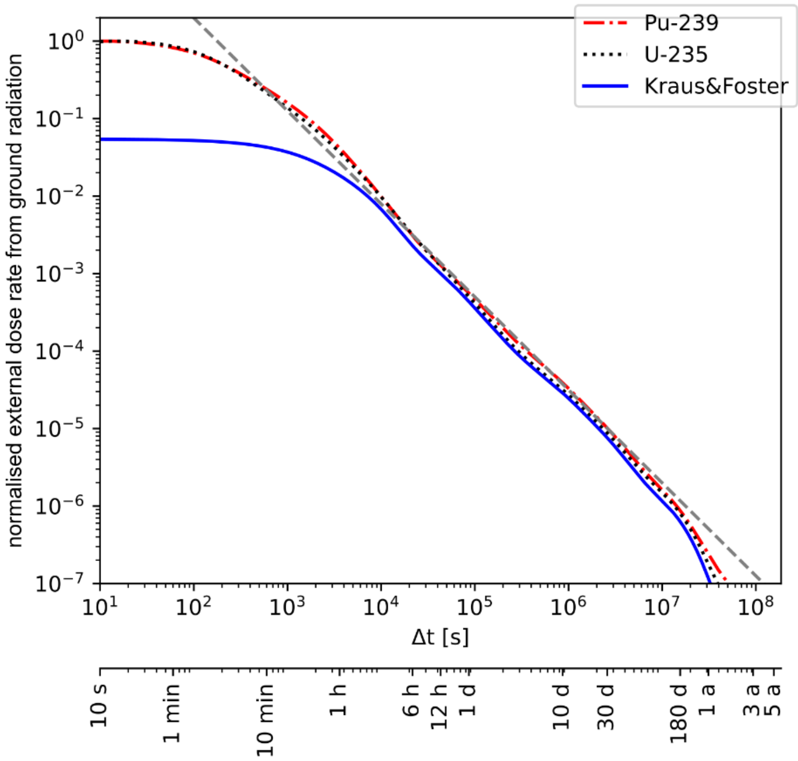


Fig. 6-5: Normalised potential gamma dose rate from ground radiation with the time Δ t after the explosion. The temporal evolution determined with a complete activity vector derived from the fission cross sections from Brown et al. (2018) is shown in black. The temporal development for an optimised activity vector of 44 nuclides used for the dispersion calculations is shown in blue. The dashed grey line shows the postulated curve $\alpha t^{-1.2}$ *similar to Glasstone and Dolan (1977)*

6.5.1.3 Inhalation

Inhalation leads to the intake of radionuclides into the body. In addition to the physical properties of the radionuclides, biochemical processes play a role here. By modelling the biochemical processes in the body as well as the radioactive decay and the radiation emitted in the body, nuclide-specific dose coefficients can be determined, typically in the unit Sv Bq^{-1}. These establish a relationship between the inhaled or incorporated activity and the effective or equivalent dose received. This dose is calculated by multiplying these dose coefficients by an age-group-specific respiratory rate ($m^3\,s^{-1}$) and the time-integrated activity concentration near the ground (Bq s m–³).

The ICRP recommends dose coefficients for the range up to 10 µm activity median aerodynamic diameter (AMAD). In addition, the chemical speciation or compound of the radionuclide also plays a role in the inhalation dose because it influences intake into the body. The ICRP dose coefficients are classified into three categories with regard to fast (F), moderate (M), or slow (S) uptake. In addition, dose coefficients are presented for various integration periods of the committed dose. The cumulative lifetime dose (up to an age of 70 years) is calculated, and the absorption class recommended in ICRP119 (2012) for the respective chemical element is assumed. It is assumed that metals are present as oxides.

The calculation of the inhalation dose does not consider local activity particle size distributions that result from varying dispersion of different particles. Instead, it is assumed that all particles contribute equally to the incorporation dose with the same dose conversion factor for 1 µm AMAD. For particles larger than 20 µm, the ICRP does not recommend dose coefficients for inhalation because the biokinetic model used by the ICRP is not valid for this range. However, Anspaugh et al. (2022) describe in detail that particles in this size range also contribute to the total dose because although they do not remain in the deep lung regions they can be absorbed into the body via the upper respiratory tract and ultimately via the gastrointestinal tract. Here, too, biochemical processes play a role that are difficult to model for these cases. This is because absorption is also largely dependent on chemical speciation, which has hardly been researched for the case of a nuclear weapon explosion. Anspaugh et al. (2022) suggest using a weighted form of the ICRP ingestion dose factors for this size range as well as for all organs that are not part of the respiratory tract. A comparison of the calculation of the effective or equivalent doses of the organs considered below (red bone marrow, thyroid, and uterus) according to Anspaugh et al. (2022) with a calculation of the inhalation dose in which the particle size is not taken into account shows that this is a simple approximation of the method of Anspaugh et al. (2022). The calculation method applied is to be regarded as conservative.

Another form of inhalation results from the possible resuspension of ground-deposited radioactive material, which is also taken into account in FDMT.

Kraus and Foster (2013) state that both the direct inhalation and resuspension contributions to the effective dose are below 1 % (0.3 % and 0.6 %, respectively) in the first 24 h.

6.5.1.4 Ingestion

When radionuclides are dispersed in the atmosphere, they may by various environmental processes directly or indirectly eventually appear on various products. For example, they can deposit on the surfaces of open-air crops (e.g. leafy vegetables) or be absorbed through the roots of plants. Moreover, radionuclides may accumulate in other foods and products, e.g., in cow milk through the animal's feed. In the RODOS programme system, radioecological modelling of all relevant processes is available within the FDMT module with which the resulting activity concentrations (Bq kg^{-1}) in agricultural products can be predicted. It should be noted that these models are essentially based on applying transfer factors, which were mainly derived from experimental observations following the Chernobyl and Fukushima reactor disasters. Also the radioecological processes depend on the physico-chemical properties of the radioactive material. Because of the extreme conditions of a nuclear weapon explosion, the physico-chemical properties of the radioactive material may be considerably different from those of nuclear power plant accidents. Among other things, the radioecological processes are related to the water solubility of the radioactive aerosol particles. In this respect, these modelling results are subject to even greater uncertainties than those of nuclear power plant accidents.

In the long term, the ingestion pathway results in human exposure to radiation. In addition to radioecology, this depends significantly on individual lifestyle and consumption habits. The associated dose can be largely reduced in the short term after an event with the help of appropriate behavioural recommendations and guidelines. According to various authors, including Glasstone and Dolan (1977), the ingestion pathway plays only a subordinate role in nuclear weapon explosions, and a direct dose calculation is not carried out in the following.

However, the ingestion exposure pathway can also play a role for the stochastic effects, particularly in the long range or in the longer term. The potential radiological consequences for the environment, which can lead to longer-term exposure via the food pathway, are therefore presented in the form of modelled exceedances, as described above, of the maximum permitted levels regarding products to be placed on the market from EURATOM 2016/52 (EU 2016 or ANoPl-Bund, BMUV 2023) for the example products “leafy vegetables” and “cow milk”.

6.5.2 Radiological criteria

The intensity of the radiological consequences of the fallout varies depending on the distance from the explosion site. In the immediate vicinity, the occurrence of deterministic effects is the main radiological consequence, which must be avoided as far as possible by means of an effective protection strategy. Both the effective dose (with a threshold value of 1000 mSv) and various organ equivalent doses can be used as radiological criteria. This includes the dose to the red bone marrow (with a threshold value of 1,000 mGy) as well as an effective dose to the foetus of 100 mSv as explained in more detail in SSK (2014). The highest doses in the prognostic dose calculation result from an assumed continuous outdoor exposure, which is adopted here to yield a conservative estimate when determining the upper limits of radiological effects, if not stated otherwise.

Although deterministic effects due to fallout are unlikely at medium to far distances from the explosion site, stochastic effects may still occur, and mitigating these is an additional protective goal. The criterion used here is generally the effective dose with protection levels of 10 mSv or 100 mSv, which are defined as radiological criteria for the measures “sheltering” and “evacuation” in the Emergency Dose Level Ordinance (NDWV 2018). The ANoPl-Bund (BMUV 2023) also provides for various other dose values (e.g. for the appropriateness of certain medical measures) and provides so-called operational intervention levels. These are memorable, measurable values (e.g. surface contamination or ambient gamma dose rate) that roughly indicate the potential exceedance of the specified dose values. In principle, the ANoPl-Bund considers the scenario of a nuclear weapon explosion as one of the reference scenarios, but the dose and operational intervention levels mentioned therein are not necessarily suitable for the present case because the primary scenarios dealt with therein are different.

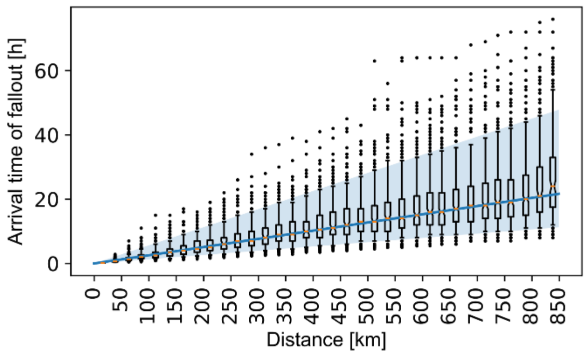
The dose and contamination values calculated below are compared with the values specified in the ANoPl-Bund (BMUV 2023), whereby the suitability of the proposed criteria and measures must be considered in a differentiated manner for this scenario, especially for the immediate vicinity. This can be seen from the fact that the dose values stated in the ANoPl-Bund are estimated in the unit “Sv” because primarily stochastic effects are considered. There are no differentiated values for the evaluation of potential deterministic consequences, which should be specified in the dose unit “Gy” (usually RBE-weighted: weighted according to relative biological effectiveness) (Ferrari et al. 2023). Internationally, a dose of 1 Gy to the red bone marrow (RBE-weighted), a foetal dose of 0.1 Gy, a tissue dose of 25 Gy at a depth of 0.5 cm, and a skin dose of 10 Gy over 100 cm^2 are defined by the IAEA in GSR Part 7 as “generic criteria” for the avoidance of deterministic effects via the external exposure pathway (IAEA 2015), in each case over a period of 10 h.

Within the scope of application of the ANoPl-Bund (BMUV 2023), it is generally assumed that deterministic effects in conventional scenarios such as NPP accidents can be avoided by preventive measures (e.g. previously defined planning zones to be evacuated immediately or preventively, as also specified by the IAEA in GSR Part 7 (IAEA 2015)). In addition, such deterministic effects can be estimated only to a limited extent with the existing prediction and assessment options (RODOS); this is due partly to the dose coefficients used by the ICRP with regard to the Sievert. No deviating RBE weights for deterministic effects with regard to radiation and tissue dependencies or dose rate effects can be taken into account.

6.5.3 Arrival times of radioactive fallout

The arrival times of fallout vary with distance from Ground Zero and roughly follow a linear relationship. To estimate this time, an effective wind speed can be defined, which describes the slope of the relationship between distance and arrival time,. Physically, this effective wind speed results from the distribution of the radioactive substances with the height above ground and the wind speeds and directions prevailing there. One method to determine these values is to average the wind speeds weighted by activity.

Fig. 6-6 shows the ensemble of observed interrelationships between the distance to Ground Zero and the arrival time of radioactive air masses, as well as a histogram of the effective wind speeds derived from this by regression, as they would occur for a near-ground 10 kT explosion within the weather situations considered. The median effective wind velocity determined in this way is approx. 40 km h^{-1}; the 90th percentile 65 km h^{-1}. In individual cases, wind situations can even occur with effective wind velocities of over 80 km h^{-1}. These effective wind velocities apply only to a 10 kT explosion. For greater explosion yields, higher effective wind velocities are also to be expected because of the expansion into higher atmospheric layers and the higher wind speeds that typically occur there. Furthermore, it is to be expected that the effective wind velocity for the 10 kT explosion also tends to be underestimated because of the meteorological input data (up to 2 km altitude).



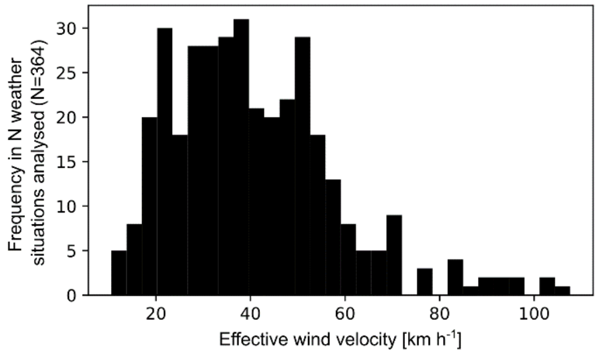


Fig. 6-6: Left: Box plot on the arrival times of fallout according to distance from Ground Zero. The extent of the box covers 75 % of the data whilst the extent of the bars covers 90 % of the data. The notch in the box (red) indicates the median. Data points that are not within the 90 % interval are shown as dots. The blue line describes a linear regression function with the slope of the effective wind velocity in the median, the blue area indicates the associated 90 % prediction interval. Right: Histogram of the observed effective wind velocities determined by linear regression in N = 364 different weather situations.

6.5.4 Development of areas with high dose rates in the first 48 h

Fig. 6-7 shows the typical temporal development of the ambient gamma dose rate from fallout after a ground-level 10 kT explosion for the dose rates 0.1 mSv h^{-1}, 1 mSv h^{-1}, 10 mSv h^{-1}, and 100 mSv h^{-1}. Typically, the area in which an ambient gamma dose rate of 0.1 mSv h^{-1} is exceeded increases in the first 24 h and then decreases whilst the area in which the ambient gamma dose rate exceeds values of 100 mSv h^{-1} begins to decrease after just a few hours. Typically, levels of 100 mSv h^{-1} are exceeded within the first 3 h at distances of a few tens of kilometres from Ground Zero whilst 100 µSv h^{-1} is exceeded at distances over 100 km within the first 12 h – 24 h.

The ANoPl-Bund (BMUV 2023) defines the operational intervention levels of 1 mSv h^{-1} (evacuation), 100 μSv h^{-1} (sheltering), and 1 μSv h^{-1} (general behavioural recommendations) for the ambient gamma dose rate. An operational intervention level is generally used to quickly estimate whether protection goals could be exceeded in the form of received (effective) doses using a measurable quantity such as the ambient gamma dose rate. The numerical values of derived guide values are therefore generally conservatively rounded figures that are easy to remember. Within the currently valid scope of application of the ANoPl-Bund, it is assumed that dose rates of 1 mSv h^{-1} or 100 μSv h^{-1} could lead to exceeding the defined criteria of 100 mSv or 10 mSv effective dose for which evacuation or sheltering indoors is considered radiologically appropriate. However, because of the rapid drop in dose rate over time as well as a possible life-threatening hazard because of incorrect evacuation in the event of a nuclear weapon explosion, application of these operational intervention levels is not advisable.

Because of the lack of spatial and temporal predictability (no or only limited warning time) as well as the pronounced dynamics of both increasing and rapidly decreasing dose rates, the dose criteria for decisions such as sheltering and evacuation in the event of a nuclear weapon explosion are applicable only to a limited extent. First, the aim is to keep as much dose as possible away from people in order to prevent life-threatening exposures or exposures that can cause deterministic effects. In addition, the operational intervention levels do not provide any further differentiation between zones in which deterministic effects typically occur and zones in which stochastic effects are more relevant.

The US FEMA Guide specifies a dose rate of approx. 100 mSv h^{-1}, which, if exceeded, defines the zone in which deterministic radiation effects may occur in the short term without protective measures (FEMA 2023). Within this zone, protective measures must be taken as quickly as possible in order to prevent deterministic effects. In addition, measures taken by emergency personnel in this zone must be justified, planned, and optimised. In an ideal situation, measures should not even be taken until the ambient gamma dose rate has fallen, thus allowing for gradually entering the areas by emergency personnel. In Germany, a reference point for the possible effective dose of emergency services are Sections 113 et seq. StrlSchG (StrlSchG 2017), which can also be found in Fire Service Regulation 500 (AFKzV 2022). It regulates a gradation depending on the intended operation purpose and sets an upper limit for the dose of 500 mSv in exceptional cases. This value is also defined internationally (IAEA 2015). In this respect, an operational intervention level of 100 mSv h^{-1} appears to make sense because this dose is quickly reached within such a zone. Outside the zone, it makes sense to define a second operational intervention level for the general appropriateness of the “sheltering” measure. The time course of the ambient gamma dose rate of the external radiation of the fallout shown in Fig. 6-5 indicates that an effective dose of 10 mSv within a period of seven days after the explosion with an initial ambient gamma dose rate (on arrival of the fallout) of 100 μSv h^{-1} is in every case clearly not reached. Nevertheless, this value should not be adjusted even for the scenario of a nuclear weapon explosion (for reasons of being a conservative estimate, ease of use of this figure, and consistency with other emergency response planning in Germany).

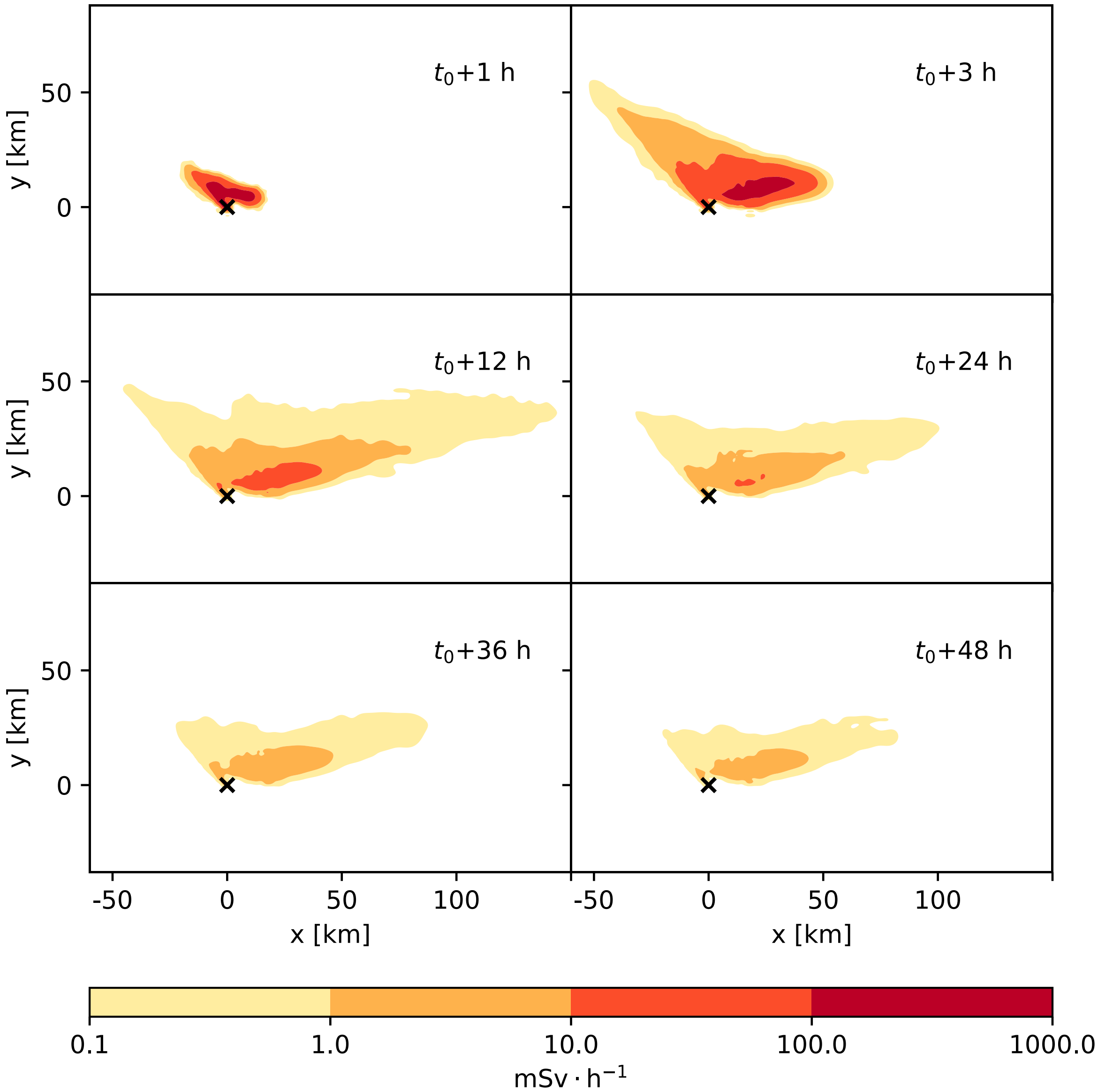


Fig. 6-7: *Contours derived from a dispersion calculation as an example for the ambient gamma dose rates 0.1 mSv h^{-1}, 1 mSv h^{-1}, 10 mSv h^{-1}, and 100 mSv h^{-1} for different times after a near-ground 10 kT explosion. The origin is Ground Zero. The contours were calculated by interpolation from predicted ambient gamma dose rates on the nested computational grid of RODOS (resolution 2 km).*

6.5.5 Effective dose

In accordance with Fig. 6-8, assuming continuous outdoor stay the effective dose resulting from the fallout for the example location could at distances up to 170 km (adults) and 180 km (children) exceed 100 mSv (90th percentile) and at distances of 270 km (adults) and 280 km (children) exceed 10 mSv. A comparison of these distances for the example location, for the location “Germany”, and for the air explosion is shown in Tab. 6-3.

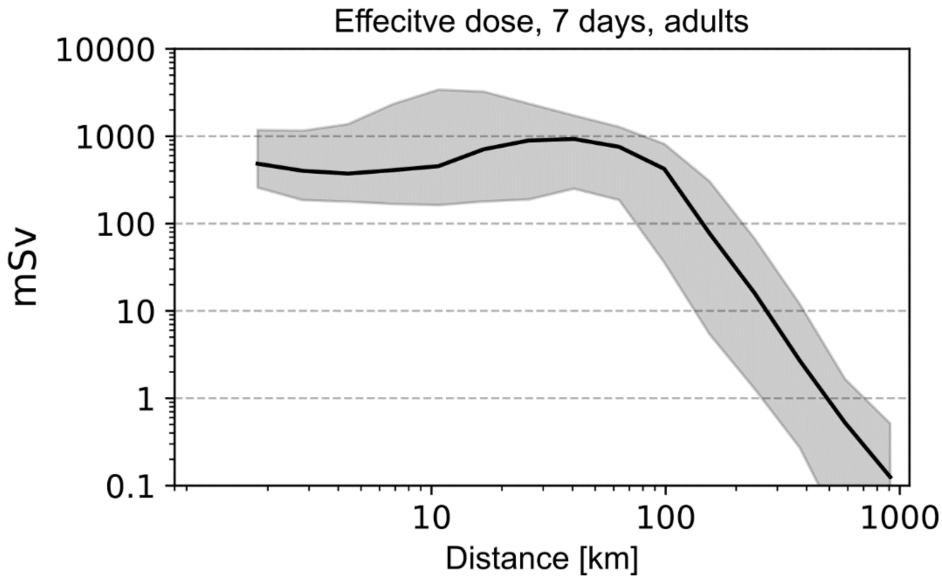


Fig. 6-8: *Effective dose over seven days for adults as a function of distance after a 10 kT near ground nuclear weapon explosion, assuming continuous outdoor exposure. The solid line indicates the median over 365 weather scenarios considered and the grey area indicates the 80 % coverage interval (from the 10th to the 90th percentile).*

This corresponds to the dose criteria for the protective measures "evacuation" and "sheltering" in accordance with NDWV (NDWV 2018) and ANoPl-Bund (BMUV 2023) and (SSK 2019). Because of the short arrival times until the radioactive fallout occurs, the expected impossibility of coordinating evacuation, the lack of protection against fallout in vehicles, and the short duration of the massively increased dose rate, it is recommended that the public in the relevant area shelters in protective rooms (such as rooms in the interior portion or basements of buildings so that they are protected from high doses. This is particularly relevant during periods of very high ambient gamma dose rates (approx. the first 48 h). In the example scenario for Germany (with an explosion site in Frankfurt) the 90th percentile estimates approximately 800,000 people exposed to doses > 100 mSv and 1.9 million people to doses > 10 mSv.

Tab. 6-3: *Statistical values (50th, 80th, 90th percentile; P50, P80, P90) of the distances for the dose criteria 10 mSv and 100 mSv for adults and infants over the scenarios considered assuming continuous outdoor exposure over seven days*

		Example location			**Germany**			**Air explosion**		
Effective dose		P50 [km]	P80 [km]	P90 [km]	P50 [km]	P80 [km]	P90 [km]	P50 [km]	P80 [km]	P90 [km]
Adults	> 10 mSv	210	268	316	201	294	326	42	145	170
	> 100 mSv	110	142	169	103	156	170	5	57	79
Infants	> 10 mSv	217	280	331	212	313	332	51	145	170
	> 100 mSv	121	156	179	108	181	195	7	71	89

When comparing the distances at which the dose criteria are typically exceeded, it becomes clear that no considerable differences are to be expected between the selected locations "Example location" (Eastern Europe, near-ground) and "Germany" (Frankfurt, near-ground), especially in the 90th percentile. Minor deviations arise because the 36 calculations for the

German location do not fully account for all prevailing weather conditions. In the case of an air explosion, the dose criteria are exceeded only at much shorter distances. For example, the median distance for the dose criterion of 100 mSv is only slightly greater than the typical range of the prompt weapon effects. The distances are higher for the higher percentiles; this can be attributed to wet deposition (*washout*).

If the measure "sheltering" were implemented for the first two or seven days after the explosion in all areas in which the predicted effective dose exceeds the value of 10 mSv in seven days, the doses would be considerably lower because of the high proportional contribution of external radiation. Fig. 6-9 shows the predicted effective dose when implementing these measures for various protective factors. The dose reduction depends on the protection factor of the shelter taken during this time. Typical protection factors range from 3 to 100 and thus correspond to a reduction in external radiation doses to between 0.33 and 0.01 of outdoor levels. It should be noted that with a sheltering period of two days the difference between a PF of 50 and 100 is only marginal because the remaining dose would then essentially be absorbed in the period between two and seven days (for which normal living habits were assumed here). At this point, the reader is reminded that the dose in the range of less than a few tens of kilometres is considerably underestimated. It must therefore be assumed that in this range doses may be obtained reaching deterministic effects, despite the results shown..

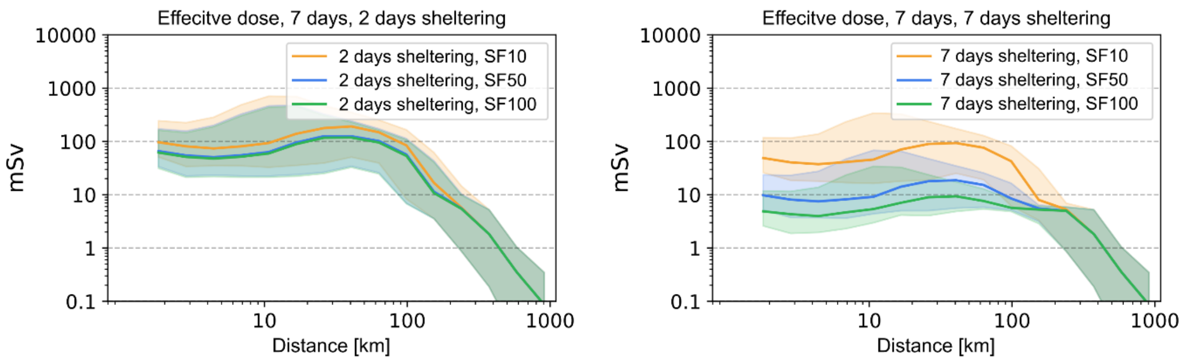


Fig. 6-9: *Effective dose over seven days for adults as a function of distance after a 10 kT near-ground nuclear weapon explosion, taking into account the measure "sheltering" for the first two days (left) or the first seven days (right) after the explosion for different protection factors (colours). The solid lines indicate the median over 365 weather scenarios considered and the coloured area indicates the 80 % coverage interval (from the 10th to the 90th percentile).*

6.5.6 Organ equivalent dose to the thyroid gland from inhaled iodine isotopes

With regard to the organ equivalent dose to the thyroid gland from inhaled iodine isotopes (in the first seven days), the dose values 250 mSv (adults) and 50 mSv (children) (NDWV 2018are defined in Germany as the radiological criteria beyond which the intake of stable potassium iodide is considered radiologically appropriate. For adults, this criterion is not exceeded in the case of a near-ground 10 kT explosion (Fig. 6-10).

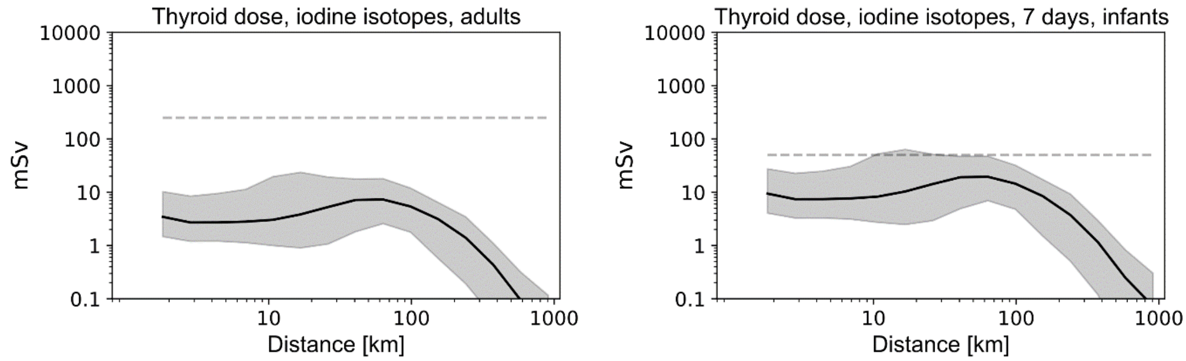


Fig. 6-10: Organ equivalent dose to the thyroid gland from iodine isotopes inhaled over seven days as a function of distance for adults (left) and infants (right) after a 10 kT near-ground nuclear weapon explosion, assuming continuous outdoor exposure over seven days. The solid line indicates the median over 365 weather scenarios considered and the grey area indicates the 80 % coverage interval (from the 10th to the 90th percentile). The dashed grey lines represent the respective dose criteria for iodine blockage of 250 mSv (adults) and 50 mSv (infants).

In rare cases, the prognosis may exceed the criterion for infants. However, this prognosis tends to overestimate the inhalation dose (because of the conservative consideration of the contribution of particles larger than 10 µm, see above). Furthermore, both the contribution of inhaled iodine isotopes to the organ dose of the thyroid gland (which is caused primarily by external exposure) and the contribution of the inhalation dose to the total effective dose are very low. Therefore, administration of stable potassium iodide should be avoided despite the possibility of exceeding the dose criterion, as potassium iodide does not offer protection against external radiation.

The activity of radioactive iodine isotopes (^{131}I, ^{132}I, ^{133}I, ^{134}I, and^{135}I) already accounts for approx. 8 % of the total activity of the radioactive fallout after 1 h. The contribution even increases up to approx. 60 h after the explosion to approx. 17 % . However, the contribution to the effective dose caused by the radioactive cloud via the inhalation pathway is only around 0.30 % in the first 24 h after the explosion (Kraus and Foster 2013). This is also because a diameter > 20 µm was assumed for approx. 88 % of the radioactive particles. Modelling for a 10 kT explosion shows that overall the inhalation of aerosol-bound iodine contributes only slightly to the effective dose and to the thyroid dose and that the intervention reference levels for iodine blockage are not likely to be reached. For higher explosion yields, the intervention reference levels for iodine blockage can theoretically be exceeded. However, the relative contribution to the thyroid dose from inhaled iodine isotopes as compared to the total dose to the thyroid from all exposure pathways is so low that iodine blockage is not recommended.

6.5.7 Organ equivalent doses as indicators of severe deterministic effects

In SSK (2014), it was deduced that a dose equivalent of 1,000 mGy[18] for the red bone marrow can be assumed as a conservative threshold value for the occurrence of serious deterministic

[18] Because of calculation method, doses can be determined only in mSv due the available and used dose conversion factors (ICRP). Because of the predominant contribution of external radiation, it can be assumed that the predicted doses are numerically equivalent to the absorbed dose to the organ or to the absorbed dose to the organ weighted with the relative biological effectiveness (RBE-weighted) in the unit “Gray” (Gy).

effects for both children and adults. The calculations suggest that this threshold can be exceeded in the 90th percentile for a 10 kT burst at distances within 95 km when assuming continuous outdoor exposure. For the scenario in Germany, the 90th percentile estimates that approx. 225,000 people could receive such an equivalent dose to red bone marrow. In contrast, for air explosions, this dose is exceeded only in a few rare cases if localised precipitation occurs at a distance of several tens of kilometres from the explosion site, thereby resulting in *washout*. Therefore, the relevant distances of the percentiles are not given in Tab. 6-4 because the predominant occurrence of non-exceeding the dose value does not allow a reliable calculation of associated distance percentiles. In the extreme case of an air explosion, the distance at which an equivalent dose of 1000 mSv to the red bone marrow was exceeded for adults was 45 km.

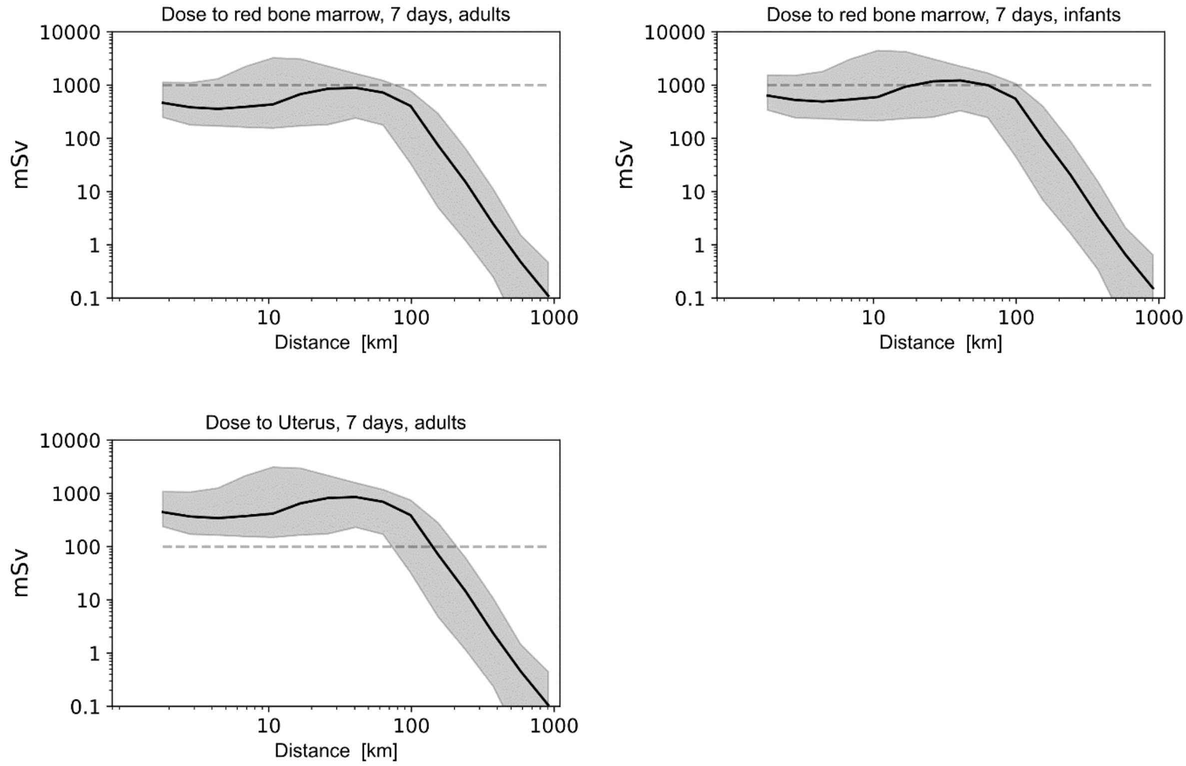


Fig. 6-11: Organ equivalent doses of the red bone marrow (top) and the uterus (bottom) within 7 days after removal for adults (left) and infants (right) after a 10 kT near-ground nuclear weapon explosion assuming continuous outdoor exposure for 7 days. The solid line indicates the median over 365 weather scenarios considered and the grey area indicates the 80 % coverage interval (from the 10th to the 90th percentile). The dashed grey lines indicate the dose criteria for deterministic effects (1,000 mGy dose to red bone marrow, 100 mSv dose to the uterus).

The equivalent dose to the uterus is regarded as a substitute for the foetus dose. For deterministic effects on the foetus, a threshold of 100 mSv was assumed by the SSK (2014). This can be exceeded in the 90th percentile for a near-ground explosion up to a distance of approx. 160 km (assuming a permanent stay outdoors) and up to approx. 75 km for an air explosion. Because of the lack of nuanced figures on population density and structure, the number of people potentially affected is not reliable and is therefore not determined here.

Tab. 6-4: Statistical values (50th, 80th, 90th percentile; P50, P80, P90) of the distances for dose criteria for deterministic effects (1,000 mGy equivalent dose to the red bone marrow, 100 mSv equivalent dose to the uterus as substitute for the foetus dose) assuming continuous outdoor exposure for seven days.

		Example location			**Germany**			**Air explosion**		
Organ equivalent dose to red bone marrow		P50 [km]	P80 [km]	P90 [km]	P50 [km]	P80 [km]	P90 [km]	P50 [km]	P80 [km]	P90 [km]
Adults	> 1,000 mGy	44	58	65	37	58	65	-	-	-
Infants	> 1,000 mGy	58	75	81	62	73	81	-	-	-
Organ equivalent dose Uterus										
Adults	> 100 mGy	106	141	162	100	153	161	3.7	53	75

6.5.8 Remaining committed dose as an indicator for the implementation of medical measures and decontamination

The ANoPl-Bund (BMUV 2023) stipulates that in the case of adults with an estimated effective committed dose above 100 mSv, radiological medical treatment in specially designated hospitals should be considered. Achieving this in the first few days after a nuclear explosion is highly doubtful. Patients with deterministic injuries and conventional life-threatening injuries have priority in all care. According to ANoPl-Bund (BMUV 2023), decorporation therapy is indicated above 200 mSv; between 20 mSv and 200 mSv, an individual case decision should be made. However, despite these specified dose values, in most cases, there is no indication for decorporation therapies following a nuclear weapon explosion because of the lack of a universal decorporation agent in the case of incorporation of various radionuclides and the predominant contribution of external radiation.

The remaining committed dose is shown in Fig. 6-12. Here, sheltering in the affected areas during the first two days with reduction of the inhalation dose and external dose by a reduction factor (0.33 or a protection factor of 3) and normal living habits with reduced time spent outdoors are assumed.

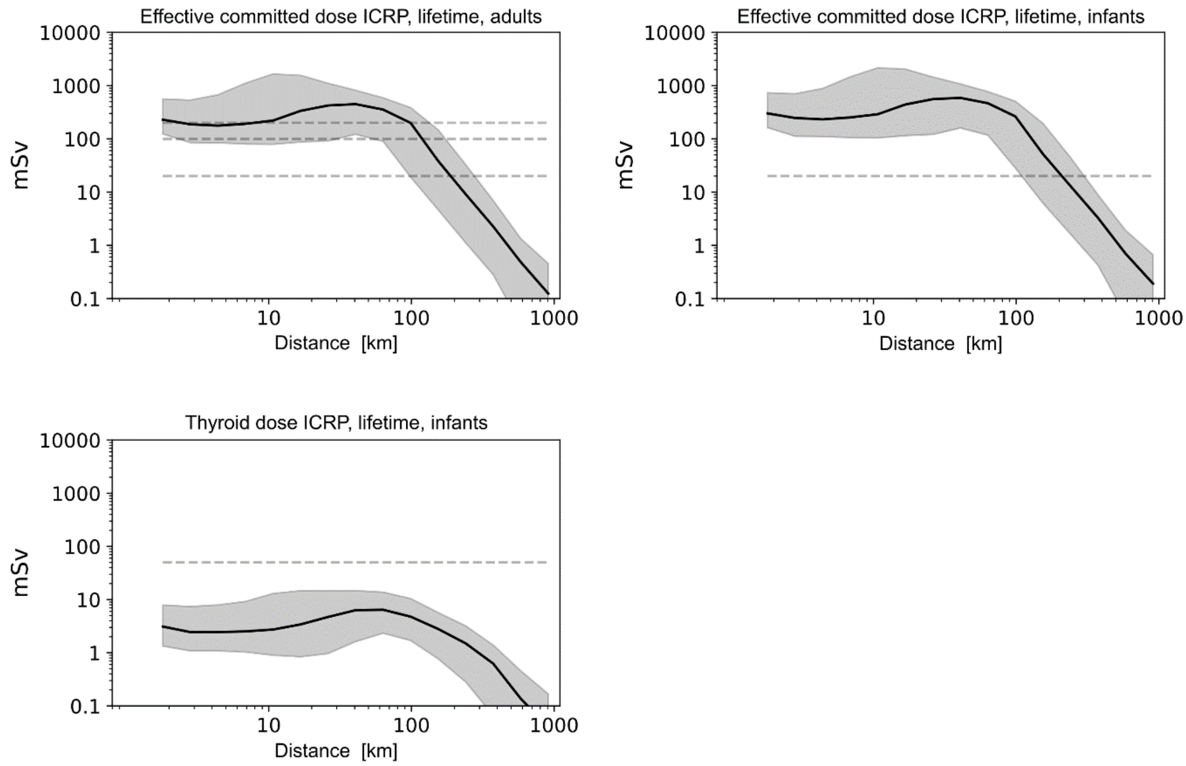


Fig. 6-12: *Effective cumulative lifetime dose according to ICRP calculation basis (top: Adults (left), infants (right), and lifetime equivalent dose to the thyroid gland for infants (bottom) as a function of the distance to the explosion site of a 10 kT nuclear weapon detonated close to the ground. The solid line indicates the median over 365 weather scenarios considered and the grey area indicates the 80 % coverage interval (from the 10th to the 90th percentile). The dashed grey lines represent the respective dose criteria for the application of medical measures as defined in the ANoPl-Bund.*

The distances at which the corresponding doses for adults may be exceeded for a near-ground explosion in the 90th percentile are calculated as 100 km, 150 km, and 220 km (Fig. 6-12, Tab. 6-5). At the 90th percentile, affected area sizes are 500 km^2, 950 km^2, and 3,000 km^2, respectively. Based on population density, the estimated numbers of affected people range from approximately 5,000–350,000, 7,500–500,000, and 11,000–1,100,000, respectively.

For children, the formal indication according to the ANoPl-Bund (BMUV 2023) for decorporation therapy exists already from 20 mSv remaining effective committed dose, which is reached within 230 km or an affected area of 3,500 km^2 in the 90th percentile (cf Fig. 6-11). In this case, too, it should be borne in mind that external radiation accounts for most of this dose and that no effective decorporation agent is available for the assumed radionuclide incorporation.

Tab. 6-5: Statistical values (50th, 80th, 90th percentile; P50, P80, P90) of the distances for lifetime follow-up doses (effective above, thyroid below) for the dose criteria for medical treatments defined in the ANoPl-Bund. For the calculation of the cumulative lifetime dose, staying inside with a protection factor of 3 for inhalation and ground radiation was assumed for the first 48 h.

Effective cumulative lifetime dose		**Example location**			**Germany**		
		P50	P80	P90	P50	P80	P90
Adults	> 200 mSv	78 km	94 km	102 km	75 km	102 km	112 km
	> 100 mSv	91 km	125 km	147 km	84 km	138 km	148 km
	> 20 mSv	152 km	201 km	216 km	145 km	216 km	247 km
Infants	> 20 mSv	165 km	213 km	226 km	161 km	233 km	259 km
Cumulative lifetime dose organ equivalent dose thyroid gland							
Infants	> 50 mSv	is not achieved					

6.5.9 Surface contamination and contamination in agricultural products

According to ANoPl-Bund, the appropriateness of agricultural measures is based on the ambient gamma dose rate. From 1 µSv h^{-1} after the passage of clouds, general measures (e.g. postponing the harvest, refraining from using surface waters as watering places for livestock or for irrigation, or covering cultivated areas) are appropriate. This value can still be exceeded at over 800 km, both for near-ground explosions and airborne explosions, especially as a result of rainfall. It should be noted that the calculations were only carried out up to distances of approx. 800 km – 1,000 km (depending on direction because of a quadratic calculation grid), and thus no statements can be made for possible exceedances beyond these distances. Marketing bans because of contamination with radionuclides are regulated in EURATOM 2016/52, and corresponding maximum permitted levels have been adopted in the ANoPl-Bund. The maximum permitted levels for cow milk are 125 Bq kg^{-1} for Sr isotopes, 500 Bq kg^{-1} for I isotopes, and 1,000 Bq kg^{-1} for Cs isotopes. These maximum permitted levels can still be exceeded at a distance of more than 800 km with an area of 36,000 km^2 in the 90th percentile. The same applies to the prognosis of contamination of leafy vegetables, the maximum permitted levels of which (750 Bq kg^{-1} for Sr isotopes, 2000 Bq kg^{-1} for I isotopes, and 1250 Bq kg^{-1} for Cs isotopes) can be exceeded at the 90^{th} percentile at a distance of over 800 km or over an area of 77,000 km^2. For the air explosion, similar values for affected distances and areas are obtained within the scope of these calculations and the given computational grid.

Overall, it can therefore be assumed that agricultural measures and behavioural recommendations would have to be recommended in the event of a 10 kT nuclear weapon explosion at a distance of over 800 km – 1,000 km.

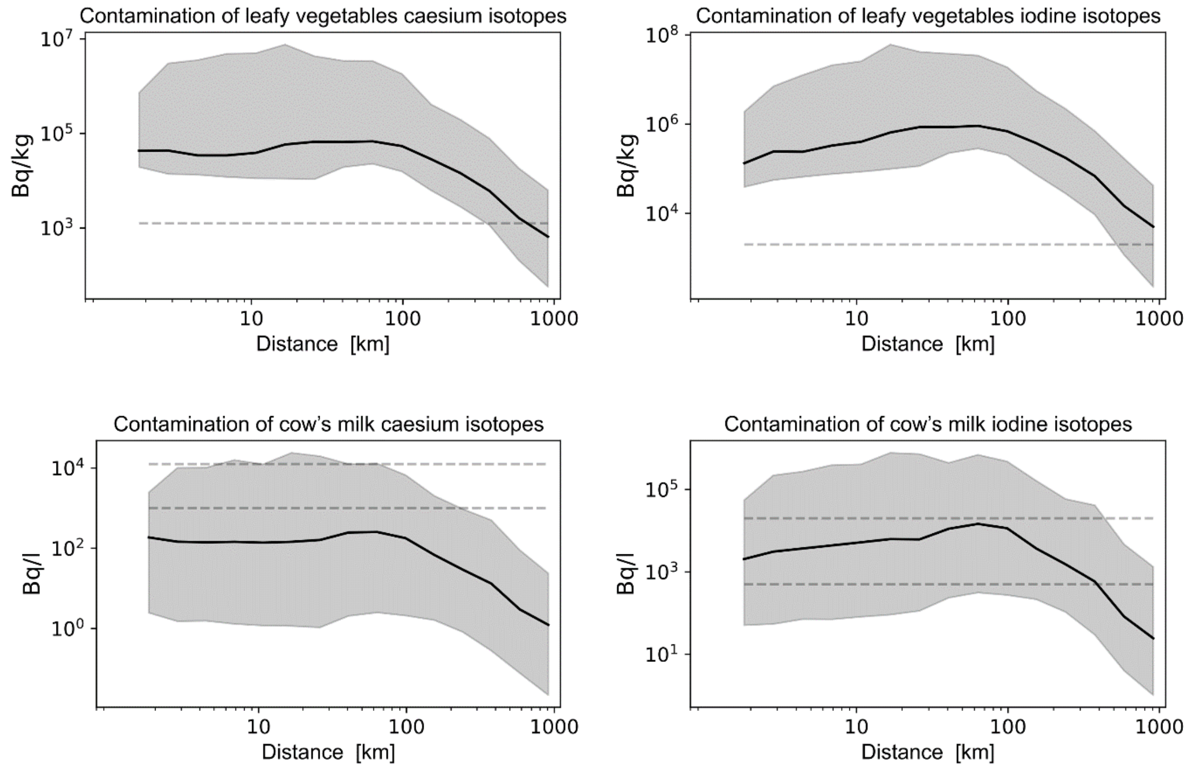


Fig. 6-13: Modelled contamination in agricultural products (leafy vegetables above, cow's milk below) for the nuclide groups caesium (left) and iodine (right) over the distance to the explosion site of a 10 kT nuclear weapon detonated near-ground. The solid line indicates the median over 365 weather scenarios considered and the grey area, the 80 % coverage interval (from the 10th to the 90th percentile). The dashed grey lines represent the specified maximum permitted levels for the marketing from EURATOM 2016/52.

6.6 Dependence of the effect distances on the explosion strength and the height of burst above ground

The explosion yield has a linear effect on the amount of radioactivity released: With double the explosion yield, approx. twice as much radioactivity is released. However, the dose rate or the dose received in areas affected by fallout does not scale linearly with the explosion yield. Stronger explosions also transport a larger proportion of the radioactivity into higher atmospheric layers. Wind speeds are usually higher there than in layers closer to the ground. There is typically also wind shear with height above ground. Predictions of affected areas under typical weather conditions are therefore highly sensitive to the estimated explosion yield, which shortly after the explosion can only be approximated. Simple rules of thumb for scaling the typical effect distances of a 10 kT explosion to other explosion yields can therefore not be generally derived. The distance from the explosion site at which dose levels are exceeded depends not only on the explosion yield but also on the prevailing weather conditions. The ATP-45[19] (Nato 2020) procedure provides a quick method to determine areas with dangerous dose rates for given explosion yields and effective wind velocities. It uses a graphical approach to estimate zones where exposures of 1.5 Gy in 4 h or 500 mGy in 24 h after fallout onset may occur.

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19 ATP: NATO Allied Tactical Publication

The following graphs, which show the modelling of surface contamination with ^{137}Cs after explosions with different input parameters (500 kT, 100 kT, 10 kT, 1 kT, in each case near-ground, and 100 kT, not near-ground) at the same explosion site and at the same time 24 h after the explosion, are intended to serve as an example of these complex relationships. A complete set of weather data from the ICON-EU weather model of the German Meteorological Service (DWD) was used for this purpose. The model domain has a height extension of up to approx. 22 km, whereas the corresponding domain in RODOS is currently only 10 km. This modelling was implemented using an adapted version of the Lagrange particle model FLEXPART (Pisso et al. 2019), which is currently not in operational use but nevertheless enables a realistic prediction for explosion yields above 30 kT for scientific purposes. In addition, unlike RODOS, the particle sizes can be defined here as a continuous distribution (in contrast to the discretised version from Tab. 6-1).

Such modelling (e.g. Fig. 6-14) clearly shows that the level of the resulting contamination changes with the explosion yield as does the extent of the affected areas and their spatial relationship to the explosion site. For this example, the wind shear with height is approx. 30°. For stronger wind shear, there would be even greater differences in the affected areas. High depositions, particularly from stronger explosions, can still be observed several hundred kilometres away because of wet deposition (*washout*). The transport height of the radioactivity also plays a role in the occurrence of wet deposition because a considerable proportion of the radioactivity is located above the cloud cover at higher explosion yields and can therefore no longer be deposited by precipitation.

This example highlights the influence of height of burst above ground, which can greatly shift affected areas and substantially reduce deposition densities – even at the same explosion yield. This is because a considerably different particle size distribution occurs in explosions above ground (Fig. 6-3). Despite this, deposition due to *washout* can result in similarly high deposition values locally and at great distances as in the case of a comparable ground-level explosion. This example demonstrates that predicting the extent and location of affected areas and the associated doses from a nuclear weapon explosion involves much greater uncertainties than predictions for nuclear power plant accidents. The availability and quality of observer reports and measurement data are crucial for effective protective measures because on the one hand they provide critical input for dispersion modelling and on the other hand they are a measure for reliability of modellings. This holds especially since measurement data typically are available early and since minimal or no warning time is expected in general.

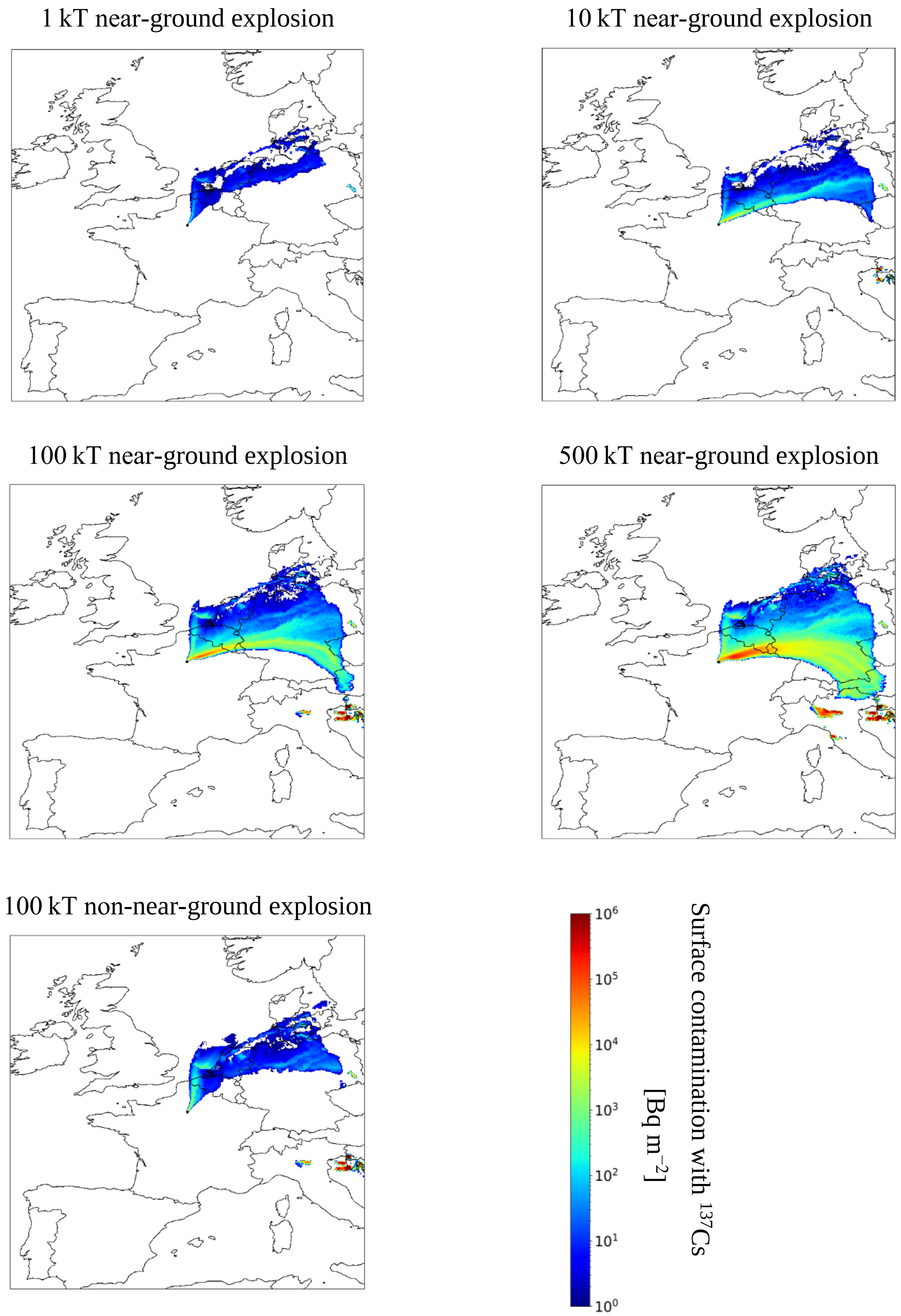

Fig. 6-14: *Modelled surface contamination with ^{137}Cs for various explosion scenarios: 1 kT, 10 kT, 100 kT, and 500 kT near-ground and 100 kT not near-ground. Contamination in the South because of local rainfall. Atmospheric dispersion calculations with an adapted version of FLEXPART and the numerical weather prediction data ICON-EU of the DWD from 19 February 2021, 12:00 UTC*

6.7 Existing planning and procedures for emergency response in the event of a nuclear explosion

In the event of a nuclear weapon explosion in Germany or in neighbouring countries, it can be assumed that NATO observers will initially estimate the explosion yield based on visual observations of the mushroom cloud forming. NATO ATP-45 (NATO 2020) provides for (military) warning and reporting procedures for this purpose so that the first reports can be expected to contain information to determine the explosion yields. Furthermore, the ATP-45 provides two graphical methods – which differ in complexity – by which the distribution of the fallout can be estimated based on an effective wind speed and direction or height-dependent wind data. Various nomograms are available in ATP-45 for this purpose. Formally, the ATP-45 provides for the definition of two zones: Zone I in which 1.5 Gy can be reached within 4 h after the arrival of the fallout and Zone II in which more than 500 mGy can be reached within 24 h. These zones are intended to assess the military or tactical impact of the fallout as well as its short- and long-term effects on the civilian population. Nevertheless, it can be assumed that Zone I roughly covers the area in which deterministic effects can be expected to occur in the short term if no measures are taken. In the event of a nuclear weapon explosion, these two zones are also shown in the radiological situation report.

With regard to the response to radiological emergencies according to the StrlSchG (StrlSchG 2017), since 2023 the ANoPl-Bund has been in force which defines the emergency response for 15 reference scenarios. Central to this is the radiological situation report of the German government, which – if fulfilled – sets out only the radiological criteria for the appropriateness of measures to protect the public for certain areas. These can then be implemented by relevant authorities, taking into account other non-radiological aspects (e.g. availability of resources or feasibility of measures). The reference scenario S14 "Nuclear weapon explosion" is listed in the ANoPl-Bund even though the provisions there do not apply to emergencies in connection with situations of tension or defence. Planning for radiological emergencies in connection with situations of tension or defence is carried out in the "Civil Defence Concept" (KZV) (BMI 2016). In 2024, new framework guidelines for the comprehensive defence (Rahmenrichtlinien für die Gesamtverteidigung – Gesamtverteidigungsrichtlinien; RRGV) were drawn up (BMI 2024). However, the provisions of the emergency plans according to StrlSchG (StrlSchG 2017) and ANoPl-Bund (BMUV 2023) may be applicable in whole or in part to radiological emergencies that occur in the context of cases of tension or defence provided that the KZV does not contain any special provisions for such radiological emergencies.

Typical for most emergency scenarios in accordance with ANoPl-Bund (BMUV 2023) is that there is a warning period or a pre-release phase. During this phase, dispersion calculations using the RODOS decision support system, in collaboration with the German Meteorological Service (DWD), can determine radiologically appropriate measures and their affected areas, especially once a source term is available. In the event of a nuclear explosion, warning times are expected to be very short or entirely absent. Nevertheless, a representative source term can be quickly estimated in such cases provided that the explosion yield is known (as described in the previous chapters). For this purpose, the RLZ-Bund requires information on observations and the situation on site (including "observer reports") in order to enable initial prognostic estimates of the radiation exposure of the public. Ideally, information is also available as to whether the explosion is near-ground or in the air. Up to now, no procedures have been established for these reporting channels, in particular for nuclear explosions in neighbouring countries,. Because of the time required for sounding the alarm, establishing the operational readiness of the RLZ-Bund, and preparing dispersion forecasts as well as assessing the situation and preparing the situation report and releasing it, it cannot be assumed that the radiological situation report will reach local disaster control authorities and the affected population any faster than 1 h–2 h after the explosion. During this time, the fallout can travel up to 200 km so that the applicability of protective measures derived from dispersion calculations for this zone is limited. This suggests that the first rapid recommendations for protective measures should be made for circular areas around the explosion site without taking the current wind direction into consideration.

As soon as fallout reaches German territory (or in the event of a nuclear weapon explosion on German territory), it can be assumed that measurement data from the closely meshed German ODL measuring network will be available almost immediately. This indicates that dispersion modelling results can be incrementally adapted; however, no automated systems are currently operational for this purpose. As the event progresses, the appropriateness of measures based on the measurement data can be checked or adjusted by reconstructing the dose based on the measurement data obtained. This includes decisions on additional protective measures such as the subsequent evacuation of the population from highly contaminated areas. However, in the vicinity of the explosion, the data transmission or the probes of the ODL measuring network itself may be impaired by the NEMP or by the destruction of infrastructure. The BfS – in co-operation with the Bundeswehr – is carrying out investigations into how sensitively the ODL measuring network would react to a NEMP and how it could be better protected (hardened) against a NEMP.

7 Findings on the health effects of past nuclear weapon explosions

Current knowledge of the consequences of nuclear weapon explosions is derived from research on the victims and survivors of the 1945 atomic bombings of Hiroshima and Nagasaki, as well as individuals and populations exposed to nuclear weapon tests. The most important data on the characteristics of the nuclear weapons used (explosive yield, height of burst, design features critical for exposure), exposure, and – if available – protective measures taken are summarised below. Epidemiological estimates of observed health effects available in the literature are also summarised. A comprehensive overview of dose estimates for local populations (up to several 100 km from the explosion site) around the 16 main test sites (except Trinity) can be found in Simon and Bouville (2002) (see Tab. A 1).

7.1 Atomic bombs in Hiroshima and Nagasaki

7.1.1 Health effects in Hiroshima and Nagasaki

7.1.1.1 The explosions over Hiroshima and Nagasaki

On 6 August 1945 at 8:15 a.m., the first atomic bomb used for military purposes (*little boy*) exploded over Hiroshima. Three days later, at 11:02 a.m. on 9 August, the second atomic bomb explosion followed over Nagasaki (*fat man*). At the time of the explosions, there were around 350,000 inhabitants in Hiroshima and around 270,000 inhabitants in Nagasaki (Tomonaga 2019). The bomb exploded over Hiroshima at an altitude of 600 m ± 20 m was based on the fission of ^{235}U, whereby two halves, each with a sub-critical mass and density, were shot at each other to create a critical mass and thus set off a nuclear chain reaction. The bomb exploded over Nagasaki at an altitude of about 503 m ± 10 m was based on the fission of ^{239}Pu. The chain reaction was initiated by compressing a low-density quantity of plutonium into high density using conventional explosives. Despite their different modes of operation, both bombs had a similar explosive yield – a yield of 16 kT ± 2 kT TNT is given for the Hiroshima bomb, and a yield of 21 kT ± 2 kT TNT for the Nagasaki bomb (Young and Kerr, 2005). Accordingly, the consequences of the explosions were similar for the inhabitants of both cities.

The energy released in an atomic bomb explosion is distributed between the resulting pressure wave, the thermal radiation, and the ionising radiation (gamma radiation and neutrons). For example, for the Hiroshima atomic bomb, it was estimated that around 50 % of the energy was distributed to the blast wave, 35 % to heat radiation, and 15 % to ionising radiation. Many individuals near Ground Zero died because of the blast wave (e.g. flying debris), thermal radiation (e.g. severe burns and subsequent fires), and ionising radiation (e.g. acute health effects, deterministic effects, or tissue reactions) (Shigematsu et al. 1995).

The number of fatalities caused by the acute consequences of the explosions is difficult to estimate. Figures frequently cited in the literature for an observation period up to the end of 1945 (approx. 5 months) are around 140,000 fatalities in Hiroshima and around 70,000 in Nagasaki (Tomonaga 2019).

7.1.1.2 Radiation doses from initial radiation

In both cases, a radiation field of gamma radiation and neutrons emerged during the chain reactions, thereby exposing the inhabitants of both cities depending on their distance from Ground Zero. Fig. 7-1 and Fig. 7-2 show the positions of the members of the cohort of atomic bomb survivors (who are still being studied today as part of the Life Span Study (LSS) to investigate the long-term effects of radiation exposure) at the time of the explosions (Cullings et al. 2017). The colour coding shows the energy doses estimated for the survivors in the DS02R1 dosimetry system. Here, the sum of the kerma of gamma radiation and neutrons in air 1 m above the ground is specified. The development of the dosimetry system was highly complex and involved, among other things, individually recording the whereabouts of individuals, modelling for individuals, and creating replicas of houses. In both cities, even within a distance of about 1,000 m from Ground Zero, some people – albeit very few – were able to survive. These people were located in places with strong shielding. This means that it was not possible to reliably estimate the radiation doses of these survivors (black dots in Fig. 7-1 and Fig. 7-2). The colon dose values shown in Fig. 7-1 and Fig. 7-2 range from less than 5 mGy to more than 2 Gy, depending on the distance to Ground Zero (Cullings et al. 2017).

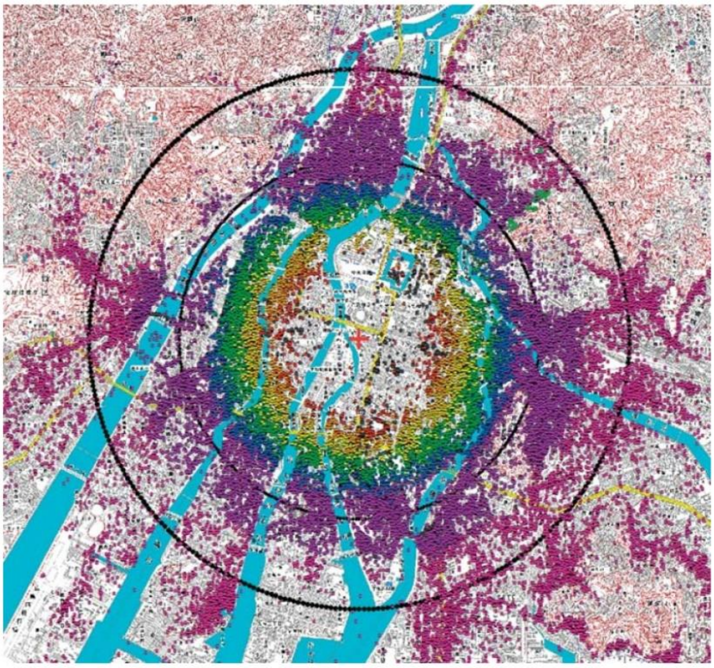

Fig. 20. Revised survivor locations in Hiroshima. Map: Digital Map 25000, Geographical Survey Institute of Japan, 2002. Circles of black dots at 2 and 3 km from hypocenter. Color key, in order of drawing, starting with bottom layer: dark gray = unknown dose; pink < 5 mGy weighted, adjusted colon dose; purple 5 to 100; blue 100 to 200; green 200 to 500; yellow 500 to 1,000; orange 1,000 to 2,000; red > 2,000.

Fig. 7-1 *Figure: Location of individuals at the time of the atomic bomb explosion over Hiroshima; these individuals are being followed as part of the Life Span Study (LSS). Red cross: Ground Zero of the explosion; Black rings: mark distances of 2,000 m and 3,000 m from Ground Zero. The colour coding of the dots represents the estimated colon radiation dose with the neutron dose factored in at a multiplier of 10: black: unknown dose; red: > 2,000 mGy; orange: 1,000 mGy – 2,000 mGy; yellow: 500 mGy – 1,000 mGy; green: 200 mGy – 500 mGy; blue: 100 mGy – 200 mGy; purple: 5 mGy – 100 mGy; violet: < 5 mGy (from Cullings et al. 2017). The urban area is highlighted in grey.*

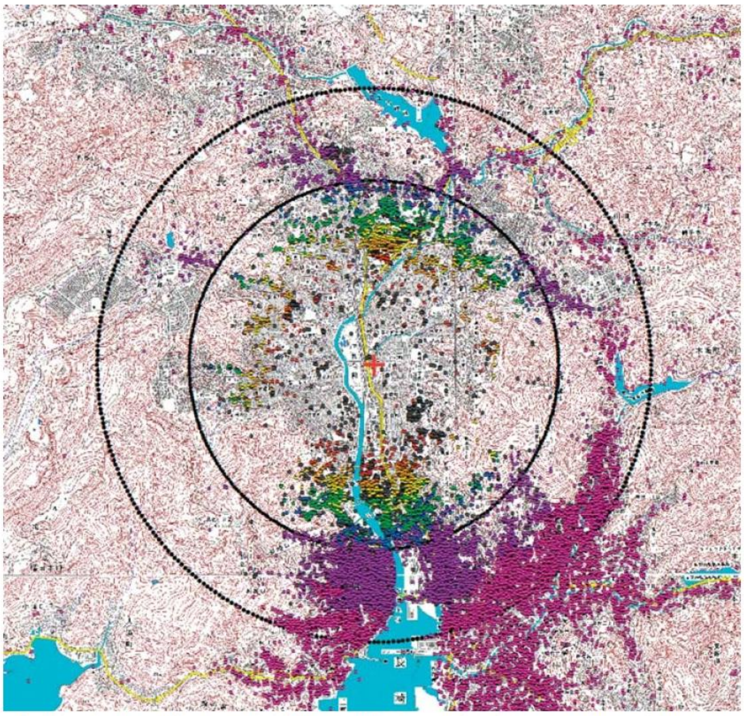

Fig. 21. Revised survivor locations in Nagasaki. Map: Digital Map 25000, Geographical Survey Institute of Japan, 2002. Circles of black dots at 2 and 3 km from hypocenter. Color key same as Fig. 20.

Fig. 7-2: *Location of individuals at the time of the atomic bomb explosion over Nagasaki; they are being followed up as part of the Life Span Study (LSS). Red cross: Ground Zero of the explosion. Black rings mark distances of 2,000 m and 3,000 m from Ground Zero. The colour coding of the dots represents the estimated colon radiation dose with the neutron dose factored in at a multiplier of 10: black: unknown dose; red: > 2,000 mGy; orange: 1,000 mGy – 2,000 mGy; yellow: 500 mGy – 1,000 mGy; green: 200 mGy – 500 mGy; blue: 100 mGy – 200 mGy; purple: 5 mGy – 100 mGy; violet: < 5 mGy (from Cullings et al. 2017. The urban area is highlighted in grey.*

7.1.1.3 Radiation doses from fallout

A comparison with reactor accidents is informative for estimating the consequences of the fallout. The Chornobyl and Fukushima reactor accidents, which involved commercial power reactors with a typical inventory of fissile material of around 100–200 t per reactor unit, released considerable quantities of radioactive material. For the radiologically relevant radionuclides ^{131}I and ^{137}Cs, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recently estimated that about 1,730 PBq of ^{131}I and 85 of PBq ^{137}Cs were released into the atmosphere during the Chornobyl accident and about about 120 PBq of ^{131}I and 10 PBq of ^{137}Cs during the Fukushima accident (UNSCEAR 2022). Whilst fallout from the accident in Japan particularly affected the immediate vicinity, comparatively large areas in Ukraine, Belarus, and Russia were contaminated after the Chornobyl accident. Also, large parts of Western Europe were affected. In Germany, particularly in southern Germany, relatively high depositions of radioactive material were observed because relatively heavy rainfall occurred as radioactive air masses moved across the country. As a result, a ^{137}Cs deposition in the order of 20 kBq m^{-2} was detected in the Munich area, whereby locally considerably higher values were observed in southern Bavaria according to the precipitation distribution (LfU 2006).

Compared with the reactor cores affected in Chornobyl and Fukushima, the bombs used over Hiroshima and Nagasaki contained relatively small quantities of fissile material (in the order of 60 kg of uranium and 10 kg of plutonium, respectively). After the explosions, this material was transported together with activation products to higher altitudes in the atmosphere (mushroom cloud) and then distributed further according to the prevailing meteorological conditions (e.g. wind direction). About 30 min. after the explosions, rainfall was reported locally; the survivors described this as black rain (e.g. B. Shizuma et al. 2012). This resulted in relatively confined areas of some 10,000 m^2 at a distance of about 3,000 m west of Hiroshima Ground Zero (Koi-Takasu) and east of Nagasaki Ground Zero (Nishiyama), where increased radioactive contamination and increased external gamma dose rate were detected.

Results of direct measurements of soil contamination from both cities are scarce, and the interpretation of these is complicated by the fact that fallout from above-ground nuclear weapons tests in the 1950s and early 1960s typically resulted in a ^{137}Cs deposition of about 4 kBq m^{-2} in the latitudes of Japan (UNSCEAR 1983). The final report on the DS86 dosimetry system discusses a soil sample from Nagasaki that was taken before the above-ground nuclear weapon tests. From this sample – corrected to the time of the explosion – a ^{137}Cs deposition of about 5 kBq m^{-2} was estimated. Measurements on samples taken later indicate higher values of up to 30 kBq m^{-2} (Roesch 1987). No values for the ^{137}Cs deposition are given for Hiroshima in the DS86 report.

About 10 years after the publication of the DS86 report (Roesch 1987), Shizuma et al. (1996) analysed more than 20 soil samples from Hiroshima. These had been collected three days after the explosion within a maximum radius of 5,300 m from Ground Zero and were therefore not affected by the fallout from the above-ground nuclear weapons tests. From the ^{137}Cs activity concentrations measured in these samples, they derived a ^{137}Cs deposition of typically 15 Bq m^{-2} for most samples. On the other hand, the only sample that was in the fallout area showed a considerably higher ^{137}Cs deposition of about 500 Bq m^{-2}.

For both cities, the results of early measurements of the ion dose rate were reported, e.g., summarised in a book published by Roesch (1987). In this book, using these measurements and assuming continuous cumulative exposure starting 1 h after the explosions, cumulative ion dose values for Hiroshima residents in those fallout areas with the highest dose rates were given as ranging from approximately $2.6 \cdot 10^{-4}$ to $7.8 \cdot 10^{-4}$ C kg^{-1} (in the original 1–3 R) (Roesch 1987, Shizuma et al. 1996). Because no detailed conversion of ion dose to absorbed dose is given in the original literature, the SSK assumes that this corresponds approximately to an absorbed dose of 10 mGy–30 mGy. For Nagasaki, the corresponding values are approx. $5.2 \cdot 10^{-3}$ C kg^{-1} to approx. $1.04 \cdot 10^{-2}$ C kg^{-1} (originally 20 R–40 R (Roesch 1987, Shizuma et al. 1996)). This corresponds approximately to an absorbed dose of 200 mGy–400 mGy. However, these dose data are subject to high uncertainties that are difficult to quantify. The dose ranges are, therefore, given only as guidelines. Neither the use of nuclear weapons in Hiroshima nor in Nagasaki can serve as an example of fallout from a near-ground nuclear weapon explosion.

7.1.1.4 Radiation doses from soil activation

In Hiroshima and Nagasaki, the neutron component of the radiation field created by the explosions caused the ground to be activated depending on its chemical composition and the distance from Ground Zero. This produced a large number of radionuclides that, depending on their physical half-life, contributed to the dose rate at the location in question. According to Imanaka et al. (2008), for the dose rate the most important radionuclides produced were ^{28}Al ($t_{1/2}$: 2.24 m), ^{56}Mn ($t_{1/2}$: 2.58 h), ^{24}Na ($t_{1/2}$: 15.0 h), and ^{46}Sc ($t_{1/2}$: 83.8 days). Using the DS02 dosimetry system, a dose rate of 6 Gy h^{-1} through activated soil was estimated for Hiroshima at Ground Zero one minute after the explosion and 4 Gy h^{-1} for Nagasaki. Just one day later, the dose rates had decreased by a factor of 1,000, and one week later by a factor of 1,000,000. This would result in a cumulative dose of 1.2 Gy in Hiroshima and 0.6 Gy in Nagasaki for a hypothetical continuous exposure at Ground Zero. A distance of 500 m from the Ground Zeros would result in a reduction of the cumulative doses by a factor of 10, a distance of 1,000 m, by a factor of 300 to 400, and a distance of 1,500 m, by a factor of 1,000. The authors concluded that the radiation doses caused by the neutron activation of the soil were relevant only for people who had entered areas within 1,000 m of the Ground Zeros within the first week after the explosions in Hiroshima and Nagasaki (Imanaka et al. 2008).

Tanaka et al. (2008) estimated the skin dose resulting from the activated soil in Hiroshima from both external radiation and skin contamination with activated soil. They assumed a layer thickness of 26 µm on the skin from contaminated soil material. For a person who spent the first seven days after the explosion at Ground Zero, the cumulative skin dose was around 0.8 Gy. 99 % of this dose was caused by external radiation, whereby 0.19 Gy was from beta radiation and 0.63 Gy from gamma radiation. Over half of the estimated skin dose occurred within the first hour after the explosion.

Based on interviews, Imanaka et al. (2012) reconstructed the routes of four people who were not originally in the city at the time of the explosion over Hiroshima but who entered the city on the same day or the next day and passed through the area near the Ground Zero. Two of the people later reported acute health effects. The authors estimated cumulative doses of 9.4 mGy and 2.6 mGy for these two individuals. For the other two people who did not report health effects after their visit to the city, the estimated radiation doses were 23.7 mGy and 4.0 mGy. The authors offered three explanations for why the doses estimated for the first two individuals were too low to explain the reported health effects: 1) these health effects were not caused by ionising radiation; 2) the authors underestimated the estimated radiation doses; 3) the dose threshold for the induction of health effects could have been drastically reduced by the presence of additional external factors.

7.1.2 Acute health consequences and causes of death until the end of 1945

As mentioned, by the end of 1945, around 140,000 people had died in Hiroshima and around 70,000 in Nagasaki as a result of the atomic bomb explosions. However, it was difficult to determine the actual causes of death of the victims, and the reported figures should be interpreted with caution. One reason for this is that for residents very close to one of the Ground Zeros at the time of the explosions, the cause of death could have been simultaneously the pressure wave, the heat wave, and the ionising radiation. It was reported that within a distance of 2,000 m from Ground Zero, almost 50 % of fatalities had multiple injuries. Considering all fatalities up to a distance of 2,000 m from Ground Zero in Hiroshima, about 89 % died within the first two weeks after the explosion; the remaining 11 % died between the 3rd and the 8th week. In addition, it was estimated that within a distance of 1,200 m from Ground Zero, around 20 % of those affected would have lost their lives because of the consequences of the blast wave and 60 % because of the consequences of the heat radiation (including the resulting fires). According to these estimates, about 20 % of those affected died as a result of exposure to ionising radiation (Shigematsu et al. 1995).
To quantify the induction of tissue reactions as a function of the radiation dose, Fujita et al. (1989) determined the radiation dose for Hiroshima at which half of the exposed individuals

died within 60 days of exposure (i.e. the $LD_{50/60}$ dose). They investigated the fate of 7,593 individuals who had resided in wooden houses in Hiroshima up to a distance of 1,600 m from Ground Zero and initially survived the atomic bomb explosion. This affected around 2,500 households, each with an average of three residents. The associated bone marrow doses were estimated using the DS86 dosimetry system, taking into account the shielding effect of the houses (Roesch 1987). 1,095 of the people included in the study died within 60 days of exposure. Based on this, the $LD_{50/60}$ bone marrow dose ranged from 2.3 Gy to 2.6 Gy. Among other things, the authors pointed out that they were unable to rule out the possibility that some of the people included in the study had not died from the effects of ionising radiation but rather from those of the heat or pressure wave. If corrected for these cases, the estimated $LD_{50/60}$ bone marrow doses would be slightly higher and would be in the range of 2.7 Gy–3.1 Gy (Fujita et al. 1989). It should be noted that in most cases, adequate medical care could not be given to the primary survivors..

Survivors experienced tissue reactions at radiation doses of several hundred mGy and higher. The severity of these reactions increased with increasing doses, and many of those affected died within a few days or weeks as a result. Typical acute symptoms during the first phase (i.e. during the first two weeks after exposure) were fatigue, nausea, and vomiting. During the second phase, the following six weeks (3rd to 8th week after exposure), symptoms such as fever, diarrhoea, haemoptysis (coughing up blood), haematemesis (vomiting blood), or blood in stool and urine, among other things, frequently occurred, among other reasons because of damage to the haematopoietic system (e.g. the bone marrow). Susceptibility to infections was increased, and many of those affected suffered hair loss. Initial signs of recovery were observed, but in particular between the 6th and 8th week after exposure complications occurred, such as pneumonia (lung inflammation), empyema (accumulation of pus), or colitis (intestinal inflammation).. In the third phase (i.e. from the 3rd month until the end of December 1945), there were increasing signs of recovery (e.g. organ damage regressed, hair growth resumed, and the number of white blood cells normalised) (Shigematsu et al. 1995).

7.1.3 Long-term health consequences

Stochastic health effects such as cancer and leukaemia are frequently cited as examples of the long-term health effects of radiation exposure. The probability of occurrence of such effects typically increases with increasing radiation dose. It is also assumed that, in contrast to tissue reactions, there is no dose threshold for stochastic health effects (i.e. that even small doses of radiation can cause such effects, albeit with a correspondingly low probability). Radiation-induced stochastic health effects can occur even decades after exposure to radiation.

To investigate these and other effects, the health of atomic bomb survivors from Hiroshima and Nagasaki continues to be monitored as part of various studies, and corresponding illness and mortality rates are being tracked. These include examinations of around 120,000 survivors as part of the "Life Span Study" (LSS), biannual clinical health examinations of a subgroup of more than 24,000 survivors as part of the "Adult Health Study" (AHS), examinations of more than 3,600 individuals who were exposed *in utero* (In Utero Cohort), examinations of almost 77,000 people born after 1945 ("Children of Survivors Study" – F1 study) and examinations of around 24,600 of these individuals, who undergo regular health checks (similar to the AHS study) ("Filial one offspring clinical study" – FOCS) (Ozasa et al. 2019).

7.1.3.1 Solid tumours

The most recent report on cancer mortality among survivors analysed mortality data from more than 86,000 survivors from 1950 to 2003 (Ozasa et al. 2012). Approximately 50,600 of these primary survivors (58 %) had died during the observation period, including about 10,900 from spontaneous and a small proportion (about 5 %) from radiation-induced solid tumours. For all solid tumours combined, an excess relative rate of 0.42 Gy^{-1} at an age of 70 years and an age at exposure of 30 years was found (referred to as excess relative risk (ERR) by Ozasa et al. (2012)) (95 % CI: 0.32 Gy^{-1} – 0.53 Gy^{-1}). The smallest dose range for which it was possible to demonstrate a statistically significant increase in cancer mortality was 0.0 Gy – 0.2 Gy for weighted colon doses (the absorbed dose from gamma radiation and ten times the absorbed dose from neutrons were added for the colon). The analysis of the existence of a possible dose threshold resulted in a dose of 0 Gy for the best estimate of a threshold. Because of the size of the cohort studied and the length of the observation time, it was possible to make statements on the radiation-induced risk of individual types of cancer. The mortality rates due to tumours in the stomach, lungs, liver, colon, breast, gall bladder, oesophagus, bladder, and ovaries were statistically significantly higher. In contrast, no increase in mortality rates was found for rectal, pancreatic, uterine, prostate, and kidney tumours (Ozasa et al. 2012).

In the report on cancer incidence among atomic bomb survivors, Grant et al. (2017) reported in the framework of the LSS results on more than 105,000 survivors derived from health data from 1958 to 2009. In this study, 22,538 cases of solid tumours were observed; of these, 992 were considered to be radiation-induced (estimated proportion 5 %). Based on a linear dose-effect model, the sex-averaged ERR per dose for all tumours together was 0.47 Gy^{-1} (95 % CI: 0.39 Gy^{-1} – 0.55 Gy^{-1}); for males, it was 0.33 Gy^{-1} (95 % CI: 0.25 Gy^{-1} – 0.42 Gy^{-1}), and for females, it was 0.60 Gy^{-1} (95 % CI: 0.49 Gy^{-1} – 0.72 Gy^{-1}). These results are consistent with the results of previous studies. In addition, the authors reported that the data for men were better described by a linear-quadratic dose-effect curve and that a linear dose-effect curve better described those for women. When averaged over both sexes, a statistically significant increase in cancer incidence was found even in the dose range from 0.0 Gy to 0.1 Gy using a linear ERR model. In summary, the authors emphasised that cancer incidence rates remain elevated in atomic bomb survivors even more than 60 years after the explosions over Hiroshima and Nagasaki.

7.1.3.2 Leukaemia

Hsu et al. (2013) investigated the incidence of leukaemia, lymphoma, and multiple myeloma in more than 113,000 survivors as part of the Life Span Study. They used 944 cases, including 176 cases of acute myeloid leukaemia (AML), 75 cases of chronic myeloid leukaemia (CML), 43 cases of acute lymphoblastic leukaemia (ALL), and 12 cases of chronic lymphocytic leukaemia (CLL) from the study period 1950–2001. For 312 leukaemia cases (excluding CLL and adult T-cell leukaemia), the authors reported a linear-quadratic dose-effect curve (driven by AML) for the ERR. At an attained age of 70 years and an age at exposure of 30 years, the linear component was 0.79 Gy^{-1} (95 % CI: 0.34 Gy^{-1} – 1.80 Gy^{-1}). 94 of the 312 cases observed were radiation-induced. In principle, the ERR for leukaemia decreased with time after exposure, whereby the authors report especially for AML for the first time that an increased ERR persisted during the study period. No evidence was found for an increased radiation-induced incidence of Hodgkin’s lymphoma or multiple myeloma.

7.1.3.3 Non-neoplastic diseases

In the aforementioned report on the mortality of Hiroshima and Nagasaki survivors, Ozasa et al. (2012) also investigated non-neoplastic diseases as possible causes of death. In the observation period from 1966–2003, they found 25,618 deaths from non-neoplastic diseases, including 14,586 deaths from cardiovascular diseases, 4,190 from respiratory diseases, and 2,226 from gastrointestinal diseases. For these endpoints, using a linear dose-effect model, the ERR values per dose were significantly increased: for all non-neoplastic diseases, 0.13 Gy^{-1}

(95 % CI: 0.08 Gy^{-1} – 0.18 Gy^{-1}), for circulatory diseases, 0.11 Gy^{-1} (95 % CI: 0.05 Gy^{-1} – 0.18 Gy^{-1}), for respiratory diseases, 0.23 Gy^{-1} (95 % CI: 0.11 Gy^{-1} – 0.36 Gy^{-1}), and for diseases of the digestive tract, 0.20 Gy^{-1} (95 % CI: 0.05 Gy^{-1} – 0.38 Gy^{-1}). In total, Ozasa et al. (2012) reported 35,685 deaths from non-neoplastic diseases, whereby 353 additional deaths were attributed to the radiation exposure of those affected.
Since 1986, cataract surgery has been documented among 6,066 atomic bomb survivors who participated in the AHS programme and did not undergo cataract surgery before 1986. By 2005, Neriishi et al. (2012) counted 1,028 such operations in this population. The mean age at exposure was 20.4 years, and the mean age at cataract surgery was 74.4 years. The data were analysed based on the weighted eye dose, whereby the neutrons were assigned a weighting factor of 10 and known risk factors that favour the occurrence of cataracts (e.g. smoking, body weight, diabetes, high blood pressure, and angina pectoris) were taken into account. Using a linear dose-effect curve, the authors reported an ERR value of 0.32 for an age at exposure of 20 years and an attained age of 70 years at a dose of 1 Gy (95 % CI: 0.17–0.52) and estimated a dose threshold of 0.5 Gy (95 % CI: 0.10 Gy – 1.05 Gy) (Neriishi et al. 2012). Studies on other groups of people (e.g. occupationally exposed to radiation) revealed higher rates of cataracts and usually no clear dose thresholds (Hamada et al. 2020).

7.1.3.4 *In utero* exposure – mental retardation and cancer mortality

In a study of 1,544 children whose mothers were pregnant at the time of the explosions in Hiroshima and Nagasaki, Otake et al. (1989) examined the mental development of the children. For example, they found 30 cases of severe mental retardation, five of which had not received any additional radiation dose from the atomic bomb explosion. 19 children were exposed between the 8th and 15th week of pregnancy, two of them had Down’s syndrome. The results allowed the interpretation that a threshold dose of about 0.4 Gy was present. In the 16th–25th week of pregnancy, severe mental retardation was lower, and the threshold dose was about 1 Gy. In contrast, there was no evidence of severe mental retardation before the eighth and after the 26th week of pregnancy.

Sugiyama et al. (2021) investigated cancer mortality for a period from 1950 to 2021 in 2,463 people who had been exposed *in utero* in Hiroshima or Nagasaki. They found a statistically significantly increased ERR per dose of 2.24 Gy^{-1} (95 % CI: 0.44–5.58) for women but no statistically significant increased ERR per dose for men. The trimester during pregnancy during which the exposure took place did not play a role here.

7.1.3.5 Results in the children of survivors

The study investigating cancer and non-cancer mortality in the descendants of the first generation of atomic bomb survivors covered a study period from 1948 to 2009 (Grant et al. 2015). Among the 75,327 children who were part of the study, 1,246 died of cancer, and 3,937 died of non-cancerous diseases during the study period. For both groups, there was no correlation between the mortality of these individuals and the radiation dose of their parents. While a relatively large number of children are included in the F1 study, and this over a relatively long follow-up period, the number of parents exposed to high doses and/or the expected effect may be too small to prove a link between parental dose and mortality of the F1 generation (Ozasa et al. 2019).

7.1.4 Summary of the findings from the atomic bombings

To date, in the context of a direct military conflict nuclear weapons have been used only twice: in August 1945, during the bombings of Hiroshima and Nagasaki. These two explosions are the only sources of information on the effects of a nuclear explosion in a populated area. They provide important insights into the appropriate radiological measures and the specific requirements for their implementation.

The explosions had yields of 16 kT TNT (Hiroshima) and 21 kT TNT (Nagasaki). By the end of 1945, around 140,000 of those affected had died in Hiroshima and around 70,000 in Nagasaki. Around 20 % of the casualties died from the effects of the blast waves and 60 % from burns. Around 20 % died from the acute health consequences of tissue reactions caused by radiation exposure. Depending on the distance to Ground Zero, radiation doses of a few mGy to many Gy occurred for short periods. Despite the high dose rates near the two Ground Zeros, some of those affected were able to survive there if they had stayed in places with strong shielding.

In Hiroshima and Nagasaki, the neutron component of the radiation field created by the explosions caused the ground to be activated depending on its chemical composition and the distance from Ground Zero. This resulted in dose rates of 4 Gy – 6 Gy per hour near the Ground Zeros; these had decreased by a factor of 1,000 one day later and by a factor of 1,000,000 one week later. At a distance of 500 m from the Ground Zeros, the cumulative radiation doses were lower by a factor of 10, at a distance of 1,000 m, by a factor of 300 to 400, and at a distance of 1,500 m, by a factor of 1,000 compared with remaining at Ground Zero.

The fallout from both explosions was low because of the low explosion yields, the heights of burst of 500 m–600 m, and the prevailing weather conditions. Therefore, neither of the nuclear weapons used in Hiroshima or in Nagasaki can serve as an example of fallout from a near-ground nuclear weapon explosion.

Depending on the radiation doses received, both tissue reactions (from a dose of several 100 mGy) and stochastic damage (mainly solid tumours and leukaemia) were observed among those affected.

As far as tissue reactions are concerned, symptoms such as exhaustion, nausea, and vomiting were observed among the survivors in the first days and weeks after the explosions, depending on the radiation dose. These were followed by fever, diarrhoea, haemoptysis (coughing up blood), haematemesis (vomiting of blood), and blood in the stool and urine. Many experienced increased susceptibility to infections, hair loss, and complications such as pneumonia, empyema (accumulation of pus), or intestinal inflammation (colitis) – even after initial signs of recovery.

Long-term stochastic late effects were investigated in more than 100,000 survivors. Over an observation period of around 50 years, around one thousand additional cases of solid tumours and around 100 additional cases of leukaemia were observed. In 86,000 survivors, more than 300 additional deaths from cardiovascular diseases were observed within just under 40 years. Other long-term health effects included the occurrence of lens opacities and mental retardation in children who had been exposed in the womb. In the offspring of survivors, there was no correlation between the mortality of these individuals and the radiation dose of their parents.

7.2 Nuclear weapons tests

7.2.1 Nuclear weapons tests by the United States and effects on the population

7.2.1.1 Trinity

Trinity was the first nuclear weapons test in recorded history. A plutonium bomb, which, according to the latest estimates, had an explosive yield of 24.8 kT ± 2 kT (Selby et al. 2021), was detonated at a low altitude (30.5 m) early in the morning (5:29 a.m.) on 16 July 1945.

Because of military secrecy, there were no warnings or evacuations of the general population. Measurement teams were tasked with measuring dose rates in the area where the cloud spread. The local depositions were estimated using local measurements of ion dose rates or gamma spectrometry of the radionuclides in the soil, along with the evaluation of film blackening. The area mainly contaminated by fallout was indicated as a zone of about 100 miles × 30 miles (Ferenc Morton Szasz, "The day the sun rose twice").
A detailed assessment of the external and internal exposures and doses of the population in New Mexico was presented in 2020 (Bouville et al. 2020, Simon et al. 2020). For the external exposures, data from Quinn (1987) based on measurements taken in the first three weeks after the explosion, as well as data from Cederwall and Petersons (1990), which supplemented the Quinn data using meteorological models, were used. All measurements were normalised to 12 h after the explosion. Exposure data for all 721 voting precincts in New Mexico at the time were estimated by interpolation and modelling (Bouville 2020, Simon 2020). Historically reported ion dose rates in mR h^{-1} were converted using a conversion factor of $6.6\ 10^{-3}$ mGy mR^{-1} for adults and slightly higher factors for children. The highest average dose rate from external exposure was in the range of 4 mGy h^{-1} (500 mR h^{-1}) at H+12 in an voting precinct in southern Torrance County (estimated distance from the explosion site approx. 100 km). For individual localised sites in sparsely populated regions north-east of the explosion site, maximum values for air kerma of 0.2 Gy to 0.3 Gy integrated over one year were estimated, which would result in maximum doses in the range of 100 mGy for the local population for the first year after considering the shielding inside houses and the duration of time spent outdoors (Simon et al. 2020, Bouville et al. 2020). These locations presumably correspond to the hotspots reported by some authors 20 miles north-east of the explosion site (Hoot Owl Canyon) (Carr 2021, Widner 2009). More than 50 % of the external dose was caused by ^{239}Np, ^{140}La, ^{95}Nb, and ^{132}I. Because of the high proportion of short-lived radionuclides in the fallout within a few hundred kilometres of the explosion site, it was assumed that most of the external exposure occurred within a few months. Averaged over the entire state of New Mexico, the exposure due to the Trinity test was comparable to that due to the explosions at the Nevada test site but it was considerably higher in some places.
For five organs (thyroid, red bone marrow, colon, stomach, lungs), doses from internal exposure in the first year were thoroughly reconstructed (e.g. based on interviews to document the dietary habits of the affected population at that time depending on their ethnicity (Potischman et al., 2020)) and estimated at the county level. The highest organ doses were determined for the thyroid gland. For thyroid doses, the consumption of cow milk played the largest role, followed by drinking water and leafy vegetables. This was attributed to the lack of warnings and consumption recommendations for the population. Thyroid doses from external exposure and inhalation were about 10 % and 5 % of the dose from the consumption of cow milk, respectively. The population-weighted average thyroid doses in the most affected districts were approx. 35 mGy – 80 mGy, depending on ethnic affiliation. Because of the inhomogeneous deposition, the estimated doses for single individuals could have been considerably larger. Organ doses (external and internal) for the colon were approximately 35 % of the thyroid doses, whilst those for the lungs, stomach, and bone marrow were each below 10 % of the thyroid doses. The comparatively high colon doses were attributed to insoluble fallout particles that remain in the colon after incorporation for a long time before excretion. The organ doses mentioned (excluding the thyroid) were contributed to primarily by ^{39}Np, ^{97}Zr, ^{237}U, ^{89}Sr, ^{140}Ba, ^{132}Te, and ^{140}La. The contributions of ^{237}U and ^{239}Np, which are not fission products, are based on a unique feature of the design of the Trinity bomb.
Cahoon et al. (2020) predicted the cancer risks (incidence) caused by the Trinity test for New Mexico residents based on the dose estimates of Simon et al. (2020) and standard risk models. For the more than 580,000 potentially exposed residents, lifetime background risks of 183,000

cancer cases (excluding thyroid cancer and non-melanocytic skin cancer) were estimated. For all solid tumours (excluding thyroid cancer and non-melanoma skin cancer), an estimated 210–460 additional cancer cases (90 % uncertainty interval) were caused by the test; for thyroid cancer, 80–530 additional cases; and for leukaemia (excluding CLL), 0–10 additional cases. The attributable proportion is, therefore, relevant only for thyroid cancer. Its average for 1945–2015 was 8.4 %, and for the four most highly contaminated counties, it was 17 % – 58 %. For other solid tumours and leukaemia, the mean attributable risks are below 0.2 %.

7.2.1.2 Nevada test site

Between 1951 and 1962, the Nevada Test Site (NTS) was used for 86 atmospheric nuclear weapons tests with a total explosive yield of 1 MT. Four more extensive studies with dose reconstructions were carried out in the 1980s; three of them were limited to the local population (up to 800 km away) and another (NCI 1997) was for the entire population of the US mainland. Simon and Bouville (2002) summarised the results as follows: For the local population, the reconstructed doses from external irradiation as a result of the fallout of all tests were below 5 mGy; maximum bone marrow doses reconstructed in a study of leukaemia cases were around 30 mGy. Internal exposure doses were generally much lower than external irradiation doses except for thyroid doses. The Utah Thyroid Study (Simon 1999) reported mean thyroid doses of 98 mGy (median 25 mGy); the highest calculated value was 4.6 Gy. It could be demonstrated that the high thyroid doses correlated with milk consumption.

Based on the National Cancer Institute (NCI) study (1997) in which the mean thyroid dose due the NTS test trials was estimated at the county level for 14 categories of age, sex, and dietary habits, no significantly increased incidence or mortality from thyroid cancer was observed in an initial analysis (Gilbert et al. 1998). However, in a follow-up analysis with extended follow-up and a total of 18,545 cancer cases, a significantly increased mortality was shown for individuals who had been exposed at an age of less than 1 year (ERR per dose 1.8 Gy^{-1} (95 % CI: 0.4 Gy^{-1} – 3.2 Gy^{-1}). In contrast, no relationship between increased thyroid exposure and mortality was shown for people over 1 year of age. The discrepancy with studies showing increased risks also for older children (e.g. after the Chornobyl accident) was attributed to the limitations of their ecological study approach (Gilbert et al. 2010). Another group studied a cohort of 12- to 18-year-old schoolchildren in three districts identified in 1965–1966. For this cohort, comprehensive individual estimates of thyroid doses (external and internal) were made for exposures from NTS trials between 1951 and 1962. For the 2,496 cohort members, a considerable dose-associated increase in the relative risk of thyroiditis and all neoplasms (including benign ones) was found. However, no significant increase in the incidence of thyroid carcinoma was shown, albeit at a small number of cases (eight in total) (Lyon et al. 2006).

7.2.1.3 Pacific

Between 1946 and 1958, the US conducted 66 nuclear weapons tests on or near the previously evacuated Bikini and Enewetak atolls of the Marshall Islands; 20 of these resulted in measurable fallout on inhabited atolls of the archipelago (Simon et al. 2010). On 1 March 1954, the most powerful nuclear weapons test conducted by the US was carried out on the Bikini Atoll under the name Castle Bravo. Although the fusion bomb used was calculated to have an explosive yield of around 6 MT, the actual explosive yield was around 15 MT (Simon and Bouville 2002); the explosion took place near the ground on an artificial island. The fallout from the explosion contaminated a radius of 32 km in the direction from which the wind came and a 531 km × 97 km area in the direction of the wind. In addition to Bikini Atoll, this also contaminated the Ailinginae (18 inhabitants), Rongelap (64 inhabitants), and Utirik (157 inhabitants) atolls inhabited by Marshallese as well as Rongerik Atoll, where 28 US soldiers were stationed.

The clinical observations made on those affected are described in great detail in the report of "Project 4.1" by Cronkite et al. (1954) and summarised below.
Because the US did not expect the islands to be contaminated, only a few radiation measuring devices were in use. This meant that the dose to those affected had mostly to be calculated. The calculated gamma dose (in air) until evacuation for Rongelap is given as 0.026 C kg^{-1}–0.045 C kg^{-1} (in the original, 102 R–175 R). Because no detailed conversion of ion dose to absorbed dose is given in the original literature, the SSK assumes that this corresponds approximately to an absorbed dose of 1,000 mGy–1,750 mGy (160 km from Ground Zero).

For Rongerik, it is 0.013 C kg^{-1}–0.027 C kg^{-1} (in the original, 50 R – 104 R), for Ailinginae, 0.014 C kg^{-1}–0.018 C kg^{-1} (in the original, 53 R – 69 R), and for Utirik, approx. 0.004 C kg^{-1} (in the original, 14 R). According to the SSK, this corresponds approximately to energy doses of 500 mGy – 1,000 mGy for Rongerik, 500 mGy –700 mGy for Ailinginae, and 100 mGy for Utirik. However, these dose data are subject to high uncertainties that are difficult to quantify. The dose ranges are, therefore, given only as benchmarks.

In the Rongelap group, approx. two thirds of those exposed reported nausea within the first two days after the fallout had fallen; 10 % suffered from vomiting and diarrhoea. One patient in the Ailinginae group also reported nausea, whereas the Utirik group and the US-Americans on Rongerik did not develop any early reactions.
In the exposed groups, tests were carried out on the number of neutrophils, lymphocytes, and thrombocytes in the blood. The detailed course of the cell counts in the blood of those affected can also be found in the aforementioned report. The first measurements in the most heavily exposed group (Rongelap) were carried out three days after fallout arrival; here, during the second week after exposure, an average drop in neutrophils to 70 % to 80 % of the reference group (unexposed Marshallese) was observed (approx. 3,900 μl^{-1}). After five weeks, there was a further significant drop to approx. 50 % of the comparison group (approx. 2,600 μl^{-1}). The age group < 5 years was, on average, more affected by a decrease than the age group > 5 years. The number of lymphocytes in the age group > 5 years had decreased to approx. 55 % of the control group on the third day (first measurement) (2,200 μl^{-1}) and did not anymore increase considerably over the entire observation period (approx. 70 days). In the age group < 5 years, the lymphocyte count at the time of the first measurement had decreased to 25 % of the reference group (1,800 μl^{-1}) but recovered in the course of the observation.
The platelet count was at the time of the first measurement (10 days after exposure) at approx. 70 % of the control group (221,000 μl^{-1}); the lowest point was after approx. four weeks at 35 % of the control group (109,000 μl^{-1}). After a further week, the value of the first measurement was reached again.
In the report, the changes in the blood counts were attributed to the external irradiation by fallout, whereas an influence of the skin beta dose and the incorporated nuclides was excluded. Radiochemical urine analyses and whole-body measurements were used to estimate the activity of incorporated radionuclides for the Rongelap group. Noteworthy are the values for ^{89}Sr (calculated for Day 1; 59 kBq – 81 kBq; in the original, 1.6 µCi – 2.2 µCi), ^{131}I (237 kBq – 414 kBq; in the original, 6.4 µCi – 11.2 µCi), and ^{140}Ba (13 kBq – 100VkBq; in the original, 0.34 µCi – 2.7 µCi) (Robbins et al. 1967). The thyroid dose of the Rongelap group was calculated at 7 Gy–14 Gy (700 rad–1,400 rad in the original) for children under 10 years of age, 3.5 Gy – 6 Gy (350 rad – 600 rad in the original) for the age group 10 – 19 years, and 1.6 Gy (160 rad in the original) for the age groups 20 – 40 years and over 40 years.
Thyroid disorders were diagnosed in 15 of 19 children in the group under 10 years of age between 1963 and 1966; however, all were benign (two atrophy, 13 goitre nodosa). In March 1965, a single case of thyroid carcinoma was diagnosed and successfully treated in a woman 20 years old at the time of the test (Robbins et al. 1967, Howard et al. 1995).

More recent dose estimates and projections of the expected health effects of all nuclear weapon tests in the Marshall Islands were published in 2010 (Simon et al. 2010). Based on estimated depositions of 63 fission products and measured dose rates at different times after the fallout, organ doses (absorbed doses) from external and internal exposure were estimated for all residents. Whilst adult permanent residents of the southern atolls received external doses of 5 mGy–12 mGy on average and those of the middle atolls doses of 22 mGy–59 mGy, the external doses in the heavily affected northern atolls were between several hundreds of mGy and over 1 Gy. The thyroid doses are particularly relevant with regard to internal exposures, which amounted to more than 7.5 Gy for the adult residents of Rongelap and were three times as high for those exposed in childhood (Simon et al. 2010). The records available on health effects among the inhabitants of the Marshall Islands did not permit a detailed epidemiological study. Land et al. (2010) calculated lifetime risks for those affected who had been exposed to fallout during the test period (1948–1958) and to residual radioactivity in the period up to 1970. For the 25,000 people potentially exposed, approximately 170 out of 10,500 estimated cancers were considered fallout-related.

In addition to the people on the aforementioned atolls at the time of the Castle Bravo test, a Japanese fishing boat was affected by the fallout. The 23 fishermen on this boat were exposed externally through direct contact with ash or radioactive material on deck as well as the incorporation of radionuclides. The whole-body gamma dose of the fishermen was estimated to be at least 170 r (1.5 Gy) and, for some fishermen, up to 700 r (6.1 Gy); more than 50 % of the dose was received on the first day. In addition, considerable amounts of radionuclides were detected in the urine, thereby suggesting incorporation (Kumatori et al. 1965). All 23 fishermen suffered from erythema, oedema, or blistering and most from erosions, ulcers, or necrosis as well as hair loss. The severity was not dependent on the presumed total dose in all cases (Messerschmidt 1960).

After exposure, the leukocyte count dropped and reached its lowest point (3,700 μl^{-1} to 800 μl^{-1} depending on the patient) four to eight weeks after falling of the fallout; a negative correlation between external gamma dose and leukocyte count was confirmed. After eight weeks, the leukocyte count increased again. The neutrophil count also decreased and was at its lowest level between Weeks 4 and 8 (approx. 200 μl^{-1}–2000 μl^{-1}); a dependence on the dose received was also shown. In addition, all patients suffered lymphopenia between Weeks 2 and 8 (Kumatori et al. 1965). One patient died of liver failure 206 days after the start of exposure; however, he and some other crew members had previously been infected with hepatitis B.

A further examination of the patients 10 years after exposure showed that in some patients, skin changes such as pigmentation, depigmentation, or telangiectasia were still visible at the sites of the beta burns. Histological findings included the loss of pigment cells but no inflammatory reactions, chronic dermatitis, or neoplasia. The peripheral blood cell counts were within the normal range with a few exceptions. Chromosome analysis in peripheral lymphocytes was carried out on 13 patients; the rate of chromosomal aberrations was considerably higher than in a comparison group, and dicentric chromosomes were present in seven patients. Only isolated abnormalities were found in further laboratory analyses; there were no permanent cases of infertility. Similarly, a whole-body measurement and an excretion analysis did not reveal any significantly increased activity from ^{137}Cs or ^{90}Sr (Kumatori et al. 1965).

7.2.2 Nuclear weapons tests by the United States and effects on the personnel involved

The US carried out 215 atmospheric nuclear weapon tests from 1945 to 1962. Initially, film dosimeters were used only for a representative sample of the participating personnel; in later tests, all participants were equipped with film dosimeters as far as possible.

With the exception of a few accidents (Castle Bravo), personnel were positioned so that they were exposed to only small amounts of initial radiation or fallout-induced radiation; combination injuries from radiation, burns, and conventional injuries were not reported.
The most recent and comprehensive evaluation of the long-term effects of initial radiation in the participants of the nuclear weapon tests was conducted with a cohort of 114,270 male military participants. The cause of death of participants in the US nuclear weapons test series Castle (1954), Crossroads (1946), Hardtrack I (1958), and Redwing (1956, Pacific Proving Ground, PPG), Greenhouse (1951), Plumbbob (1957), Upshot-Knothole (1953, Nevada Test Site, NTS), and Trinity (1945, New Mexico) was investigated up to and including 2010. More than half of the personal dosimeters analysed were exposed to a gamma dose of < 5 mSv and only 33 people were exposed to a dose of > 300 mSv. As of 31 December 2010, 66.0 % of the persons considered were deceased. The authors did not find a significantly increased standardised mortality rate associated with radiation exposure for the causes of death considered or for all-cause mortality and mortality from malignant neoplasms (Boice et al. 2022). Similarly, a study was published in 2000 with approx. 70,000 male participants from five of the eight test series mentioned above (Greenhouse, Upshot-Knothole, Castle, Redwing, Plumbbob). Also here, compared with an equivalently large military comparison cohort, no significant excess mortality because of cancer or leukaemia was found (according to the authors, however, a “trend” with regard to leukaemia was noticeable) (Thaul et al. 2000).
An isolated study of military participants in the “Desert Rock” exercise, which took place as part of Plumbbob “Smoky”, found a significantly increased rate of lymphocytic leukaemia without CLL among participants (SMR = 1.89; CI: 1.24–2.75) (Caldwell et al. 2016). Here, the soldiers were about 4.5 km away from Ground Zero when the explosion occurred and then stayed in the immediate vicinity as part of the exercise.

An older study examined the excess mortality of participants in the Crossroads Test and found a significant 4.6 % increase in mortality among the participants but was unable to attribute this to radiation exposure (Johnson et al. 1996).

7.2.3 Nuclear weapons tests by the Soviet Union

The Semipalatinsk test site in Kazakhstan has been used by the Soviet Union for nuclear weapons tests since 1949. By 1962, 111 atmospheric tests (25 of them near-ground) with a total explosive yield of 6.6 MT had been carried out. Four tests are held responsible for 95 % of the exposure of the local population (29 August 1949, 24 September 1951, 12 August 1953, and 24 August 1956). The 1956 test is said to have led to the hospitalisation of around 600 people in Ust-Kamenogorsk (approx. 400 km from the test site) because of acute radiation sickness (Yan 2019). However, ESR dosimetry in the tooth enamel of 30 residents of this city revealed only doses of up to approx. 120 mGy (Zhumadilov et al. 2009 and Zhumadilov et al. 2013). According to a comparative analysis of several dose reconstruction methods (Stepanenko et al. 2006), in the most highly contaminated village (Dolon, approx. 100 km from the test site), an average of approx. 500 mGy from external exposure can be assumed as a result of the 1949 test. Land et al. (2008, 2015) reconstructed thyroid doses from external exposure and ingestion in a cohort of over 2,000 people living in villages affected by fallout. Mean estimated thyroid doses were around 300 mSv, and maximum doses were over 4 Gy; for doses above 0.1 Gy, contributions from internal exposure, mainly from ingestion of dairy products, generally dominated over external exposure.
A historical cohort of around 20,000 residents of exposed localities in the vicinity of the test site and of comparison localities revealed evidence of various long-term health effects (various cancers and cardiovascular effects) (Grosche et al. 2015, Bauer et al. 2005, Grosche et al. 2011).

Apsalikov et al. (2019) reported a new cohort comprising more than 200,000 directly exposed individuals and 150,000 offspring. However, no further results have been published.

Other Soviet Union test sites were located at Novaya Zemlya, where the largest explosion of a thermonuclear weapon to date took place, and at Kapustin Yar. Both sites are fairly remote, and little information is available on local and regional exposures from the tests (Simon and Bouville 2002).

7.2.4 Nuclear weapons tests by the United Kingdom

Between 1952 and 1958, the UK carried out 21 atmospheric nuclear weapons tests: 12 in Australia and nine in or near Kiribati (overview in Kendall et al. 2004). Further tests after 1958 were carried out at the Nevada test site. The UK also supported nuclear weapons tests by the US near Kiribati. In 1983, an epidemiological study was set up with over 20,000 male military personnel and civilian employees who had stayed at the test sites at defined periods of time (some of which extended well beyond the last test), whereby presence at the time of a test explosion was not a requirement (Kendall et al. 2004). The control group of approx. 20,000 individuals included military personnel who were also deployed in (sub)tropical areas and matched for date of birth and rank. Only 23 % of the participants have dose records available; 8 % received doses above 1 mSv with a mean gamma radiation dose of 9.9 mSv. About 100 participants had recorded doses above 50 mSv – including two with about 300 mSv (Gillies and Haylock 2022, Kendall et al. 2004). The most recent evaluation (Gillies and Haylock 2022) covers follow-up from 1952 to 2017 and compares mortality due to various cancer and non-cancer conditions, as well as cancer incidence between participants and controls and between participants and men in the general UK population. Compared with the control group, participants showed a slightly increased overall mortality (RR = 1.02; 90 % CI: 1.00–1.05; p = 0.04) and a non-significant increase in mortality from all cancers combined (RR = 1.03; 90 % CI: 1.00–1.07; p = 0.07), whereby the latter is dominated by increased mortality from lung, stomach, and prostate cancer. In addition, they showed a non-significant increase in mortality because of leukaemia (excluding CLL) (RR = 1.26; 90 % CI 0.98–1.43; p = 0.16); this was due mainly to mortality from CML (RR = 2.43; 90 % CI 1.43–4.13; p = 0.003). The authors argue that the recorded exposures are too low to explain the effects observed.

The total explosion yield of the tests in Australia was less than 0.2 MT. According to Simon and Bouville (2002), the doses from external irradiation for the local population were not determined for all test series; in the cases where estimates are available, these are below 1 mGy. Between 1957 and 1962, the Kiribati Islands were used by the UK and the US for tests with a total explosion yield of around 30 MT. There is no information on exposure of the general population (Simon and Bouville, 2002).

7.2.5 Further nuclear weapons tests

France carried out four atmospheric nuclear weapons tests and 13 underground test explosions at two test sites in the Algerian Sahara between 1960 and 1966. Dose estimates for the population are not known. Between 1966 and 1974, France used the Mururoa and Fangataufa atolls in French Polynesia as test sites. In total, 46 atmospheric and 137 underwater tests were carried out. Doses were measured for several atolls ranging from 120 km to over 1,000 km away. The average whole-body doses for the population were less than 1 mGy (Simon and Bouville 2002). Recently, the association between thyroid dose and differentiated thyroid carcinoma (DTC) in exposed regions of French Polynesia was re-evaluated following the declassification of records (de Vathaire et al. 2023). With a mean thyroid dose of approx. 5 mGy and 395 cases of DTC diagnosed between 1983 and 2016, the case-control study did not suggest any clear association between thyroid dose and DTC risk. Model calculations estimated that the French nuclear weapons tests could be associated with 2.3 % of the lifetime risk of DTC.

Between 1964 and 1988, China carried out 34 nuclear weapons tests at the Lop Nor test site; 22 of these were above ground. The average whole-body doses for the population were less than 1 mGy (Simon and Bouville 2002).

There is no knowledge of exposed individuals or possible health consequences from other countries (including North Korea, India, Pakistan, and Israel) that may have conducted nuclear weapons tests.

7.2.6 Summary of findings from nuclear weapons tests

Nuclear weapon tests were carried out in sparsely populated areas; only in exceptional cases did they lead to exposure of the population to doses in the potentially lethal dose range (several Gy) (see Tab. A 1). In general, the maximum doses from external exposure from fallout at distances between about 100 km and up to several hundred of kilometres from the explosion site were several hundred mGy. When consumption warnings were omitted, considerable thyroid doses were observed in the affected areas (up to several Gy). The contribution of inhalation to the thyroid dose is considered low. In general, the relative importance of internal exposure, especially through ingestion, increases with distance from the explosion site. Anspaugh et al. (2022) assume that with current knowledge and appropriate behaviour, internal exposure through the ingestion pathway would be largely avoidable even in the event of unexpected nuclear explosions.

8 Health and psychosocial effects and measures to avoid or reduce them

Applying the extended health concept of the WHO of 1948 (i.e. “Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity”), sections 8.1 to 8.4 first deal with the somatic effects of nuclear weapon explosions. Another section on the possible psychosocial consequences follows (see Section 8.5).

The somatic effects of nuclear weapon explosions are based on the resulting fireball and extremely hot heat wave, the direct and indirect consequences of the blast wave, the release of initial radiation, the formation of radionuclides that can contaminate larger regions as fallout, and the activation of soil in the vicinity. The radii around the explosion site within which seriously hazardous and potentially fatal effects can occur depend on explosion yield and height as well as other factors (e.g. geology, building density, and weather conditions) and have similar dimensions for heat effect, pressure, and initial radiation (see Chapter 5). People in these areas are, therefore, affected mostly by combination damage. As a result, more people will die at a given radiation dose than would be the case without additional trauma. This must be taken into account in the following comments on radiation effects. People living in areas affected by fallout are less likely to suffer from a combination of radiation effects, injuries, and burns. External irradiation by radionuclide deposition dominates the radiation effects in the first few days, while the relative importance of ingestion and, sometimes, inhalation increases later on.

Health effects of radiation in fallout areas can be effectively reduced in the short term through simple behavioural measures – “get inside, stay inside, stay tuned” (sheltering). In the central fallout area, extremely high, life-threatening radiation intensities will be registered in the first few hours. After about one to two days, these subside to a level that allows evacuation based on radiological criteria. In the medium term, the supply of uncontaminated food is important.

8.1 Effects of ionising radiation

8.1.1 Acute radiation sickness

The health effects of exposure to ionising radiation depend on the total dose, the dose rate, the radiation quality, and the part of the body that was irradiated. Also, individual factors (e.g. genetics, lifestyle, and medical history) influence the effects experienced by those involved. Therefore, all dosage information given below should be understood as a rough guide. After whole-body exposure or large-volume exposure of the trunk of the body, acute radiation syndrome (ARS) develops at dose levels above approx. 1 Gy (with gamma or high-energy X-rays). The symptoms of these become clinically relevant from approx. 2 Gy. Acute radiation syndrome follows a specific time course with a prodromal and latency phase before the manifest disease, whereby the duration of these phases has prognostic relevance. The different manifestations of the disease, depending on the dose, its diagnosis, and treatment options, are described in detail in SSK 2022a. Only an overview is provided here.

Sub-clinical characteristic changes in the blood count are observed from approx. 0.5 Gy and symptomatic manifestations in the haematopoietic system from approx. 1 Gy. The haematopoietic manifestation of ARS is based on the high radiosensitivity of lymphocytes and the loss of the ability of stem cells in the bone marrow to divide. These stem cells are responsible for the formation of new lymphocytes, granulocytes, and thrombocytes. The lack of new formation with a simultaneous natural decrease in the various differentiated cell types in the blood leads to massive impairment of the immune system, risk of bleeding, and, with a reduction of erythrocytes, suboptimal oxygen supply to the tissues. Early estimates of the dose for whole-body exposure leading to death in the absence of medical care in 50 % of those affected within 60 days ($LD_{50/60}$) were approximately 3.5 Gy (Cronkite 1982). With an exposure of approximately 3.5 Gy, the cause of death is due mainly to bone marrow failure (Di Carlo et al. 2011a), and death occurs within two to six weeks. Recovery of bone marrow function is possible, provided that surviving stem cell compartments are present (a few per cent are sufficient) and the critical phase of susceptibility to infection and bleeding has been overcome. Medical care includes the prevention of infections, the use of antibiotics, antivirals, and antifungals, the management of fluid balance, and the administration of blood transfusions. These measures can approximately double the $LD_{50/60}$ (Hall 2000, Dainiak et al. 2003).

Modern treatment approaches are based on cytokines (i.e. cell type-specific growth factors such as granulocyte colony stimulating factor (G-CSF), granulocyte-macrophage colony stimulating factor (GM-CSF), erythropoiesis-stimulating agents, and thrombopoietin mimetics (Dainiak and Albanese 2022, MacVittie and Farese 2021). These promote the recovery of remaining stem cell compartments in the bone marrow. In the US, the Food and Drug Administration (FDA) has approved the active substances filgrastim, pegfilgrastim, sargramostim, and romiplostim for expected haematological damage following radiation exposure[20]. There is currently no comparable authorisation from the European Medicines Agency (EMA). In Europe, filgrastim and pegfilgrastim are authorised for certain indications, including neutropenia in cancer patients, and romiplostim for chronic immune thrombocytopenic purpura. However, these medications are unlikely to be widely available during a mass casualty incident. In particular, to the knowledge of the SSK, there is no stockpile of cytokines and presumably also no stockpile of supportive therapeutics (either in Germany or in the EU) that would be sufficient to supply the expected number of affected persons in the event of a nuclear weapon of 10 kT exploding in a large city.

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[20] WHO: National stockpiles for radiological and nuclear emergencies: policy advice. https://www.who.int/publications/i/item/9789240067875, last accessed on 16 September 2024

In acute exposures above approx. 5 Gy in addition to the potentially irreversible haematological manifestation, an impairment of the gastrointestinal system occurs; this is due mainly to a loss of the ability of cells of the intestinal mucosa to divide. The loss of the epithelial barrier leads to severe gastrointestinal symptoms such as diarrhoea, infections, sepsis, and bleeding. The treatment options are limited and at doses above approx. 8 Gy – 10 Gy, the gastrointestinal symptoms lead to death within a few days. An estimation of the $LD_{50/7–14}$, which leads to the death of 50 % of those affected within 7–14 days, resulted in 9.6 Gy [9 %, CI: 5.7 Gy–17.2 Gy]. In addition to gastrointestinal effects, at these doses also impairment of the cerebrovascular system contributes to the lethal effect (Di Carlo et al. 2011a).
The mechanisms of cerebrovascular symptoms are still poorly understood. Nausea and vomiting, which occur rapidly after exposure and even at relatively low doses, are due to stimulation of the vomiting centre (chemoreceptor trigger zone) – presumably because of serotonin release in the gastrointestinal tract.

Under the auspices of the EU, a handbook, "METREPOL, MEdical TREatment ProtocOLs for radiation accident victims" (Fliedner et al. 2001), was compiled in 2001. It defines diagnostic and therapeutic guidelines based on the pathophysiology of the affected organ systems. Degrees of severity – referred to as "response categories" according to METREPOL – can usually only be reliably diagnosed during the course of the disease (up to approx. three weeks). A revision of the handbook, which is said to take into account newer treatment concepts, is currently being discussed (Stenke et al. 2022, Lebaron-Jacobs and Herrera-Reyes 2022).

8.1.2 Importance of stem cell transplantation

The NCRP Report 98 (1989) indicates an $LD_{50/60}$ of 3.2 Gy–3.6 Gy with minimal medical care, 4.8 Gy–5.4 Gy with sufficient care, and > 5.4 Gy after stem cell transplantation. The potential benefit of stem cell transplantation in the treatment of acute radiation sickness is currently the subject of controversial debate because bridging treatments with cytokines, transfusions, and supportive therapies have shown similar success. It can be assumed that the $LD_{50/60}$ is around 7 Gy if all currently available medical care options are exhausted. An $LD_{50/60}$ of 8.8 Gy was even estimated for the ARS patients among the liquidators in the Chornobyl reactor accident (Satyamitra et al. 2022, Di Carlo et al. 2011b), whereby some of the liquidators received a bone marrow transplant. However, experts intensely questioned the effectiveness of these transplants. According to the Nuclear Accident Committee of the European Society for Blood and Marrow Transplantation, bone marrow or stem cell transplantation is neither an emergency measure within the first few days nor is it indicated in case of irreversible damage to another organ system. Concerning a comparison of the expected $LD_{50/60}$ estimates after a reactor accident and a nuclear weapon explosion, differences in the dose rate must be taken into account, in addition to the differences in the number of individuals affected and the care options. At present, allogeneic stem cell transplantation is to be regarded[21] as an individual treatment option for individual patients in centres familiar with radiation injuries.

8.1.3 Beta radiation and skin effects

Skin damage after radiation exposure occurs as "local radiation injury" (LRI), as cutaneous radiation syndrome with whole-body exposure, or as "beta burns" (Iddins et al. 2022). LRI are similar to thermal or electrical burns and can easily be confused with them at first. LRI occur

[21] https://www.ebmt.org/sites/default/files/2018-03/EBMT%20Nuclear%20Accident%20Committee%20Pocket%20Guide%202017.pdf, last accessed on 16 September 2024

frequently in the environment of occupational accidents caused by point sources with high dose rates, but they do not play a role in exposure after the use of nuclear weapons. Instead, exposure to localised fallout on unprotected (and also protected) skin is to be expected if the fallout is not removed as quickly as possible. In the case of direct skin contact, the effect of beta emitters likely predominates, and there is increased damage to the upper layers of the skin. Such damage appears locally with delay and at very high doses. First signs just a few hours after isolated exposure to ionising radiation indicates a high dose. However, with the exception of pure fallout, a combination of heat radiation and ionising radiation is to be expected when nuclear weapons are used. In addition to the acute consequences, such as acute desquamation, blistering, epilation, and radioulcera, long-term consequences are to be expected. These include radiodermatitis and the loss of skin and mucosa functions such as sweating and secretion. After the atomic bombings of Hiroshima and Nagasaki, a severe form of keloid formation was observed after the burn wounds had healed. These were probably not the consequences of “beta burns” (radiation damage primarily because of beta emitters) because there was no relevant fallout in either city but rather a combination of “flash burn” (initial thermal burn during detonation of the nuclear weapon or heat flash) and exposure to external ionising radiation.

There are currently no approved specific therapies for beta burns, cutaneous radiation syndrome, or LRI (Iddins et al 2022). In some cases, strategies involving the local application of ointments and other local medicines, customised wound dressings, and even cellular therapies have been successfully implemented for minor radiation injuries. The most promising measure with regard to beta burns is to stop the exposure as soon as possible. Any short-term form of rapid decontamination (dry decontamination, self-decontamination, removal of contaminated clothing) is important. This always takes priority over a delayed, thorough decontamination. Therapies should be interdisciplinary – preferably involving experienced doctors specialising in burn surgery, plastic surgery, and dermatology, as well as radiation oncology experts with experience in the treatment of complications following radiotherapy – and, if possible, include experts in medical physics. Therapies involving the application of mesenchymal stem cells (MSC) and dose-dependent surgical tissue removal have proven successful for massive localised skin damage, particularly in the case of deeper injuries (Benderitter et al. 2010). For individual patients, these individualised and complex therapies may also be possible after the use of a nuclear weapon. However, they are currently not available for many injured individuals because of technical and financial constraints. Modulating (disease-modifying) medications (MSC and related medications) are currently among the most promising forms of therapy. The medications and cellular components used in this process could also become part of future stockpiles.

8.1.4 Health effects after incorporation

In general, inhalation and incorporation play a lesser role than external exposure in the vicinity of the nuclear explosion and in the early phase. Some of the measures to reduce external exposure (e.g. staying in protective rooms, self and gross decontamination by changing clothes and brushing off) can also reduce inhalation and incorporation. Information on professional decontamination, including wounds, can be found in the SSK Radiation Emergency Medicine Handbook (SSK 2022a). If the protective room absolutely must be left, FFP 3/FFP 2 masks can provide protection against inhalation and incorporation (SSK 2023b). However, the relevant exposure comes from the “ground shine”; FFP 3/FFP 2 masks may, therefore, not lull the wearer into a false sense of security. In addition, food and drinking water should be consumed only from stocks. Freshly harvested fruit and vegetables from contaminated regions are to be avoided. The packaging of foodstuffs that enter protective rooms from outside should be decontaminated.

Because of the predominant importance of external irradiation, the use of decorporation therapeutics in the event of a nuclear weapon explosion is also likely to play no or, at most, a minor role. These medications are downstream of acute care and require appropriate resources and optimised special diagnostics. In addition to potassium iodide, decorporation medications such as Prussian blue, DTPA (in the form of Ca-DTPA and Zn-DTPA), and possibly other medications for special applications are available in national and international stockpiles. There is no medication that can remove radioactive contamination from all substances. Therefore, an individual diagnosis through excretion analysis, including a complex estimation of the avoidable subsequent exposure (extrapolation of the expected dose over 50 years), is necessary. Adsorbents or induction of diarrhoea or forced diuresis also play no relevant role according to the assessment of the SSK.

The prophylactic administration of stable potassium iodide is also of secondary importance, as explained in the SSK recommendation on iodine blockage in the event of a nuclear weapon explosion (SSK 2022b).

In later phases, the relative importance of incorporation versus external exposure becomes greater in the fallout area, especially through the ingestion of contaminated food.

8.1.5 Long-term effects

People who have survived acute radiation sickness may show delayed effects of acute radiation exposure (DEARE). DEARE is still a poorly studied chronic disease with a broad and diverse spectrum of possible symptoms that can manifest months or years after radiation exposure and which can be progressive (Micewicz et al. 2019, Sridharan et al. 2021). Various organs, including the lungs, kidneys, heart, liver, and brain, can be affected, and possible clinical symptoms include pulmonary fibrosis, heart disease, high blood pressure, diabetes mellitus, endocrine dysfunction, neurocognitive changes, and cataracts, all of which occur with varying incidences. In contrast to ARS, the incidence of which rises steeply within a narrow dose window, the course of DEARE is variable even in laboratory animals with the same genetic background, lifestyle, and irradiation conditions. It is assumed that chronic inflammatory reactions play an important role in the development of DEARE. Damage to blood vessels and endothelial tissue, radiation-induced senescence, and premature ageing probably also play a role. To date, there are no authorised medications for the treatment of DEARE; substances from the groups of antioxidants, phytoestrogens, and others are being investigated experimentally.

8.2 Burns

During the use of nuclear weapons, thermal burns can be caused both initially by the heat flash (flash burns) and subsequently by secondary sources of fire. Flash burns, in particular can lead to severe large-area burns if the affected person is exposed without protection. This can result in life-threatening burn shock, which requires immediate intensive medical treatment (Tejiram et al. 2023). In addition, lethal infections can occur, especially in combination with radiation exposure. Because intensive medical treatment in the aftermath of a nuclear weapon use can most likely not be guaranteed to a sufficient extent or not at all, it may have to be decided how the resources limited by the given circumstances can be used for the largest possible number of patients (Becker et al. 1990). After the atomic bomb was dropped on Hiroshima (Messerschmidt 1984), the incidence of burn injuries caused by thermal radiation was around 80 % for those outdoors but only around 20 % for those inside buildings.

8.3 Blast trauma

For the frequency of injuries caused by the blast wave, this ratio is approximately 20 % (outdoors) and 55 % (indoors), the reverse of that for burns. However, it heavily depends on the type of building and the precise location within a building (Messerschmidt 1984). The potential effects of the pressure pulse on humans are manifold and can cause severe physical damage. Direct effects include injuries to organs such as the lungs, gastrointestinal tract, and ears caused by the rapid change in pressure. There is also a risk of trauma from impact with structures or from flying or falling objects. The longer duration of the pressure pulse in nuclear weapon explosions compared with conventional explosive devices increases these dangers by increasing the probability of direct injuries. In addition, the increased generation of flying debris contributes to an increase in indirect injuries, thereby markedly amplifying the overall impact of the pressure pulse on the human body (Glasstone and Dolan, 1977). Severe blast injuries can quickly lead to death, and the flying debris usually causes highly microbially contaminated wounds, which significantly increase the risk of infection later on (Beaven and Parker 2015).

8.4 Combination of radiation injuries with burns and other injuries

The combination of radiation exposure with other injuries including burns (Radiation Combined Injury, RCI) significantly increases mortality at given doses compared with the single effect of radiation, even if the additional injury itself would cause low mortality (Di Carlo et al. 2010; Kiang and Olabisi 2019). Adverse synergy effects are often observed. For example, in experiments with dogs, it was observed that after a burn covering 20 % of the body surface, which was itself only slightly lethal (12 %), mortality increased to over 70 % if a whole-body irradiation of 1 Gy, which is not lethal on its own, was also applied (Brooks et al. 1952). Radiation can cause wound healing disorders and significantly prolong wound healing times. Elevated radiation doses can exacerbate injuries and infections through immunosuppression and multi-organ failure. Also, systemic inflammatory reactions that are difficult to control because of an upregulation of pro-inflammatory cytokines (cytokine storm; Rios et al. 2022) are discussed. Infections are also a cause of such synergistic effects. Even small doses increase the likelihood of infections occurring, and injuries and burns promote the transfer of intestinal bacteria into the bloodstream (Di Carlo et al. 2011a).

Combination injuries are particularly relevant for people who are in the border zone of initial radiation. During “Operation Plumbbob Priscilla”, the effect of combination trauma caused by nuclear weapon explosions was investigated in pigs (Mc Donnel et al. 1961). Pigs exposed to a dose of approx. 0.8 Gy showed no change in wound healing or increased mortality from wounds or burns. In the group with approx. 2.9 Gy, there was also no increased mortality because of wounds (27 % of the wounded animals vs 37 % of the non-wounded animals died). However, mortality was increased in the group with burns covering >10 % of the body area (42 % with burns vs 25 % without burns). For wounds, it was reported that these often became infected in the further course and thus contributed to increased mortality. In the categories of higher radiation exposure, almost all animals died; complete analysis was therefore not possible. However, a correlation of the survival time with the burnt area at a comparable radiation dose was shown.

The disproportionately worsened prognosis in combination of radiation with burns was also shown in other animal experiments (Messerschmidt 1977).

8.5 Psychosocial consequences of nuclear disasters

Every disaster can lead to mental illnesses among the population and emergency personnel. These range from anxiety disorders and depression to suicidal tendencies and post-traumatic stress disorders and various rather unspecific stress-related physical symptoms such as nausea, stomach problems, headaches, sleep disorders, and loss of appetite.

Radiation and uncertainty in dealing with radiation are particular anxiety triggers. According to the Fukushima Health Management Survey[22], the following stress factors[23] were also found:

- a lack of knowledge regarding the dispersion and effects of the radiation
- overestimation of radiological risk
- concern for one’s own health and/or for relatives
- lack of reliable information on the current radiological emergency
- protective measures such as evacuation and resettlement, along with the resulting consequences due to altered living conditions and structures
- criticism of the authorities involved and the bodies responsible, with a corresponding loss of trust
- discrimination and stigmatisation, that e.g. may occur when individuals are labelled as “victims,” “evacuees,” or if they are labeled as “contaminated,” thereby causing anxiety among others, after having been exposed to radiation.

The latter stress factors played a special role in Japan after the Fukushima accident against the backdrop of the severe stigmatisation and discrimination of the atomic bomb survivors of Hiroshima and Nagasaki, which was reappraised belatedly.,

In any major disaster, changes in the social living conditions of the population (e.g. the avoidance of outdoor sports activities, evacuation, and resettlement) can lead to an increase in lifestyle diseases such as obesity and the resulting consequences (e.g. increased cardiovascular diseases, metabolic disorders such as diabetes).

In the phase immediately following a nuclear explosion and the associated inferno with thousands of deaths and victims with conventional injuries and/or potentially fatal acute radiation consequences, medical first aid takes centre stage – if it can be provided at all given the chaos with massive destruction of infrastructure. The psychological stress for those affected and the emergency personnel is enormous (Messerschmidt 1984). Emergency personnel play a major role in psychological first aid; they have the initial contact with the affected individuals and should, therefore, already during their training acquire basic skills in psychological first aid and radiation emergency management (BBK 2013).

The acute psychosocial support that follows the care first responders provide begins immediately after the event. For major incidents, it is usually provided by trained members of the crisis intervention teams (KIT), emergency counselling, and/or emergency psychology. This group of people should also undergo in-depth training in radiation emergency management (SSK 2023a).

Acute psychosocial support is followed by medium- and long-term psychosocial after-care, which may take weeks or months and should be scientifically monitored. As the experience of caring for atomic bomb survivors has shown (Honda 2002, Tomonaga 2019), such long-term psychosocial care is particularly important after the use of nuclear weapons and the associated uncertainties, lack of information, and fears of long-term health consequences. Post-traumatic stress disorders and guilt complexes towards the deceased and their families were frequently observed in the survivors. Some of these even persisted for the rest of their lives.

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[22] https://fhms.jp/en/fhms/, last accessed on 11 September 2024

[23] https://www.bfs.de/DE/themen/ion/notfallschutz/folgen/psychosozial/psychosozial.html, last accessed on 11 September 2024

The “Fukushima Health Management Survey”[24] can be used to estimate the scale of such after-care programmes. In the Fukushima reactor accident, similar to a nuclear explosion a combination of other stressors/exposures occurred in addition to radiation exposure –. However, the level of radiation exposure[25] was several orders of magnitude lower than would be expected from a nuclear weapon explosion.
A key component of the “Fukushima Health Management Survey” is the “Comprehensive Health Checkup” with annual health checks, which has been offered to a group of around 200,000 affected people from the evacuated areas since 2011, the year of the disaster. However, at around 35 %, the participation rate was already not very high in 2011 and fell to 17 % in 2021.

The main result of the follow-up checks concerning somatic disorders was an increase in the incidence of increased body weight and obesity with associated secondary diseases, presumably because of a reduction in physical activity and a change in eating habits. The Comprehensive Health Checkup revealed age- and circumstance-adjusted hazard ratios for the risk of becoming overweight after seven years of evacuation of 1.44 (95 % CI: 1.24–1.66) for men and 1.66 (95 % CI: 1.47–1.89) for women (Nagao et al. 2024).

Those affected were also offered a systematic “Mental Health and Lifestyle Survey”[26]. At 21 %, the participation rate was lower than initially in the “Comprehensive Health Check-up”. In 2012, the evaluation revealed many adults who reported sleep problems (39 %) and depression (24 %). These decreased to 27 % and 18 %, respectively, in 2021. In 2012, 21 % of men reported problematic alcohol consumption; this was still 18 % in 2021. Behavioural problems (22 % in 2011 and 8 % in 2021) and fears about the future (24 % in 2012, 10 % in 2022) played a major role for schoolchildren.

One of the lessons learned after the Chornobyl and Fukushima reactor accidents is that particular attention must be paid to vulnerable groups and “worried wells”, who complained of health complaints without having had any health-relevant exposure to radiation. The group of vulnerable people includes children and pregnant women from contaminated areas, people with pre-existing conditions, people who are unable to follow risk communication (either mentally or linguistically), first responders and clean-up workers, evacuees, and people with pre-existing mental health conditions as well as the employees of the facilities causing the accident and their families (WHO 2020). Inadequate information and communication about radiation risks also leads to a large number of people seeking help who are not relevantly exposed to radiation and whose worries and fears can exceed the capacities of medical care facilities (WHO 2020). Fears felt by first responders, medical support staff providing further care, or even by physicians due to insufficient education and further training in radiobiological principles or radiation protection aspects may even lead to refusal of care. This is a key reason for establishing and further developing the qualifications "radiation emergency doctors" and "radiation emergency experts", which would be obtained by further training.

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24 https://fhms.jp/en/fhms/, last accessed on 11 September 2024

25 Six workers at the Fukushima Daiichi reactor plant received effective doses of more than 250 mSv. The highest individual dose was 680 mSv, and the median effective dose in the first year was 13 mSv. For the adult population of Fukushima Prefecture, the highest annual effective dose was 3.8 mSv, and the median effective dose in the first year after the event was 2 mSv (UNSCEAR 2020 Report)

26 https://fhms.jp/en/fhms/, last accessed on 11 September 2024

9 General protective measures

9.1 Protection zone classification according to FEMA guide

For planning protective measures, categorisation into zones according to the FEMA guide for responding to a nuclear weapon explosion (see Section 4.2.1) is appropriate. These zones are categorised according to the radiation exposure (Radiation Zones) and the effect of the blast wave (Blast Zones) (Fig. 9-1).

The figure shows an inner dangerous radiation zone (DRZ) with dose rate values above 100 mSv h^{-1} and a sourrounding hot zone (HZ) with dose rate values of 0.1 mSv h^{-1} – 100 mSv h^{-1}. In the centre of the DRZ, people can quickly absorb doses that are sufficient to develop acute radiation syndrome (ARS). This risk is much lower outside the DRZ. According to the FEMA guidelines for a nuclear weapon explosion with an explosive yield of 10 kT, the extent of these zones in the event of fallout is several tens of kilometres for the DRZ and several hundred kilometres for the HZ (both in the direction of the wind). Whilst the DRZ shrinks again within the first 3 h, the HZ continues to grow and begins to shrink only after about 48 h. After about two weeks, the extent of the HZ is still several tens of kilometres; a DRZ is no longer present.

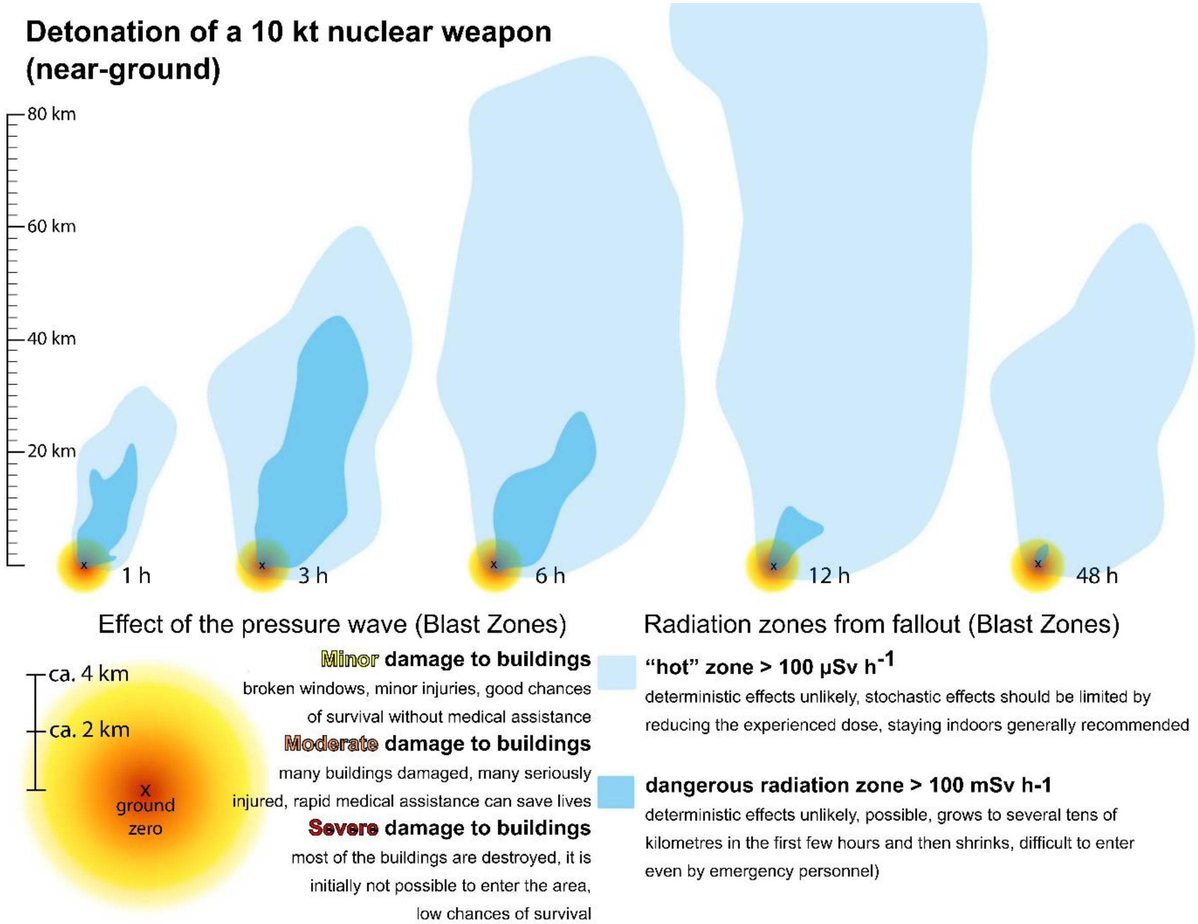

Fig. 9-1: Illustration and description of the five planning zones according to FEMA 2023

With regard to blast wave damage, the FEMA guide distinguishes between concentric zones with a central "severe" damage zone with a radius of around 800 m for a 10 kT explosion, a "moderate" damage zone of 800 m–1,600 m, and a "light" damage zone of 1,600 m–4,200 m. In the central zone, most of the simple buildings have been completely destroyed, and the probability of survival is low because of the high radiation exposure. However, this does not apply to individuals deep inside stable buildings that are structurally unaffected by the explosion (e.g. cellars, underground car parks, underground railway shafts). In the zone of moderate damage, early medical assistance can positively affect the number of survivors despite massive destruction and fires. In the outer zone of minor damage, the explosion leads to broken window panes and minor injuries. Survival is possible there, even without emergency medical aid.

9.2 Preparations by citizens

To be prepared for the event of a nuclear weapon explosion and its effects, rooms with a high level of stability and shielding effect, which offer suitable protection in the emergency, should be identified and designated at the usual whereabouts (e.g. at home or work). The following items should be available there in preparation for such an event:

- An emergency supply of food and drinking water in accordance with the current recommendations of the civil protection organisation (Stock up on food and drink – BBK (bbk.bund.de)).
- Additional water for decontamination (also for pets) – if possible, in a room with drainage/collection facilities outside the selected protective room.
- Plastic bags for any contaminated clothing and as a makeshift toilet.
- A change of clothes and shoes.
- Materials and medicines (for first aid and daily needs).
- Tools and technical aids such as a torch, spare batteries, battery-powered radio, and smartphone.
- Small stock of FFP 2 and FFP 3 masks.

It makes sense to discuss preparations for a nuclear explosion within the family and among friends and neighbours. Furthermore, concepts for kindergartens and schools need to be developed, communicated, and practised. Everyone must be aware that, at least in the immediate area around the explosion site, protected places must be sought quickly to protect against the fallout. Family members may, therefore, have to spend the first 24 h–48 h in different places. For example, meeting points should be agreed upon in advance so that they can reunion after their separate stays at different protected locations This preparation is particularly important for children and adolescents. Protection concepts for daycare centres, kindergartens, and schools must be developed and practised. Parents should also be involved to prevent them from setting off on their own to look for their children in the period of highest radiation exposure. Name tags should be attached to the clothing of young children in particular in order to make it easier to identify them after separation.

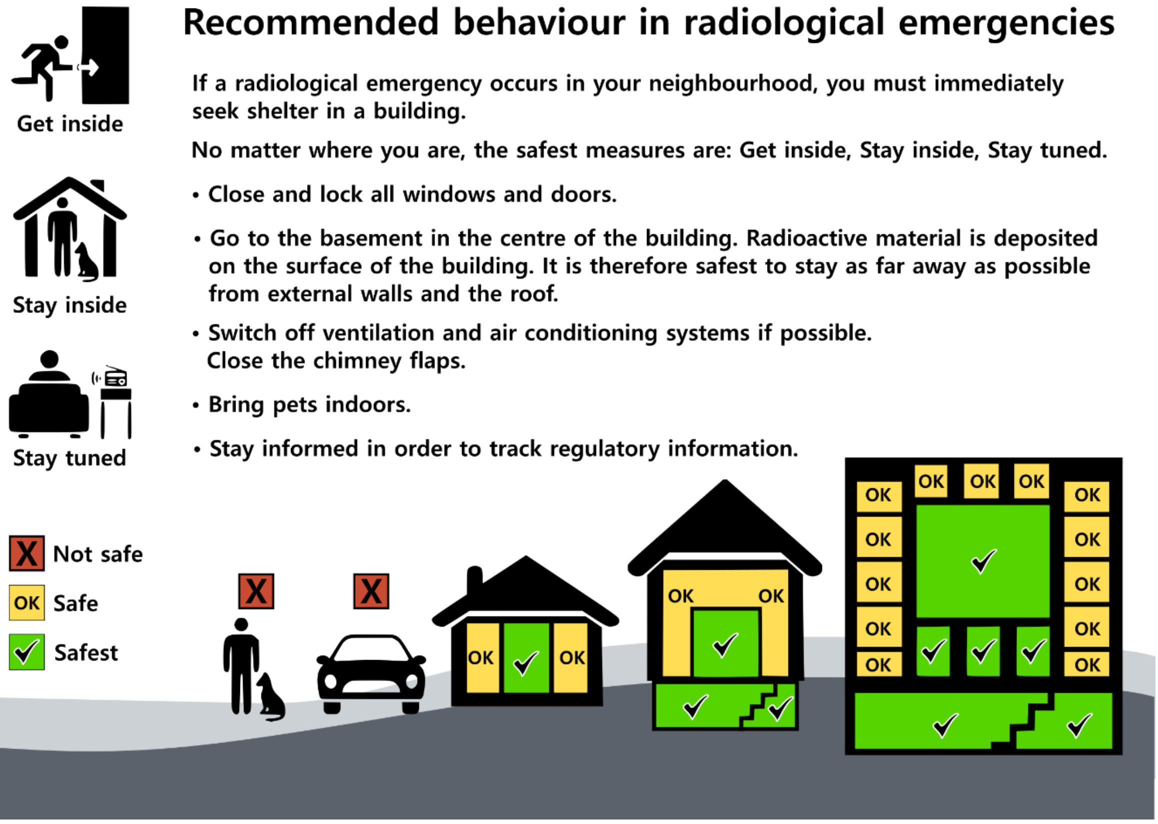

Fig. 9-2: Behavioural recommendations according to FEMA 2023

The NEMP generated directly by the nuclear weapon explosion can damage electrical and electronic installations and devices also far outside the zone of maximum damage. A damage radius for this cannot be clearly defined; however the following trends can be noted:

1.) Devices connected to power or data lines (e.g. mobile phone during charging via power supply unit) can be affected even at a distance of several kilometres unless the respective installations are specially hardened against a NEMP.

2.) The damage radius is considerably smaller for devices that are not connected to unprotected installations – in particular, for battery or hand crank-operated FM radios.

Official information will be issued in parallel on all available channels. It is therefore advisable to try out all means of communication that still appear to be intact.

The SSK strongly recommends that you inform yourself in advance about all issues relating to a nuclear explosion.

9.3 Early protective measures (within the first 24 h)

The individual measures to be taken immediately after the explosion of a nuclear weapon depend on the time since explosion and the distance of the present location from Ground Zero, as well as any shielding provided by terrain formations and structural conditions (cf Chapter 5). Individual protective measures must be aimed at protecting against ionising radiation and thermal radiation – based on the FEMA damage zones (cf Section 9.1) – especially in the "dangerous" radiation zone, which extends up to several tens of kilometres, as well as against the high or moderate risk from the blast wave, which extends up to several kilometres (cf Fig. 5-4, Chapter 5).

As soon as an extremely bright flash of light brighter than sunlight is perceived, the “duck and cover” rule applies outdoors (i.e. one should immediately take up a protected position as possible and remain there for about one minute). If there is an alarm or information about an imminent nuclear explosion, one should go to rooms that offer protection from the explosion (e.g. cellars, underground car parks, and underground stations or rooms inside the house). These also provide good protection against radioactive fallout that spreads somewhat later. In any case, the instructions of the authorities, which can be obtained via available means of communication (e.g. battery-powered radio, Internet), should be followed.

In the event of a nuclear weapon explosion, the following effects occur almost immediately:

- **Neutron and gamma radiation pulse**: immediate onset, over after a few seconds – imperceptible.
- **Flash of light/heat impulse**: immediate onset, lasts up to 10 s. This is kept out even by thin, non-transparent materials; however, depending on the material, these can ignite.

Depending on the distance, several seconds may pass after the first perception of the flash of light before the **pressure wave** arrives.

When the flash of light is perceived, only a moment to a few seconds remain to:

- Take cover immediately and cover face and body if possible (**duck and cover**) to protect oneself from further damage from the heat wave, which may last several seconds, and from the blast wave that will arrive shortly (around 5 s at a distance of 2 km).

When looking directly into the flash of light, the glare causes “blindness”, which often subsides only after several minutes. Sighted people should guide affected persons.

Depending on the distance from the explosion site and the weather conditions, there is a time window of minutes to hours before **fallout** arrives so that, in most cases, there is enough time to find a suitable room to stay **(find a protective space)**:

The most important protection recommendation is:

- Looking for suitable cover, if possible in the house, cellar, or underground car park, remaining there for at least 24 h, and listening for information from the authorities **(look for information).**

Individuals who have been directly exposed to fallout outdoors and are therefore contaminated should immediately decontaminate themselves by brushing off and then removing their outer clothing and stowing it in a plastic bag before entering a protective room to minimise the spread of contamination. If possible, any assumed contamination of skin or hair that was unprotected or possibly affected during decontamination should be washed-off (e.g. by showering). Pets that may be contaminated should also be brushed off outside a protective space first and then washed if possible. However, this should not be done in a room designated for the presence of people (see ICRP[27]).

27 https://www.icrp.org/page.asp?id=613, last accessed on 3 December 2024

The danger posed by radioactive fallout decreases rapidly over time. Therefore, if no further information is available, those affected should initially remain in the protective space for at least 24 h. In any case, the instructions of the authorities, which can be obtained via available means of communication (e.g. battery-powered radio, Internet), should be followed.

In the event of immediate dangers such as fire and unstable buildings, leaving the protected areas and searching for new ones may be necessary. As little time as possible should be spent outdoors and in areas with little protection (e.g. vehicles). Regardless of their design, motor vehicles do not provide suitable radiation protection because of their low shielding effect (see ICRP[29]) but can nevertheless be helpful as a temporary place to stay to reduce direct contamination from fallout when outdoors.

The SSK recently commented on the use of respiratory masks to protect the population in the event of a nuclear weapon explosion (SSK 2023b). It recommends that FFP 2 masks be kept available by everyone. Respiratory masks can reduce the intake of radioactive particles during nuclear explosions. In particular, they should be worn if there is insufficient protection against the ingress of radioactivity from outside air or if it is necessary to leave indoor or protective areas. If available, masks with an exhalation valve and the higher protection class (FFP 3) are preferable. However, the use of masks should not lead to a false sense of security because they can reduce only the dose due to the inhalation of radioactivity but not the level of external exposure. In contrast, the SSK does not consider the intake of iodine tablets (iodine blockage of the thyroid gland) a relevant protective measure because of the low dose contribution of radioactive iodine isotopes (SSK 2022b).

9.4 Protective measures for first responders and emergency personnel

In the centre of the “dangerous” radiation zone (cf Section 9.1), medical first aid is initially not or hardly possible because of the massive destruction of buildings and infrastructure as well as the high dose rates of up to several Sv h^{-1}. However, in the border area of the HZ and within it, medical first aid may be indicated, especially for the treatment of injured individuals with conventional trauma and burns, under consideration of triage measures. This applies in particular if deterministic radiation damage to first responders and emergency personnel is not to be expected based on estimates of possible radiation doses.

First responders and emergency personnel should first seek shelter and await instructions from the authorities.

Emergency personnel will generally be able to act only several hours after the event. The PPE required for this depends on the local conditions and, therefore, the expected risk at the place of use. In the area affected by the destructive impact of a nuclear weapon, particular attention must be paid to self-protection during the rescue of people from debris, as well as to the radiological risk that must be measured and assessed. The unique nature of the rapidly decreasing dose rate requires an assessment of the hazard that differs considerably from other radiological hazards. Thorough preparation conducted outside the “dangerous” radiation zone (cf Section 9.1) before entry combined with rapid personnel rotations based on predefined dose thresholds offers a viable approach to minimising individual radiation exposure.

For areas in which there is only a radiological risk, it is referred to the information in the “Handbook for medical care and education” (SSK 2022a) (in particular Chapter 12 on self-protection and the use of personal protective equipment). For CBRN situations, the federal government provides PPE for the crews of federal civil defence vehicles. Their components are described on the BBK website [28].

Determining the dose (using an alarm dosimeter if possible) and avoiding the incorporation of radioactive substances are particularly important in radiation protection.

Because of the extent of the damage caused by nuclear explosions and possibly also the limited possibilities for self-protection, the psychological strain on emergency personnel in the event of nuclear explosions is quite high. In extreme cases, the consequences of this exposure are similar to those of victims (see Section 8.5). However, preventive measures initiated at an early stage as part of initial and further training can help to reduce the risk of long-term consequences in the form of post-traumatic stress disorder (PTSD) (SSK 2022a).

9.5 Evacuation after the acute phase and its limitations

Seeking out basements and protective spaces is considered the best protective measure for the time shortly after the explosion of a nuclear weapon. The duration for which these protective spaces should be used depends on several factors, including the proximity to the explosion site, the shielding effect of the protective room, and the supply of drinking water, food, and medicines. If the shielding room has low shielding and the dose rate is high, evacuation may be advisable during the first 24 h (Buddemeier and Dillon 2009). However, the risks of such an evacuation should not be underestimated. Without further information, the best option is to stay in suitable protective spaces for about 24 h. This is particularly true given a potentially destroyed infrastructure and other obstacles that could massively hinder an evacuation.

Self-evacuation is strongly discouraged. The authorities must appropriately plan an evacuation and it should be carried out only if a considerable reduction of potential risks is expected. Among other things, this requires knowledge of the exact location and intake capacity of safe areas as well as reliable estimates of the time required for evacuation routes because, unlike houses, vehicles do not provide sufficient protection against radiation from the fallout. Evacuation from contaminated areas at the wrong time must be avoided. During self-evacuations, there is also a risk of entering highly contaminated areas or having an accident.

In the event of a nuclear explosion, scenarios similar to the reactor and natural disaster at Fukushima are to be expected, albeit at a much larger extent : At the Fukushima accident, the transport times for the evacuation of hospital patients requiring, among others, intensive care were up to several days because of the damage caused by the tsunami (Boilley 2013). It is therefore necessary to plan upcoming evacuations after nuclear weapon explosions with particular care to check their feasibility and, if necessary, to refrain from them even if the reference levels of radiation exposure are exceeded. In any case, the procedures required for an evacuation should be practised regularly.

If the behavioural recommendations of the SSK are followed, there is a high probability that many individuals can avoid acute, life-threatening radiation exposure. This not only prevents avoidable deaths but also considerably reduces the expected overloading of all supply structures and is, therefore, a key factor in responding appropriately to the use of nuclear weapons. In particular this key message requires early, repeated, and sustained education of the population before such an event. Further information on informing the public can be found in the Chapter 0, which deals with risk and crisis communication.

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[28] https://www.bbk.bund.de/DE/Themen/CBRN-Schutz/CBRN-Faehigkeiten/Schutzausstattung/schutzausstattung_node.html, last accessed on 16 September 2024

10 Status of national and international preparations for the health care of victims and emergency personnel

Previous plans for health care following large-scale disasters involving radiation exposure have focussed on accidents, particularly nuclear power plant accidents, where relatively few people are expected to be affected by external exposures that can lead to deterministic damage (SSK 2017). Monitoring potentially contaminated persons and reducing internal radiation exposure through iodine blockage and a marketing ban on contaminated food play a relatively large role. These plans and preparations are only partially applicable to the local and regional situation following a nuclear weapon explosion in which many exposed persons with deterministic radiation damage or combination trauma are to be expected. This applies in particular to areas affected by the initial effect or by fallout within the first 24 to 48 h. In contrast, in areas farther from the nuclear explosion, the applicability is high in many aspects – with the exception of iodine blockage.

10.1 General measures

In 2011, as part of an EU-funded project, an international working group called "SHAMISEN – Nuclear Emergency Situations – Improvement of Medical And Health Surveillance" published recommendations for preparatory measures and health monitoring of the population in the event of a reactor accident (Liutsko 2021). These recommendations can be partially transferred to the scenario of a nuclear explosion.

The individual recommendations are based on two requirements: 1) to create a culture of radiation protection among radiation protection experts, healthcare workers, occupationally exposed persons, and the general public. Above all, this requires improving radiation protection training for healthcare workers. 2) to ensure that radiation protection measures always do more good than harm to those affected. The second recommendation, in particular, sounds obvious but was not sufficiently taken into account when the decision was made to evacuate the Fukushima prefecture on a large scale.

With regard to the planning of follow-up measures for the health care of the public after a serious radiation accident, the SHAMISEN working group recommends distinguishing between "surveillance" in the form of regular individual "check-ups" of the health and well-being of those affected and epidemiological studies on those affected for the purpose of gaining scientific knowledge.

10.2 Medical care

In its recommendation "Required medical capacities for the care and support of the population in radiological and nuclear emergencies" (SSK 2017), the SSK estimated the number of people affected in an emergency following accidents, including nuclear power plant accidents, and following a terrorist or otherwise motivated act involving radioactive substances. This recommendation did not include the scenario "explosion of a nuclear weapon". For the scenario "accident at a German nuclear power plant", it was assumed that there would be no cases of ARS among the general population but possibly a relatively small number among personnel working on the plant premises. Measurement capacities for screening and dose assessment for up to 200,000 individuals and evacuation strategies for up to 200,000 individuals would be required.

In contrast, in its 2023 statement "National Stockpiles for Radiological and Nuclear Emergencies: Policy Advice" (WHO 2023), the WHO published detailed estimates of those affected by the explosion of a 1 kT and 10 kT bomb. This includes casualty figures (Tab. 10-1), the estimate of which is based on a publication by Waselenko et al. 2004. As shown in the table caption for Tab. 10-1, the estimates assume a nuclear explosion in the centre of a city with two million inhabitants.

Those affected by the fallout are likely to include people directly exposed to radiation (cf Tab. 10-1). In the “Hazard Prediction Assessment Capability Program” calculations, relatively simple assumptions are made about the terrain (flat surface) and thus the lack of shielding possibilities because of terrain and infrastructure. In addition, dose-reducing individual protective measures (“protect and cover up”, “seek protective rooms”) are not considered.

It is noteworthy, that in this estimate, the survivors can be divided into three groups of comparable size: 1) those who require clinical medical care (doses above 1 Gy and combined injuries), 2) those who require outpatient monitoring and possibly medical care in the longer term (dose range 0.25 Gy – 1 Gy), and 3) those who have no physical damage requiring treatment but require psychosocial support (doses below 0.25 Gy).

Tab. 10-1 Estimated casualty figures for a city with two million inhabitants in the event of the explosion of a 1 kT and 10 kT nuclear weapon (according to WHO 2023)

Patient category	**Radiation dose (Gy)**	**Number of patients**	
		1 kT detonation	**10 kT detonation**
Combination injuries[a] (minimal to intensive medical care)	all	1,000–3,000	15,000–24,000
Direct fatalities	All	> 7,000	> 13,000
Fallout (health effects)			
only supportive palliative care possible	≥ 10	18,000	45,000
Intensive medical care	5–10	19,500	79,400
Specialised clinical care	3–5	33,000	108,000
Standard clinical care	1–3	66,000	70,000
Outpatient care	0.5–1	82,500	139,000
Epidemiological monitoring	0.25–0.5	106,000	147,000
Medical and psychological after-care for those affected	< 0.25	> 150,000	> 270,000

[a] *Combination injuries from radiation injuries with burns and/or blunt trauma*

For the medical care of radiation emergencies (based on various scenarios without the use of nuclear weapons), the SSK 2023 recommended in its recommendation “Medical management of radiation emergencies – Requirements and organisational matters” that a network with a central coordination office be set up to provide adequate medical care for patients in radiation emergencies and that minimum requirements be placed on the hospitals involved (SSK 2023a). With regard to the creation of such a networkthat is equipped to care for hundreds of thousands of people after the use of a nuclear weapon, the network proposed by the SSK 2023 can represent a first step and requires a considerable expansion of the contact points.

Concerning equipping hospitals with infrastructure, equipment/materials, and staff, the SSK recommended, among other things

- to create a nationwide two-tier network of clinics with sufficient equipment to care for radiation emergency patients (radiation emergency centres): 20 to 30 clinics ready to accept radiation emergency patients (radiation emergency centres level 1) and five to seven special facilities in large clinics (radiation emergency centres level 2)
- to create and maintain provisions for special emergency care that are not available in the current standard equipment of the hospitals (e.g. suitable room organisation and routing, decontamination facilities, special measuring equipment, sufficiently stocked depots for medication, devices and medical material, personal protective equipment)
- to set up teams consisting of qualified doctors, medical technologists, nurses, paramedics, medical physicists, technicians, radiation protection experts, and crisis intervention staff in the participating hospitals for the care of radiation emergency patients
- to form mobile teams to support the care of radiation emergency patients; radiation protection experts from institutions outside of radiation emergency centres can also be involved in these.

Concerning the establishment of a central coordination centre, among other things, the SSK recommended :

- to enable the coordination centre to provide the necessary information on available treatment capacities, the available equipment and personnel in the clinics, and the current availability of mobile experts to support emergency care on-site
- to have the coordination centre carry out the Germany-wide distribution of radiation emergency patients based on available treatment capacities (recorded daily) and the current equipment and personnel resources in the participating clinics

In the event of nuclear weapon explosions in or near Germany, the assumptions on the required capacities on which the above recommendations are based could be greatly exceeded. For this reason, also clinics that have not yet prepared for the role of a radiation emergency centre must be involved and prepared accordingly.

1.1 Stockpiling and storage

In its Radiation Emergency Handbook, the SSK commented in detail on the stockpiling of specific medications required to treat radiation emergency patients (SSK 2022a). These recommendations also fall far short of the requirements if nuclear weapons are used.

Also, in 2023, the WHO issued the statement “National Stockpiles for Radiological and Nuclear Emergencies: Policy Advice (WHO 2023)”. With regard to preparation for nuclear weapons uses, it recommends stockpiling cytokines such as G-CSF or GM-CSF for the treatment of acute radiation syndrome, primarily for those who have been exposed to radiation doses of more than 3 Sv (Tab. 10-1). However, the estimated number of such patients, more than 200,000, appears to be too high (see Section 10.2) for such medication.

Cytokines for the treatment of ARS are most effective when used early (i.e. within two days of radiation exposure). This is not a prophylactic outpatient therapy but rather a form of treatment that must be embedded in an inpatient clinical concept.

G-CSF is a medication for the treatment of chemotherapy-induced white blood cell deficiency. So far, it has been approved only in the US for treating acute radiation syndrome. The SSK sees a need for action here (e.g. to examine the adoption of the US authorisation of G-CSF and other authorised medications into European pharmaceutical law or the authorisation of extensive off-label use of this medication in the event of a disaster).

Furthermore, the SSK recommends against storing large quantities of these medications are not available at radiation accident centres. Therefore, depots should be established or procedures should be developed to enable their procurement through a central control centre (such as the coordination centre listed above).

10.3 Biological dosimetry, incorporation measurements

Biological dosimetry offers the possibility of retrospectively assessing the need for treatment after radiation exposure. It thus supports medical decision-making in the choice of available treatment options (SSK 2022a). However, procedures such as chromosome analysis, micronucleus testing, and others are complex and can be carried out only in a few specialised facilities. They also require special logistics for sample taking and preservation, and the results are available only after a few days. Therefore, in the case of nuclear explosions, these procedures are suitable only to a limited extent for the initial diagnosis in many affected persons, but they are nevertheless important, e.g., in the care of patients with suspected ARS.

The situation is similar regarding the incorporation detection in whole-body counters or via excretion measurements (SSK 2022a). These methods are offered by only a few measuring stations, require complex measuring techniques, and are time-consuming. Both incorporation measurement and decorporation therapy play a subordinate role after the use of nuclear weapons.

To fulfil the need to take measurements as early as possible, the SSK recommended carrying out initial, indicative measurements at the emergency site using mobile measuring devices (SSK 2022a). It is desirable to have such devices available at the incorporation measuring points and to be ready to measure around the clock. Even with measuring devices typically used by disaster response organisations, measurements of the dose rate in the environment that is caused by radionuclides in the body of an individual can give an indication of the magnitude of the body activity. For the clinical management of patients, the SSK also recommended that radiation emergency physicians be trained in clinical triage procedures. Relevant here are the appropriate documentation of clinically relevant symptoms and their assessment, as well as the early measurement of basic clinical parameters that at least allow for a preliminary evaluation of the expected clinical course (e.g. differential blood count, inflammatory markers, and specialised biomarkers for biological dosimetry if available).

In addition, via the RLZ-Bund or a tool for individual dose reconstruction provided for emergency centres, it is possible, in principle, to calculate the doses received by individuals in emergency centres based on georeferenced measurement data. In the present scenario, the use of such a tool is particularly indicated because of the rapid availability of measurement data compared with other scenarios (e.g. through the stationary ODL measuring network). It remains to be evaluated whether the tool can be used at its current stage of development in the event of a nuclear weapon explosion and what limitations it may be subject to in this respect.

10.4 Emergency stations

In Germany, emergency centres are an essential part of disaster prevention planning for accidents in nuclear facilities and other emergencies with a large number of affected individuals (SSK 2022a). They follow a standardised nationwide concept, which is intended to simplify any necessary cross-state deployment (IMK 2014a).

Depending on the situation, emergency centres are set up in pre-planned buildings outside an area affected by the release of radioactive substances and, if necessary, in reception areas. Their respective locations should be conveniently situated with separate access and exit pathways and sufficient parking facilities. Based on scenario-specific estimates of potentially affected persons, continuous operation must be provided for the care of up to 1,000 people within 24 h in the event of a serious nuclear power plant accident (SSK 2017).

In the event of a nuclear weapon explosion, the location of an emergency centre cannot be planned in advance; this generally depends on the particular situation. During the use of nuclear energy in Germany, the reactors were distributed fairly homogeneously across the country – at least in West Germany. Accordingly, plannings exist for emergency centres assigned to the nuclear power plants. This concept of Germany-wide emergency stations should be reactivated and optimised not only with regard to the use of nuclear weapons but generally for radiation accidents with many people affected. Some federal states, such as Bavaria and Baden-Württemberg, have already carried out exercises to ensure the continued readiness of emergency centres. However, in the eastern federal states, additional emergency centres need to be included in the disaster control preparedness planning.

10.5 Psychosocial emergency care

Psychosocial emergency care (PSNV) measures are intended to help the affected persons and the emergency services to cope with a stressful event as well as possible and to prevent or at least mitigate as far as possible permanent consequences such as post-traumatic stress disorder (PTSD) (SSK 2022a). Even somatically healthy but unsettled individuals need informative and appropriate crisis and risk communication.

The preparation and organisation of PSNV is a major challenge. In an acute situation, by appropriate guidance for those seeking help it must be prevented that a rush of worried individuals impedes the care of exposed persons who require specific radiological treatment or also blocks other healthcare provisions. In the months and years following the use of nuclear weapons, large groups of those affected (see also chapter 0) will require psychosocial after-care.

10.6 Documentation and organisation of after-care programmes

In the event of nuclear explosions, large population groups are exposed to different levels of radiation. If we extrapolate the estimates of the SSK for those exposed to terrorist use of a dirty bomb (SSK 2017) to the explosion of a nuclear weapon, up to several hundred thousand individuals who require medical treatment because of varying degrees of radiation overexposure and/or blast or burn trauma can be expected. In addition, there are several hundreds of thousands of affected people who require psychosocial care (cf Section 4.1).

The associated tasks can be accomplished only if they are planned and prepared in advance in peacetime. Preparation could include:

- The development and availability of a procedure for the early individual documentation of the clinically and radiologically relevant parameters of radiation exposure and concomitant damage, in the sense of an extended core data set for disaster medicine (cf S2 Guideline Disaster Medicine 2023)[29].
- The establishment of a digital register that can be automatically filled with data from the extended electronic patient file. This register should
  a) allow *ad hoc* analyses from which recommendations for the treatment of individual patients in an emergency situation can be derived in the sense of a "learning system"
  b) later serve to systematically and scientifically analyse the previously limited knowledge on the health consequences of the explosion and radiation exposure in the medium and higher dose range.

[29] This documentation should be available digitally, independent of the power grid, and capable of being carried by the individual concerned (e.g. as a chip card or app)

To this end, institutions should be selected in advance (cf. Liutsko et all. 2021), that

- create the necessary conditions for digital data collection, test the developed systems and practise using them
- organise regular “check-ups” of both the somatic and mental health of registered exposed persons (analogous to the Life Span Study after the atomic bombs on Hiroshima and Nagasaki)
- carry out scientific analyses of the collected data. In this context, the consideration of suitable control groups of non-exposed persons is urgently recommended.

11 Status of preparations for risk and crisis communication

According to Section 106 StrlSchG (StrlSchG 2017), the BMUV is responsible for setting up a radiological situation centre, which is responsible for providing the population with the information specified in Section 112, para. 3 StrlSchG in the event of a regional or supra-regional emergency. Because of its far-reaching effects, a nuclear weapon explosion is always a supra-regional emergency, according to reference scenario S14 of the ANoPl-Bund (BMUV 2023). The scenario is based on a nuclear explosion triggered by criminal and terrorist acts or an accident. On principle, the reference scenarios and regulations of the ANoPl-Bund do not include emergencies arising from situations of tension and defence. The regulations of the ANoPl-Bund may nevertheless apply if no special regulations for radiological emergencies are included in the civil defence concept. Concerning the recommendations for informing the public it is assumed that these are based on the Radiation Protection Act and the ANoPl-Bund – particularly because the impacts of a terrorist nuclear attack are expected to be similar to those of a sudden nuclear strike during a state of tension or defence. Nevertheless, civil defence should make further preparations and, in particular, work out the differences between the assumed scenarios and take these into consideration.

Whilst Section 106, para. 2 No. 7, in conjunction with Section 112, para. 3 StrlSchG (StrlSchG 2017) defines only communication in an emergency, and in terms of crisis communication, Section 105 StrlSchG regulates communication in preparation for an emergency in terms of risk communication.

Risk communication is the exchange of information about, among other things, possible risks,, associated dangers, and risk minimisation (i.e. protection against such dangers). It can be carried out both independently of an incident in preparation for possible emergencies as well as during and after an emergency as part of crisis communication. The aim of risk communication is to enable those (potentially) affected by an emergency to weigh their options for dealing with risks and make informed decisions. The aim of crisis communication is to exchange event-related information to prevent or limit damage during an emergency. It contains information on the current situation, official measures and directives, protective measures, and messages relating to risk communication.

11.1 Event-independent risk communication

To enable the population to make a fact-based risk assessment regarding a nuclear weapon explosion and prepare for it in an appropriate manner, a proactive, continual risk communication is necessary, similar to the case with flood hazards or the need to stockpile for the event of a blackout. This should be standardised by the responsible federal and state authorities. To ensure this standardisation of communication, the content and means of communication should be developed jointly under the leadership of a federal authority (e.g. the BBK).

Risk communication should cover at least the following questions and topics:

- What are nuclear weapons, and how do they work? (This information should include the difference between a nuclear weapon and a radiological dispersal device (dirty bomb))
- What scenarios of a nuclear explosion are conceivable?
- What radiological and non-radiological effects can be expected from a nuclear weapon explosion?
- What determines the extent of these effects?
- What protective measures can be taken?
- Which of these protective measures can be prepared and how?
- What are the chances of survival and health risks, and what do they depend on?
- How are warnings issued in the event of a nuclear explosion, and how is information provided in the event of an explosion?
- Where can I find further sources of information and background material?

Overall, when compiling the information, care should be taken to provide a fact-based assessment of the chances of survival in the event of a single nuclear weapon explosion. This is highly important because risk perception, especially of radiological effects, is influenced by various factors in the population and can differ from the risk assessment of experts (IAEA 2020).

The broadest possible media mix should be used to disseminate this information. This includes printed materials such as brochures, guides, posters, and emergency cards for the home and office, as well as extensive electronic information on a website dedicated to the topic. This information should be hosted either under an authority domain (e.g. bbk.bund.de) or a separate domain (similar to jodblockade.de) and contain answers to frequently asked questions (FAQ) and links to background information (e.g. basic information on radioactivity).

Depending on the medium, care should also be taken to convey the information as clearly as possible and in understandable language using infographics, maps, explanatory videos, icon boxes, and the like. This includes translation into English and other relevant languages as well as the production of accessible information.

The information generated in this way is to be disseminated as part of an extensive campaign. Examples include:

- social media posts (e.g. via Instagram or YouTube) with facts and figures on the topic (Did you know that…?) or explanatory videos and podcasts
- poster campaigns
- press conferences
- direct mailings
- action days (e.g. on the occasion of the warning day)

Because schools and similar institutions should be made particularly aware of the need for protective measures and corresponding preparations, teaching materials with information for students and teaching staff should also be developed.

Similarly, emergency personnel should be specifically informed about the risks, effects, and protective measures in the event of a nuclear explosion. Even emergency personnel often have only limited knowledge of radiological hazards or nuclear weapons and their effects.

11.2 Crisis communication

Detailed recommendations on crisis communication in general can be found in the BMI Guidelines on Crisis Communication (BMI 2014) in the event of nuclear emergencies in the Guidelines on Public Information (SSK 2007), as an example.

In the event of a nuclear explosion, crisis communication must address questions regarding radiological hazards and other concerns. Whilst the destructive effects of light flashes, heat radiation, and pressure waves are immediately perceptible, considerable uncertainty is to be expected among the population and emergency services regarding radiological effects. To alleviate these uncertainties, crisis communication should answer at least the following questions as quickly as possible:

- Which area is (potentially) affected by radiological impacts and which is not?
- How should you behave to minimise the risk?
- What protective measures should be taken?
- When will the danger be over?
- Where can I get help?

In the event of a nuclear weapon explosion, it can be assumed that the communications infrastructure would be severely damaged. For reasons of redundancy, preparations should be made for disseminating information via as many independent means of communication as possible (e.g. radio, mobile phones, loudspeaker vans, leaflets). When choosing the means of communication, it must be taken into consideration that the population in the affected areas may have to seek shelter indoors for some time to protect themselves from the initial radiological effects. For example, dropping leaflets could lead to those affected leaving the protection of the buildings too early to obtain information.

12 Literature

AFKzV 2022 — Ausschuss für Katastrophenschutz, Feuerwehrwesen und zivile Verteidigung (AFKzV). Feuerwehr-Dienstvorschrift FwDV 500. Einheiten im ABC-Einsatz. https://www.sfs-w.de/projektgruppe-feuerwehr-dienstvorschriften/vom-afkzv-verabschiedet-und-zur-einfuehrung-in-den-laendern-empfohlen.html?no_cache=1&download=FwDV500_AFKzV_2022-03-16_final.pdf&did=86, last accessed on 08.12.2020

Anspaugh et al. 2022 — Anspaugh LR, Bouville A, Thiessen KM, Hoffman FO, Beck HL, Gordeev KI, Simon SL. A Methodology for Calculation of Internal Dose Following Exposure to Radioactive Fallout from the Detonation of a Nuclear Fission Device. Health Phys. 2022 Jan 1;122(1):84-124, doi: 10.1097/HP.0000000000001503

Apsalikov et al. 2019 — Apsalikov KN, Lipikhina A, Grosche B, Belikhina T, Ostroumova E, Shinkarev S, Stepanenko V, Muldagaliev T, Yoshinaga S, Zhunussova T, Hoshi M, Katayama H, Lackland DT, Simon SL, Kesminiene A. The State Scientific Automated Medical Registry, Kazakhstan: an important resource for low-dose radiation health research. Radiat Environ Biophys. 2019 Mar;58(1):1-11, doi: 10.1007/s00411-018-0762-5, Epub 2018/11/18

AWMF 2023 — Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e. V. (AWMF). S2k-Leitlinie Katastrophen-medizinische prähospitale Behandlungsleitlinien. Version 1.1, Stand: 30.04.2023, gültig bis 29.04.2028. https://register.awmf.org/de/leitlinien/detail/001-043, last accessed on 17.12.2024

Bauer et al. 2005 — Bauer S, Gusev BI, Pivina LM, Apsalikov KN, Grosche B. Radiation exposure due to local fallout from Soviet atmospheric nuclear weapons testing in Kazakhstan: solid cancer mortality in the Semipalatinsk historical cohort, 1960-1999. Radiat Res. 2005 Oct;164(4 Pt 1):409-19, doi: 10.1667/rr3423.1, Epub 2005/09/29

BBK 2013 — Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (BBK). Katastrophenmedizin. Leitfaden für die ärztliche Versorgung im Katastrophenfall. 6. Auflage. 2013

BBK 2014 — Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (BBK). Rahmenkonzept für den CBRN-Schutz (ABC-Schutz) im Bevölkerungsschutz. Stand 2014, Druck 2016. https://www.bbk.bund.de/SharedDocs/Downloads/DE/Mediathek/Publikationen/CBRN/rahmenkonzeption-cbrn-schutz.pdf?__blob=publicationFile&v=7, last accessed on 05.12.2024

Beaven and Parker 2015 — Beaven A, Parker P. Treatment principles of blast injuries. Surgery for major incidents. Volume 33, Issue 9, p. 424-429. 2015

Becker et al. 1990	Becker W, Buescher T, Cioffi W, WF M, Pruitt BA J. Combined Radiation and Thermal Injury After Nuclear Attack. In: Treatment of Radiation Injuries. Plenum Press, New York, 1990
Benderitter et al. 2010	Benderitter M, Gourmelon P, Bey E, Chapel A, Clairand I, Prat M, Lataillade JJ. New emerging concepts in the medical management of local radiation injury. Health Phys. 2010 Jun;98(6):851-7, doi: 10.1097/HP.0b013e3181c9f79a, Epub 2010/05/07
BMI 1962	BMI. Jeder hat eine Chance. Hrsg.: Bundesamt für zivilen Bevölkerungsschutz in Bad Godesberg im Auftrag des Bundesministers des Innern (BMI), Bad Godesberg, 1962
BMI 2014	Bundesministerium des Innern (BMI). Leitfaden für Krisenkommunikation. http://www.bmi.bund.de/SharedDocs/Downloads/BVS/DE/Krisenkommunikation/Krisenkommunikation.pdf;jsessionid=7F8611B2AC02E039BA48BE1F89337A51.2_cid295?__blob=publicationFile
BMI 2016	Bundesministerium des Innern (BMI). Konzeption Zivile Verteidigung (KZV) vom 24.08.2016. https://www.bmi.bund.de/SharedDocs/downloads/DE/veroeffentlichungen/themen/bevoelkerungsschutz/konzeption-zivile-verteidigung.pdf?__blob=publicationFile&v=2, last accessed on 05.12.2024
BMI 2024	Bundesministerium des Innern und für Heimat (BMI). Rahmenrichtlinien für die Gesamtverteidigung - Gesamtverteidigungsrichtlinien - (RRGV). https://www.bmi.bund.de/SharedDocs/downloads/DE/veroeffentlichungen/themen/sicherheit/RRGV.html, last accessed on 16.12.2024
BMK 2020	Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, Österreich (BMK). Bundesgesetz über Maßnahmen zum Schutz vor Gefahren durch ionisierende Strahlung (Strahlenschutzgesetz 2020 – StrSchG 2020). Bekanntmachung im Bundesgesetzblatt Nr. BGBl. I Nr. 50/2020 Teil I, Datum der Kundmachung 17.06.2020
BMK 2022	Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (BMK). Gesamtstaatlicher Notfallplan. Nuklearwaffeneinsatz in größerer Entfernung zu Österreich. Wien, 2022
BMU 2001	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Bekanntmachung der Dosiskoeffizienten zur Berechnung der Strahlenexposition. RS II 1-11413/28 vom 23. Juli 2001, Banz Nr. 160a und b vom 28.08.2001

BMUV 2023 Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz. Allgemeine Verwaltungsvorschrift für einen Allgemeinen Notfallplan des Bundes nach § 98 des Strahlenschutzgesetzes (ANoPl-Bund) vom 10. November 2023. Bekanntmachung im BAnz AT 23.11.2023 B1

Boice et al. 2022 Boice JD, Cohen SS, Mumma MT, Chen H, Golden AP, Beck HL, Till JE. Mortality among U.S. military participants at eight aboveground nuclear weapons test series. Int J Radiat Biol. 2022;98(4):679-700, doi: 10.1080/09553002.2020.1787543, Epub 20200803

Boilley 2013 Boilley D. Notfallplan und Evakuierung. https://www.acro.eu.org/wp-content/uploads/2013/12/Fukushima_GPI_Deutsch.pdf, , last accessed on 05.12.2024

Bouville et al. 2020 Bouville A, Beck HL, Thiessen KM, Hoffman FO, Potischman N, Simon SL. The Methodology Used to Assess Doses from the First Nuclear Weapons Test (Trinity) to the Populations of New Mexico. Health Phys. 2020 Oct;119(4):400-27, doi: 10.1097/HP.0000000000001331, Epub 2020/09/04

Brooks et al. 1952 Brooks JW, Evans EI, Ham WT, Jr., Reid JD. The influence of external body radiation on mortality from thermal burns. Ann Surg. 1952 Sep;136(3):533-45, doi: 10.1097/00000658-195209000-00018, Epub 1952/09/01

Brown et al. 2018 Brown DA, Chadwick MB, Capote R, Kahler AC, Trkov A, Herman MW, Sonzogni AA, Danon Y, Carlson AD, Dunn M, Smith DL, Hale GM, Arbanas G, Arcilla R, Bates CR, Beck B, Becker B, Brown F, Casperson RJ, Conlin J, Cullen DE, Descalle MA, Firestone R, Gaines T, Guber KH, Hawari AI, Holmes J, Johnson TD, Kawano T, Kiedrowski BC, Koning AJ, Kopecky S, Leal L, Lestone JP, Lubitz C, Márquez Damián JI, Mattoon CM, McCutchan EA, Mughabghab S, Navratil P, Neudecker D, Nobre GPA, Noguere G, Paris M, Pigni MT, Plompen AJ, Pritychenko B, Pronyaev VG, Roubtsov D, Rochman D, Romano P, Schillebeeckx P, Simakov S, Sin M, Sirakov I, Sleaford B, Sobes V, Soukhovitskii ES, Stetcu I, Talou P, Thompson I, van der Marck S, Welser-Sherrill L, Wiarda D, White M, Wormald JL, Wright RQ, Zerkle M, Žerovnik G, Zhu Y. ENDF/B-VIII.0: The 8 th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data. Nuclear Data Sheets. 2018;148:1-142, doi: 10.1016/j.nds.2018.02.001

Buddemeier and Dillon 2009 Buddemeier BR, Dillon MB. Key Response Planning Factors for the Aftermath of Nuclear Terrorism. United States: N. p. 2009, doi: 10.2172/966550

Buddemeier 2018	Buddemeier BR. Nuclear Detonation Fallout: Key Considerations for Internal Exposure and Population Monitoring. United States: N. p. 2018, doi: 10.2172/1460062
Cahoon et al. 2020	Cahoon EK, Zhang R, Simon SL, Bouville A, Pfeiffer RM. Projected Cancer Risks to Residents of New Mexico from Exposure to Trinity Radioactive Fallout. Health Phys. 2020 Oct;119(4):478-93, doi: 10.1097/HP.0000000000001333, Epub 2020/09/04
Caldwell et al. 2016	Caldwell GG, Zack MM, Mumma MT, Falk H, Heath CW, Till JE, Chen H, Boice JD. Mortality among military participants at the 1957 PLUMBBOB nuclear weapons test series and from leukemia among participants at the SMOKY test. J Radiol Prot. 2016 Sep;36(3):474-89, doi: 10.1088/0952-4746/36/3/474, Epub 2016/06/30
Carr 2021	Carr AB. Thirty Minutes Before the Dawn. Nuclear Technology. 2021;207(sup1):S1-S23, doi: 10.1080/00295450.2021.1927625
Cederwall and Peterson 1990	Cederwall RT, Peterson KR. Meteorological modeling of arrival and deposition of fallout at intermediate distances downwind of the Nevada Test Site. Health Phys. 1990 Nov;59(5):593-601, doi: 10.1097/00004032-199011000-00010, Epub 1990/11/01
Cronkite 1982	Cronkite E. The effects of dose, dose rate, and depth dose upon radiation mortality. In: The control of exposure of the public to ionizing radiation in the event of accident or attack, NCRP Proceedings. 1982
Cronkite et al. 1954	Cronkite EP, Bond VP, Browning LE, Chapman WH, Cohn SH. Study of response of human beings accidentally exposed to significant fallout radiation. Final report. https://apps.dtic.mil/sti/citations/AD0465295, last accessed on 05.12.2024
Cullings et al. 2017	Cullings HM, Grant EJ, Egbert SD, Watanabe T, Oda T, Nakamura F, Yamashita T, Fuchi H, Funamoto S, Marumo K, Sakata R, Kodama Y, Ozasa K, Kodama K. DS02R1: Improvements to Atomic Bomb Survivors' Input Data and Implementation of Dosimetry System 2002 (DS02) and Resulting Changes in Estimated Doses. Health Phys. 2017 Jan;112(1):56-97, doi: 10.1097/HP.0000000000000598
Dainiak et al. 2003	Dainiak N, Waselenko JK, Armitage JO, MacVittie TJ, Farese AM. The hematologist and radiation casualties. Hematology Am Soc Hematol Educ Program. 2003:473-96, doi: 10.1182/asheducation-2003.1.473, Epub 2003/11/25
Dainiak and Albanese 2022	Dainiak N, Albanese J. Medical management of acute radiation syndrome. J Radiol Prot. 2022 Jul 19;42(3), doi: 10.1088/1361-6498/ac7d18, Epub 2022/06/30

de Vathaire et al. 2023	de Vathaire F, Zidane M, Xhaard C, Souchard V, Chevillard S, Ory C, Rachedi F, Nunez S, Leufroy A, Noel L, Guerin T, Shan L, Bost-Bezeaud F, Petitdier P, Soubiran G, Allodji R, Ren Y, Doyon F, Taquet M, Gardon J, Bouville A, Drozdovitch V. Assessment of Differentiated Thyroid Carcinomas in French Polynesia After Atmospheric Nuclear Tests Performed by France. JAMA Netw Open. 2023 May 1;6(5):e2311908, doi: 10.1001/jamanetworkopen.2023.11908, Epub 20230501
DiCarlo et al. 2010	DiCarlo AL, Ramakrishnan N, Hatchett RJ. Radiation combined injury: overview of NIAID research. Health Phys. 2010 Jun;98(6):863-7, doi: 10.1097/HP.0b013e3181a6ee32, Epub 2010/05/07
DiCarlo et al. 2011	DiCarlo AL, Maher C, Hick JL, Hanfling D, Dainiak N, Chao N, Bader JL, Coleman CN, Weinstock DM. Radiation injury after a nuclear detonation: medical consequences and the need for scarce resources allocation. Disaster Med Public Health Prep. 2011 Mar;5 Suppl 1(0 1):S32-44, doi: 10.1001/dmp.2011.17, Epub 2011/03/22
DiCarlo et al. 2021	DiCarlo AL, Homer MJ, Coleman CN. United States medical preparedness for nuclear and radiological emergencies. J Radiol Prot. 2021 Dec 6;41(4), doi: 10.1088/1361-6498/ac0d3f, Epub 2021/06/22
Dolan 1972	Dolan PJ. DNA EM-1 Capabilities of Nuclear Weapons. Defense Nuclear Agency Effects Manual Number 1, DNA EM-1, Defense Nuclear Agency, 1. Juli 1972. https://archive.org/details/DnaEm1CapabilitiesOfNuclearWeapons/DNA%20EM%201%20Capabilities%20of%20Nuclear%20Weapons%20_%20Philip%20J.%20Dolan/page/n1/mode/2up, last accessed on 11.12.2024
EU 2016	Verordnung (Euratom) 2016/52 des Rates vom 15. Januar 2016 zur Festlegung von Höchstwerten an Radioaktivität in Lebens- und Futtermitteln im Falle eines nuklearen Unfalls oder eines anderen radiologischen Notfalls und zur Aufhebung der Verordnung (Euratom) Nr. 3954/87 des Rates und der Verordnungen (Euratom) Nr. 944/89 und (Euratom) Nr. 770/90 der Kommission
FEMA 2023	Federal Emergency Management Agency (FEMA). Planning Guidance for Response to a Nuclear Detonation. Third edition. https://www.fema.gov/sites/default/files/documents/fema_nuc-detonation-planning-guide.pdf, last accessed on 28.09.2023
Ferrari et al. 2023	Ferrari C, Manenti G, Malizia A. Sievert or Gray: Dose Quantities and Protection Levels in Emergency Exposure. Sensors (Basel). 2023 Feb 8;23(4), doi: 10.3390/s23041918, Epub 2023/03/01

Fliedner et al. 2001	Fliedner TM, Friesecke I, Beyrer K. Medical Management of Radiation Accidents. Manual on the Acute Radiation Syndrome. The British Institute of Radiology, Alden Group, Oxford, U.K., 2001
Freiling 1961	Freiling EC. Particle formation and fractionation in air bursts. In: Radioactive fallout from nuclear weapon tests. Proceedings of a Conference Held in Germantown, Maryland, November 15-17, 1961. Ed. Klement, A.W. Jr. . https://www.osti.gov/servlets/purl/4837321/
Fujita et al. 1989	Fujita S, Kato H, Schull WJ. The LD50 associated with exposure to the atomic bombing of Hiroshima. J Radiat Res. 1989 Dec;30(4):359-81, doi: 10.1269/jrr.30.359, Epub 1989/12/01
Gilbert et al. 1998	Gilbert ES, Tarone R, Bouville A, Ron E. Thyroid cancer rates and 131I doses from Nevada atmospheric nuclear bomb tests. J Natl Cancer Inst. 1998 Nov 4;90(21):1654-60, doi: 10.1093/jnci/90.21.1654, Epub 1998/11/12
Gilbert et al. 2010	Gilbert ES, Huang L, Bouville A, Berg CD, Ron E. Thyroid cancer rates and 131I doses from Nevada atmospheric nuclear bomb tests: an update. Radiat Res. 2010 May;173(5):659-64, doi: 10.1667/rr2057.1, Epub 2010/04/30
Gillies and Haylock 2022	Gillies M, Haylock RGE. Mortality and cancer incidence 1952-2017 in United Kingdom participants in the United Kingdom's atmospheric nuclear weapon tests and experimental programmes. J Radiol Prot. 2022 Feb 23;42(2), doi: 10.1088/1361-6498/ac52b4, Epub 20220223
Glasstone and Dolan 1977	Glasstone S, Dolan PJ. The Effects of Nuclear Weapons. Third edition. Department of Defense, Washington, D.C. (USA); Department of Energy, Washington, D.C. (USA). 1977, doi: 10.2172/6852629
Grant et al. 2015	Grant EJ, Furukawa K, Sakata R, Sugiyama H, Sadakane A, Takahashi I, Utada M, Shimizu Y, Ozasa K. Risk of death among children of atomic bomb survivors after 62 years of follow-up: a cohort study. Lancet Oncol. 2015 Oct;16(13):1316-23, doi: 10.1016/s1470-2045(15)00209-0, Epub 2015/09/19
Grant et al. 2017	Grant EJ, Brenner A, Sugiyama H, Sakata R, Sadakane A, Utada M, Cahoon EK, Milder CM, Soda M, Cullings HM, Preston DL, Mabuchi K, Ozasa K. Solid Cancer Incidence among the Life Span Study of Atomic Bomb Survivors: 1958-2009. Radiat Res. 2017 May;187(5):513-37, doi: 10.1667/rr14492.1, Epub 2017/03/21

Grosche et al. 2011	Grosche B, Lackland DT, Land CE, Simon SL, Apsalikov KN, Pivina LM, Bauer S, Gusev BI. Mortality from cardiovascular diseases in the Semipalatinsk historical cohort, 1960-1999, and its relationship to radiation exposure. Radiat Res. 2011 Nov;176(5):660-9, doi: 10.1667/rr2211.1, Epub 2011/07/27
Grosche et al. 2015	Grosche B, Zhunussova T, Apsalikov K, Kesminiene A. Studies of Health Effects from Nuclear Testing near the Semipalatinsk Nuclear Test Site, Kazakhstan. Cent Asian J Glob Health. 2015;4(1):127, doi: 10.5195/cajgh.2015.127, Epub 2015/05/08
Gsponer 2006	Gsponer A. Fourth Generation Nuclear Weapons: Military effectiveness and collateral effects. http://arxiv.org/abs/physics/0510071, last accessed on 11.12.2024
Hall 2000	Hall EJ. Radiobiology for the Radiologist. Lippincott Williams & Wilkins, 2000, ISBN 9780781726498
Hamada et al. 2020	Hamada N, Azizova TV, Little MP. An update on effects of ionizing radiation exposure on the eye. Br J Radiol. 2020 Nov 1;93(1115):20190829, doi: 10.1259/bjr.20190829, Epub 2019/11/02
Hansen 1945	Hansen C. The Swords of Armageddon: U.S. Nuclear Weapons Development Since 1945 Chukelea Publications, Sunnyvale, CA, 1945
Hoffmann 1987	Hoffmann M. Kernwaffen und Kernwaffenschutz. 4. überarbeitete Auflage. Militärverlag der DDR, Berlin, 1987, ISBN 9783327003138
Honda et al. 2002	Honda S, Shibata Y, Mine M, Imamura Y, Tagawa M, Nakane Y, Tomonaga M. Mental health conditions among atomic bomb survivors in Nagasaki. Psychiatry Clin Neurosci. 2002 Oct;56(5):575-83, doi: 10.1046/j.1440-1819.2002.01057.x
Howard et al. 1995	Howard JE, Heotis PM, Scott WA, Adams WH. Medical status of Marshallese accidentally exposed to 1954 Bravo fallout radiation: January 1988 through December 1991 Brookhaven National Lab, Upton, New York, 1995
Hsu et al. 2013	Hsu WL, Preston DL, Soda M, Sugiyama H, Funamoto S, Kodama K, Kimura A, Kamada N, Dohy H, Tomonaga M, Iwanaga M, Miyazaki Y, Cullings HM, Suyama A, Ozasa K, Shore RE, Mabuchi K. The incidence of leukemia, lymphoma and multiple myeloma among atomic bomb survivors: 1950-2001. Radiat Res. 2013 Mar;179(3):361-82, doi: 10.1667/rr2892.1, Epub 2013/02/13
IAEA 2015	International Atomic Energy Agency (IAEA). Preparedness and Response for a Nuclear or Radiological Emergency. General Safety Requirements, No. GSR Part 7. Wien, 2015, ISBN 978–92–0–105715–0

IAEA 2020	International Atomic Energy Agency (IAEA). Arrangements for Public Communication in Preparedness and Response for a Nuclear or Radiological Emergency. General Safety Guides, No. GSG-14. Wien, 2020, ISBN 978-92-0-109019-5
ICRP 2012	International Commission on Radiological Protection (ICRP). Compendium of Dose Coefficients Based on ICRP Publication 60. ICRP Publication 119. Ann ICRP 41(Suppl):1-130, Elsevier, Oxford, 2012, ISBN 9781455754304, doi: 10.1016/j.icrp.2012.06.038
ICRP 2020a	International Commission on Radiological Protection (ICRP). Radiological Protection of People and the Environment in the Event of a Large Nuclear Accident. Update of ICRP Publications 109 and 111. ICRP Publication 146. Ann. ICRP 49(4), Sage Publishing, London, 2020a, ISBN 9781529767582
ICRP 2020b	International Commission on Radiological Protection (ICRP). Dose Coefficients for External Exposures to Environmental Sources. ICRP Publication 144. Ann. ICRP 49(2), Sage Publishing, London, 2020b, ISBN 9781529741230
Iddins et al. 2022	Iddins CJ, DiCarlo AL, Ervin MD, Herrera-Reyes E, Goans RE. Cutaneous and local radiation injuries. Journal of Radiological Protection. 2022;42(1), doi: 10.1088/1361-6498/ac241a
Imanaka et al. 2008	Imanaka T, Endo S, Tanaka K, Shizuma K. Gamma-ray exposure from neutron-induced radionuclides in soil in Hiroshima and Nagasaki based on DS02 calculations. Radiat Environ Biophys. 2008 Jul;47(3):331-6, doi: 10.1007/s00411-008-0164-1, Epub 20080327
Imanaka et al. 2012	Imanaka T, Endo S, Kawano N, Tanaka K. Radiation exposure and disease questionnaires of early entrants after the Hiroshima bombing. Radiat Prot Dosimetry. 2012 Mar;149(1):91-6, doi: 10.1093/rpd/ncr370, Epub 20110912
IMK 2014	Arbeitskreis V (AK V) „Feuerwehrangelegenheiten, Rettungswesen, Katastrophenschutz und Zivile Verteidigung“ der Innenministerkonferenz (IMK) (IMK). Rahmenempfehlungen zu Einrichtung und Betrieb von Notfallstationen (RE-NFS), Stand: 20.08.2014. https://www.innenministerkonferenz.de/IMK/DE/termine/to-beschluesse/14-12-11_12/anlage4zu34.pdf?__blob=publicationFile&v=2, last accessed on 17.12.2024
Izrael 2002	Izrael YA. Radioactive Fallout after Nuclear Explosions and Accidents, Chapter 1. Elsevier Science, 2002, ISBN 9780080540238
Jodoin 1994	Jodoin VJ. Nuclear cloud rise and growth. Dissertation. U.S. Air Force Institute of Technology, 1994

Johnson et al. 1996	Johnson JC, Thaul S, Page WF, Crawford H, Institute of Medicine Committee on the CNT. Mortality of Veteran Participants in the Crossroads Nuclear Test. National Academies Press (US), Washington (DC), 1996
Kendall et al. 2004	Kendall GM, Muirhead CR, Darby SC, Doll R, Arnold L, O'Hagan JA. Epidemiological studies of UK test veterans: I. General description. J Radiol Prot. 2004 Sep;24(3):199-217, doi: 10.1088/0952-4746/24/3/001, Epub 2004/10/30
Kiang and Olabisi 2019	Kiang JG, Olabisi AO. Radiation: a poly-traumatic hit leading to multi-organ injury. Cell Biosci. 2019;9:25, doi: 10.1186/s13578-019-0286-y, Epub 2019/03/27
Kraus and Foster 2013	Kraus T, Foster K. Analysis of Fission and Activation Radionuclides Produced by the Detonation of a Uranium-Fueled Improvised Nuclear Device and Identification of the Top Dose-Producing Radionuclides. https://narac.llnl.gov/content/mods/publications/research-and-development/LLNL-JRNL-640177.pdf, last accessed on 27.07.2022
Kristensen and Korda 2022a	Kristensen HM, Korda M. Russian nuclear weapons, 2022. Bulletin of the Atomic Scientists. 2022a;78(2):98-121, doi: 10.1080/00963402.2022.2038907
Kristensen and Korda 2022b	Kristensen HM, Korda M. United States nuclear weapons, 2022. Bulletin of the Atomic Scientists. 2022b;78(3):162-84, doi: 10.1080/00963402.2022.2062943
Kumatori et al. 1965	Kumatori T, Ishihara T, Ueda T, Miyoshi K. Medical Survey of Japanese Exposed to Fall-out Radiation in 1954. A report after 10 Years. National Institute of Radiological Sciences https://www.osti.gov/opennet/servlets/purl/16063545-1OYKpv/16063545.pdf, last accessed on 11.12.2024
Land et al. 2008	Land CE, Zhumadilov Z, Gusev BI, Hartshorne MH, Wiest PW, Woodward PW, Crooks LA, Luckyanov NK, Fillmore CM, Carr Z, Abisheva G, Beck HL, Bouville A, Langer J, Weinstock R, Gordeev KI, Shinkarev S, Simon SL. Ultrasound-detected thyroid nodule prevalence and radiation dose from fallout. Radiat Res. 2008 Apr;169(4):373-83, doi: 10.1667/RR1063.1, Epub 2008/03/28
Land et al. 2010	Land CE, Bouville A, Apostoaei I, Simon SL. Projected lifetime cancer risks from exposure to regional radioactive fallout in the Marshall Islands. Health Phys. 2010 Aug;99(2):201-15, doi: 10.1097/HP.0b013e3181dc4e84, Epub 2010/07/14

Land et al. 2015 Land CE, Kwon D, Hoffman FO, Moroz B, Drozdovitch V, Bouville A, Beck H, Luckyanov N, Weinstock RM, Simon SL. Accounting for shared and unshared dosimetric uncertainties in the dose response for ultrasound-detected thyroid nodules after exposure to radioactive fallout. Radiat Res. 2015 Feb;183(2):159-73, doi: 10.1667/RR13794.1, Epub 2015/01/13

Lebaron-Jacobs and Herrera-Reyes 2022 Lebaron-Jacobs L, Herrera-Reyes E. The METREPOL criteria-are they still relevant? J Radiol Prot. 2022 Jan 19;42(1), doi: 10.1088/1361-6498/ac3bc2, Epub 2021/11/22

LfU 2006 Bayer. Landesamt für Umwelt (LfU). Bericht über die Veränderungen der Radioaktivität in Böden seit dem Reaktorunfall von Tschernobyl vor 20 Jahren. https://www.lfu.bayern.de/strahlung/tschernobyl_und_mehr/tschernobyl_bayern/doc/bodenschutzbericht_2006.pdf, last accessed on 11.12.2024

Liutsko et al. 2021 Liutsko L, Oughton D, Sarukhan A, Cardis E. The SHAMISEN Recommendations on preparedness and health surveillance of populations affected by a radiation accident. Environ Int. 2021 2021/01/01/;146:106278, doi: https://doi.org/10.1016/j.envint.2020.106278

Lyon et al. 2006 Lyon JL, Alder SC, Stone MB, Scholl A, Reading JC, Holubkov R, Sheng X, White GL, Jr., Hegmann KT, Anspaugh L, Hoffman FO, Simon SL, Thomas B, Carroll R, Meikle AW. Thyroid disease associated with exposure to the Nevada nuclear weapons test site radiation: a reevaluation based on corrected dosimetry and examination data. Epidemiology. 2006 Nov;17(6):604-14, doi: 10.1097/01.ede.0000240540.79983.7f, Epub 2006/10/10

MacVittie and Farese 2021 MacVittie TJ, Farese AM. Recent advances in medical countermeasure development against acute radiation exposure based on the US FDA animal rule. J Radiol Prot. 2021 Nov 10;41(4), doi: 10.1088/1361-6498/ac20e0, Epub 2021/08/26

Magee 1953 Magee JL. Mechanisms of fractionation U.S. AEC Report M-7140 Los Alamos Scientific Lab., New Mex., United States, 1953

McDonnel et al. 1961 McDonnel G, Crosby W, Tessmer C, Moncrief Jr. W, Baker H. Effects of nuclear detonations on a large biological specimen (swine). Walter Reed Army Inst of Research Washington DC, 1961. https://apps.dtic.mil/sti/citations/AD0460308, last accessed on 12.12.2024

Messerschmidt 1960 Messerschmidt O. Auswirkungen atomarer Detonationen auf den Menschen: ärztlicher Bericht über Hiroshima, Nagasaki und den Bikini-Fall-out. Thiemig, 1960

Messerschmidt 1977 Messerschmidt O. Kombinationsschäden als Folge nuklearer Explosionen. Zivilschutz Forschung. Osang Verlag, Bad Honnef-Erpel, 1977

Messerschmidt 1984 — Messerschmidt O. Biologische Folgen von Kernwaffenexplosionen. Pathogenese, Klinik und Therapie. Perimed, Erlangen, 1984

Micewicz et al. 2019 — Micewicz ED, Iwamoto KS, Ratikan JA, Nguyen C, Xie MW, Cheng G, Boxx GM, Deriu E, Damoiseaux RD, Whitelegge JP, Ruchala PP, Avetisyan R, Jung ME, Lawson G, Nemeth E, Ganz T, Sayre JW, McBride WH, Schaue D. The Aftermath of Surviving Acute Radiation Hematopoietic Syndrome and its Mitigation. Radiat Res. 2019 Apr;191(4):323-34, doi: 10.1667/RR15231.1, Epub 2019/02/08

Nagao et al. 2024 — Nagao M, Okazaki K, Ohira T, Nakano H, Hayashi F, Shimabukuro M, Sakai A, Hosoya M, Kazama JJ, Takahashi A, Maeda M, Yabe H, Ohto H, Kamiya K, Yasumura S. Association between evacuation and becoming overweight after the Great East Japan Earthquake: a 7-year follow-up of the Fukushima Health Management Survey. Public Health. 2024 Jul;232:170-7, doi: 10.1016/j.puhe.2024.04.029, Epub 2024/05/25

NATO 2020 — North Atlantic Treaty Organisation Standardization Office (NATO). Warning and Reporting and Hazard Prediction of Chemical, Biological, Radiological and Nuclear Incidents (Operators Manual). NATO ATP-45, zugangsbeschränkt. https://nso.nato.int/, last accessed on 12.12.2024

NCI 1997 — National Cancer Institute (NCI). Estimated Exposures and Thyroid Doses Received by the American People from Iodine 131 in Fallout Following Nevada Atmospheric Nuclear Bomb Tests. A Report from the National Cancer Institute. U.S. Department of Health and Human Services, Bethesda, 1997

NDWV 2018 — Verordnung zur Festlegung von Dosiswerten für frühe Notfallschutzmaßnahmen (Notfall-Dosiswerte-Verordnung NDWV) vom 29. November 2018 (BGBl I S. 2034, 2172)

Neriishi et al. 2012 — Neriishi K, Nakashima E, Akahoshi M, Hida A, Grant EJ, Masunari N, Funamoto S, Minamoto A, Fujiwara S, Shore RE. Radiation dose and cataract surgery incidence in atomic bomb survivors, 1986-2005. Radiology. 2012 Oct;265(1):167-74, doi: 10.1148/radiol.12111947, Epub 2012/08/10

Otake et al. 1989 — Otake M, Yoshimaru H, Schull WJ. Prenatal Exposure to Atomic Radiation and Brain Damage. Congenital Anomalies. 1989;29(4):309-20, doi: 10.1111/j.1741-4520.1989.tb00751.x

Ozasa et al. 2012 — Ozasa K, Shimizu Y, Suyama A, Kasagi F, Soda M, Grant EJ, Sakata R, Sugiyama H, Kodama K. Studies of the mortality of atomic bomb survivors, Report 14, 1950-2003: an overview of cancer and noncancer diseases. Radiat Res. 2012 Mar;177(3):229-43, doi: 10.1667/rr2629.1, Epub 2011/12/17

Ozasa et al. 2019	Ozasa K, Cullings HM, Ohishi W, Hida A, Grant EJ. Epidemiological studies of atomic bomb radiation at the Radiation Effects Research Foundation. Int J Radiat Biol. 2019 Jul;95(7):879-91, doi: 10.1080/09553002.2019.1569778, Epub 2019/01/25
Pennington et al. 2022	Pennington HM, Klennert L, Cochran LD. Distances to Prompt Effects for a Nuclear Device. United States, Web. 2022, doi: 10.2172/1845378
Pisso et al. 2019	Pisso I, Sollum E, Grythe H, Kristiansen NI, Cassiani M, Eckhardt S, Arnold D, Morton D, Thompson RL, Groot Zwaaftink CD, Evangeliou N, Sodemann H, Haimberger L, Henne S, Brunner D, Burkhart JF, Fouilloux A, Brioude J, Philipp A, Seibert P, Stohl A. The Lagrangian particle dispersion model FLEXPART version 10.4. Geoscientific Model Development. 2019;12(12):4955-97, doi: 10.5194/gmd-12-4955-2019
Potischman et al. 2020	Potischman N, Salazar SI, Scott MA, Naranjo M, Haozous E, Bouville A, Simon SL. Methods and Findings on Diet and Lifestyle Used to Support Estimation of Radiation Doses from Radioactive Fallout from the Trinity Nuclear Test. Health Phys. 2020 Oct;119(4):390-9, doi: 10.1097/HP.0000000000001303, Epub 2020/09/04
Quinn 1987	Quinn VE. Analysis of nuclear test TRINITY radiological and meteorological data. United States, Web. 1987, doi: 10.2172/5893506
Rios et al. 2022	Rios CI, Hollingsworth BA, DiCarlo AL, Esker JE, Satyamitra MM, Silverman TA, Winters TA, Taliaferro LP. Animal Care in Radiation Medical Countermeasures Studies. Radiat Res. 2022 Nov 1;198(5):514-35, doi: 10.1667/RADE-21-00211.1, Epub 2022/08/25
Robbins et al. 1967	Robbins J, Rall JE, Conard RA. Late effects of radioactive iodine in fallout. Combined clinical staff conference at the National Institutes of Health. Ann Intern Med. 1967 Jun;66(6):1214-42, doi: 10.7326/0003-4819-66-6-1214
Roesch 1987	Roesch WC. U.S.–Japan joint reassessment of atomic bomb radiation dosimetry in Hiroshima and Nagasaki: vols. 1 and 2. Hiroshima: Radiation Effects Research Foundation, 1987
Rolph et al. 2014	Rolph GD, Ngan F, Draxler RR. Modeling the fallout from stabilized nuclear clouds using the HYSPLIT atmospheric dispersion model. J Environ Radioact. 2014 Oct;136:41-55, doi: 10.1016/j.jenvrad.2014.05.006, Epub 20140528

Satyamitra et al. 2022	Satyamitra MM, DiCarlo AL, Hollingsworth BA, Winters TA, Taliaferro LP. Development of Biomarkers for Radiation Biodosimetry and Medical Countermeasures Research: Current Status, Utility, and Regulatory Pathways. Radiat Res. 2022 May 1;197(5):514-32, doi: 10.1667/RADE-21-00157.1
Selby et al. 2021	Selby HD, Hanson SK, Meininger D, Oldham WJ, Kinman WS, Miller JL, Reilly SD, Wende AM, Berger JL, Inglis J, Pollington AD, Waidmann CR, Meade RA, Buescher KL, Gattiker JR, Vander Wiel SA, Marcy PW. A New Yield Assessment for the Trinity Nuclear Test, 75 Years Later. Nuclear Technology. 2021;207(sup1):321-5, doi: 10.1080/00295450.2021.1932176
Shibata et al. 2012	Shibata K, Iwamoto O, Nakagawa T, Iwamoto N, Ichihara A, Kunieda S, Chiba S, Furutaka K, Otuka N, Ohsawa T, Murata T, Matsunobu H, Zukeran A, Kamada S, Katakura J-i. JENDL-4.0: A New Library for Nuclear Science and Engineering. Journal of Nuclear Science and Technology. 2012;48(1):1-30, doi: 10.1080/18811248.2011.9711675
Shigematsu et al. 1995	Shigematsu I, Ito C, Kamada N, Akiyama M, Sasaki H. Effects of A-Bomb Radiation on the Human Body. Harwood Academic Publishers, Chur, Switzerland/Bunkodo, Tokyo, 1995, ISBN 3–7186–5418–0
Shizuma et al. 1996	Shizuma K, Iwatani K, Hasai H, Hoshi M, Oka T, Okano M. 137Cs concentration in soil samples from an early survey of Hiroshima atomic bomb and cumulative dose estimation from the fallout. Health Phys. 1996 Sep;71(3):340-6, doi: 10.1097/00004032-199609000-00011
Shizuma et al. 2012	Shizuma K, Endo S, Fujikawa Y. Isotope ratios of (235)U/(238)U and (137)Cs/(235)U in black rain streaks on plaster wall caused by fallout of the Hiroshima atomic bomb. Health Phys. 2012 Feb;102(2):154-60, doi: 10.1097/HP.0b013e31822c514a
Simon 1999	Simon S. Uncertainty in the University of Utah’s Nevada Test Site studies. In: Ron E, Hoffman FO, Hrsg. Uncertainties in radiation dosimetry and their impact on dose-response analyses Dept. of Health and Human Services, Public Health Service, National Institutes of Health, National Cancer Institute, Bethesda, Md. : U.S., 1999, Seiten 202– 16
Simon and Bouville 2002	Simon SL, Bouville A. Radiation doses to local populations near nuclear weapons test sites worldwide. Health Phys. 2002 May;82(5):706-25, doi: 10.1097/00004032-200205000-00016
Simon et al. 2010	Simon SL, Bouville A, Land CE, Beck HL. Radiation doses and cancer risks in the Marshall Islands associated with exposure to radioactive fallout from Bikini and Enewetak nuclear weapons tests: summary. Health Phys. 2010 Aug;99(2):105-23, doi: 10.1097/HP.0b013e3181dc523c, Epub 2010/07/14

Simon et al. 2020	Simon SL, Bouville A, Beck HL, Melo DR. Estimated Radiation Doses Received by New Mexico Residents from the 1945 Trinity Nuclear Test. Health Phys. 2020 Oct;119(4):428-77, doi: 10.1097/HP.0000000000001328, Epub 2020/09/04
Spriggs and Egbert 2020	Spriggs G, Egbert S. Total Residual Radiation Source Term Produced by the Hiroshima Detonation. Technical Report LLNL-TR-814785 https://www.osti.gov/servlets/purl/1668494, last accessed on 13.12.2024
Spriggs et al. 2020	Spriggs GD, Neuscamman SJ, Nasstrom JS, Knight KB. Fallout Cloud Regimes. Technical Report LLNL-JRNL-813959. https://www.osti.gov/servlets/purl/1771428, last accessed on 13.12.2024
Sridharan et al. 2021	Sridharan V, Johnson KA, Landes RD, Cao M, Singh P, Wagoner G, Hayar A, Sprick ED, Eveld KA, Bhattacharyya A, Krager KJ, Aykin-Burns N, Weiler H, Fernandez JA, Griffin JH, Boerma M. Sex-dependent effects of genetic upregulation of activated protein C on delayed effects of acute radiation exposure in the mouse heart, small intestine, and skin. PLoS One. 2021;16(5):e0252142, doi: 10.1371/journal.pone.0252142, Epub 20210524
SSK 1992	Strahlenschutzkommission. Modelle, Annahmen und Daten mit Erläuterungen zur Berechnung der Strahlenexposition bei der Ableitung radioaktiver Stoffe mit Luft oder Wasser zum Nachweis der Einhaltung der Dosisgrenzwerte nach § 45 StrlSchV. Veröffentlichungen der Strahlenschutzkommission, Band 17, Gustav Fischer Verlag, Stuttgart, 1992, ISBN 3-437-11419-0
SSK 2007	Strahlenschutzkommission (SSK). Leitfaden zur Information der Öffentlichkeit in kerntechnischen Notfällen. Empfehlung der Strahlenschutzkommission, verabschiedet in der 220. Sitzung der SSK am 05./06.12.2007. Bekanntmachung im BAnz Nr. 152a vom 08.10.2008
SSK 2014	Strahlenschutzkommission (SSK). Planungsgebiete für den Notfallschutz in der Umgebung von Kernkraftwerken. Empfehlung der Strahlenschutzkommission, verabschiedet in der 268. Sitzung der SSK am 13./14.02.2014. urn:nbn:de:101:1-201403101200. Bekanntmachung im BAnz AT 21.05.2014 B4
SSK 2017	Strahlenschutzkommission (SSK). Erforderliche medizinische Kapazitäten für die Versorgung und Betreuung der Bevölkerung im radiologischen und nuklearen Notfall. Empfehlung der Strahlenschutzkommission, verabschiedet in der 287. Sitzung der Strahlenschutzkommission am 23./24.03.2017. urn:nbn:de:101:1-201804238529. Bekanntmachung im BAnz AT 10.04.2018 B4

SSK 2019	Strahlenschutzkommission (SSK). Abgeleitete Richtwerte für Maßnahmen zum Schutz der Bevölkerung bei Ereignissen mit Freisetzungen von Radionukliden. Empfehlung der Strahlenschutzkommission, verabschiedet in der 303. Sitzung der Strahlenschutzkommission am 24./25. Oktober 2019. urn:nbn:de:101:1-2020040313335986790823. Bekanntmachung im BAnz AT 22.04.2020 B3
SSK 2022a	Strahlenschutzkomission (SSK). Schutzstrategien bei Nuklearwaffeneinsatz - Schutzwirkungen von Iodblockade und partikelfiltrierenden Halbmasken, verabschiedet in der 319. Sitzung der Strahlenschutzkommission am 29. März 2022. https://www.ssk.de/SharedDocs/Beratungsergebnisse/DE/2022/2022-03-29_Stgn_Iodtabletten.html
SSK 2022b	Strahlenschutzkomission (SSK). Strahlennotfallmedizin Handbuch für die medizinische Versorgung und Ausbildung, verabschiedet in der 319. Sitzung der Strahlenschutzkommission am 28. August 2022. https://www.ssk.de/SharedDocs/Beratungsergebnisse/DE/2022/2022-09-05_Empf_Strahlennotfallmedizin.html
SSK 2023a	Strahlenschutzkomission. Medizinisches Management von Strahlennotfällen – Voraussetzungen und Organisation. Empfehlung der Strahlenschutzkommission, verabschiedet in der 327. Sitzung der Strahlenschutzkommission am 11./12. September 2023. https://www.ssk.de/SharedDocs/Beratungsergebnisse/DE/2023/2023-09-12_Empf_Medizinisches_Notfallmanagement.html
SSK 2023b	Strahlenschutzkommission. Schutzstrategien bei Nuklearwaffeneinsatz - Verwendung von Atemschutzmasken zum Schutz der Bevölkerung bei Explosion nuklearer Waffen. Empfehlung der Strahlenschutzkommission, verabschiedet in der 323. Sitzung der Strahlenschutzkommission am 03.02.2023. https://www.ssk.de/SharedDocs/Beratungsergebnisse/DE/2023/2023-02-07_Empf_FFP_Masken.html
SSM 2023	Strål Säkerhets Myndighetens (Swedish Radiation Safety Authority) (SSM). Radiological Consequences of Fallout from Nuclear Explosions. https://www.stralsakerhetsmyndigheten.se/en/publications/reports/radiation-protection/2023/202305e/, last accessed on 13.12.2024
Stenke et al. 2022	Stenke L, Hedman C, Lagergren Lindberg M, Lindberg K, Valentin J. The acute radiation syndrome-need for updated medical guidelines. J Radiol Prot. 2022 Jan 25;42(1), doi: 10.1088/1361-6498/ac4ac6, Epub 20220125

Stepanenko et al. 2006 — Stepanenko VF, Hoshi M, Bailiff IK, Ivannikov AI, Toyoda S, Yamamoto M, Simon SL, Matsuo M, Kawano N, Zhumadilov Z, Sasaki MS, Rosenson RI, Apsalikov KN. Around Semipalatinsk nuclear test site: progress of dose estimations relevant to the consequences of nuclear tests (a summary of 3rd Dosimetry Workshop on the Semipalatinsk nuclear test site area, RIRBM, Hiroshima University, Hiroshima, 9-11 of March, 2005). J Radiat Res. 2006 Feb;47 Suppl A:A1-13, doi: 10.1269/jrr.47.a1

StrlSchG 2017 — Gesetz zum Schutz vor der schädlichen Wirkung ionisierender Strahlung (Strahlenschutzgesetz - StrlSchG) vom 27. Juni 2017 (BGBl. I S. 1966), das zuletzt durch die Bekanntmachung vom 3. Januar 2022 (BGBl. I S. 15) geändert worden ist

Sugiyama et al. 2021 — Sugiyama H, Misumi M, Sakata R, Brenner AV, Utada M, Ozasa K. Mortality among individuals exposed to atomic bomb radiation in utero: 1950-2012. Eur J Epidemiol. 2021 Apr;36(4):415-28, doi: 10.1007/s10654-020-00713-5, Epub 2021/01/26

Tanaka et al. 2008 — Tanaka K, Endo S, Imanaka T, Shizuma K, Hasai H, Hoshi M. Skin dose from neutron-activated soil for early entrants following the A-bomb detonation in Hiroshima: contribution from beta and gamma rays. Radiat Environ Biophys. 2008 Jul;47(3):323-30, doi: 10.1007/s00411-008-0172-1, Epub 20080522

Tejiram et al. 2023 — Tejiram S, Tranchina SP, Travis TE, Shupp JW. The First 24 Hours: Burn Shock Resuscitation and Early Complications. Surg Clin North Am. 2023 Jun;103(3):403-13, doi: 10.1016/j.suc.2023.02.002, Epub 20230321

Thaul et al. 2000 — Thaul S, Page WF, Crawford H, O'Maonaigh H, Institute of Medicine Committee to Study the Mortality of Military Personnel Present at Atmospheric Tests of Nuclear W. In: The Five Series Study: Mortality of Military Participants in U.S. Nuclear Weapons Tests National Academies Press (US), Washington (DC), 2000,

Tomonaga 2019 — Tomonaga M. The Atomic Bombings of Hiroshima and Nagasaki: A Summary of the Human Consequences, 1945-2018, and Lessons for Homo sapiens to End the Nuclear Weapon Age. Journal for Peace and Nuclear Disarmament. 2019;2(2):491-517, doi: 10.1080/25751654.2019.1681226

UNSCEAR 1982 — United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Exposures resulting from nuclear explosions. In: Ionizing radiation: sources and biological effects. 249 –332, United Nations, New York, 1982, ISBN

UNSCEAR 2022	United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources, effects and risks of ionizing radiation. UNSCEAR 2020/2021 Report to the General Assembly, with Scientific Annexes, VOLUME II Scientific Annex B: Levels and effects of radiation exposure due to the accident at the Fukushima Daiichi Nuclear Power Station: implications of information published since the UNSCEAR 2013 Report. United Nations, New York, 2021, ISBN 978-92-1-139208-1
WHO 2020	World Health Organization (WHO). A framework for mental health and psychosocial support in radiological and nuclear emergencies. Geneva, 2020, ISBN 9789240015456
WHO 2023	World Health Organization (WHO). National stockpiles for radiological and nuclear emergencies: policy advice. Geneva, 2023, ISBN 978-92-4-006787-5
Widner 2009	Widner TE. The world's first atomic blast and how it interacted with the Jornada Del Muerto and Chupadera Mesa. In: Lueth VW, Chamberlin RM, Lucas SG, Hrsg. Geology of the Chupadera Mesa. New Mexico Geological Society 60 th Annual Fall Field Conference Guidebook, 2009, Seiten 425-8
Yan 2019	Yan W. The nuclear sins of the Soviet Union live on in Kazakhstan. Nature. 2019 Apr;568(7750):22-4, doi: 10.1038/d41586-019-01034-8
Young und Kerr 2005	Young R, Kerr G. Reassessment of the atomic bomb radiation dosimetry for Hiroshima and Nagasaki Dosimetry system 2002. DS02. Volume 2. Japan, 2005 551°Seiten
Zhumadilov et al. 2009	Zhumadilov K, Ivannikov A, Zharlyganova D, Zhumadilov Z, Stepanenko V, Apsalikov K, Ali MR, Zhumadilova A, Toyoda S, Endo S, Tanaka K, Okamoto T, Hoshi M. ESR dosimetry study on population of settlements nearby Ust-Kamenogorsk city, Kazakhstan. Radiat Environ Biophys. 2009 Nov;48(4):419-25, doi: 10.1007/s00411-009-0235-y, Epub 20090626
Zhumadilov et al. 2013	Zhumadilov K, Ivannikov A, Stepanenko V, Zharlyganova D, Toyoda S, Zhumadilov Z, Hoshi M. ESR dosimetry study of population in the vicinity of the Semipalatinsk Nuclear Test Site. J Radiat Res. 2013 Jul 1;54(4):775-9, doi: 10.1093/jrr/rrt008, Epub 20130211
ZSKG 1997	Zivilschutz- und Katastrophenhilfegesetz vom 25. März 1997 (BGBl. I S. 726), das zuletzt durch Artikel 144 der Verordnung vom 19. Juni 2020 (BGBl. I S. 1328) geändert worden ist

Tab. A 1: Overview of the estimated dose of nuclear weapons tests

Test area	Test, test series, or sum of all tests	Location of potential exposure (e.g. towns, villages, islands)	Averaged external whole-body exposure (mGy)	Thyroid dose for children (1 - 2a) (Gy)	Approximate number of exposed persons	Estimated collective whole-body dose (person-Gy)	Estimated collective thyroid dose (children 1 - 2 a) (person-Gy)	Literature
Bikini and Enewetak Atolls, Marshall Islands	BRAVO test (1 March 1954)	Rongelap Atoll	1900	50	64	122	–	Lessard et al. (1985), Conard (1975)
		Rongerik Atoll	810	no children	28	23	–	"
		Ailinginae Atoll	1,110	13	18	20	–	"
		Utrik Atoll	110	6.7	157	17	–	"
"	Castle series (1954)	selected atolls						Breslin and Cassidy (1955), Population data: RMI (1989)
"		Ailinglaplap	1.7	–	1,300	2.2	–	"
"	"	Ailuk	41	–	400	16.4	–	"
"	"	Kwajalein	8.2	–	1,300	10.7	–	"
"	"	Likierp	14.5	–	640	9.3	–	"
"	"	Majuro	3.1	–	3,400	10.5	–	"
"	"	Wotje	16.8	–	360	6.0	–	"
"	"	all atolls	13.6	–	14,000 all atolls	191 all atolls	–	"
Semipalatinsk, Kazakhstan		Selected villages, towns						
	29 August 1949	Dolon	900	1–2.2	850	765	35–77	Stepanov et al. (2001)
	all tests	"	2,200		306	2,000		Bouville et al. (2000) [a]

Test area	Test, test series, or sum of all tests	Location of potential exposure (e.g. towns, villages, islands)	Averaged external whole-body exposure (mGy)	Thyroid dose for children (1 - 2a) (Gy)	Approximate number of exposed persons	Estimated collective whole-body dose (person-Gy)	Estimated collective thyroid dose (children 1 - 2 a) (person-Gy)	Literature
"	29 August 1949	Kanonerka	210	0.35–0.7	2,400	500	35–70	Stepanov et al. (2001)
	all tests	"	840		1,200	1,000		Bouville et al. (2000) [a]
"	24 September 1951	Kaynar	70	3–3.8	450	32	54–68	Stepanov et al. (2001)
"	12 August 1953	Sarzhal	180	–	630	110	–	Stepanov et al. (2001)
	all tests	"	1,200		830	970		Bouville et al. (2000) [a]
Semipalatinsk, Kazakhstan	12 August 1953	Kara-Aul	130	–	2,400	310	–	Stepanov et al. (2001)
	all tests	"	360		2,300	240		Bouville et al. (2000) [a]
"	24 August 1956	Ust-Kamenogorsk	56	–	130,000	7,300	–	Stepanov et al. (2001)
"	24 August 1962	Semipalatinsk (City)	0.2	–	145,000	30	–	Stepanov et al. (2001)
	all tests	"	3.7		163,000	610		Bouville et al. (2000) [a]
"	44 tests	Altai Region (Russia), 58 administrative units	18.6	–	2,200,000	41,200	–	Shoikhet et al. (1999)
Nevada, test area, US	all tests	ORERP Phase I area	2.8	–	180,000	500	–	Anspaugh et al. (1990)

Test area	Test, test series, or sum of all tests	Location of potential exposure (e.g. towns, villages, islands)	Averaged external whole-body exposure (mGy)	Thyroid dose for children (1 - 2a) (Gy)	Approximate number of exposed persons	Estimated collective whole-body dose (person-Gy)	Estimated collective thyroid dose (children 1 - 2 a) (person-Gy)	Literature
"	"	ORERP Phase I + II area	0.6	0.007 (all days)	20,000,000	12,000	140,000 (all ages)	Anspaugh (2000), Whicker et al. (1996)
"	"	St. George, Utah	15.8	0.25 (all ages)	4,900	77.4	1200 (all ages)	Whicker et al. (1996), Beck und Krey (1983)
Emu Field, Maralingan, and Monte Bello Islands, Australia	Selected population centres							
	All test series 1952–1957	Broome	0.18	0.020 (all ages)	3,340	0.60	66.8 (all ages)	Wise and Moroney (1985)
"	"	Noonkanbh	0.16	0.018 (all ages)	75	0.01	1.4 (all ages)	"
"	"	Onslow	0.10	0.011 (all ages)	543	0.06	6.0 (all ages)	"
"	"	Pt. Hedland	0.23	0.025 (all ages)	1,367	0.32	34.2 (all ages)	"
Novaya Zemlya and Kasputin Yar, Russia	all tests	–	–	–	–	–	–	Details in the main text (Simon and Bouville 2002)
Christmas and Malden Islands, Kiribati	all tests	Nearby islands/atolls	–	–	–	–	–	"

Test area	Test, test series, or sum of all tests	Location of potential exposure (e.g. towns, villages, islands)	Averaged external whole-body exposure (mGy)	Thyroid dose for children (1 - 2a) (Gy)	Approximate number of exposed persons	Estimated collective whole-body dose (person-Gy)	Estimated collective thyroid dose (children 1 - 2 a) (person-Gy)	Literature
Johnston Atoll, US	all tests	None (Hawaii is the closest with 1,330 km)	–	–	–	–	–	"
Reggane, Algeria	all tests	very few inhabited places near the test site (mainly the village of Reggane)	–	–	–	–	–	"
Lop Nor, China		Selected towns, villages						
	all tests	Anxi	0.02	–	60,000	1.2	–	Zheng et al. (1996)[b], UNSCEAR (2000)
"	"	Yumenzhen	0.03	–	159,000	4.8	–	"
"	"	Jinta	0.11	–	99,000	10.9	–	"
"	"	"Jiayuguan	0.11	–	89,000	9.8	–	"
"	"	Shenyang	–	0.022	–	–	–	Liu und Zhu (1996)[c], Bouville et al. (2000)
"	"	Xining	–	0.02	–	–	–	"
"	"	Lanzhou	–	0.025	–	–	–	"
Mururoa and Fangataufa Atoll, French Polynesia		Atolls/islands throughout the archipelago						

Test area	Test, test series, or sum of all tests	Location of potential exposure (e.g. towns, villages, islands)	Averaged external whole-body exposure (mGy)	Thyroid dose for children (1 - 2a) (Gy)	Approximate number of exposed persons	Estimated collective whole-body dose (person-Gy)	Estimated collective thyroid dose (children 1 - 2 a) (person-Gy)	Literature
	2 July 1966	Gambier Islands	3.4	–	40	0.14	–	Bourges (1997), UNSCEAR (2000)
"	8 August 1971	"	0.9	–	68	0.061	–	"
"	2 July 1967	Tureia Atoll	0.7	–	516	0.36	–	"
	12 June 1971	"	0.9	–	545	0.49	–	
"	17 July 1974	Tahiti	0.6	0.0068	84,000	50.4	11 (assuming 2 % is between 1–2 years)	UNSCEAR (1979), Bouville et al. (2000)

[a] The data originally comes from G.D. Vdovichenko, Dept. of Radiation Hygiene of the Ministry of Kazakhstan, 480008, Alamata, Kazakhstan

[b] Zheng Y, Yongze M, Jiangchen L. Long range atmospheric transportation and fallout of nuclear test debris. Presented at the 4th SCOPE-RADTEST international workshop. Beijing, China; 1996.

[c] Liu Y, Zhu C. Environmental contamination and health effect from iodine-131 in fallout in China. Presented at the 4th SCOPE-RADTEST international workshop. Beijing, China; 19–21 October 1996

13 List of abbreviations

AHS	Adult Health Study
ALL	Acute lymphoblastic leukaemia
AMAD	activity median aerodynamic diameter
AML	acute myeloid leukaemia
ATF	Analytical task force
ANoPl-Bund	General Emergency Plan of the federal government
ARS	acute radiation syndrome
ATP	Allied Tactical Publication of NATO
BBK	Federal Office of Civil Protection and Disaster Assistance
BfS	Federal Office for Radiation Protection
BMI	Federal Environment Ministry
BMUV	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
BNoPL	Special emergency plan of the federal government
CBRN	Chemical, biological, radiological, nuclear
CLL	Chronic lymphoblastic leukaemia
CML	Chronic myeloid leukaemia
DEARE	delayed effects of acute radiation exposure
DHS	Department of Homeland Security
DRZ	dangerous radiation zone
DTC	differentiated thyroid carcinoma
DWD	German Meteorological Service (DWD)
EMA	European Medicines Agency
EMP	Electromagnetic pulse
ERR	excess relative risk or excess relative rate
FDA	Food and Drug Administration

FDMT	Food and Dose Model terrestric
FEMA	Federal Emergency Management Agency of the US
FOCS	Filial one offspring clinical study
G-CSF	granulocyte colony stimulating factor
GM-CSF	granulocyte-macrophage colony stimulating factor
HEU	highly enriched uranium
HOB	height of burst
HZ	hot zone
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IMIS	Integrated measurement and information system for monitoring radioactivity in the environment
CI	confidence interval
CIT	Crisis intervention teams
KZV	Civil defence concept
LD	lethal dose
LDZ	light damage zone
LRI	local radiation injury
LSS	Life Span Study
MDZ	moderate damage zone
MIRV	Multiple independently targetable re-entry vehicle
MSC	mesenchymal stem cells
NCI	National Cancer Institute
NDWV	Emergency Dose Level Ordinance
NEMP	Nuclear electromagnetic pulse
PPE	Personal protective equipment
PSNV	Psychosocial emergency care
PTSD	post-traumatic stress disorder

RBE	relative biological effectiveness
RKI	Robert Koch Institute
RLZ-Bund	Federal Radiological Situation Centre
RR	relative risk
RRGV	Framework guidelines for overall defence – overall defence guidelines
SDZ	severe damage zone
PF	Protective factors
SMR	Standardised mortality ratio
SSK	German Commission on Radiological Protection
SSM	Strålsäkerhetsmyndigheten, Swedish Radiation Safety Authority
TREE	Transient Radiation Effects on Electronics
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UVB-CBRN	UnterstützungsverBund CBRN
ZSKG	Federal Civil Protection and Disaster Relief Act