Proceedings of 4th International Conference CNDCGS'2024
ISSN 2669-2023 (print) / ISSN 2538-8959 (on-line) / DOI 10.3849/cndcgs.2024.621

Some Problems with the CBRN Risk Quantification in Terms of Stochastic and Deterministic Effects Taking into Account the Health Impact of Individual Agents

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Abstract

The total risk of Chemical, biological, radiological, and nuclear defense (CBRN) has to be expressed using relevant quantities and units introduced for each of their components, t.e., chemical (C), biological (B), radiological (R) and nuclear (N). Their specific properties characterise their ability to move in the environment and inflict harm on persons affected. While in the case of R and N components, the danger is induced by radiation, the assessment of the hazards from C and B agents is much more complicated. The paper discusses the quantification of CBRN risk as a whole, paying attention to two possible consequences of exposure-initiating harms: stochastic (late) and deterministic effects (tissue reactions). The main aim of the paper was to point out the inconsistencies between the concept of risk assessment of the group of agents C and B and the group R and N of the CBRN family including the lack of the rigorous evaluation of deterministic and stochastic health effects of chemical and biological substances.

KEY WORDS: *CBRN threats, population safety, biological effects, stochastic effects, deterministic effects, risk, radiation exposure.*

Citation: Sabol, J., Bajura, J., Nejedlý, J. (2024). Some problems with the CBRN risk quantification in terms of stochastic and deterministic effects taking into account the impact of individual agents. In Proceedings of the Challenges to National Defence in Contemporary Geopolitical Situation, Brno, Czech Republic, 11-13 September 2024. ISSN 2538-8959. DOI 10.3849/cndcgs.2024.621.

1. Introduction

Efforts to assess and quantify the harmful effects of dangerous substances are directed mainly towards single agents. In contrast, real-world environmental and personal exposures under everyday situations, especially in case of an accident or terrorist attack, may present several different difficulties simultaneously. The combined exposures may lead to health risks that differ from those expected from the simple addition of the individual risks. This can also be applied to CBRN (C-chemical, B-biological, R-radiological, and N-nuclear) agents whose individual components, such as C and B on one side and R and N on the other, interact with living tissues quite differently [1,2]. Whether processes and modes of interactions occurring at high exposure levels (depending on concentration, intake or external exposure) are important, as well as at the low exposure levels set for the public, workers, or rescue teams, is difficult to answer. A scientifically sound extrapolation from these high to low-dose levels should be based on dose-effect relationships of the relevant agents alone and in combination. In general, so far, this information is not fully recognised and available. The existing database on combined effects is rudimentary, mainly descriptive and rarely covers exposure ranges large enough to make direct inferences about present-day low-dose exposure situations.

The paper discusses problems in quantifying overall CBRN biological effects where specific damage of separate components can differently contribute to the total harm of the affected persons caused by different agents. Even in scientific literature, one can find expressions such as CBRN risk without mentioning the contributions from specific components.

Chemical hazards and toxic substances pose a wide range of health hazards (such as irritation, sensitisation, and carcinogenicity) and physical hazards (such as flammability, corrosion, and explosibility).

Peer-review under responsibility of General Jonas Žemaitis Miltitary Academy of Lithuania and University of Defence, Czech Republic

In order to ensure CBRN safety of people, information about the identities and hazards of the agents must be available and understandable to all who may be in the place contaminated. Various international and national standards have been developed to control these substances so that their impact on people and the environment is minimised to an acceptable level. However, in the case of the mixture of various CBRN substances, it is more difficult to take into account the contribution to the total risk at both low and high levels of exposure, which may lead to stochastic (probabilistic, late) effects and evaluate total deterministic (acute) effects.

In principle, this concept should be similar to the effects of radiation, which have been studied in more detail than the effects of chemical or biological agents. This was possible due to a very sophisticated system of quantities and units that reflected both physical and biological responses to radiation exposure in terms of relevant biological effects. Here, there is a specific quantity of effective dose with the unit of Sv (sievert), which reflects the measure of overall stochastic effects. Other quantities distinguish between the contribution of external radiation (ambient dose equivalent) and internal exposure (committed effective dose). Their sum then represents the total exposure. Both doses can be assessed based on modelling or monitoring by sophisticated detection and spectrometry techniques with extremely high sensitivities which are far below the radiation background.

The present situation in quantifying and assessing stochastic effects due to the R and N agents is discussed and analysed in order to find a way in which experience from this area can be used in the evaluation of the danger of C and B components where, so far, attention was mainly concentrated on protection against deterministic effects. The preliminary results based on many statistical reviews of results published in scientific literature and other available data clearly indicate that low-level exposure to C and B agents may also produce stochastic (late) effects.

At very low exposure, no visible harm is observed. Still, it has been proved that even these exposures are harmful since they contribute to the increased level of cancer occurrence with a certain probability, which is proportional to the dose received. At much higher levels (above a threshold) of radiation exposure, deterministic effects occur with the probability of 100% with severity proportional to the exposure. The health effects of low-dose radiation, less than 100 mSv, have been debated as to whether they are beneficial or detrimental because sample sizes were not large enough to allow epidemiological detection of excess effects, and there was a lack of consistency among the available experimental data.

In addition to stochastic effects usually characterised by a linear relationship between the probability of effect occurrence and the exposure, the deterministic effects appear only above a certain threshold. Below this value of exposure, this probability is zero [3,4]. Above the threshold level, the probability is one, but the severity is approximately linear in relation to the dose in Gy. This is illustrated in Fig. 1 (based on [3]).

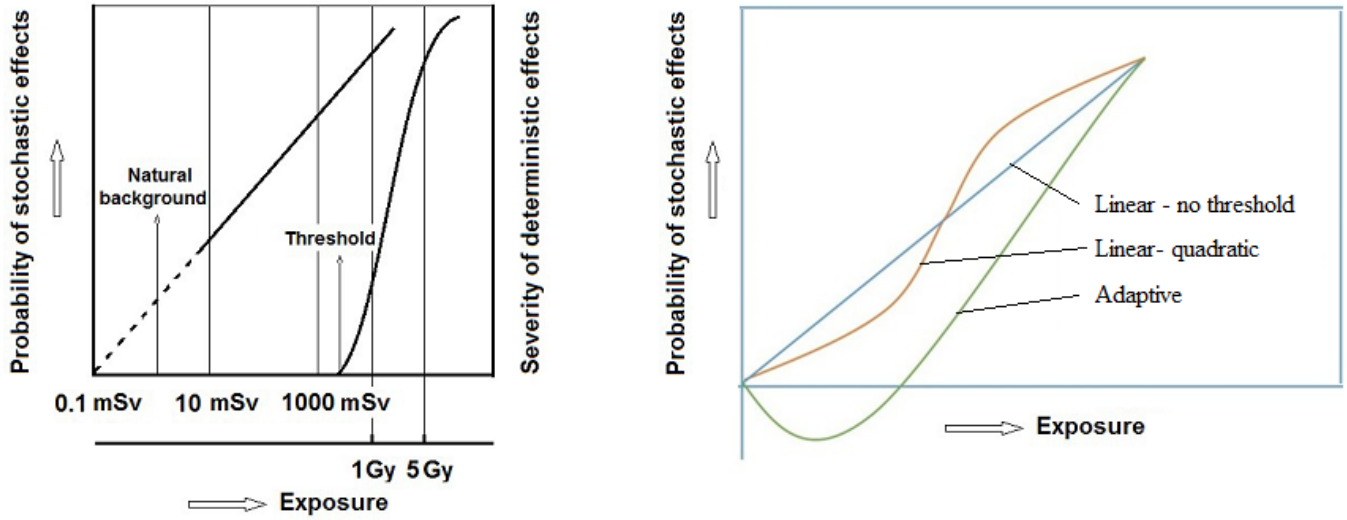

Fig. 1. Relationship between the probability of stochastic effects and low exposure (a) and the severity and high exposure level (b). Compared to the situation with R and N agents, there has been nothing like this studied in such detail regarding C and B components.

The probability of stochastic effects at very low exposures (comparable with natural background and lower) cannot be established reliably since the probability of occurrence is very low (Fig. 1a). This approach implies that all exposure to ionising radiation is harmful, regardless of how low dose is, and that the effect is cumulative over a lifetime. A linear no-threshold (LNT) model is usually applied in routine radiation protection applications. According to this concept, the approximation of linearity is usually adopted here, although, in principle, the shape of the response may show both linear-quadratic or adaptive forms (Fig. 1b).

2. Some characteristics of CBRN agents

Characteristics of effects of any CBRN agent depend on its type, amounts (exposure) and interactions with the human tissues. Assessment starts with identifying and classifying hazards, which must be related to the dose-effect and dose-response information available for the identified risks. Once the potential for exposure has been characterised, it should be quantified and compared with an established safe exposure level. The degree to which it exceeds that level is a measure of the risk. Even if the assessed risk is regarded as acceptable, there is the possibility that the situation will change with time, so it is important to monitor potentially harmful exposures.

Dangerous materials can be silent killers. Almost every household and workplace has varying amounts of chemicals that, if spilt or combined, will cause great harm and even death. One must know how to recognise these agents, where they may be found, and what to do or not do about hazardous material spills. The situation is much more complicated if dangerous materials belong to the CBRN category and are uncontrollable because of accidental or intentional release.

A common characteristic of most CBRN agents is that they are difficult to recognise or detect once released. For example, they may be an odourless, colourless chemical, biological agent, or radioactive material emitting radiation that cannot be seen or felt. One also has to recognise the difference between dangerous materials used in industry, research and other fields where they are beneficial. There are special legislative, administrative and technical mechanisms to control them and minimise their deleterious effects on workers, population and the environment. On the other hand, some CBRN agents have been specifically developed for military use.

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The CBRN agents are considered to be part of weapons of mass destruction (WMD), weapons with the capacity to inflict death and destruction on such a massive scale and so indiscriminately that their very presence in the hands of a hostile power can be considered a grievous threat.

2.1. Chemical Agents

Chemical toxic substances pose a wide range of health hazards (such as irritation, sensitisation, and carcinogenicity) and physical hazards (such as flammability, corrosion, and explosibility). Chemical agents fall into four categories: choking agents, blister agents, blood agents, and nerve agents. Choking agents irritate the nose, throat, and lungs when inhaled and include chlorine (Cl), chloropicrin (PS), diphosgene (DP), and phosgene (CG) [5,6,7,8].

VX is one of the nerve agents which are the most toxic of the known chemical warfare agents. It is tasteless and odourless. Exposure to VX can cause death in minutes. As little as one drop of VX on the skin can be fatal.

Chemical Warfare Agents (CWAs) are designed to restrict and disrupt operations. They can affect everyone whose skin or respiratory system is exposed. CWAs are far more dangerous than toxic industrial chemicals (TICs) but are more restricted in manufacture. In a terrorist incident, the exact CWA present may not initially be known, so the extent of the exposure of first responders requires expert assessment at the scene based, among other things, on sensors, eyewitness accounts and the symptoms of casualties.

In the case of chemical accidents or the use of dangerous chemicals for terrorist attacks, mainly deterministic effects are studied. Many kinds of stochastic effects, including an increased rate of cancer occurrence among those who inhaled or were in contact with chemical agents, were not scrutinised in the way done with ionising radiation sources. This is mainly because so many chemicals have a very specific impact on the human organism that it is almost impossible to consider all possible factors. Moreover, such studies require the evaluation of statistical data collected under strict conditions for many decades. In any case, the deterministic effects of most chemical agents are well known and serve as a basis for developing relevant protection measures to minimise the consequences of exposure to chemical agents.

2.2. Biological agents

Biological hazards vary in how they transfer from host to host -some through inhalation and ingestion, others through skin cuts or abrasions. The hazard presented to first responders and medical staff by blood-borne viruses such as HIV, hepatitis and viral haemorrhagic fever is unrelated to terrorism [9].

The response to biological attacks involves several distinct steps depending on the specific circumstances of the biological attack. It may include early warning and detection measures/systems, identification of the agent(s) involved, epidemiology, first response, law enforcement, the response of the public health system/veterinary system/systems in the area of plant protection/systems related to food chain security, decontamination, incident investigation and forensics, and measures needed to ensure short and long-term recovery.

The targets of a biological attack can be humans, animals or plants. That includes the possibility of biological attacks on the food chain. Second, biological agents are disease factors (living organisms that infest a host and multiply there)—their effect is normally delayed by several days (latency period), and the onset of symptoms may or may not be specific to the disease. Thirdly, contact between infected victims and healthy individuals (animals, crops) can spread disease. This creates a broad range of possible scenarios for biological weapons attacks that need to be taken into account when addressing response strategies.

Historically, biological weapons were often used clandestinely. In such an attack, recognising that a deliberate agent

release has occurred is often difficult. The features of the outbreak may not differ much from a natural disease outbreak, particularly if the disease is endemic in the region where the attack occurred. In case of food chain contamination, it can take days to weeks to identify the original source of the contamination, and sometimes, it may never be possible.

Because of the spread of the infection during the latency period, the disease spreads from its origin to remote locations—quite different from a radiological or chemical incident. This has a major impact on the pattern of a disease outbreak and its spread, given today's global transportation systems for humans and animals as well as crops and related products. Biological agents can be released by using specially designed dissemination devices that create a localised primary contamination of air, water or on surfaces (spraying devices, certain types of bombs, etc.). Such devices can be improvised, but the effective dissemination of biological agents remains a technical hurdle that terrorists have so far found difficult to master.

2.3. Radiological agents

Ionising radiation is a type of energy released by atoms in the form of electromagnetic waves or particles. People are exposed to natural sources of ionising radiation, such as in soil, water, and vegetation, as well as in human-made sources, such as x-rays in medical devices. Ionising radiation has many beneficial applications, including its use in medicine, industry, agriculture, and research. As the use of ionising radiation increases, so does the potential for health hazards if not properly used or contained. Acute health effects such as skin burns or acute radiation syndrome can occur when doses of radiation exceed very high levels [4,10].

Radiological agents include radioactive materials that emit ionising radiation, which have applications in many fields, especially in industry and medicine. They include high-activity radionuclides, which may attract the attention of potential terrorists (Fig. 2).

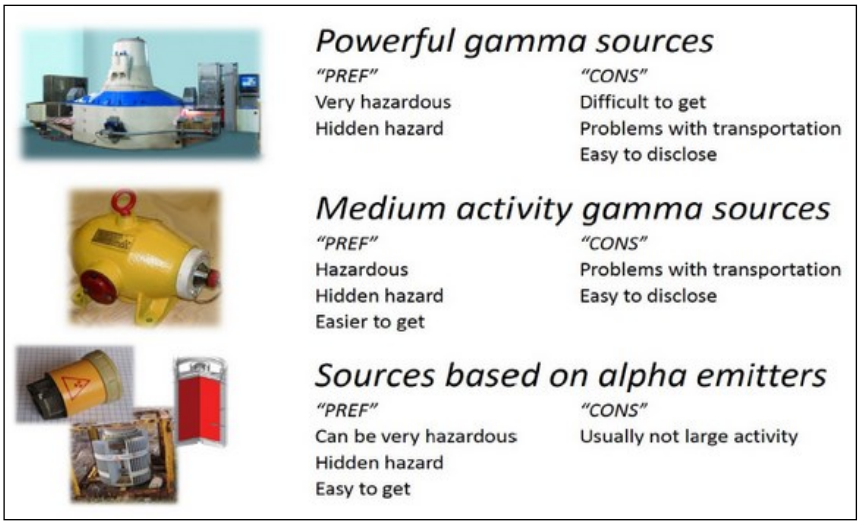

Fig. 2. Radioactive sources are likely to be attractive to terrorists. "Pref" refers to reasons terrorists might prefer each source, and "con" refers to reasons a source is less likely to be selected [11].

It includes only radioactive sources; other radiation sources, such as X-ray machines or charged particle accelerators, are not included in this category of agents. Radiological agents include radioactive materials that emit ionising radiation, which have applications in many fields, especially in industry and medicine. It includes only radioactive sources; other radiation sources, such as X-ray machines or charged particle accelerators, are not included in this category of agents. This may cause some confusion because radiology is usually based on both types of radiation sources. We would suggest changing this term when using it in relation to CBRN from radiological to radioactive agents.

2.4 Nuclear agents

These agents are attributed to fissionable materials used in nuclear reactors, where fission is controlled and used to produce energy. Since the process is accompanied by high-intensity radiation and the production of vast amounts of radioactive materials, such installations should be used under strict safety and security conditions. Under normal situations, the release of radioactivity to the environment contributes only a fraction of the doses that the population receives from other radiation sources, including environmental radioactivity and cosmic radiation. However, in the case of an accident, sabotage or terrorist attacks, many high-activity radionuclides are spread into the surrounding areas. The exposure near such a damaged reactor can reach such levels that ionising radiation can reach doses, causing death to affected people. The main components of the nuclear reactor and other essential parts of NPP are shown in Fig. 3.

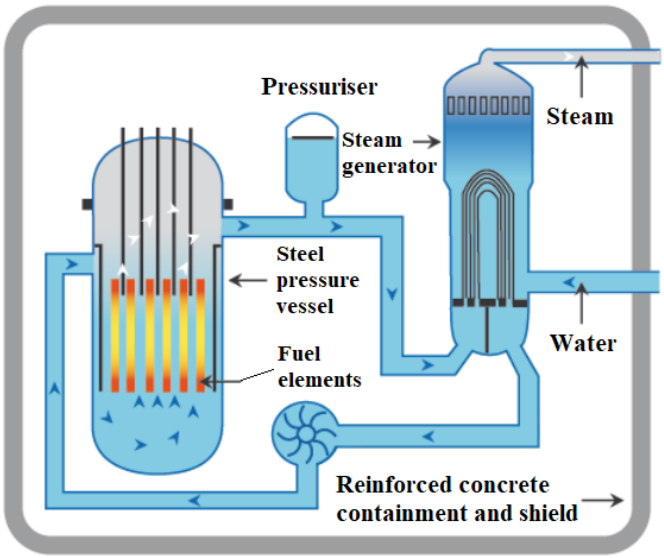

Fig. 3. An example of a typical pressurised water reactor used at a nuclear power plant (based on [12]).

In principle, but at a much lower level, a similar situation is characterising nuclear modular reactors and research reactors used for scientific experiments, training of nuclear personnel, and production of radionuclides.

From what has been mentioned above, it is clear that component N within the CBRN group represents radioactive materials with the same consequences as radiological agents. Component N is also associated with people's exposure. Some of them, in close vicinity to the explosion, will be irradiated immediately by radionuclides released from the damaged nuclear reactors or by the explosion of nuclear weapons based on spontaneous fission or fusion. In principle, we have to be ready for potential danger from using these weapons based not only on fission but also on fusion, which is utilised in hydrogen bombs. Such a thermonuclear bomb produces enormous explosive power, including the release of vast amounts of radioactive materials.

As to the consequences of atomic bomb explosions, there are warnings from the use of these weapons in bombing two Japanese cities - Hiroshima and Nagasaki - at the end of the Second World War in 1945 [13,14]. The bombings of these two cities killed between 129,000 and 226,000 people, most of whom were civilians. The resulting deterministic effects also included more than 100,000 directly affected people. At least the same number of people were affected by stochastic effects, contributing to the increase of cancer and hereditary damage by far above their normal incidence among the population.

Other valuable data related to the radiation exposure and radioactive contamination of vast areas were obtained from nuclear power plant (NPP) accidents in Chernobyl in the former USSR (1986) [15] and Fukushima in Japan (2011) [16,17].

3. Biological effects

It has already mentioned the importance of distinguishing between stochastic and deterministic biological effects. Stochastic (random) – health effects that occur randomly and for which the probability of the effect occurring, rather than its severity, is assumed to be a linear function of dose without threshold. Hereditary effects and cancer incidence are examples of stochastic effects.

Deterministic (non-stochastic) –health effects, the severity of which varies with the dose and for which a threshold is believed to exist. The severity of these effects (rather than probability) increases with dose. The time of health harm initiated by severe exposure always occurs, although the time of its appearance may differ depending on the individual agents used, as illustrated in Fig. 4 (based on [18]). While in the areas of R and N components, there has been developed a compact system of quantification of health impact, so far, no such system is available for the quantification of biological effects resulting from C and B agents in terms of distinguishing between stochastic and deterministic effects.

Conclusions

Our approach to assessing stochastic effects reflects some ideas expressed in recent publications. In the case of chemical agents, where understanding stochastic processes is particularly relevant to genotoxic carcinogenesis, the assumption of a linear dose-response relationship at low dose (exposure) has often been adopted. However, more complicated quantification of stochastic effects is related to the effects of chemical and especially biological materials, which include very specific agents such as bacteria, viruses, fungi, and internal human parasites.

It is well known that the R and N components (in both cases, radioactive materials emitting ionising radiation) of the CBRN family are well studied, including their stochastic and deterministic effects (non-stochastic). On the other hand, C and B agents have completely different origins and cause health effects in entirely altered processes. This is why we cannot consider that CBRN agents present a homogenous group of dangerous substances. When more components are involved, assessing the total CBRN impact in a unified is difficult.

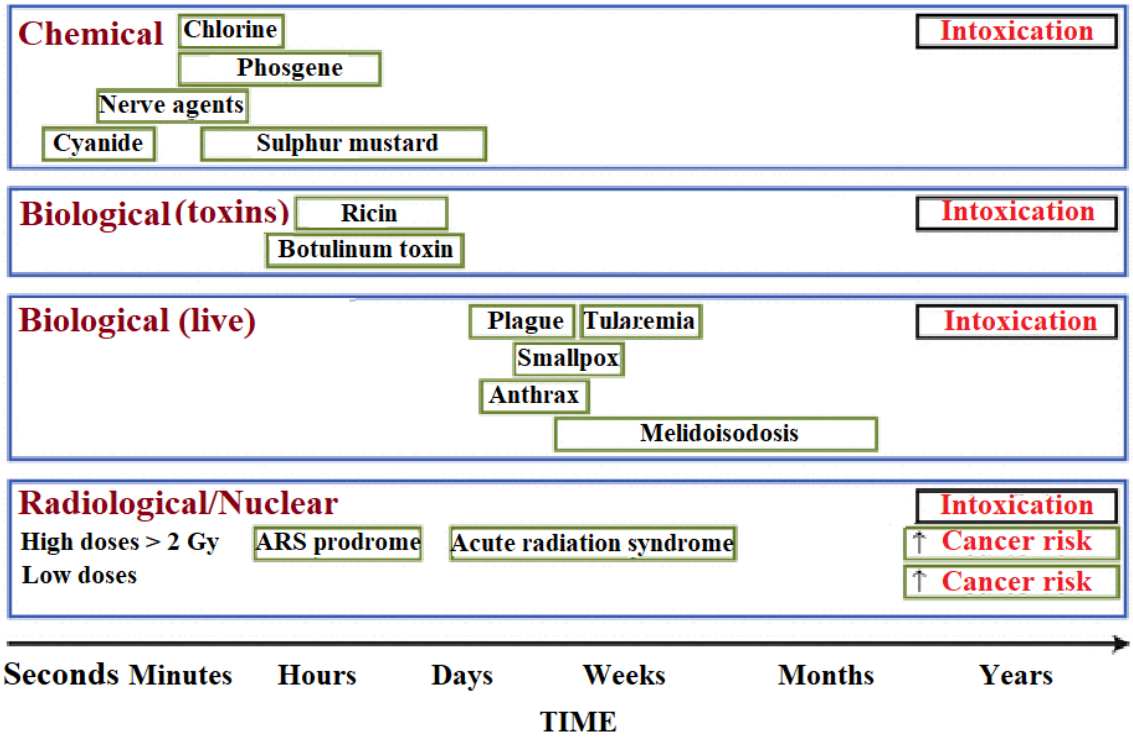

Fig. 4. A summary of the latency and incubation periods for specific CBRN agents (ARS – Acute Radiation Syndrom).

The paper discussed the quantification of CBRN agents as a whole, paying attention to two possible consequences of exposure-initiating effects appearing later, with a certain probability, and the effects that occur shortly after the interaction with CBRN agents.

To summarise all of the above, although the group of CBRN hazardous substances is quite often taken as a single unit, the quantification of the degree of health damage caused by components C and B is still inconsistent. Especially when it comes to comparison with R and N components, where there is a scientifically conceived system of quantities and units that reflects both stochastic and deterministic effects. The authors of the article point to these inconsistencies and justify the need for a more balanced approach to all CBRN agents. Therefore, it will be necessary to assess the overall risk as a result of the effects of CBRN comprehensively as a whole.

Acknowledgments

This work was conducted and supported by the EU Horizon Project CHIMERA – Comprehensive Hazard Identification and Monitoring System for Urban Areas (HORIZON-CL3-2022-DRS-01-08).

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