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TOWARDS FORTY YEARS OF KRŠKO NPP OPERATION – AN OVERVIEW OF POPULATION EXPOSURES TO RADIATION

OB KONCU ČETRTEGA DESETLETJA DELOVANJA NE KRŠKO - PREGLED SEVALNE IZPOSTAVLJENOSTI PREBIVALSTVA

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Keywords: Krško NPP, NEK, radioactivity monitoring, radioactivity releases, dose assessment, population exposures, history of doses.

Abstract

In this article, the influence of a controlled magnetic field on gadolinium plates was modelled and simulated to be used in magnetic refrigeration installations. This is a state-of-the-art technology that does not use refrigerants and does not work based on vapour compression, which is based on the operation of the magnetocaloric properties of the material used; in the case below, this material, in the form of a flat plate, has certain magnetocaloric properties and under the influence of magnetic induction can be used successfully in such innovative installations. The advantages of using gadolinium in the form of a flat plate in a magnetic regenerator and thermal energy dissipation on its surface under the controlled magnetic field's influence were studied.

Povzetek

V prispevku so predstavljene omejitve za radioaktivne izpuste iz Nuklearne elektrarne Krško, ki so z manjšimi spremembami v veljavi od začetka delovanja. Monitoring, ki se izvaja v okolici elektrarne,

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se ni bistveno spremenil od poznih osemdesetih let. Predstavljeni so zbrani podatki o radioaktivnosti v tekočinskih in atmosferskih izpustih. Zbrani podatki o ocenjenih dozah kažejo, da so skozi leta bili v uporabi različni pristopi ocenjevanju doz, vendar vsi dokazujejo, da so doze prebivalstva bile vedno bistveno manjše od avtoriziranih mejnih doz.

1 INTRODUCTION

The construction of the Krško Nuclear Power Plant (Krško NPP, NEK) started in 1975 and was concluded in 1981. The first criticality took place in September 1981, and the first synchronization with the grid occurred in October 1981. In 1982, numerous tests were performed and, finally, in January 1983, NEK started commercial operation. One year later (in January 1984), the regular operation of NEK was approved.

The introduction of nuclear energy was a great challenge for involved scientific and technical experts, legislators, and all domestic companies acting either as contractors or subcontractors during the construction and later, supporting the operation and maintenance of NEK. Besides nuclear safety, one of the most important challenges was how to define legal restrictions regarding the radiation influence of NEK on the population and environment and how to establish proper control mechanisms to ensure and verify that the restrictions are followed. Although in the former Yugoslavia adopting relevant legislation and rules regarding nuclear and radiation safety took almost a decade, the very basic requirements for the safe operation of NEK were established and were set early, before the start of the operation. Later, the requirements were additionally elaborated, but, as we will see, the original restrictions have not been altered.

2 LEGAL RESTRICTIONS

The first limit for the radiation impact of NEK on the environment was established ten years before the official start of regular operation in the Location Permit issued by the National Secretariat for Urbanism of Slovenia in 1974. The Location Permit required that the (effective) dose[i] from the radioactive releases of NEK on the border of the restricted protective zone (500 m from the reactor axis) and beyond shall not exceed 50 µSv per year. The Location Permit also required that reference (pre-operational) measurements be performed and possible consequences of NEK operation (radioactivity releases and distribution) on the surface and underground waters in Krško and Zagreb basins estimated and assessed. Due to the lack of national regulations regarding the use of nuclear energy at that time, relevant regulations from the country of origin of installed equipment (i.e., the USA), or applicable recommendations from the International Atomic Energy Agency should be used in cases in which appropriate national regulations were insufficient or non-existent. It was optimistically foreseen that the investors (i.e.,

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[i] *Effective dose* is a quantity used to describe the consequences of exposure of human being to ionising radiation and considers external and internal exposure. It is used for low doses and represents the measure of probability for the occurrence of radiation-induced cancer and genetic effects. The unit for effective dose is the sievert (Sv). For reference, the global annual average is 2.4 mSv.

Slovenia and Croatia) would find the solution and decide on the location of the final repository for all future radioactive waste from NEK before commissioning the plant.

The limit for the effective dose established in the Location Permit has never been changed and remains valid. In 1988, an additional requirement was added in connection with the construction of temporary storage for Low and Intermediate Level Radioactive Waste. According to this requirement, the annual effective dose from external radiation at the NEK fence shall not exceed 200 µSv. The storage is still in operation.

During the construction period of NEK, rules were adopted related to monitoring and limits of contamination in the environment and exposure limits for the population from different practices. In the decision regarding the approval of regular operation of NEK (February 1984), additional restrictions regarding liquid effluents from NEK to the Sava River were set:

- For all radionuclides except ^{3}H (Tritium), ^{14}C and dissolved gases: 200 GBq per year and 80 GBq in a calendar quarter,
- For ^{3}H: 20 TBq per year, 8 TBq in a calendar quarter.

Annual limits for activity releases in gaseous releases were not set explicitly in the decision. Instead, NEK was required to provide computational models for the dilution of releases during normal operation and the dispersion of releases during the potential accident that could serve as a basis for the dose calculation to the public. In response to this requirement, NEK has developed models based on the recommendations from the US Nuclear Regulatory Commission that were used for establishing the annual limits for activities in gaseous releases from NEK. The annual limits for activities in gaseous releases were officially confirmed in 1989 and were as follows:

- For ^{131}I (Iodine): 18.5 GBq per year,
- For aerosols (radionuclides with $T_{1/2}$>8 d): 18.5 GBq per year,
- For noble gases: the annual limit is calculated from the dose limit (50 µSv per year) on the border of the restricted protective zone according to adopted models,
- For ^{3}H and ^{14}C there were no explicit limits for released activities.

These limits were in force until 2007, when the limits for liquid effluents were modified to allow for a longer (18 months, previously 12 months) fuel cycle in NEK. The annual limit for the ^{3}H release was increased, while the limit for other liquid releases was decreased. The new (and still valid) limits for liquid effluents are:

- For all radionuclides except ^{3}H, ^{14}C and dissolved gases: 100 GBq per year, 40 GBq in a calendar quarter,
- For ^{3}H: 45 TBq per year,
- For ^{14}C: no explicit limit.

Since 2007, the limits for gaseous releases and liquid effluents are a part of the Radiological Effluent Technical Specifications (RETS), a document related to radiological safety, monitoring, effluents, and reporting requirements. This document must be approved by a regulatory body for a valid operating licence and must be continuously maintained to reflect possible modifications and compliance with legal requirements.

We can see that “the history” of dose and radioactive release limits for NEK is quite short and, except for the adjustment related to the introduction of 18-month fuel cycle, there has been no change of limits from the beginning of NEK operation. The reason is not in the indifference and passivity of the authorities but the professional knowledge of involved experts and adoption of internationally approved approach during the initial licensing process and initial operation of the plant.

The author aims to review available data on emissions from NEK and compare it with available data on doses of the population in the NEK neighbourhood. We made such a comparison ten years ago, *[1]*, and we would like to update data and verify conclusions from the previous paper.

3 MONITORING

The NEK must provide proof that it is complying with the imposed restrictions. Therefore, it is obliged to measure the emissions of radionuclides and report them to the regulatory body, and also to provide an independent assessment of effects to the environment and population. Monitoring, therefore, consists of the measurements of the plant releases (a measurement of emissions), sampling, and measurements in the plant neighbourhood (a measurement of immissions in the environment), evaluation of these measurements, as well as total dose assessment for members of the public based on collected data and/or computational models. Objectiveness and validity of results have been ascertained with the involvement of independent and authorised organizations (experts) in the monitoring implementation, evaluation of data and dose assessment.

Requirements for monitoring in environment and emissions reporting have been in force from the very beginning of the operation of NEK. The programme of sampling and measurements, which has been verified and approved annually, has been based on a generic (and extensive) programme in the relevant rules from 1986 and the rules from 2007. The main difference between these rules is not in the content of the monitoring programme itself but the introduction of the additional requirements related to the quality and reliability of measurements. The rules were updated in 2018 when Council Directive 2013/59/Euratom was adopted in Slovenian legislation.

Monitoring in the environment covers a 12 km circle around the plant and extends 30 km downstream of the River Sava. It includes:

- external dose measurements with passive and active detectors,
- sampling and measurement of radioactivity in the air (aerosols and iodine),
- sampling and measurement of radioactivity in the river Sava (water, sediments, fish),
- sampling and measurement of soil,
- sampling and measurement of drinking water (wells and water supplies),
- sampling and measurement of atmospheric precipitations and deposits,
- sampling and measurement of food and milk (locally produced).

In Figure 1, sampling locations for monitoring are presented (from *[2]*). Comparison of this figure with the figure from the report, *[3]*, from 1991 reveals that the number of sampling points has not changed substantially from the late 1980s, and that sampling positions are not changed for the majority of "old" locations.

In addition to sampling, monitoring also includes external dose measurements with passive TL detectors and continuous active detectors (energy compensated GM tubes) for external dose rate measurements. While the active detectors are a part of the early warning system in Slovenia and were not operational until the late 1990s, the network of TL detectors around NEK (57 locations, up to 10 km from the plant) has just slightly been changed from the 1990s.

In support of monitoring and emergency preparedness, one meteorological station is situated inside the plant and three in the vicinity of the plant. The data from these stations serve for computational modelling required in dose assessment.

All data from monitoring are collected and evaluated through authorised organizations on a regular basis. Evaluated data from environment monitoring and data on NEK emissions are used for the dose assessment of members of the public in the neighbourhood of NEK. Evaluated monitoring data, as well as results of dose assessment, are published on an annual basis as a report, which is also publicly available through the NEK internet site.

Data from continuous detectors in the early warning system from all parts of Slovenia are publicly available on the internet, *[4]*.

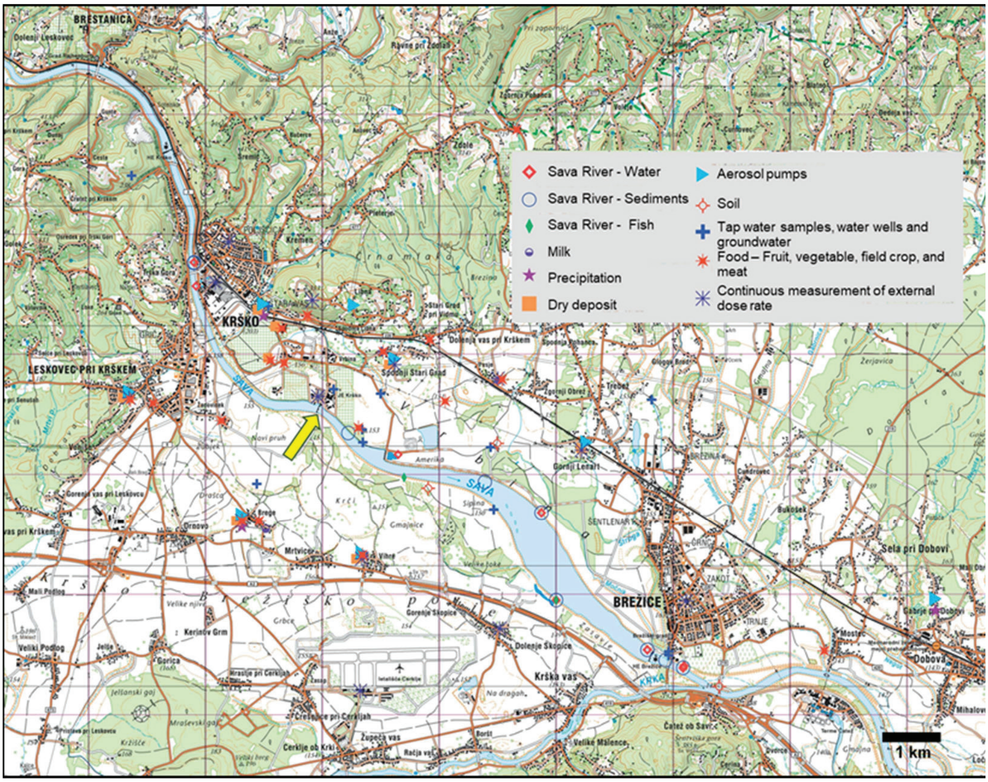

Figure 1: *Current map of NEK neighbourhood with the distribution of places where different samples are regularly taken as a part of NEK monitoring, [2]. The position of NEK is marked with an arrow.*

4 OVERVIEW OF EMISSIONS FROM NEK

As stated, for the purpose of monitoring, NEK provides data on released activities in all liquid effluents and gaseous releases from the beginning of operation (first criticality). All releases are continuously measured and data are collected. Released activity depends on many factors, but the most important factors are fuel quality, leaks from the primary system, produced power, trips and power excursions, the efficiency of liquid and gaseous waste processing, the chemistry of the primary system, and also an implementation of outages, and remediation of possible equipment failures.

4.1 Liquid effluents

The history of annual activity releases in liquid effluents of NEK from 1983 to 2019 (data from *[5]*) is presented in Figure 2. We can see that the annual releases of fission and activation products (Figure 2a) have been steadily decreasing since the first years of operation. However, even the highest value (13.4 GBq in 1985) was a mere 6.7% of the annual limit (200 GBq per year until 2007). The values in 2008 and 2009 (the last one not presented in the figure) were under 100 MBq (less than 0.1% of the valid annual limit 100 GBq per year). The main contributors to annual releases were (and still are) activation products such as ^{58}Co and ^{60}Co (Figure 2c), and fission products ^{134}Cs and ^{137}Cs (Figure 2d). The released activity of ^{131}I (Figure 2b) was always at least ten times lower and, in the last two decades, appears in the liquid effluents only occasionally.

While the annual released activity of almost all radionuclides in liquid effluents has decreased substantially since the beginning of the operation, this does not apply to ^{3}H (Figure 2e). The reason is in a direct connection between ^{3}H production and energy production in NEK. The released activity was always close (40% to 80%) to the valid limit (20 TBq until 2007). In connection with the introduction of the 18-month fuel cycle, the Slovenian Nuclear Safety Administration has changed the limit to 45 TBq.

4.2 Gaseous releases

The history of annually released activities in gaseous releases of NEK from 1983 to 2019 (data from *[5]*) is presented in Figure 3. The most important radionuclides are noble gases (^{133}Xe, ^{133m}Xe, ^{41}Ar), which are limited indirectly through effective dose on the NEK fence, and ^{3}H (no limit). The highest releases of noble gases (Figure 3a) were in the mid-1990s (up to 25 TBq), while the current values are around 1 TBq.

Similarly as in liquid effluents, an annual release of ^{3}H in gaseous releases does not show any decrease (Figure 3b). After the introduction of an 18-month fuel cycle, the annually released activity is around 2.5 TBq. History of releases of ^{14}C (Figure 3c), in contrast, shows an initial decrease from the first value of 400 GBq (1985) in the 1980s but has not substantially changed in the last two decades. The annual release is around 100 GBq.

Annual releases of ^{131}I (not presented in Figure 3) have been under 1 MBq since 2001. In the 1990s, these values were much higher, up to 2.7 GBq in 1996, which is 15% of the limiting value (18.5 GBq per year). In 1996, to our knowledge, was also the highest release activity of aerosols (20 MBq, 0.1% of limiting value). Annual activity releases of aerosols in the last decade are about MBq or less.

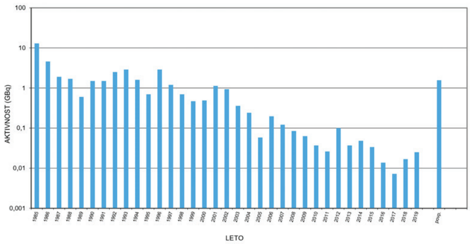

Figure 2a: Fission and activation products. The annual limit (200 GBq) was changed to 100 GBq 2007.

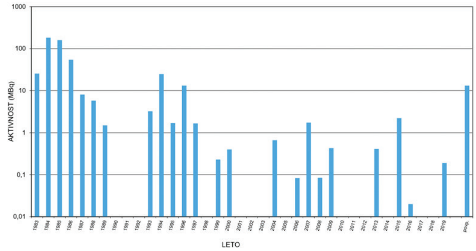

Figure 2b: Iodine (^{131}I equivalent). The release is limited by the total limit for fission and activation products.

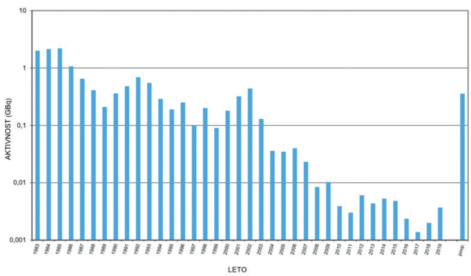

Figure 2c: Cobalt (^{60}Co equivalent). The is limited by the total limit for fission and activation products.

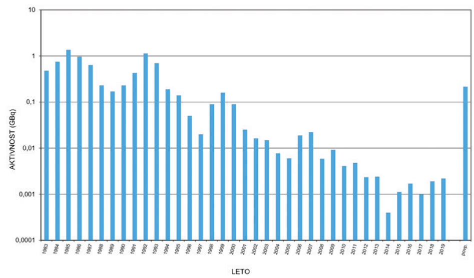

Figure 2d: Caesium (^{137}Cs equivalent). The release is limited by the total limit for fission and activation products.

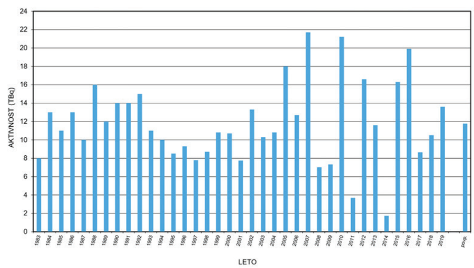

Figure 2e: ^{3}H (Tritium). The annual limit (20 GBq) was changed to 45 GBq in 2007.

Figure 2: *Annual activity releases in liquid effluents of NEK for 1983-2019 (from [5]).*

Annual releases of ^{14}C are presented in Figure 3c. Releases were much higher in the 1980s than in the 1990s and later, when annual gaseous releases were 0.1 TBq per year or less. An annual limit has not been established for this radionuclide (the same also applies to other nuclear power plants) and the impact on population doses was not properly evaluated until 2002.

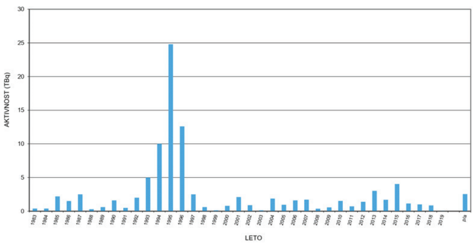

Figure 3a: Noble Gases. The release is limited indirectly through a limited effective dose (50 µSv per year) on the border of the restricted area.

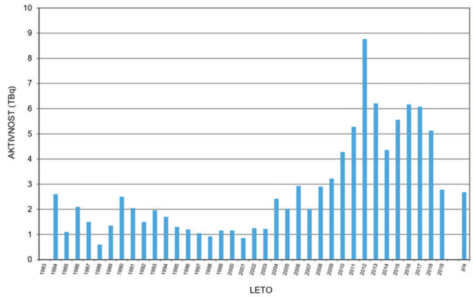

Figure 3b: ^{3}H (Tritium). The annual limit has not been established.

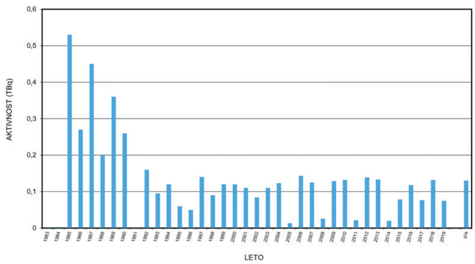

Figure 3c: ^{14}C. The annual limit has not been established.

Figure 3: *Annual activity releases in gaseous releases of NEK from 1983 to 2019 (from [5]).*

5 COMPARISON OF ASSESSED DOSES

Data from the monitoring of emissions from NEK and immissions of radionuclides into the environment serve as a starting point for the evaluation of doses to the general population in the neighbourhood of NEK. This assessment is done by authorised organisations and finally submitted to the regulatory body through NEK. We will not discuss in detail methods or methodology of dose assessment in the past but merely present the data compiled from the available report on the evaluation of the radiological monitoring of the Krško Nuclear Power Plant in the 1980s, *[3]*, and available national annual reports on the radiation and nuclear safety in the Republic of Slovenia, *[6]*.

5.1 Doses from liquid releases

In Figure 4, doses from NEK liquid releases are presented with total doses from all releases (including gaseous). We can see that until 1994 almost all dose from NEK was associated with liquid releases. It was related to local fishermen and their families, and the most important radionuclide for this exposure pathway is ^{137}Cs.

However, we must point out that the total dose is not always a realistic term. It is not always possible to simply add doses from different exposure pathways since the complete dose assessment includes dose estimates for different and distinct critical groups of people. Comparison with data on Figure 2 can therefore hardly support the observable increase of annual doses in the first half of the 1990s in Figure 4.

Doses from liquid releases were practically constant through the second half of the 1990s and diminished for almost an order of magnitude in 2002, which also applies to the total dose from NEK. Both changes were the consequence of the changed methodology for dose assessment.

If we consider the last decade, the contribution of ^{14}C to doses from liquid releases and to total doses was prevailing from 2013 to 2016 but became minimal in 2017.

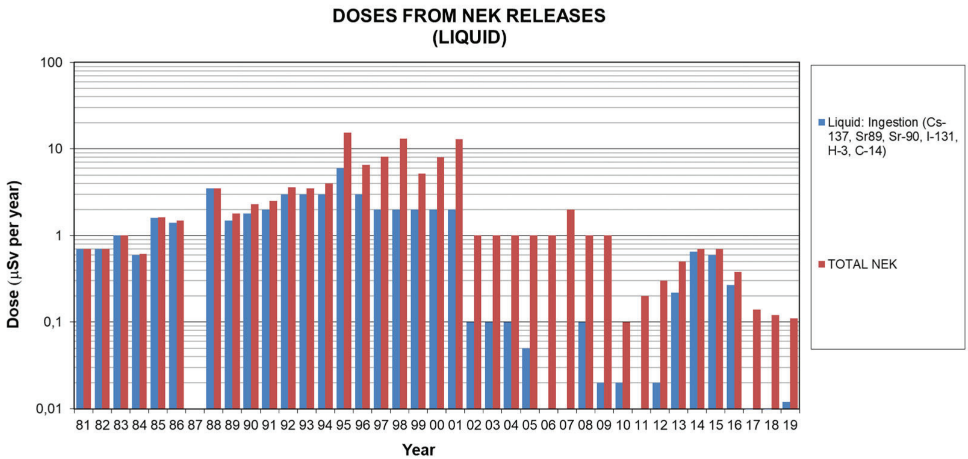

Figure 4: *Annual doses of the population in the NEK neighbourhood due to liquid releases ([3], [6]).*

5.2 Doses from gaseous releases

Available data on annual doses from gaseous releases from NEK are presented in Figure 5. After 1994 (and until 2001), the most important exposure pathway was external exposure from the cloud of noble gases. Data in Figure 3a reveals that the release of noble gases was high in 1993 to 1996, but not in 1997 and afterward. However, assessed doses from noble gases were high until 2001.

After 2001, the most important pathway was the ingestion of radionuclides from gaseous releases transferred to vegetation. The most important radionuclide in this respect is ^{14}C, which becomes a part of the food chain. ^{14}C was not included in the evaluation before 2002, and its contribution was not regularly measured until the last decade. Contribution to the dose in 2002 (and in the following years) was estimated based on analogous results with other nuclear power plants. This was also the consequence of the methodology change mentioned in the discussion of the doses from liquid releases. In this period, the inhalation dose from ^{3}H was comparable to the estimated dose from ^{14}C.

In the previous decade, the doses from gaseous releases were related mostly to ^{14}C. These doses were assessed from measurements in the environment and could be considered realistic values for the NEK neighbourhood.

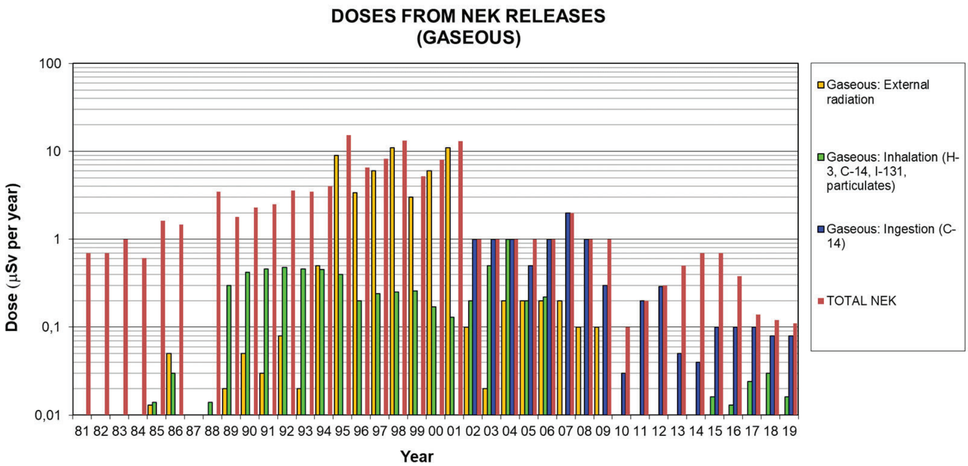

Figure 5: *Annual doses of the population in the NEK neighbourhood due to gaseous releases ([3], [6]).*

5.3 Importance of pathways

In Figure 6, doses from liquid and gaseous releases are presented together with estimated total doses from NEK releases. The scale in the figure is linear to enable easier comparison of release pathway importance through the period from 1981 to 2019.

In Figure 6, we can see that until 1994, total annual doses were approximately 2 to 4 µSv per year. The most important contribution was the ingestion dose due to liquid effluents. From 1995 to 2001, total doses were from 5 to 15 µSv per year, but the most important contribution comes from external exposure to gaseous releases (up to 11 µSv per year). This was the external exposure to radiation from a cloud of noble gases released from the plant. The assessed ingestion dose due to liquid releases was still high (2 to 6 µSv per year).

From 2002 to 2019, total doses are (less than) 1 to (less than) 2 µSv per year. The most important contribution is the ingestion dose due to the release of ^{14}C. The estimate considers the transfer of ^{14}C from air to local vegetation and food chain and ^{14}C in liquid releases which is consumed by local fishermen. All other pathways contribute much lower doses.

We can also see that estimated doses have never come close to the authorised limit. Even the highest estimated dose (from 1995) represents only 30% of the authorised limit.

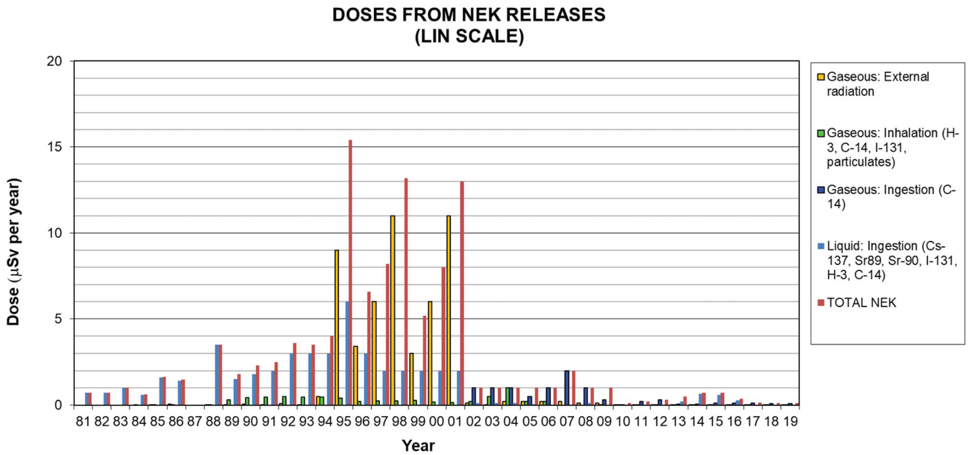

Figure 6: *Annual doses of the population in the NEK neighbourhood due to all releases ([3], [6]). The scale is linear to enable easier comparison of release pathways importance.*

5.4 Comparison with natural background and global contamination

Measurements of radioactivity in the neighbourhood of NEK provide us also with the data that enable us to assess natural radiation background. Similar data are available also for Ljubljana and other parts of Slovenia.

Figure 7 presents annual external exposures to radiation measured with the TLDs in the neighbourhood of NEK, average external exposures in Slovenia (also measured with TLDs) and estimated annual external doses due to contamination from nuclear tests and Chernobyl releases in the NEK neighbourhood. The highest contribution of contamination to external dose was in 1986 (after Chernobyl) when the annual external dose from contamination was estimated to 325 µSv. We can see that the annual external dose, as measured with the TLDs in the NEK neighbourhood, was regularly slightly below the Slovenian average. We can also see that the contribution of external radiation to dose was significant only in the 1980s.

In Figure 8, the total annual doses to the population in the NEK neighbourhood from NEK operation are compared to total doses from natural sources (natural background) and total doses due to contamination from nuclear tests and Chernobyl releases. We can see that measured natural background (2440 to 2530 µSv per year, which is practically the same as measured in Ljubljana) was always the main contributor to the total dose of population. In 1986, when the Chernobyl accident happened, the contribution of total contamination was 570 µSv (in Ljubljana even 720 µSv!), while is the estimated current value is about 10 µSv per year. The highest estimated annual dose from NEK (15.4 µSv in 1995) was 31% of the administrative dose limit and only 0.6% of natural background, while the (overestimated) annual doses from recent years (less than 0.15 µSv) present only 0.3% of administrative dose limit and 0.006% of natural background.

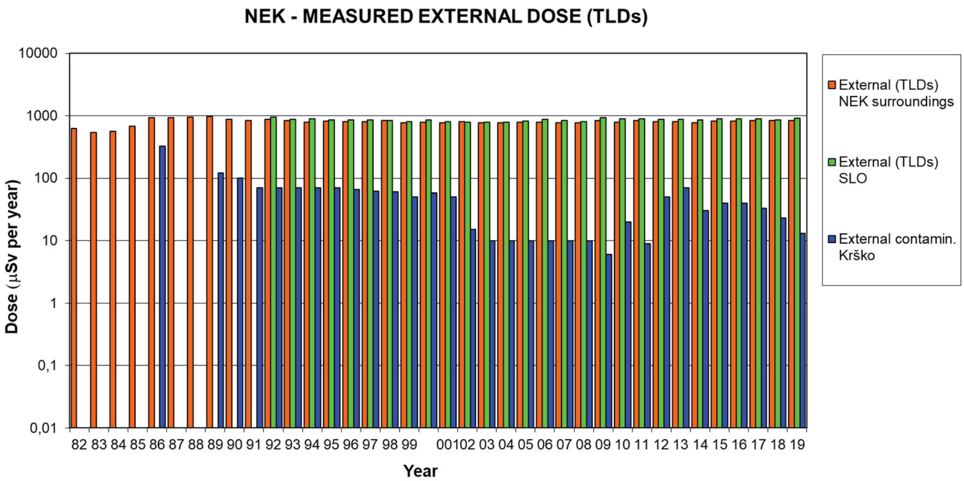

Figure 7: *Comparison of average annual external doses measured in the neighbourhood of NEK (57 TLDs), average external doses measured in Slovenia to annual external doses contamination estimated from measurements of soil contamination in NEK neighbourhood ([3], [6]).*

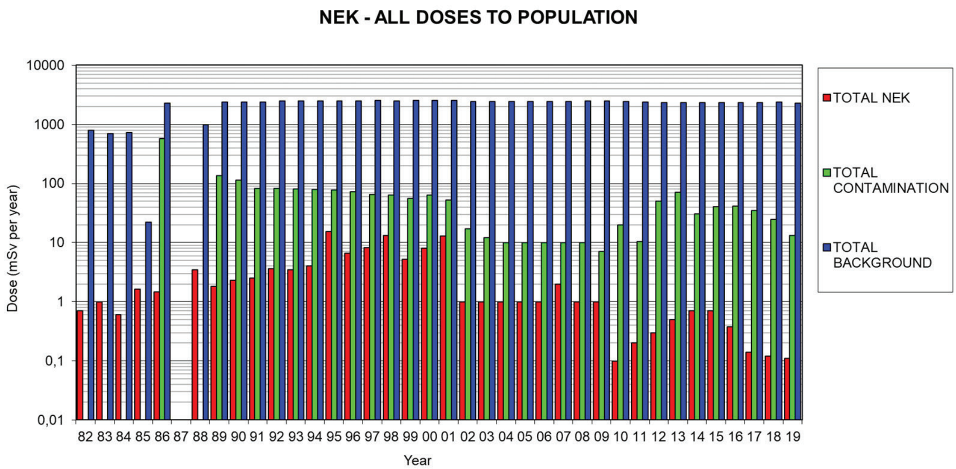

Figure 8: *Comparison of annual doses of the population in the neighbourhood of NEK from exposure to natural sources, general contamination from nuclear tests and Chernobyl releases, and nuclear power plant.*

6 CONCLUSIONS

We have seen that initial limitations imposed on the operation of NEK remain valid and, except in the case of liquid discharge of ^{3}H, there was no need to modify them.

NEK successfully operates within these limitations with releases, which are well below the limiting values.

The scope and extent of monitoring have not changed substantially from the mid-1980s; therefore, old data remain compatible with recent measurements.

We can recognise different approaches to dose evaluation in certain periods of monitoring history. Therefore, doses from different periods are not always directly comparable.

According to the available data, except in the late 1990s, estimated doses to the population were always only a few percent points of the authorised dose limit, which is 50 μSv per year.

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