FACTORS CONTRIBUTING TO THE REDUCTION OF OCCUPATIONAL EXPOSURES AT DUKOVANY NPP

Karla Petrová, State Office for Nuclear Safety, Senovazne namesti 9, 11000 Prague, Czech Republic, karla.petrova@sujb.cz,
Libor Urbančík, State Office for Nuclear Safety, Regional Center Brno, tr. kpt. Jarose 5, 60200 Brno, Czech Republic, libor.urbancik@sujb.cz,
Vladimír Kulich, CEZ plc, Duhová 4, Prague, Dukovany Nuclear Power Plant, 67550 Dukovany, Czech Republic, vladimir.kulich@cez.cz,
Dagmar Fuchsová State Office for Nuclear Safety, Regional Center Brno, tr. kpt. Jarose 5, 60200 Brno, Czech Republic, dagmar.fuchsova@sujb.cz

Abstract

The recent ISOE issue of the ISOE Information Sheet, the European Dosimetric Results for 2006 as well as other official ISOE papers including the journals Occupational Exposures at Nuclear Power Plants, Annual Reports of the ISOE Programme, illustrate the fact that collective doses at the Czech nuclear power plants are very low and maintained at a stable level for a long time. Progress to date has placed the Czech Republic reactors at the top of the group of light and heavy water reactors in the world. Because of owning these results, the Czech Republic has a special responsibility, which involves explaining these results to the OECD nuclear society (OECD NEA ISOE), dealing with these results inside that society, and sharing experience related to dose reduction with both the ISOE and IAEA communities. Considering the fact that the Temelin NPP started its commercial operation in 2002, the main part of these results was obtained from the first Czech nuclear power plant, the Dukovany NPP. Achievement of good results is not a matter of common occurrence but rather comes from a concurrence of many factors.

This paper describes the causes of achieving such low collective doses and the ways used for a further optimization process reducing occupational exposure at the Dukovany NPP from the beginning of operation up to now. The objective of this contribution is to explain the approaches leading to reduced occupational radiation exposure, measures which have been implemented and what is needed for the maintenance of excellent results in the future. It is possible to identify three main areas and eight main sources affecting collective dose values. There are one objective and two specific causes for low exposures:

1. Objective cause:
   - General arrangement
   - Structural materials
   - Fuel integrity
2. Specific cause influenced by the state regulation:
   - Legislative support
   - Operational safety culture
   - Well-thoughtout system of radiological monitoring
   - Effective radiological event feedback
   - Effective education and training
3. Specific cause uninfluenced by the state regulation:
   - Modified water chemistry of the primary circuit adopted by the licensee
   - Licensee's system of radiation work debriefing

All the items specified above contribute to a unique concurrence of circumstances leading to the constantly low occupational exposures at the Czech nuclear power plants. The paper discusses all factors involved in these good results.

1. Introduction

The following message has been published in the Information System on Occupational Exposure of the OECD Nuclear Energy Agency in 2004 [1]: *"During the period, VVER reactors from the Czech Republic showed a low average outage dose, which falls below 200 man·mSv for the first time."* In the light of this message it has been recognized that, in terms of safety performance indicator Collective Effective Dose, the Czech Republic ranks very high in the world within the category of light and heavy reactors. An analysis has been performed by the State Office for Nuclear Safety (hereinafter referred to as the “SONS”) to explain the existence of such low doses at the Czech nuclear power plants (hereinafter referred to as the “NPP”) with the aim of strengthening this trend. Several causes influencing the value of this indicator have been found. It is possible to categorize these causes into three areas. The first area includes objective causes, the second covers specific causes influenced by the state regulator SONS and the third which is beyond SONS’s competence, comprises specific causes uninfluenced by state regulation.

2. <u>Objective cause</u>

2.1. General arrangement

The Russian project of pressurized water reactors (hereinafter referred to as the “PWR”) also known as VVER or WWER is a unique type of PWR and is quite different from unified western PWR types. Main differences of the Russian VVER concept are as follows:

2.1.1. More open space inside primary part. Components and equipment of the VVER primary circuit are not as close to each other as in classic PWRs.

2.1.2. Horizontal steam generators. Huge water capacity of the primary circuit is provided.

2.1.3. 200% redundancy in facilities of the Emergency Core Cooling System (hereinafter referred to as the “ECCS”). VVER ECCS can hold a huge water volume similarly to the primary circuit space.

The spacious facility mentioned above in the end reduces contact of workers with radioactive equipment inside containment during outages for refueling and maintenance. This result emerged from a discussion with experts from Finland in Brno and Dukovany in 2007. The Finnish VVER Loviisa is practically the same NPP type as Dukovany NPP with very similar dose rates from the primary facilities; maintenance activities are also similar in both NPPs, but differences in collective effective doses between both NPPs are probably due to closer space under the classic Loviisa NPP containment. The Dukovany NPP is VVER 440, type V213, and it is provided by the hidden containment built into the NPP construction. From the general arrangement of both NPPs it is apparent that the Dukovany NPP has a more open workplace layout in the primary part. The Slovak (15–year mean: 0.56 $man\cdot Sv\cdot year^{-1}$), and Hungarian results (15–year mean: 0.6 $man\cdot Sv\cdot year^{-1}$) for the indicator collective effective dose are similar to the Czech value (15–year mean: 0.31 $man\cdot Sv\cdot year^{-1}$) and the three NPPs are the same type of VVER, V213, and they have significantly lower values of that indicator than Loviisa NPP having the 15–year mean 0.96 $man\cdot Sv\cdot year^{-1}$. It means that the collective effective dose is approximately two times higher for the Loviisa NPP than for the mean of Czech, Slovak and Hungarian values. The situation of other VVERs is quite different because of another type of VVER; Armenian, Ukrainian, Bulgarian, etc. NPPs are mainly V230 type.

2.2. Structural materials

Activated corrosion products are the first component of the radioactive inventory to which radiation workers are exposed. Radionuclide ^{60}Co appears to be the most problematic radionuclide of all because of its physical properties. Considering that the concentration of radionuclide ^{60}Co in the primary coolant depends on content of metallic cobalt in primary circuit structural materials, the concentration of cobalt in steels is of primary importance. Therefore, ŠKODA Works, the developer of Dukovany NPP, laid stress on low cobalt content in structural materials from the beginning of building the NPP. All structural materials of the primary circuit were analyzed for cobalt content and the results were processed into technical standards. Now, these technical standards and derived technical conditions are part of the FSAR (Final Safety Analysis Report). Measurements of cobalt content in primary construction steels show that it varies in the range of 0,017 – 0,021 %, whereas the Czech technical standards allow < 0.05 %. Low cobalt content has been controlled for each structural material which could be in contact with the primary coolant. Thus the low cobalt content in steels contributes to its low content in corrosion layers and, consequently, to a low cobalt concentration in primary circuit water. Table 1 presents typical values of volume activities in the primary circuit of the Czech NPPs.

Table 1 – Primary coolant samples from Dukovany NPP Unit 1 and Temelin NPP Unit 1

Radionuclide	Volume activity [Bq/l]	
	Dukovany NPP	Temelin NPP
^{110m}Ag	20	166
^{58}Co	140	54
^{60}Co	64	36
^{51}Cr	330	925
^{59}Fe	65	108
^{54}Mn	360	62
^{95}Nb	93	78
^{95}Zr	73	176
^{122}Sb	< 3	11120
^{124}Sb	< 2	615

From Table 1 it is evident that ^{60}Co concentrations are really low at the units of both NPPs. Differences in concentrations of antimonies are not known yet. Other radionuclides in Table 1 are comparable. Fig. 1 shows the same example for Dukovany Unit 4 during 2006.

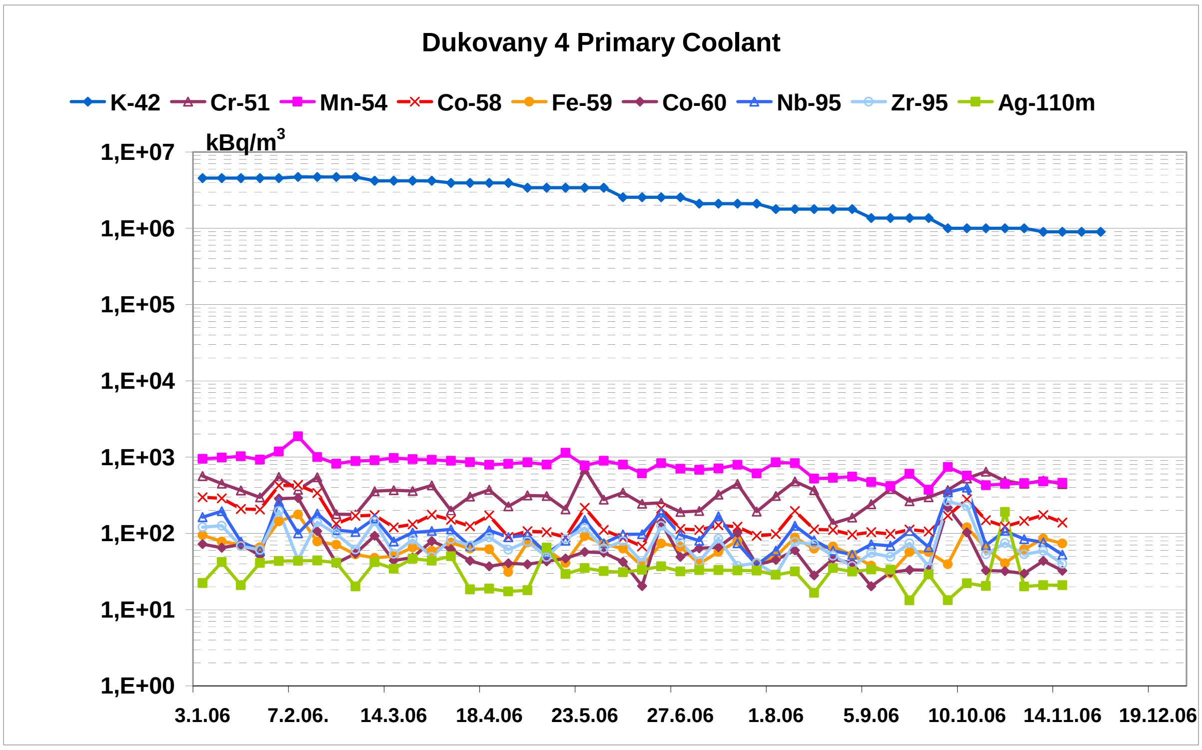

Fig. 1 – Volume activities of radionuclides in coolant of the Dukovany NPP primary circuit, Unit 4, 2006

Figs 2 (mean values of hot legs surface activities) and 3 (mean values of cold legs surface activities) give concentrations of the radionuclides present in corrosion layers expressed as surface activities of each particular radionuclide. The measurements presented in the three figures were all made in Dukovany NPP Unit 4 and correspond to the results from all other nuclear units in the Czech Republic.

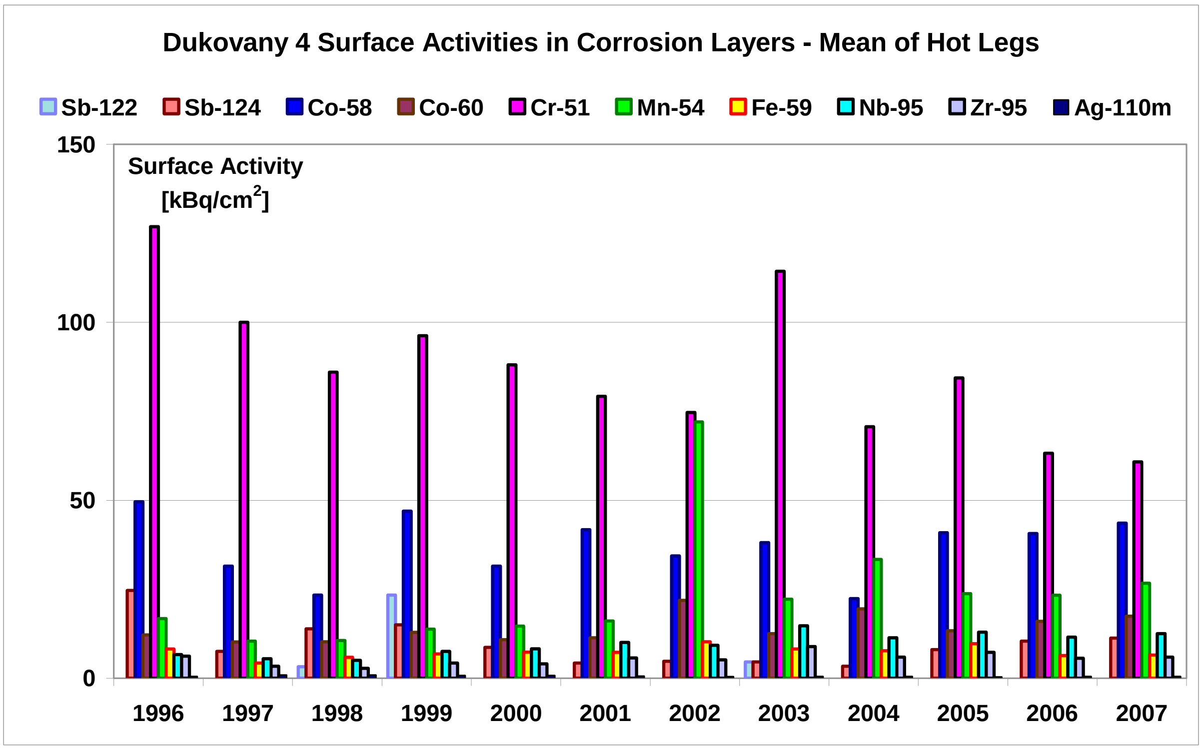

Fig. 2 – Surface activities of essential radionuclides on primary circuit surfaces of the Dukovany NPP, hot legs of Unit 4, 1996 – 2007

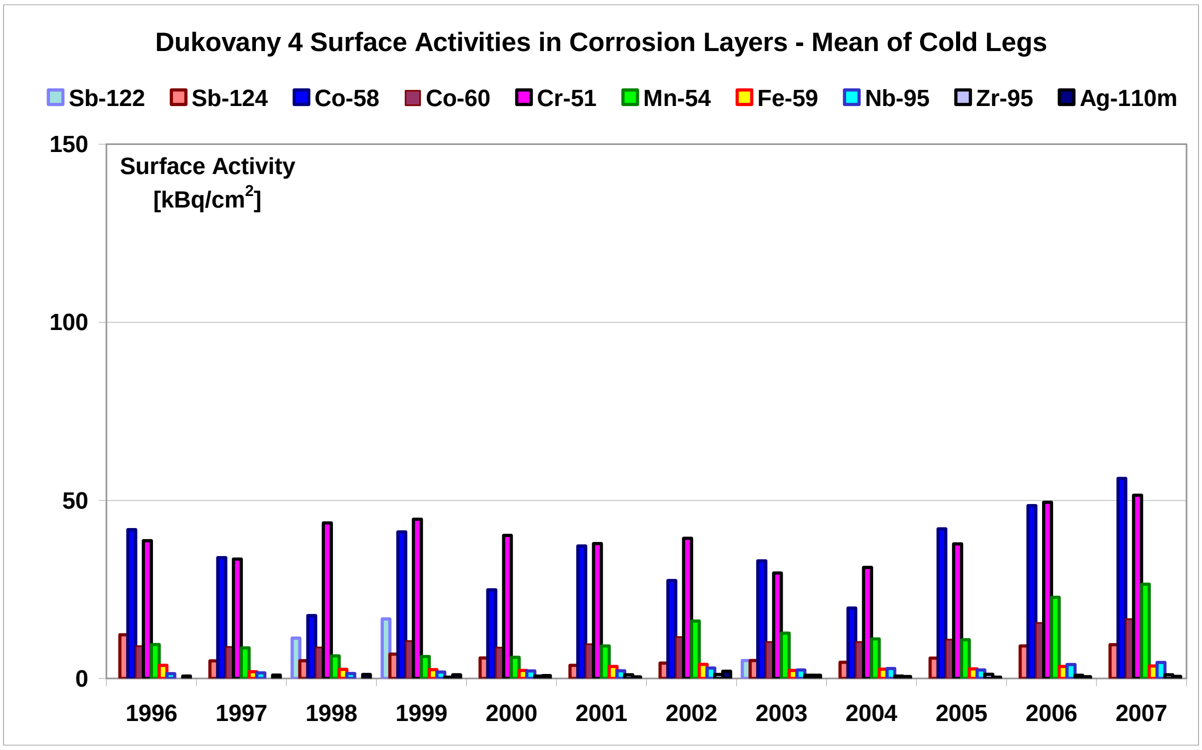

Fig. 3 – Surface activities of essential radionuclides on primary circuit surfaces of the Dukovany NPP, cold legs of Unit 4, 1996 – 2007

2.3. Fuel integrity

Fission products constitute the second of objective reasons for radiation workers' exposure, and this is significantly influenced by fuel integrity. Fuel integrity is assessed by means of the indicator Fuel Reliability Indicator (hereinafter referred to as the "FRI") which is extensively used as a tool measuring leakages of fission products through the fuel cladding. Fig. 4 shows FRI values as the fuel integrity rate at Dukovany and Temelin NPPs.

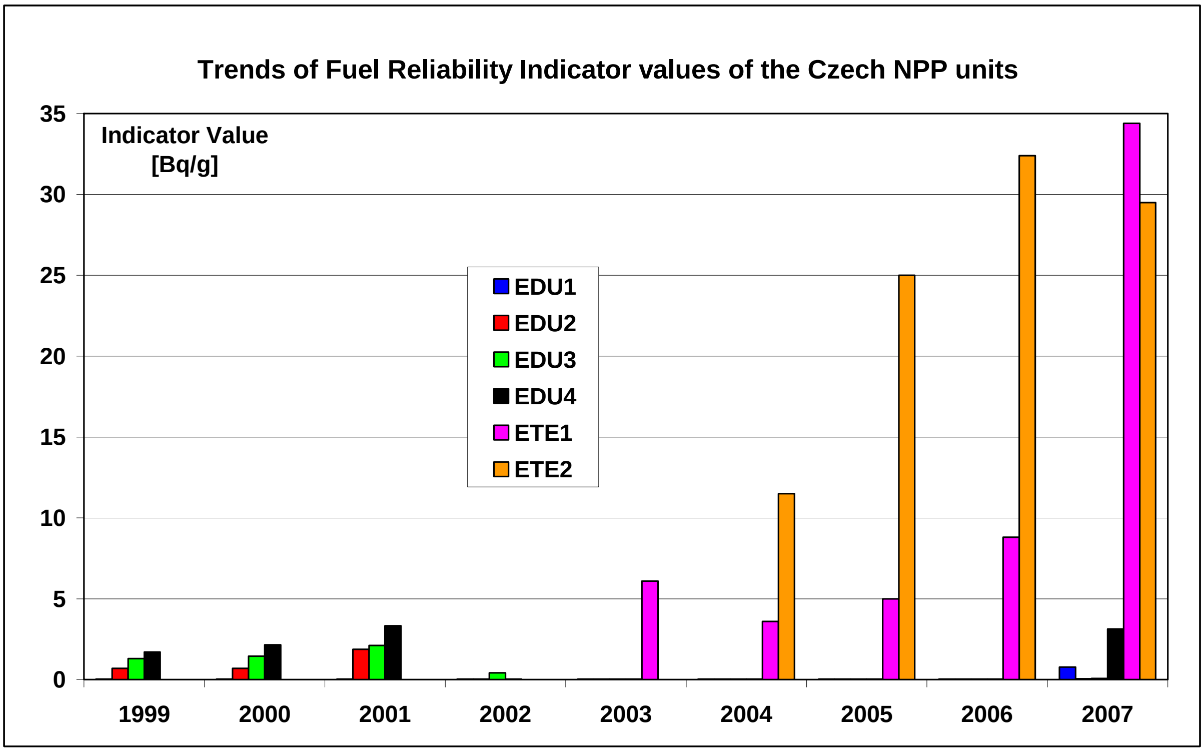

Fig. 4. FRI values at Dukovany and Temelin NPPs during 1999 – 2007

This implies that nowadays fuel at the Dukovany NPP is tight, and fuel at the Temelin NPP is operated with small gaseous leakages similarly to the Dukovany NPP at the beginning of its operation. Strict measures to prevent leaks from fuel have been adopted at the Temelin NPP in a way similar to that used at the Dukovany NPP years ago.

3. <u>Specific cause influenced by the state regulation</u>

3.1. Legislative support

In order to maintain the favorable circumstances leading to a low cobalt concentration in structural materials of the Czech NPPs the SONS has adopted a special chapter in the decree on technical safety in nuclear facilities related to cobalt contents in these materials. Based on legislation, each structural material used in the Czech NPPs is approved of and controlled for cobalt content. This rule naturally applies to the construction of any new NPP. This measure is in accordance with the IAEA Safety Guide [2].

Another example of the state's involvement in reducing workers' exposure to radiation is the presence of radiation officers directly at classified activities in controlled areas of the Czech NPPs. In 2002 and 2005 the SONS adopted amendatory acts to the existing decrees that strengthened the role of radiation officers. The SONS believes that this legislative intervention has influenced further dose reduction at the Czech NPPs (Fig. 8).

3.2. Operational safety culture

The release of materials from the surfaces of PWR primary circuits at a start-up and shutdown is a well-known phenomenon, but details of the mechanism controlling the phenomenon are less well understood. However, it is common knowledge that any change in core power load has an impact on migration of deposits inside the primary circuit. Scrams and events with radiological impacts have influenced dose values, including the collective effective dose. Reduction of scrams and events is a matter of operational safety culture and at the same time it is the matter of exposure reduction. There is no simple indicator revealing a relationship between scrams, events and collective effective dose (hereinafter referred to as the “S”) value, because only low values of collective effective doses are achieved at the Czech NPPs. However, both the SONS and the CEZ plc believe that operational safety culture is a factor strongly influencing the collective effective dose whose low value correlates with low numbers of scrams and events. Table 2 presents all scrams and events including those with a radiological impact. Number of the events with a radiological impact is very small, for INES ≥ 1 none, for INES = 0 one or two per year. Every INES = 1 are technological events without any radiological impact, so far.

Table 2 – Number of events and number of unplanned scrams at the Dukovany and Temelin NPP units

	2000	2001	2002	2003	2004	2005	2006	2007
INES = 0	**21/-**	**17/-**	**12/26**	**13/34**	**12/42**	**19/42**	**14/31**	**19/24**
INES = 1	**0/-**	**1/-**	**2/1**	**1/2**	**0/1**	**0/3**	**0/1**	**1/2**
INES > 1	**0/-**	**0/-**	**0/0**	**0/0**	**0/0**	**0/0**	**0/0**	**0/0**
Scram number	**1/-**	**0/-**	**0/-**	**1/13**	**0/2**	**1/0**	**0/1**	**2/1**

3.3. Well-thoughtout system of radiological monitoring

The Czech legislative framework is corresponding with the European legislation. According to the Community-level provisions, the Czech legislation distinguishes six types of monitoring as follows:

3.3.1. Workplace monitoring
3.3.2. Personal monitoring
3.3.3. Monitoring of discharges
3.3.4. Monitoring of nuclear facility vicinity
3.3.5. Monitoring of fomite clearance
3.3.6. Emergency monitoring

The SONS as well as the CEZ plc each has worked out its own set of safety performance indicators on the basis of the above mentioned types of monitoring. These indicators have been processed with respect to the IAEA TECDOC 1141 [3]. Only Workplace Monitoring and Personal Monitoring are important for the purpose of this paper, and are discussed here. In the schematic diagram (Fig. 5) measuring points at Dukovany NPP Unit 4 are shown; the dose rate values obtained in the period from 1999 to 2007 are presented in Fig. 6.

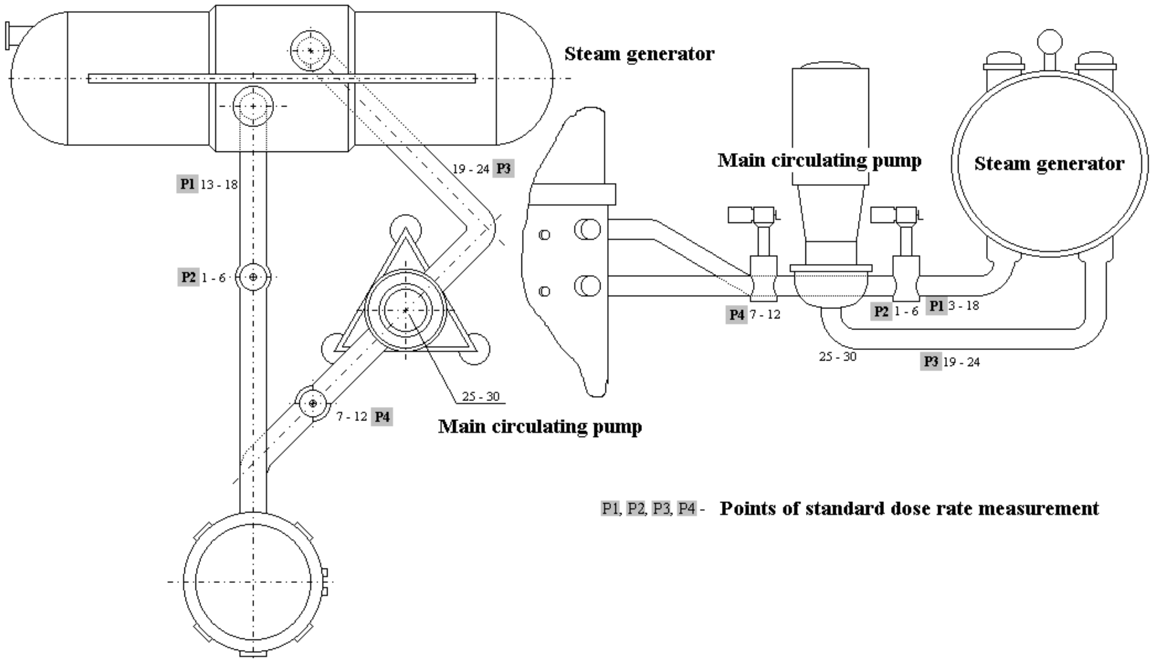

Fig. 5 – Dose rate measuring points according to the Dukovany NPP monitoring program

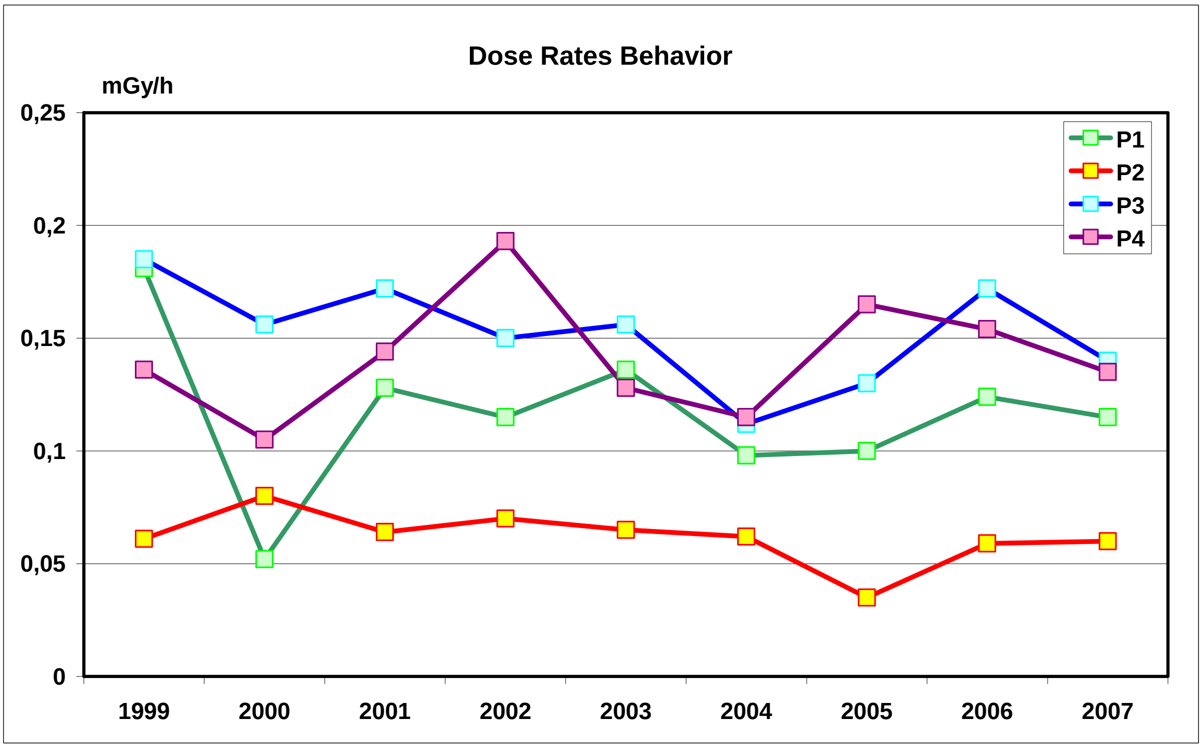

Fig. 6 – Dose rates measured directly on the main circulating loop insulation (insulation thickness, approx. 160 mm) at measuring points P1, P2, P3, and P4, 6th loop, Unit 4, Dukovany NPP, at about 50 hrs after unit shutdown

As seen in Fig. 6, the dose rates from the loop are relatively low. Lower dose rates from the hot leg are a remarkable fact valid for each loop.
The Czech Atomic Act came into force in June 1997. With this event, the real ALARA planning also took effect. The Czech Atomic Act was worked out into implementing legislation, i.e. decrees and governmental regulations. Decree No. 307/2002 Coll., in amendment No. 499/2005 Coll., on radiation protection, has implemented requirements related to the ALARA principle. Since 1997, each licensee has been required to include this principle into his working procedures. According to the Czech legislation, each radiation work should be assessed under the conditions of utilizing an ALARA analysis. Fig. 7 shows ALARA planning at the Dukovany NPP and the courses of real values obtained for all four units.[1]
As follows from Fig. 7, ALARA planning includes both yearly and monthly plans covering, of course, partial planning for the NPP staff as well as the workers of suppliers. The total value of the collective effective dose entering into the planning is the sum of all doses expected to be received by all radiation workers inside the controlled area. As apparent from Fig. 8, in 2002 with the new legislation in the field of radiation protection, a significant change in S values occurred, because the new decrees established the assessment of radiation protection performance with greater accuracy than before. Also the reduction of major radiation works at Dukovany NPP units after reasonable revision linked with ALARA analysis was carried out at the same time. The good results achieved by then became even better.

3.4. Effective radiological event feedback

The mechanism of event feedback is implemented by both the licensee and the regulator but naturally in a different way. The licensee operates Event Commissions, each of them acting at a particular NPP site. Each commission works with two subgroups. The higher subgroup is established by the NPP management for dealing with more important issues, while the lower subgroup is involved in common

[1] The Temelin NPP is not considered here because of its commercial operation shortness and lack of long time data. However, the same approach is adopted in both NPPs, and S values are lower at Temelin NPP than at Dukovany NPP. That way Temelin NPP contributes to the Czech good results in the field of radiation protection.

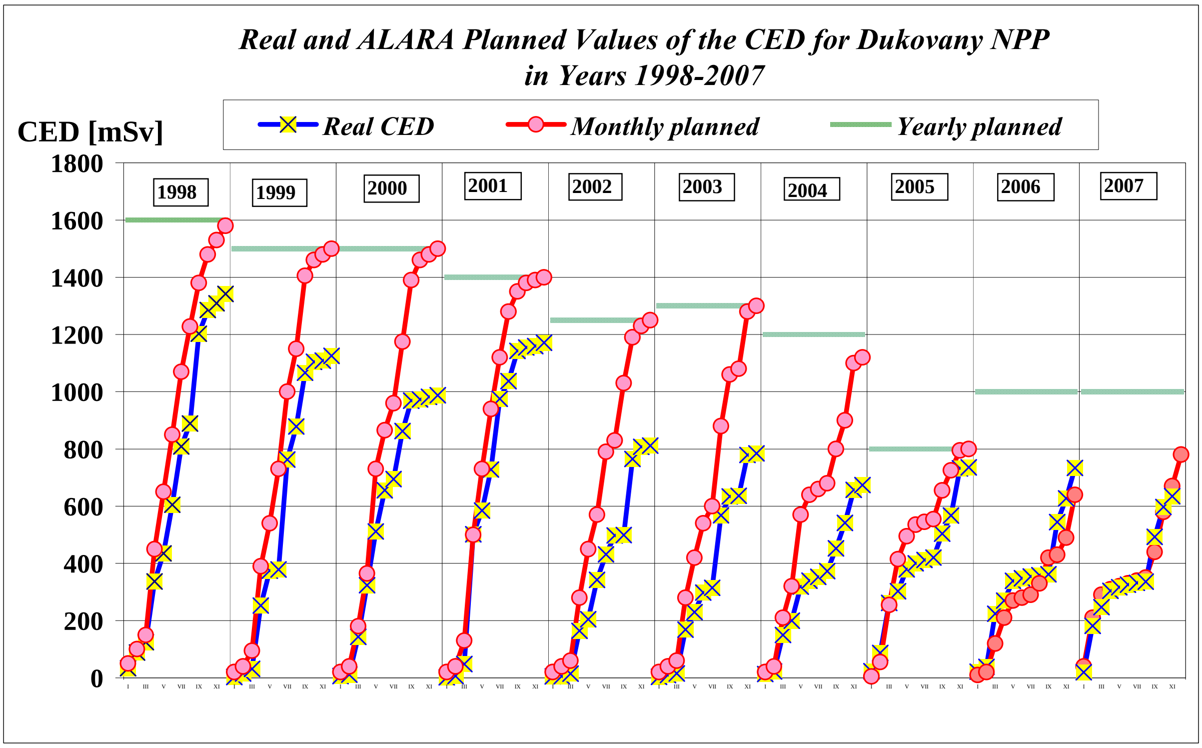

Fig. 7 – Actual and ALARA planned S values for all persons entering controlled areas and for all units at Dukovany NPP during the period 1998 – 2007

matters, which are always INES < 0, i.e., out of the INES scale. The SONS has its own commission assessing independently rightness and thoroughness of the licensee's corrective measures. Both sides use a system of notification and a system of inspections in order to prevent event repetitions or any event occurrence. The total numbers of events has been low and without any significance in terms of safety (see Table 2).

3.5. Effective education and training.

An important factor influencing the achieved radiation protection level at the Czech NPPs is education and training of radiation workers and radiation officers supervised by the SONS. Radiation workers entering the controlled area take a course focused on both radiation protection and right and safe behavior inside the controlled area. The course is completed by a written test provided by the licensee. There are two ranks of radiation officers in the Czech Republic: the lower-rank radiation officer with direct responsibility for radiation protection (RODR) and the higher-rank radiation officer (RO). The former is responsible for the group of radiation workers inside the controlled area and is subordinate to the higher radiation officer who is directly responsible to the SONS. His competences also involve communication with the SONS about daily agenda at NPP sites and preparation of all documents required by the nuclear legislation. Officers of both ranks must attend a special expert course in order to acquire an appropriate qualification by passing a state examination guaranteed by the SONS. The SONS administrative decision for issuing a license to both categories of officers is valid for up to ten years. The SONS has the legal right to take away the license in case of a serious offence in the field of radiation protection. Such a case has not occurred so far.

4. <u>Specific cause uninfluenced by the state regulation</u>

4.1. Modified water chemistry of the primary circuit adopted by the licensee

Original water chemistry of the primary circuit in accordance with the project was based on a rolling high-temperature pH value. This pH value was originally changed with changing values of boron acid and potassium hydroxide in the coolant and pH varied in the range of 6.8 to 7.5. From the operational data it is obvious that the high-temperature pH_{300} value increases from initial 6.8 – 6.9 up to 7.4 – 7.5 at the end of the reactor campaign. The coordinated boron/potassium standard water chemistry did not ensure constant physical-chemical conditions and constant behavior of chemical compounds in the primary coolant during the reactor cycle. The building–up of corrosion layers and subsequent radiation fields from primary equipment was not under control due to an uncontrolled creation of corrosion products and their migration along the primary circuits in the Czech NPPs. Deposit migration along the primary circulating loops uncontrollably increased and decreased radiation workers' exposures. This feature of the VVER water chemistry has been recognized 20 years ago. Corrective measures were adopted immediately after this issue discovery in co-operation with the Nuclear Research Institute Řež plc [4]. A new modified water chemistry control of the primary coolant was proposed with a goal to maintain stable physical-chemical conditions of the primary coolant during the whole reactor campaign. The choice of the optimal pH_{300} value has been the result of plant data analysis as well as mathematic modeling. It is pH_{300} = 7.2 for VVER440, type V213, and pH_{300} = 7.1 for VVER1000, type V320. The modified water chemistry assumes that, at the beginning of the reactor campaign, the total alkalinity value is kept at the maximum allowed level of 20 ppm of K^+ equivalent until this optimal pH_{300} is reached. From this moment till the end of the reactor campaign, such alkalinity is maintained which corresponds to pH_{300} values in the narrow range of 7.2 ± 0.1 for VVER440 and 7.1 ± 0.1 for VVER1000. Measures regulating high-temperature pH values were adopted and implemented at the Dukovany NPP in the years 1992 – 1995. Nowadays, the pH value is kept in a very tight range around 7.2. The Table 3 shows recent specified pH values.

Table 3 – High-temperature pH_{300} value limited in TechSpecs (TS) of the Dukovany NPP

Operational pH value	**1st intervention level for pH**	**2nd intervention level for pH**
7.1 – 7.3	**6.9 – 7.1; 7.3 – 7.5**	**< 6.9; > 7.5**
Optimum 7.2	**Restore specified optimal value up to 48 hrs.**	**Recover value into the 1st intervention level up to 24 hrs.**

In conclusion, the modified water chemistry keeps compounds containing activated corrosion and fission products in poorly soluble and slowly moveable forms. This inhibits the corrosion behavior of structural materials of the primary circuit in the VVER primary coolant. By implementing this

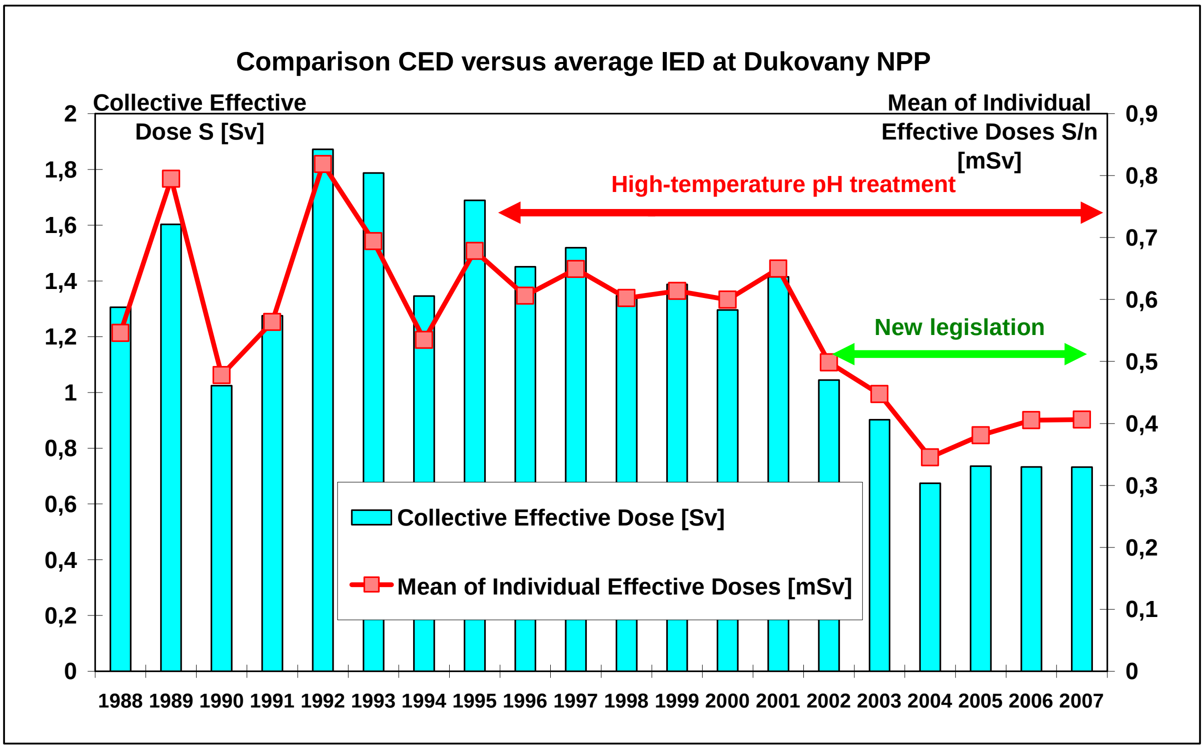

Fig. 8 – Collective effective dose and the mean of individual effective doses at four units of the Dukovany NPP, for IED > 0.05 mSv, from 1988 to 2007

measure the radiation workers' exposure has been reduced. It is interesting to note that the licensee's activities aiming at water chemistry improvement, which had a very positive impact on collective effective dose reduction, have not been initiated by the SONS. However, as required by the Czech legislation, every licensee should regularly follow trends in the R&D. Both the fulfillment of legal obligation by the licensee and the good engineering approach have been met in the case described here. Impacts of those measures are illustrated in Fig. 8. The S (CED) value is influenced by several factors, including the number of radiation workers entering the controlled area (RCA). To eliminate this fact, a new indicator, i.e., the IED mean $\bar{S} = \frac{S}{n}$, was introduced. If the time derivative of the IED mean $\dot{S} = \frac{d\bar{S}}{dt}$ equals 0, $\dot{S} = 0$, then the S value is not affected by the number of radiation workers entering RCA. As seen from Fig. 8 there is no effect of the radiation worker number on S.

4.2. Licensee's system of radiation work debriefing

The licensee has a very strong tool for self-assessment, which is regular debriefing after radiation work. Also this licensee's activity, which has not been initiated by the SONS, significantly contributes to maintenance of a high standard of radiation protection in the Czech Republic.
The licensee has organized other activities strengthening his approach to the radiation protection and radiation safety as follows:

- Repeated OSART missions
- Repeated WANO missions
- ASSET mission

These missions have been focused on the then achieved levels of both nuclear safety and radiation protection in the Czech NPPs.

5. Conclusions

Great progress in radiation protection at the Czech NPPs has been made in recent years. Reduction of radiation exposure has mainly been achieved by a concurrence of several factors discussed above and summarized as follows:

5.1. Responsible engineering approach of both the licensee and the national authority, the SONS
5.2. Effective maintenance of the achieved good results in the field of radiation protection
5.3. Consistent performance of state supervision

The Czech NPPs are operated safely and reliably.

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