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► **To cite this version:**

Philippe Lestaevel, Christelle Huet, Veronique Lejeune, Carole Moreno, Carmen Villagrasa, et al..
Cosmic radiation exposure of airline crews in France over the period 2015–2019. Radioprotection,
2023, 58 (4), pp.317-325. 10.1051/radiopro/2023027 . irsn-04349615

HAL Id: irsn-04349615

<https://irsn.hal.science/irsn-04349615>

Submitted on 18 Dec 2023

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**EXPOSITION DES PERSONNELS NAVIGANTS AUX RAYONNEMENTS COSMIQUES EN FRANCE SUR LA
PÉRIODE 2015-2019**

COSMIC RADIATION EXPOSURE OF AIRLINE CREWS IN FRANCE OVER THE PERIOD 2015-2019

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Résumé

Le flux de particules cosmiques augmente avec la latitude et l'altitude et est significativement plus élevé à bord des avions qu'au niveau du sol. De plus, son intensité dépend de l'activité solaire et des éruptions. Du fait de leur activité professionnelle, les personnels navigants (PN) peuvent recevoir une dose annuelle de quelques millisieverts. Ainsi, la directive européenne adoptée en 1996 impose aux compagnies aériennes d'évaluer la dose. La dose efficace est estimée à l'aide de différents moyens expérimentaux et de calcul. En France, elle est réalisée par le système informatisé d'évaluation en vol de l'exposition aux rayonnements cosmiques SIEVERTPN, qui transmet à SISERI, le registre national des doses, la dose efficace mensuelle de chaque PN. La dose efficace annuelle moyenne des PN français est de 2,19 mSv en 2019, soit entre les limites standards admissibles fixées pour le public et la limite fixée pour les personnes exposées professionnellement. La dose efficace reçue par les PN français les plus exposés a augmenté au cours de la période 2015-2019 et cela pourrait être dû à l'effet du cycle solaire, à des changements de temps de vol du personnel ou au modèle d'avion. On peut également noter que davantage d'équipages techniques (PNT) que commerciaux (PNC) ont reçu une dose supérieure à 5 mSv sur la période 2016 à 2019. Notre étude indique que le nombre de PN ayant reçu une dose supérieure à 5 mSv a également augmenté sur la période 2016 - 2019. Certains paramètres, pouvant affecter l'évaluation de la dose efficace des PN, ne sont pas pris en compte dans les calculs de SIEVERTPN, comme l'effet Forbush ou l'emplacement dans l'avion. Enfin, plusieurs facteurs laissent présager une diminution des doses reçues par les PN français dans les années à venir, comme le pic d'activité du 25ème cycle solaire attendu en juillet 2025. Cependant, certains événements inattendus, comme la guerre en Ukraine, peuvent modifier cette prédiction.

Abstract

Cosmic particle flux increases with latitude and altitude and is significantly higher on-board aircraft than at ground level. Furthermore, its intensity depends on solar activity and eruptions. Due to their professional activity, flight crews (FCs) may receive an annual dose of some millisieverts. Therefore, the European directive adopted in 1996 requires the aircraft operators to assess the dose. The effective dose is to be estimated using various experimental and calculation means. In France, it is carried out by the computerized system for flight assessment of exposure to cosmic radiation SIEVERTPN, which sends to SISERI, the national dose registry, the monthly effective dose of each crew member. The average annual effective dose of French FCs was 2.19 mSv in 2019, i.e., between the standard permissible limits set for the public and the limit set for occupationally exposed persons. The effective dose received by the most exposed French FCs increased during the period 2015-2019 and that could be due to the solar cycle effect, changes in the staff flight time or the aircraft model. It can also be noted that more technical flight crews (TFCs) received a dose greater than 5 mSv over the 2016 to 2019 period than commercial flight crew (CFCs). Our study indicates that the number of FCs having received a dose greater than 5 mSv also increased over the period 2016 to 2019. Some parameters, that may affect the assessment of the aircrew effective dose, are not considered in SIEVERTPN calculations, as for example the Forbush decreases and the location in the plane. Lastly, several factors lead us to expect a decrease in the doses received by French aircrew staff in the coming years, such as the peak activity of the 25th eleven-year solar cycle expected in July 2025. However, some unexpected events, as for instance the war in Ukraine, can alter this prediction.

Keywords: aircraft crew exposure / occupational / dosimetry / solar cycle / gender

1. Introduction

Galactic cosmic rays are highly energetic particles

Ionizing radiation originating from various phenomena travels through space and therefore continuously bombards the Earth's atmosphere. Overall, all particles composing the cosmic rays (CR), mainly energetic charged particles (mostly proton and He nuclei, up to 10^{21} eV) have sufficient energy to penetrate earth's magnetosphere and to produce secondary particle shower deep in the atmosphere until sea level. There are two main sources of energetic charged particles): (1) the ever-present galactic and extra galactic components that likely originate from explosions of supernovae and galactic nuclei, and (2) transient solar events, known as flares or coronal mass ejections (CME) whose radiative effects in our atmosphere usually last several hours. At 35 000 feet above sea level (about the cruising altitude of subsonic commercial aircrafts), the effective dose rate typically ranges from 2 to 10 μ Sv/h depending primarily on latitude, altitude, and the level of solar activity (ICRU 84, 2010). Because of the decreasing shielding from the magnetosphere (towards charged particles) with latitude, the dose rate increases with latitude up to 60°. The dose rate, because of atmosphere attenuation, decreases from about 20-25 km (altitude of the Regener-Pfotzer maximum corresponding to the maximal dose rate in atmosphere) to sea level. The impinging charged particle components of the

galactic and extragalactic rays are modulated by the sun's magnetic field protecting our solar system according to sun activities. The intensity of solar activity waxes and wanes according to an average eleven-year cycle.

The regulation is transposed for airline flight crews

In 1990, the International Commission on Radiological Protection (ICRP) recommended that flying crews (FCs) be classified as occupationally exposed (ICRP, 1991). This ICRP recommendation was transposed into European regulations by the European Directive No. 96-29 EURATOM of May 13, 1996 (European Commission, 1996), which substantially amended the standards governing the European health protection of workers against the effects of ionizing radiation. Concerning the protection of FCs, article 42 states that: 'Each Member State shall make arrangements for undertaking operating aircraft to take account of exposure to cosmic radiation of aircrew who are liable to be subject to exposure over 1 mSv per year'. This directive was transposed into French law by the order no. 2001-270 of March 28, 2001 (Ordonnance, 2001). A French decree of December 2003 (J Off, 2003) states that: (1) the individual exposure of any aircrew likely to be exposed to an effective dose >1 mSv per year must be assessed, (2) the effective dose must be assessed for each flight using a calculation method based on flight data provided by the airlines (date, duration, location, etc.) and (3) the calculation method must take into account the influence of the normal solar activity and effects of solar energetic particle (SEP) events classified as ground-level events (GLE). The SIEVERT system was then developed by IRSN to provide a dosimetry service to French airlines and was the first world-wide operational system starting in 2001 (Bottollier-Depois *et al.*, 2007) and including also GLE dose evaluation (Lantos and Fuller, 2004). The French airlines were in charge of the assessment of the aircrew effective dose from the dose calculated for each flight with SIEVERT system and of their transmission to the French national dose registry. French regulations have evolved through the decree of July 17, 2013, applicable on July 1, 2014, which imposes a significant change in the system. Under this new regulation, effective doses must no longer be assigned to FCs by the airlines but by an approved organization which is also in charge of their transmission to the national dose registry. In this context, IRSN has carried out a complete redesign of the SIEVERT system to a new application, SIEVERTPN, to meet the new regulatory requirements.

The dose monitoring is performed by calculation method

Although monitoring of the occupational exposure of FCs could be possibly performed by measurement means such as personal passive dosimetry or *in situ* monitoring with fixed instrumentation on board, monitoring based on calculations is mandatory in French regulation. As a matter of fact, since the radiation field at aviation altitude is very complex in terms of particle composition and energy range, dose assessment based on measurement remains a challenging task and presents some drawbacks compared to calculation methods. Individual dosimeters, in addition to the costs, can be forgotten or even lost by FCs, or frequently exposed to X-rays luggage control system inducing either over or under dose evaluation. Dosimeters are calibrated against an imperfect estimator of the effective dose, either the personal or ambient dose equivalent. For all that reasons, in countries applying the recommendation on FC dose monitoring, dose monitoring is performed by calculation. Effective doses are usually calculated monthly using computer codes that take into account flight parameters such as altitude, latitude, and solar activity. Several web-based platforms, such as PANDOCA, AVIDOS, PCAIRE or SIEVERTPN, have been developed in different countries for dosimetry services. These dose calculator systems use a 3D grid of the atmosphere in terms of effective dose rate which allows, knowing the flight route, to estimate the integrated dose on a given flight based. The 3D grid is either generated by simulation using Monte Carlo particle transport codes (Fluka, PHITS, PLANETOCOSMICS), an analytical calculation code such as LUIN or PLOTINUS or using a database of

measurements converted into effective dose (FDOScalc and PCAIRE). In those codes, the geomagnetic shielding is evaluated through the effective vertical cut-off rigidity geomagnetic either calculated with codes such as PLANETOCOSMICS or from literature data. The solar activity modulation is assessed with heliocentric potential or ground neutron monitor data. Additional models are used to take into account the solar activity. All these codes have been validated against large set of measurements performed with a tissue-equivalent proportional counter (TEPC) (Wissmann *et al.*, 2004; Bottollier *et al.*, 2004) and also through code intercomparison exercises (Eurados 2012 and 2021). The relative differences between measured and calculated values were mostly found to be within $\pm 30\%$ (Bottollier-Depois *et al.*, 2004, Lillok *et al.*, 2007). The overall agreement between the codes for the galactic and extra galactic components was found to be better than $\pm 20\%$ from the median (Eurados, 2012). The agreement between the codes is considered quite satisfactory; dose estimates in radiation protection generally have uncertainties from $\pm 20\%$ to $\pm 30\%$. For GLE dose estimation, larger discrepancies were found among codes, up to 70 %, with median values of the calculated route doses for H*(10) of 161 μSv and 123 μSv (Eurados, 2021).

This paper describes the cosmic radiation exposure of aircrew in French airline companies over the period 2015-2021 (i.e., most of the decreasing phase of the solar activity in solar cycle 24) obtained from SIEVERTPN (System of information and evaluation per flight of exposure to cosmic radiation in air transport) calculations and recorded in SISERI (Information system for monitoring occupational exposure to ionizing radiation: French national dose registry). In addition, possible causes of exposure increase during the studied period are analyzed.

2. Materials and methods

In France, aircrew members are subject to occupational radiation protection surveillance if (i) they are employed by an airline company under the French law, and (ii) they are likely to exceed the effective dose of 1 mSv per year. The obligation to assess the doses received by personnel lies with the employer. The airline must also take measures to keep the doses of the personnel low by appropriate flight planning and crew allocation. The studied population consisted of flight personnel working in France for an airline company with at least one effective dose registered in SISERI between 2015 and 2021. The effective doses were estimated using SIEVERTPN. As introduced above, SIEVERTPN is a calculation tool that allows assessing the doses due to cosmic radiations received during flights according to the routes taken that are made available on a server dedicated to airlines access. In short, the company prepares monthly two files: one containing the information of flights completed and one listing the presence of aircrew members on these flights. Each month, they are sent to the SIEVERTPN application *via* FTP or by download. The doses are evaluated for each flight according to flight characteristics. The calculation of the flight dose is based on a 3D grid of effective dose rates of cosmic radiation up to an altitude of 80 000 ft computed by EPCARD software (Schraube *et al.*, 2002). In SIEVERTPN, airspace is divided into cells of altitude, longitude, and latitude to form a 3D grid consisting of a mesh of 265 000 cells. Each cell is 1000 feet in altitude, 10° in longitude and 2° in latitude. An effective dose rate value is monthly assigned to each cell. The SIEVERTPN application evaluates the time spent by the aircraft in each cell and deduces the dose received. In the event of a significant solar flare, a specific grid is created using the SIGLE model (Lantos and Fuller, 2004). Once the flight file is processed by SIEVERTPN, the monthly effective dose received by each crew member is calculated thanks to the information on their presence on the flights. Then, a file containing the monthly effective dose of each crew member is automatically generated by SIEVERTPN and sent to SISERI. Over the 2015-2021 period, the data from 7 to 13 French airlines per year have been transmitted to SISERI. In the SISERI database, workers are identified by their company, their last name, their first name and by their

registration number in the national identification directory of natural persons. Some additional information is available in SIEVERTPN and/or in SISERI, such as the number of flight hours, the categories of FCs, i.e., technical flight crews (TFCs) or commercial flight crews (CFCs), the occupation (airline technical aircrews, aircraft captains, stewards, flight attendants, cabin managers) or the type of aircraft.

3. Results

The number of monitored FCs increased over the 2015-2019 period and has decreased since 2020, probably due to the COVID-19 crisis (Fig. 1). Likewise, the average annual effective dose steadily increased between 2015 and 2019 (1.98 mSv to 2.19 mSv). In 2020, it decreased by 54% due to the decrease in air traffic linked to COVID-19. In 2021, the average annual effective dose slightly increased compared to 2020 (12%), due to improved health conditions and the re-increased of air traffic. In 2019, the FCs account for nearly 48% of the total occupational collective dose in France whereas “only” 31% in 2020 and 28% in 2021 (Lestaevel *et al.*, 2022).

This study focuses on the most FCs exposed and is limited to the 2015-2019 period, to avoid biases linked to the decline in activity in the sector in 2020 and 2021 due to the COVID-19 pandemic.

Between 2015 and 2019, the average annual individual effective dose of the 100 most exposed FCs increased (5.2 mSv in 2019 *versus* 4.0 mSv in 2015, i.e., 30%); over the same period a slight increase in annual flight time was observed (753 hours in 2019 *versus* 740 hours in 2015, i.e., 1.7%) (Fig. 2).

In 2015, no FCs received an annual effective dose above 5 mSv. Over the period 2016 to 2019, 169 FCs received an effective dose above 5 mSv by year. Most of these FCs were technical flight crews (TFCs): 109 TFCs *versus* 60 commercial flight crew (CFCs). Between 2016 and 2019, the number of CFCs tends to increase year over year (Fig. 3).

The ratio of male to female FCs does not change over time (approximately equal to 1 over the 2015-2019 period) (data not shown). In contrast, the proportion of female staff who received a dose greater than 5 mSv changes over time. In 2018 and 2019, this proportion of female staff was 25% compared to 8% in 2017 and 0% in 2016 (Fig. 4).

Of the 109 TFCs who received an annual effective dose above 5 mSv between 2016 and 2019, 73 % are airline technical aircrews and 14% are aircraft commanders (Fig. 5A). In French airlines companies, all airline technical aircrews represent about 56 % of TFCs (data not shown). Of the 60 CFCs who received a dose above 5 mSv, 52% of them are stewards, 41% are flight attendants and 7% are cabin managers (Fig. 5B).

Over the period 2016 to 2019, most FCs with an effective dose above 5 mSv worked mainly on long-haul aircraft with flight profiles (altitude) and destinations from Europe to North America and Asia, resulting in higher exposure. To a lesser extent, they have worked on medium-haul airliners (Fig. 6).

4. Discussion

The annual exposure of FCs, is, in France, among the highest occupational exposures compared to workers in other activities such as nuclear power plant or industry. Air transport in France has been continuously increasing over the period of study, with a drastic drop in air traffic which will not be compensated by 2021 due to the worldwide health crisis linked to COVID-19 pandemic. Collective dose

of French FCs represents nearly 48 % of total occupational collective dose in 2019. This result can be compared to those observed in other countries, where collective dose of FCs represented nearly 58 % of total collective dose in 2018 (data available on ESOREX platform: <https://esorex-platform.org/charts/g2>). Our results show that the average annual effective dose of French FCs (2.19 mSv in 2019) is between the standard permissible limits set for the public (1 mSv) and the limit set for occupationally exposed persons (20 mSv). The comparison with other countries is not straightforward for different reasons (geographical location and extent of the country, airline practices, commercial and tourist development of the country ...). Nevertheless, these results are in the same range that values from the literature. According to the responses to the UNSCEAR Occupational Exposure Survey from 22 countries, the average annual effective dose of FCs was 2.7 mSv for the period 2010–2014 (UNSCEAR, 2022). In a German cohort study, covering 12 981 aircrew members from 2004 until 2015, Wollschläger et al. showed that the average annual effective dose was 2.25 mSv (range 0.01 - 6.39 mSv) (Wollschläger *et al.*, 2018). In Canada, the survey of cosmic radiation exposure of Air Canada pilots in 2009 showed that 93.8% of the pilots received more than the public limit of 1 mSv (*versus* 83.2 % for French FCs in 2019) and 54% received between 2.5 and 3.5 mSv (Bennett *et al.*, 2013). However, due to the dip in the vertical cutoff rigidity over Canada, it places Canada in the highest area of exposure to cosmic radiation in the world.

In this study, different factors that could explain the increase in the effective dose received by the most exposed French FCs during the period 2015-2019 have been investigated, such as the solar cycle, changes in the staff flight time or the aircraft model and thus the route. Some explanations are given below.

First, the total time spent in flight could influence the rise of average annual effective dose observed in the present study. Air transport has been continuously increasing during these last few years in France ([Statistiques du trafic aérien | Ministères Écologie Énergie Territoires \(ecologie.gouv.fr\)](https://www.ecologie.gouv.fr/statistiques-du-traffic-aerien)) as well as in other countries. In Ireland, during the years 2002–2005, an increase in the total number of flights per year was also observed, resulting in a 75% increase in the number of FCs receiving doses above 1 mSv (Colgan *et al.*, 2007). In the present study, we showed that the average number of flight hours increased slightly over 2015-2019 (Figure 2). Therefore, it can't explain the consequent effective dose increase.

Apart from the total time spent in flight, the solar cycle can influence the FCs individual annual dose. The magnitude of cosmic radiation getting to the Earth depends on the sun's activity at a particular period. The sun constantly ejects particles with an intensity which varies according to a cycle of about eleven years (solar cycle). The cosmic radiation reaching the Earth is less when solar activity is strong and *vice versa*. In the present study, the period, which was analyzed regarding the most FCs exposed, i.e., 2015-2019, covers the decreasing phase of solar cycle 24 (its maximum was in the year 2014 and its minimum in 2019). Consequently, the ambient dose rate from high altitude radiation increased during the monitoring period. The average annual effective dose of French aircraft crew personnel increased from 2015–2019 by 11%. Previously, for German aircrew, the average annual effective dose during the middle of the decreasing phase of solar cycle 23 (2004) was 1.9 mSv and increased during its minimum (2009) to 2.3 mSv (Frasch *et al.*, 2014) thus 21%. Also, high altitudes and latitudes are associated with higher dose values. The comparison of the effective route doses between 2004 and 2009 showed an increase from 25 to 30 μ Sv (20%) on the trans-equatorial route Frankfurt–Johannesburg, and from 50 to 78 μ Sv (56%) on the polar route Frankfurt–New York (Frasch *et al.*, 2014). From SievertPN data, an increase from 48 μ Sv to 62 μ Sv (29%) is observed between 2014 and 2019 for the route Paris-New-York whereas it remains stable over the same period for the route Paris-Johannesburg (27 μ Sv).

It can also be noted that in absolute value, more TFCs received a dose greater than 5 mSv over the 2016 to 2019 period than CFCs. TFCs have a qualification for a given type of aircraft (for example Airbus A380 or Airbus A320, etc.). The TFCs having received a dose greater than 5 mSv are those working mainly on long-haul jumbo jets and, to a lesser extent, workers on medium-haul airliners. In 2018, Los Angeles, San Francisco, New York, Washington, Mexico City, Shanghai, Abidjan, and Johannesburg were the possible destinations on these jumbo jets from Paris. Unlike TFCs who only have a qualification for one type of aircraft (long-haul type, medium-haul type), CFCs fly on several types of aircraft and quite several of them are trained on large aircraft long-haul carriers. Thus, it is easier for the airline company to adapt the CFC flight planning. The differentiation between long- and medium-haul flights is difficult since CFCs are distributed to all categories of flights. They perform about one or two long-haul flights per month (compared to about five flights per month for TFCs) (data not shown). Previous studies have demonstrated, for example in Finnish airline personnel, that the median cumulative individual estimate dose was 18.5 mSv among cockpit (i.e., TFCs) and 14.5 mSv among cabin crew (i.e., CFCs) from 2001-2014 (Tolibov *et al.*, 2017). Oksanen *et al.* obtained annual doses of 2.19 mSv (1.08–2.83 mSv) for pilots and 2.27 mSv (0.72–3.1 mSv) for cabin crew in Finland (Oksanen, 1998). Thus, the difference of dose exposure between TFCs and CFCs is not always clear, and it depends, on the one hand, on the destinations of the companies, and on the other hand, on the practices of the company.

The proportion of female workers was about 52 % for the whole French monitored FCs and the male/female ratio remained relatively unchanged over the period 2016 to 2019 (data not shown). According to an ILO report, the gender ratio in the civil aviation has, on average, remained relatively also unchanged (Seligson, 2019). Between 2016 and 2019, the whole French male FCs monitored had a higher average annual effective dose (2.20 mSv) than female (2.02 mSv) (data not shown). In Germany, over the period 2004-2009, male cabin crew had also a higher average annual effective dose (2.2 – 2.4 mSv) than female cabin crew (1.9 – 2.4 mSv) (Frasch *et al.*, 2014). Wollschläger *et al.* show that female aircrew members' drop in average effective dose around age 35 may correspond to an increase in social or family responsibilities with potentially more short-haul flights or part-time employment (Wollschläger *et al.*, 2018). In the light of these results, the annual doses of FCs vary significantly with gender, possibly due to shorter flight times for female. Despite this, our study indicated that the number of female FCs having received a dose greater than 5 mSv increased over the period 2016 to 2019. These female FCs are exclusively CFCs. In the United States, between 1992 and 1996, about 84% of flight attendants were female with an annual average effective dose of 0.36 mSv (Grajewski *et al.*, 2015). Among the 24 female FCs employed by a French airline with a dose above 5 mSv in 2019, nine performed flights, but not only, between France and Japan.

Limitations of the study

As mentioned, aircrew effective doses were estimated by calculation means. Thus, some parameters that may affect the assessment of the effective dose are not considered.

First, the shock wave effect associated with CME leading to a significant decrease in the continuous galactic and extra galactic components impinging Earth is not considered. This effect is known as Forbush decreases (FDs) (Forbush, 1958). The maximum observed decrease in counting rate on ground neutron monitors typically ranges from a few percent to 20 % and exceptionally up to 30 %, depending on the size, the strength, and the proximity of the CME to the Earth. The decrease occurs rather suddenly, within a few hours or less, but the return to the previous level takes days or even weeks. These types of events are more frequent and longer than solar energy particles events. As an example, during the solar cycle 23 (1997-2007), 123 FDs were detected against 16 GLE events (GLE 55 to GLE 70). The impact of FDs on individual exposure has not been yet evaluated. Regarding GLE, if the

maximal dose rate can reach tens of mSv/h at the flight altitudes (as for example for the Feb. 1956 event, the most intense GLE of the 20th century), since 2000, only four events have been considered in SIEVERTPN dose evaluation leading at maximum to double the flight dose on a transatlantic flight. For the worst case GLE, a maximum effective dose was estimated to 1.2 mSv for US aircrew personnel (Anderson *et al.*, 2014).

In addition, Monte Carlo simulations (Ferrari *et al.*, 2004) and measurements (Kubancak *et al.*, 2014) of the ambient dose equivalent $H^*(10)$ at different positions inside the aircraft have shown that it is up to 19% higher at the front (and back) of the cabin (where TFCs are located) than in the central part (where CFCs are located). These differences are due to the aircraft shielding, the luggage load, the amount of fuel, etc. As the location in the plane is not considered in SIEVERTPN calculations, it is therefore likely that the difference in dose between the two categories of personnel (TFC and CFC) is even more pronounced than the one observed in that study.

Expected future trends

Several factors lead us to expect a decrease in the doses received by French aircrew staff in the coming years. First, although air traffic has recovered from the drastic decline due to the pandemic, it still appears to be below 2019 levels ([QlikView Printing \(ecologie.gouv.fr\)](https://www.ecologie.gouv.fr)). Moreover, the 25th eleven-year solar cycle began after a minimum of solar activity observed in December 2019. The peak activity of this new cycle is expected in July 2025. This means that the dose rates should decrease until 2025. In addition, the Covid-19 pandemic marked the end of the operation of the A380 by French airlines on which the doses were higher, even if other types of aircraft, such as 777, were able to take over. Finally, the SIEVERTPN system has been updated with the new ICRP 103 weighting coefficients in place of the ICRP 60 weighting coefficients from July 2021 (ICRP, 2007). The modification of the proton and neutron weighting coefficients leads, under identical conditions to cosmic radiation exposure, to a decrease in the effective dose value of the order of 20 to 30% depending on the flight characteristics (Meier and Matthia, 2019).

However, it should be kept in mind that unexpected events (as was the case with the Covid pandemic) can alter these predictions. For instance, the war in Ukraine has had an impact on international air transport and has forced to modify some routes to bypass Russian airspace. For a Paris to Tokyo flight, it is possible to fly south to Turkey or Kazakhstan and return north to the pole. This itinerary has consequences on the flight time (count about 14 hours instead of 11) and on the doses received. If the outbound flight is less dosing, the return is up to twice as much. We can therefore observe a possible effect on the average annual effective dose in 2022.

5. Conclusion

After an increase in aircrew exposure over the 2015-2019 period, several factors suggest that cosmic radiation exposure for these workers should decrease in the coming years. The evaluation of the occupational exposure for the year 2022, scheduled for the first half of 2023, should already provide us with elements of comparison.

The health effects of these low dose exposure on FCs remains to be delineated. Except for the study by Wollschläger *et al.* (2018), no large epidemiological study on the long has term has been conducted on this specific exposed population. This would be of interest, especially with the significant although quite narrow range of exposure, as demonstrated in the present study.

In any case, another category of workers, for whom no dosimetric monitoring is performed, deserves to be studied: “the frequent flyers”, i.e., the persons who, for professional duties, regularly travel by plane on commercial flights. Exposures for these individuals may exceed 1 mSv per year (Tate *et al.*, 2021). A pilot study to objectivize these exposures and possibly move towards a modification in the regulations could be also proposed.

Conflict of interest

The authors declare they have no conflict of interest.

Funding

This work was supported by Institute of Radioprotection and Nuclear Safety

Informed consent

This article contains no experimental studies involving human subjects.

Ethical approval

Ethical approval was not required.

Authors' contribution

P Lestaevel: study design, analysis, writing original draft. C Huet: analysis, writing and reviewing original draft. V Lejeune: data collection and analysis. C Moreno: investigation, reviewing original draft. Carmen Villagrasa: writing and reviewing original draft. J Feuardent: reviewing original draft. F Trompier: writing and reviewing original draft.

Acknowledgments

We would like to thank all people who helped us in any way during this study.

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Figure 1: Distribution of numbers (histogram bars) and average annual effective doses (\pm SD) (in mSv) of FCs (curve) over the period 2015 to 2021

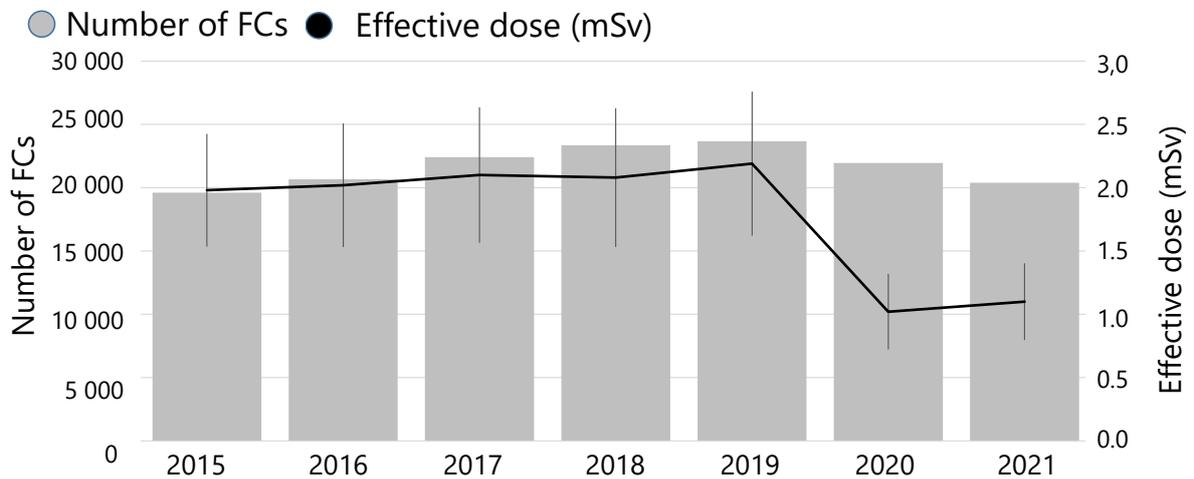


Figure 2: Average annual effective doses (\pm SD) (in mSv) of FCs (curve) as a function of the average number of flight hours (histogram bars) for the 100 most exposed aircrew each year over the period 2015 to 2019

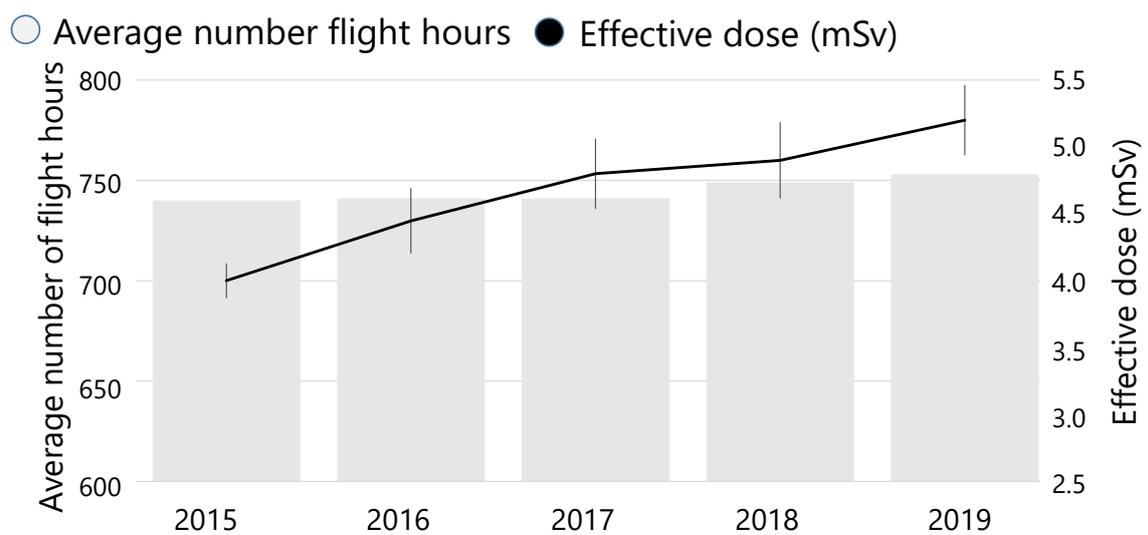


Figure 3: Number of FCs having received an effective dose greater than 5 mSv according to their type (TFCs or CFCs) over the period 2016 to 2019

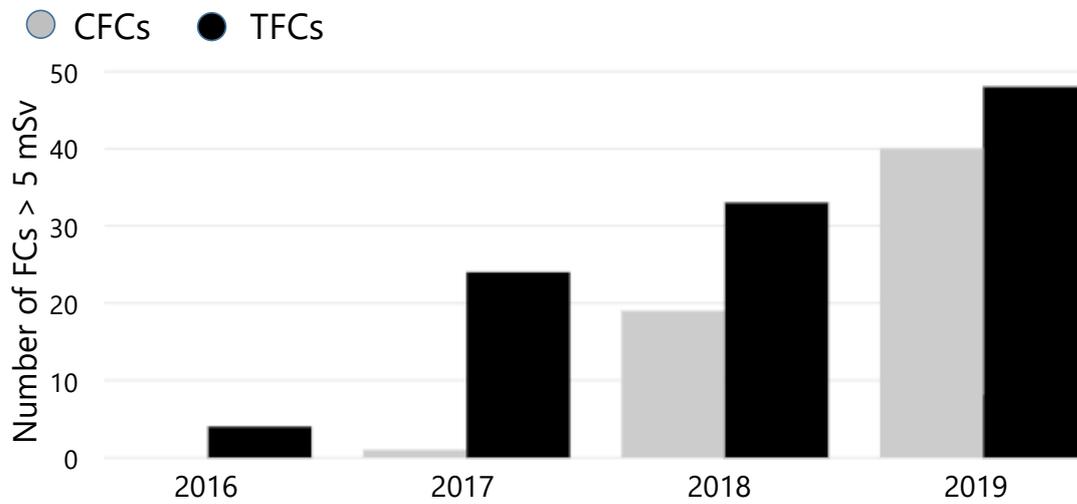


Figure 4: Number of FCs having received an effective dose greater than 5 mSv according to their type (Man or Woman) over the period 2016 to 2019

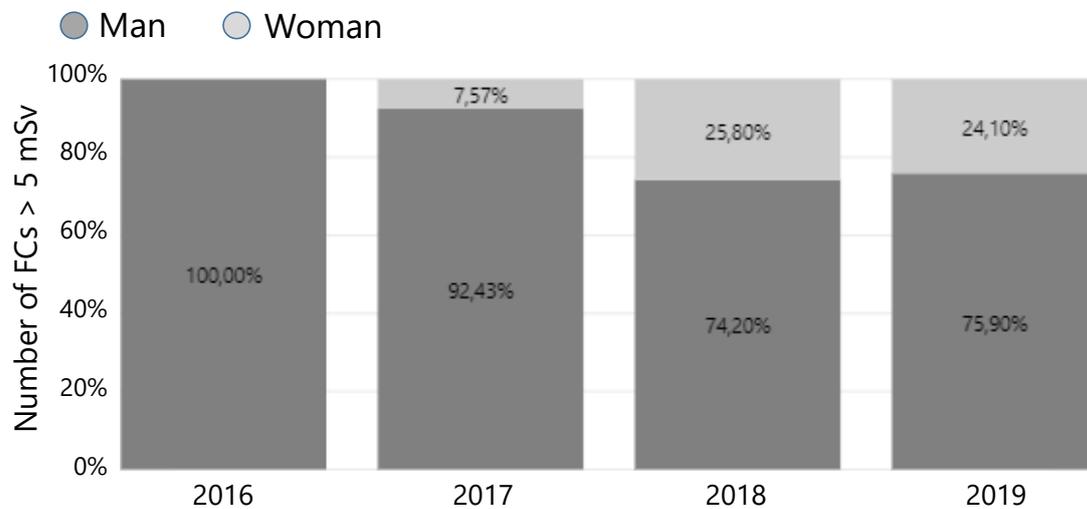


Figure 5: Number of TFCs (A) and CFCs (B) who received an effective dose greater than 5 mSv by occupation over the period 2016 to 2019

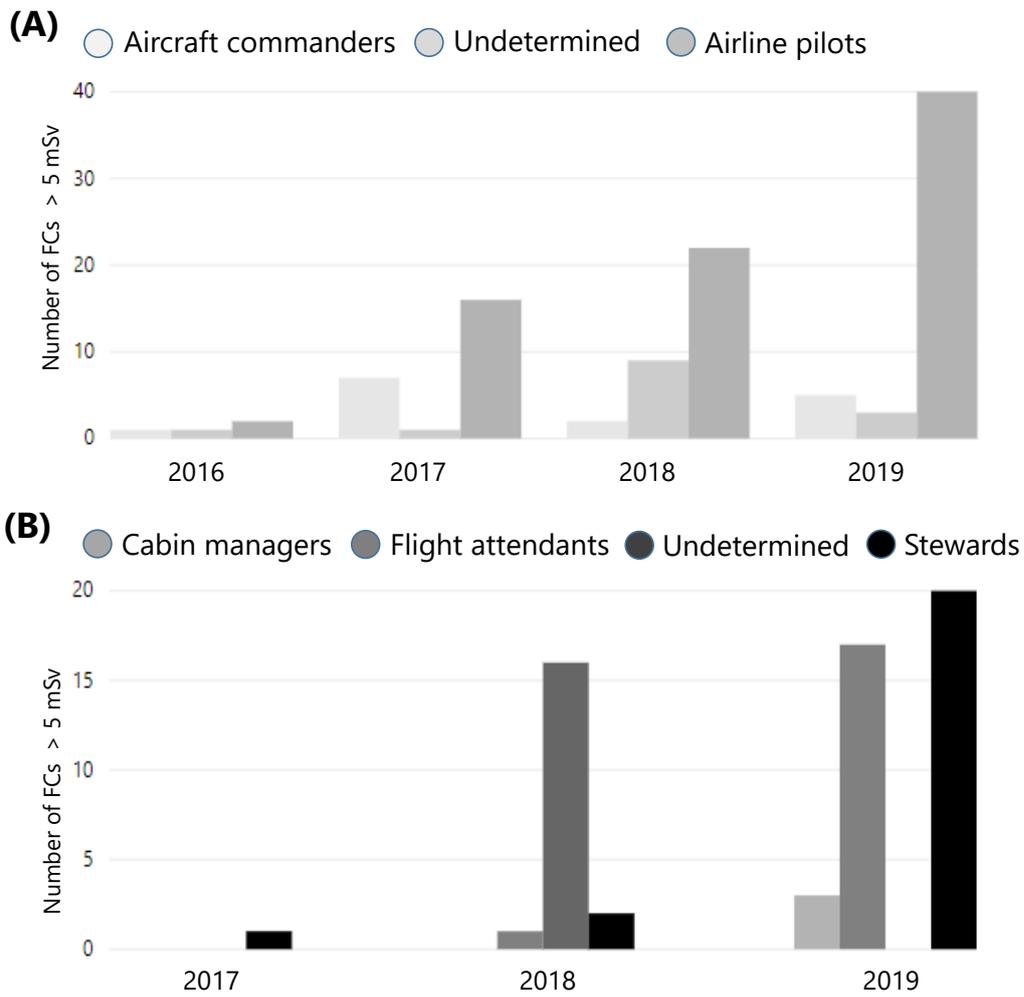


Figure 6: Number of TFCs who received an effective dose greater than 5 mSv by type of aircraft over the period 2016 to 2019

