Istraživanja i projektovanja za privredu

ISSN 1451-4117

DOI:10.5937/jaes0-36057

www.engineeringscience.rs

publishing

Journal of Applied Engineering Science

Vol. 20, No. 4, 2022

Original Scientific Paper

Paper number: 20(2022)4, 1013, 1073-1082

IDENTIFICATION AND ASSESSMENT OF OCCUPATIONAL SAFETY RISKS IN CASE OF FAILURE TO CAPTURE AN ORPHAN SOURCE OF IONIZING RADIATION

Miroslav Tomek*, Eleonóra Benčíková, Jan Strohmandl, Pavel Tomášek*

Faculty of Logistics and Crisis Management, Tomas Bata University in Zlín, nám. T. G. Masaryka 5555, 760 01 Zlín, Czech Republic

** tomasek@utb.cz*

Occupational safety and health belong to fundamental human rights. This fully applies to the protection of employees and other persons, which operate or are located in facilities for the collection of scrap metal. The founder of the landfill or the employer has an irreplaceable place in the field of protection of persons against the effects of ionizing radiation. Based on the identification and assessment of occupational safety risks in the event of failure to ensure timely detection of an orphan source of ionizing radiation, the operator must assess all risk factors with emphasis on radiation. At the same time, it must take specific regime measures, which would minimize the impact on people and the environment. The article deals with the causes of failure the system of protection against the effects of ionizing radiation. The assessment of these causes is performed using the fault tree analysis method with the application of Boolean equations. The result of solving the problem is the calculation of the failure of the regime protection system in the devices, intended for the collection of scrap metal, caused by human error as a result of intentional or negligent actions of the operator and insufficient training in the areas of control of measuring devices, principles of correct use of detection devices, insufficient visual identification of potentially dangerous objects. The contribution of this paper is in the design of appropriate regime measures eliminating the consequences of non–capturing a source of ionizing radiation.

Keywords: contamination, protection, radiation, risk, safety

1 INTRODUCTION

Creation of a safe and non–hazardous working environment and working conditions by an appropriate organization of occupational safety and health (hereinafter referred to as “OSH”) and taking risk prevention measures is a legal duty of every employer. The safety and health protection of employees applies also to so–called “third par-ties”, which enter the premises of any legal or entrepreneurial natural person [1]. To this fact in collection yards, which are focused on waste management, occurs quite often. The issue of waste collection and sorting is addressed in the author's work [2], collection planning and the choice of transport routes is addressed in the author's work [3], municipal waste collection is addressed in the works of the authors [4]. The issue of nuclear waste in relation to disposal is addressed in the works of authors [5].

Risk prevention means all measures resulting from legal and other regulations to ensure OSH and from the measures of the employer, which aim to prevent risks, eliminate their or minimize the effects of irremediable risks [6]. This fully applies to equipment intended for the collection of scrap metal, where employees are endangered not only by physical, chemical, but also radioactive risks. Employees in these areas may be exposed to ionizing radiation from orphan sources, which are brought to these places by collection vehicles [7].

The founders of waste collection yards are obliged to use safety, organizational, legal, regime and technical measures, including working conditions, social relations, and with the assessment of the effects of the working environment constantly search for hazardous factors and processes of the working environment and working conditions, identify the causes and sources of possible threats to human health, which are found in them.

The most important legal regulations in the field of OSH with the capture of iron scrap or contaminated municipal waste include laws and legal norms, for example [6,8,9,10]. It is also possible meet the problem being solved also in articles and publications for example [7,11,12,13].

The need to deal with source of ionizing radiation (hereinafter referred to as “SIR”) is also evidenced by the fact that 163 extraordinary cases related to the management of SIR were investigated in the Czech Republic through the State Office for Nuclear Safety between 2015 and 2019 (Table 1) [14].

Table 1. Extraordinary cases in the years 2015 to 2019 in connection with SIR (note: at the time of elaboration, the authors of the article did not have data for 2020, see [14])

Finds and seizures of radioactive substances or objects contaminated by them, eventually in connection with the loss of control over SIR	Year				
	2015	2016	2017	2018	2019
Total emergencies	36	22	42	31	32

Finds and seizures of radioactive substances or objects contaminated by them, eventually in connection with the loss of control over SIR	Year				
	2015	2016	2017	2018	2019
Of which collectors transporting scrap iron	20	8	19	9	8
Of which collectors of municipal waste collection trucks	10	11	17	18	16
Other	6	3	6	4	8

To minimize the risk of contamination by orphan radioactive sources in the field of waste management, the employer must seek and evaluate risks. He is also obliged to take appropriate measures to minimize them and subsequently eliminate them.

The aim of the authors was to use the above methods to point out the possible causes of failure of the regime protection regime within OSH when capturing or finding an orphan source of ionizing radiation and outline appropriate regime measures.

2 MATERIALS AND METHODS

The crucial moment of the imbalance of the system lies in the initiation phase, thus failing to ensure timely capture of the orphan SIR at the entrance to the first facility in the entire recycling system, i.e. to the scrap metal collection yard.

Each causal dependence of the occurrence of a negative phenomenon can be described as a sequence of consecutive states of the system in the following order: danger → threat → initiation → injury → damage [15].

States in the causal dependence [16,17] of the occurrence of a negative phenomenon as individual phases and the consequences of potential abandonment SIR through a scrap recycling system (Table 2) they represent a sequence of development from danger to the occurrence of damage.

Fault tree analysis (hereinafter referred to as “FTA”) deals with the identification of conditions and factors, which cause or may cause, possibly contribute to the occurrence of a specified peak event [18,19]. The peak event is the output of a combination of all input events and is the subject of interest, under which the tree of fault conditions develops. At the next levels, the initial intermediate events are gradually deduced, while at the lowest level, there are basic events or events that are no longer developed [20,21].

Table 2. Description of states in the causal dependence of the occurrence of a negative phenomenon (source in–house)

State	Description
Danger	Ionizing radiation that is emitted with an orphan source
Threat	The orphan source of ionizing radiation is passed to the scrap recycling system
Initiation	The orphan source of ionizing radiation is taken over into the scrap recycling system
Injury	Damage to human health
	Contamination of scrap, handling and transport equipment
	Environmental contamination
Damage	Irreversible damage to human health, death
	Melt contamination
	Contamination of finished products

The investigated undesirable phenomenon represents the failure of the system of regime protection of equipment for collecting scrap metal, either at the level of measures of a technical nature or organizational measures, which results in a peak FTA event — penetration of abandoned SIR into the facility area. At the first level of intermediate events, in addition to failure or failure to perform control by the radiation portal monitor (stationary detector), an undeveloped event is also considered, when the SIR was placed in the area illegally without the operator's knowledge, e.g. outside the operating hours of the facility, intentional smuggling in another type of waste, etc.

At the next level, two major input events have been identified that can cause a stationary detector to fail control. The portal monitor either cannot detect ionizing radiation or cannot detect it due to its limited technical possibilities, e.g. in the case where neutron detectors are not also incorporated into the assembly. Most conventional gantry monitors are designed for γ radiation detection only. If the scrap shipment contains neutron sources based on ^{241}AmBe (α, N) or ^{238}PuBe (α, N) emitters, which are used e.g. in soil moisture probes, such SIR may not be detected at all.

The inability to detect ionizing radiation by a portal radiation monitor can be caused by various negative factors that can be generated by all involved objects: the detector itself, the vehicle, the load, the control software and the operator [22]. Vehicle throughput speed through the detection gate higher than 5 $km.h^{-1}$, ambient temperature outside the operating temperature range of the detector (especially frost below -20 °C), neglect of regular inspection of the device or slow start–up of the operating system after a computer failure with control software installed, it everything can cause SIR to penetrate through the detectors. Possible ways of shielding SIR in the vehicle's cargo area were also investigated (Fig. 1). A specific basic event was also considered, when the activity of SIR is so low that its non–capture represents a negligible risk.

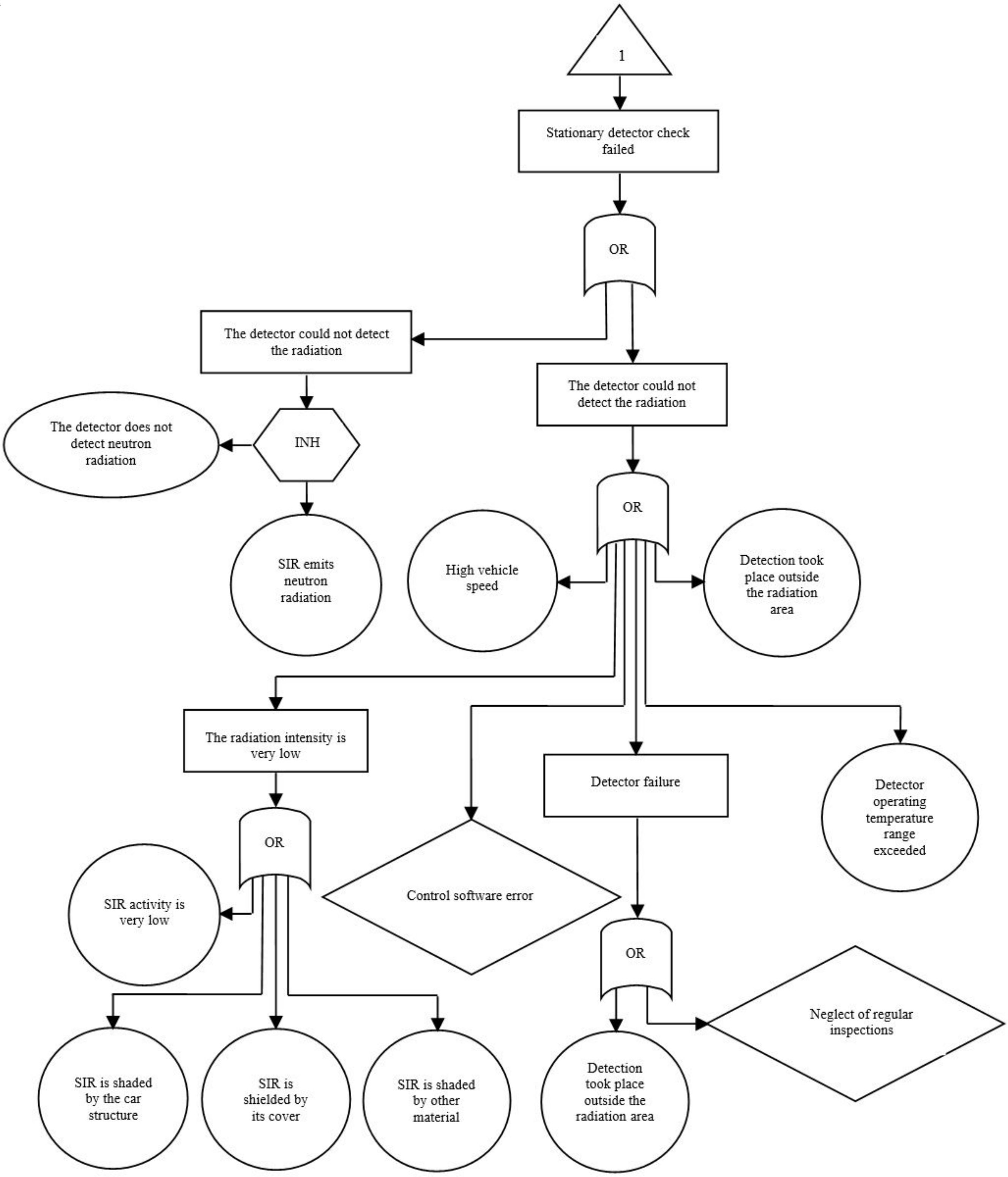

Fig. 1. ETA - transfer 1

If the stationary detector check did not take place, even though it is installed at the entrance to the device, it may be an intentional violation of the operator's work duties, which either ignored the detector out of service or did not pay attention to the passing vehicle. If the portal monitor is not installed, the analysis at other levels investigates the causes of failure of other types of ordered controls.

The state of the detector out of operation can be caused by a failure of the electric power source, including the backup system, mechanical damage to sensors or cabling, or another functional disorder that arose as a result of negligence of regular inspection or unpredictable failure.

Visual inspection failures can be preceded by two major inputs:

- Operator either did not see in delivery truck the SIR,
- Operator registered the object, however, did not identify it as a potentially dangerous SIR.

The analysis of the causes of non–recognition of SIR revealed possible shortcomings in the area of marking SIR with warning symbols, availability of documentation and operator training.

If neither a visual inspection nor a manual detector has been performed at the entrance to the device without the gantry monitor installed, it may again be an intentional or negligent action by the operator, but also a case where no inspection has been ordered. Such an intermediate event may occur if the delivery has been declared free of metals. During normal acceptance, the SIR could easily escape the attention of the operator.

Possible causes of manual detector failure were investigated at the levels of fatal equipment failure, inability of the instrument to detect radiation due to its limited technical capabilities and inability to detect radiation from various causes, including possible methods of shielding SIR, influencing detection by instrumental influences, setting inappropriate measuring range and more (Fig. 2).

Levels of solution activities with SIR:

- The investigated undesirable phenomenon represents a failure of the system of regime protection of scrap metal collection equipment, whether at the level of measures of a technical nature or organizational measures, the consequence of which is the peak event FTA [23] — penetration of the orphan SIR to the areal of the facility. At the first level of intermediate events, in addition to failure or failure to perform control by radiation portal monitor (stationary detector), a further undeveloped event is considered when the SIR was placed in the area illegally without the operator's knowledge, e.g. outside the operating hours of the device, intentional smuggling in other types of waste, etc.
- At the next level, two major input events have been identified that can cause a stationary detector to fail control. The portal monitor either cannot detect ionizing radiation or cannot detect it due to its limited technical possibilities, e.g. in the case when into the set are also not included neutron radiation detectors. Most conventional gantry monitors are designed for detection only γ radiation. If the scrap shipment contains neutron sources based on ^{241}AmBe (α, N) or ^{238}PuBe (α, N) emitters, which are used, for example, in soil moisture probes, such SIR may not be detected at all. The inability to detect ionizing radiation by a portal radiation monitor can be caused by various negative factors that can be generated by all involved objects: the detector itself, the vehicle, the load, the control software and the operator. Vehicle through speed on the detection gate higher than 5 km.h^{-1}, ambient temperature outside the operating temperature range of the detector (especially frost below -20 °C), neglect of regular inspection of the device or slow start–up of the operating system after a computer failure with control software installed, everything can cause SIR to penetrate through the detectors. Possible ways of shielding SIR in the vehicle's cargo area were also investigated. A specific basic event was also considered, when the activity of SIR is so low that its non–capture represents a negligible risk.
- If the inspection by the stationary detector did not take place, even though it is installed at the entrance to the device, it may be an intentional violation of the work duties of the operator, which either ignored the detector out of service or did not pay attention to the passing vehicle. If the portal monitor is not installed, next–level analysis investigates the causes of failure of other types of ordered controls.
- Visual inspection failures can be preceded by two major inputs:
    - The operator either did not see the SIR in the van.
    - Registered the subject, but did not identify it as a potentially dangerous SIR.
- Analysis of the causes of non–recognition of SIR revealed possible shortcomings in the area of marking SIR with warning symbols, availability of documentation and operator training.
- If neither a visual inspection nor a manual detector has been performed at the entrance to the device without the portal monitor installed, it may again be an intentional or negligent action of the operator, but also a case where no inspection was ordered. Such an intermediate event may occur if the delivery has been declared free of metals. During normal acceptance, SIR could easily escape the attention of the operator.

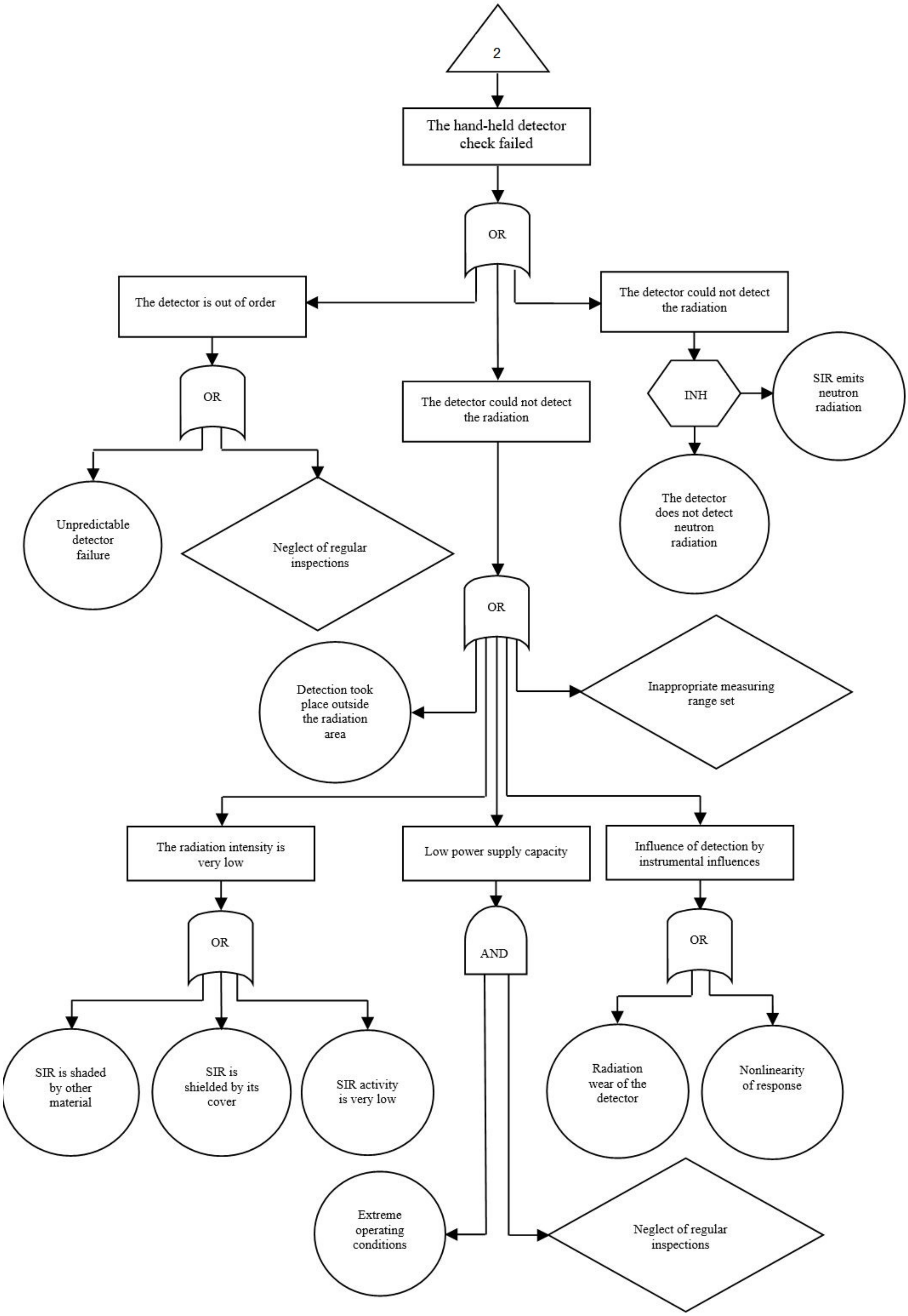

Fig. 2 FTA - transfer 2

- Possible causes of failure of control by hand detector were investigated at the levels of fatal equipment failure, inability of the instrument to detect radiation due to its limited technical capabilities and inability to detect radiation from various causes, including possible methods of shielding SIR, influencing detection by equipment influences, setting inappropriate measuring range and more.

Boolean reduction was used to find the complete set of minimal critical cut (hereinafter referred to as “MCC”) [24,25,26], which is based on the phenomenal description of logical connections displayed in the fault tree. First, the peak event was expressed G_0 as a combination of the immediate cause, which can cause it, and conditioning intermediate events (1). Signs were used instead of intersection and unification symbols “times” and “plus”:

$$G_0 = A + G_1 + G_2 \tag{1}$$

They were then gradually inserted into the equation for intermediate events $G_1, G_2, \dots G_{23}$ a combination of their immediate causes, until the logical expression consisted only of basic or undeveloped events (2):

$$G_0 = A + D.E + F + G + H + I + L + M + N + O + P + Q + B + J + K + C(R + S + X + Y$$
$$+Z + AA + T.U + B + V + P + Q + D.E + G + W + O + N + L + AB.Q + AC + AD) \tag{2}$$

After simplifying the resulting expression using the principle of unification of phenomena was compiled a set MCC (3):

$$\sum MCC = \{A\},\{B\},\{F\},\{G\},\{H\},\{I\},\{J\},\{K\},\{L\},\{M\},\{N\},\{O\},\{P\},\{Q\},\{D,E\},\{C,R\},$$
$$\{C,S\},\{C,V\},\{C,W\},\{C,X\},\{C,Y\},\{C,Z\},\{C,AA\},\{C,AC\},\{C,AD\},\{C,T,U\} \tag{3}$$

The severity of each MCC expresses the number of elementary phenomena of the cut, the so–called cut order. First–order MCCs are usually more critical (serious) than second–order or higher–order sections [27].

3 RESULTS

In order to identify all reasonably possible combinations of human factor errors and failures of active or passive elements of the system, a list of basic and further undeveloped events was compiled (Table 3) [20] and defined the terms that characterize the tree of fault states [27]:

Critical section — a finite set of basic, further undeveloped or otherwise analyzed events, which, if it occurs simultaneously, leads to the occurrence of a peak event.

- Minimal critical section — a finite set of elementary events, which is itself a critical section, but at the same time none of its own subset is a critical section.

Table 3. List of basic and further undeveloped events [21] (* L = human factor error, A = active element failure, P = passive element failure)

Tag	Event description	Frequency	Type *	Tag	Event description	Frequency	Type *
Q	Neglect of regular inspections	4	L	Y	The workplace lacks operational documentation	1	L
P	Unpredictable failure	3	A	W	Inappropriate measuring range set	1	L
L	SIR activity is very low	2	-	X	Insufficiently trained staff	1	L
G	Detection took place outside the radiation area	2	L	A	Illegal placement of SIR in the area	1	L
D	The detector does not detect neutron radiation	2	A	AD	Nonlinearity of response	1	A
B	Intentional neglect of operator duties	2	L	V	The staff was not present at the acceptance	1	L

Tag	Event description	Frequency	Type *	Tag	Event description	Frequency	Type *
E	SIR emits neutron radiation	2	-	I	Detector operating temperature range exceeded	1	P
O	SIR is shaded by other material	2	P	AC	Radiation wear of the detector	1	A
N	SIR is shielded by its cover	2	P	Z	Symbols have been erased by wear and tear	1	P
T	The delivery was declared free of metals	1	L	J	Power failure	1	P
U	The delivery included SIR	1	P	AA	The manufacturer did not specify the symbols	1	L
AB	Extreme operating conditions	1	P	F	High vehicle speed	1	L
H	Control software error	1	A	M	SIR is shaded by the car structure	1	P
C	Other types of inspections are ordered	1	-	R	SIR was not visible in the delivery	1	P
K	Mechanical damage to the detector	1	A	S	A strange or atypical type of SIR	1	P

The peak event was marked as G_0, individual intermediate events $G_1, G_2, \ldots G_{23}$ (Table 4) and basic or further undeveloped events as *A, B, … AD*. Identical elementary events were marked with the same mark, which made it possible to express the frequency of their occurrence. The gates of the logical sums then represent the unification operation and the gates of the logical conjunction is intersection.

Table 4. Indication of peak and intermediate events (source in–house)

Indication	Event description	Indication	Event description
G0	The orphan SIR penetrated into the facility area	G12	Check failed
G1	Stationary detector check failed	G13	The SIR operator did not recognize
G2	The stationary detector check did not take place	G14	No inspection was ordered
G3	The detector could not detect the radiation	G15	The operator did not fulfil his obligations during the acceptance
G4	The detector could not detect the radiation	G16	The detector is out of order
G5	The detector is out of order	G17	The detector fails to detect the radiation
G6	Other types of checks failed	G18	The detector could not detect the radiation
G7	The radiation intensity is very low	G19	The staff did not have enough information about the appearance of SIR
G8	Detector failure	G20	SIR was not equipped with warning symbols
G9	Detector malfunction	G21	The radiation intensity is very low
G10	Visual inspection failed	G22	Low power supply capacity
G11	There was no visual inspection or inspection with a hand–held detector	G23	Influence of detection by instrumental influences

The detected MCC set contains fourteen first–order cut, eleven second–order cut, and one third–order cut. The percentage probability of a peak event with a stationary detector installed can be expressed according to relation (4) by assessing the number of minimum critical first–order sections against the total number of detected minimum sections in the solved system:

$$P_{G_0} = \sum MCC_1 \times \frac{100}{\sum MCC} \tag{4}$$

If such a detector is not installed, we must consider the development of causes only for the occurrence of G_6 (other types of controls failed). Such an event can be caused without considering the unification of the phenomena of 17 single elementary causes out of the total number of 20 causes in the development of events conditioned by the regulation of other types of controls. The probability of the occurrence of a peak event without a stationary detector at the input can then be expressed by relation (5):

$$P_{G_6} = \sum MCC_{C_1} \times \frac{100}{\sum MCC_C} \tag{5}$$

Thus, it can be stated that the peak event in operation with the radiation portal monitor installed can be caused in 53.8% of cases by the occurrence of a single basic event. In devices without a stationary detector at the input, the peak event can be caused by a single elementary cause in up to 85% of cases.

Another criterion for the qualitative assessment of the severity of MCC is the type of elementary phenomena considered. In general, we can arrange the elementary phenomena according to their type with regard to the severity of their consequences and frequency of occurrence in an order based on the experience that human factor errors occur more often than active element disorders and that active elements are more prone to disorders than passive elements [27].

The severity of the MCC according to the type of cause of failure was also evaluated with regard to the frequency of occurrence of a common cause (Table 5). The most critical possible elementary causes of the penetration of orphan SIR into the premises include neglect of regular inspection of the detector, its unpredictable failure, neglect of operator duties, detection performed outside the ionizing radiation, shielding radiation by the source cover or other material and general inability to detect the type of emitted ionizing radiation.

Table 5. Evaluation of severity MCC (source in–house)

Order	Tag	Event description	Frequency	Type
1.	Q	Neglect of regular inspection of the detector	4	L
2.	P	Unpredictable detector failure	3	A
3.	G	Detection took place outside the radiation area	2	L
4.	B	Intentional neglect of operator duties	2	L
5.	D	The detector does not detect neutron radiation	2	A
6.	O	SIR is shaded by other material	2	P
7.	N	SIR is shielded by its cover	2	P
8.	Y	The workplace lacks operational documentation	1	L
9.	W	Inappropriate measuring range set	1	L
10.	X	Insufficiently trained staff	1	L
11.	A	Illegal placement of SIR in the area	1	L
12.	V	The staff was not present at the acceptance	1	L
13.	AA	The manufacturer did not mark the SIR with warning symbols	1	L
14.	F	High vehicle speed	1	L

Possible failures of the human factor in the first–order MCC were also included in the group of serious causes.

4 DISCUSSION

The minimization of extraordinary cases in the area of SIR management and the resulting risks presupposes the adoption of appropriate technical and regime measures, which must be implemented on the basis of an assessment of occupational safety work and reliability of systems using appropriate analytical methods.

The conducted FTA unequivocally confirmed that the high level of technical measures and equipment with detection means significantly reduces the vulnerability of the investigated system. In the solved case, the biggest problem was that mostly hand–held detectors are available. It is suitable to replace these detectors with stationary ones in the future, but their acquisition depends mainly on the financial possibilities of the founders of the respective area. The use of hand–held detectors is very closely related to the human factor and its connection to regime protection. Furthermore, it is appropriate to pay attention to technical protective elements, which can ensure the protection of the building from unwanted "visits" with emphasis on mechanical restraint systems and emergency alarm and security systems.

The most serious possible causes of failure of the regime protection system in scrap metal collection facilities are almost three quarters of human error and are the result of intentional or negligent operator action and insufficient training in measuring instruments, principles of proper use and visual identification of potentially dangerous objects. The extension of time (15, 30 minutes or more) exposure to hazardous substances without immediate action significantly the ecological consequences, soil and groundwater contamination increase [28].

It follows from the above that facility operators must pay maximum attention to the processing of relevant documentation related to the security of the facility (for example, the regime of entry of persons and entry of vehicles, etc.). Furthermore, it must pay due attention to well–developed guidelines for the activities of employees of the facility, which must determine the appropriate regime of maintenance, inspections, handling and use of technical means (stationary and hand–held detectors). It is necessary to demonstrably acquaint employees with the relevant documents and require their correct application. And last but not least, to increase the frequency and scope of its inspection activities in the above–mentioned facilities.

5 CONCLUSIONS

The safety and health protection not only of employees working in metal waste collection points, but also of other persons entering the building must be ensured in full and in accordance with the relevant legal regulations of the state. These regulations must be specified by the founder or employer specified in the form of directives for the operation of each collection facility. Regime measures must also be an integral part of them. Regime measures must include, inter alia, a process for identifying and assessing risks, including in terms of ionizing radiation. A variety of risk analysis methods can be used to assess these risks. The authors used the method of fault tree analysis FTA in the article. Using this method, they found that the most significant factor contributing to the breach of regime measures is the human factor. The results of the analysis show that the employer must, among other things, ensure regular training of its employees with regard to prevention, as required by the relevant legislation. In addition to the principles of preventive maintenance, it is appropriate to include in the training program ways of effective and efficient use of detection devices [29]. In addition, the operator must rigorously monitor the fulfilment of the functional du-ties of each employee of the collection facility and draw immediate consequences if non–fulfilment of these duties is found.

6 ACKNOWLEDGMENTS

This work was supported by the Technology Agency of the Czech Republic (VI04000080); Tomas Bata University in Zlín (RVO/FLKŘ/2022/03, RVO/FLKŘ/2022/02, IGA/FLKŘ/2022/001) and by Department of Population Protection of Faculty of Logistics and Crisis Management at Tomas Bata University in Zlín.

7 REFERENCES

[1] Bányai, T., Tamás, P., Illés, B., Stankevičiūtė, Ž., Bányai, Á. (2019). Optimization of municipal waste collection routing: Impact of industry 4.0 technologies on environmental awareness and sustainability. Int. J. Environ. Res. Public Health, 16. https://doi.org/10.3390/ijerph16040634.

[2] Bueno–Delgado, M.V., Romero–Gázquez, J.L., Jiménez, P., Pavón–Mariño, P. (2019). Optimal path planning for selective waste collection in smart cities. Sensors, 19. https://doi.org/10.3390/s19091973.

[3] Rai, R.K., Nepal, M., Khadayat, M.S, Bhardwaj B. (2019). Improving municipal solid waste collection services in developing countries: A case of Bharatpur Metropolitan City, Nepal. Sustain. 11. https://doi.org/10.3390/su11113010.

[4] Das, S., Bhattacharyya, B.K. (2015). Optimization of municipal solid waste collection and transportation routes. Waste Manag. 43. https://doi.org/10.1016/j.wasman.2015.06.033.

[5] Porterfield, D., Yano, K., Mao, K., Wharry, J. (2018). Investing in a permanent and sustainable nuclear waste disposal solution. Prog. Nucl. Energy, 108, p. 474–479.

[6] Czechia (2006). Act No. 262/2006 Coll. The Labour Code. Collection of Laws. Amount 84/2006.

[7] Jakubčík, M., Benčíková, E., Mihoková Jakubčeková, J., Tomek, M. (2020). System improvement of protection of employees against ionizing radiation from organ sources in scrap metal collection facilities. Waste Forum, 1, 33–44.

[8] Czechia (2001). Act No. 185/2001 Coll. On waste and amending certain other laws. Collection of Laws. Amount 71, 4074–4113.

[9] Czechia (2016). Act No. 263/2016 Coll. Atomic Act. Collection of Laws. Amount 102.

[10] Czechia (2016). Decree No. 422/2016 Coll. Decree on radiation protection and security of a radionuclide source. Amount 172/2016.

[11] State Office for Nuclear Safety (2017). Finding and capture of radionuclide sources in equipment intended for the construction, collection and processing of metal scrap, Radiation protection Recommendations DR–RO–4.1 (Rev.1.0). Ref. SÚJB/OS/20195/2017. Praha.

[12] Profi Press (2019). How to proceed when finding nuclear material in scrap. Waste. 2, p. 31–34. from: *https://www.sujb.cz/fileadmin/sujb/docs/radiacni-ochrana/dokumenty/Odpady_0219_31-35_opr.pdf*, accessed on 2020-10-06.

[13] International Atomic Energy Agency (2011). Control and Management of Radioactive Material Inadvertently Incorporated into Scrap Metal, Proceedings of an International Conference. Vienna, from: *https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1502_web.pdf*, accessed on 2021-01-09.

[14] State Office for Nuclear Safety. Annual reports. State Office for Nuclear Safety, Prague. 2015–2019, from: *https://www.sujb.cz/dokumenty-a-publikace/vyrocni-zpravy*, accessed on 2021-01-11.

[15] Klener, V. et al. (2000). Principles and practice of radiation protection, first ed. State Office for Nuclear Safety, Prague.

[16] Markulik, S., Kozel, R., Solc, M., Pacaiova, H. (2016). Causal dependence of events under management system conditions. MM Sci. J. https://doi.org/10.17973/MMSJ.2016_10_201620.

[17] Dafoe, A. (2018). Nonparametric Identification of Causal Effects under Temporal Dependence. Sociol. Methods and Res. 47. https://doi.org/10.1177/0049124115613784.

[18] Liu, Y., Fan, Z.P., Yuan, Y., Li, H. (2014). A FTA–based method for risk decision–making in emergency response. Comput. Operations Res. 42. https://doi.org/10.1016/j.cor.2012.08.015.

[19] Haegeman, K., Marinelli, E., Scapolo, F., Ricci, A., Sokolov, A. (2013). Quantitative and qualitative approaches in Future–oriented Technology Analysis (FTA): From combination to integration? Technolog. Forecast. Soc. Change. 80. https://doi.org/10.1016/j.techfore.2012.10.002.

[20] Sinay, J., Vargová, S. (2012). Identification of factors of stages of causal dependence of the occurrence of a negative phenomenon. Spectrum. Association of Fire and Safety Engineering, Ostrava;12. p. 49–51.

[21] Czechia (2007). ČSN EN 61025. Fault state tree analysis (FTA). Czech Standards Institute, Prague.

[22] Jakubčík, M. (2019). Mode of Protection against Ionizing Radiation from Orphan Sources in Metal Scrap Collectors. Zlín. Bachelor's thesis. TBU in Zlín.

[23] Sánchez, A., Lozano, M., Villar, P., Herrera, F. (2009). Hybrid crossover operators with multiple descendents for real–coded genetic algorithms: Combining neighborhood–based crossover operators. Int. J. Intell. Syst. 24.

[24] Liu, Y., Fan, Z.P., Yuan, Y., Li, H. (2014). A FTA–based method for risk decision–making in emergency response. Comput. Operations Res. 42. https://doi.org/10.1016/j.cor.2012.08.015.

[25] Trnecka, M., Trneckova, M. (2018). Data reduction for Boolean matrix factorization algorithms based on formal concept analysis. Knowledge–Based Syst. 158. https://doi.org/10.1016/j.knosys.2018.05.035.

[26] Ivanov, I., Pal, R., Dougherty, E.R. (2007). Dynamics preserving size reduction mappings for probabilistic Boolean networks. IEEE Trans. Signal Process. 55. https://doi.org/10.1109/TSP.2006.890929.

[27] Vintr, Z. (2015). Predictive reliability analyzes and possibilities of their use: Analysis of the tree of fault states. 1. Czech Society for Quality, Prague, from: *https://www.csq.cz/fileadmin/user_upload/Spolkova_cinnost/Odborne_skupiny/Spolehlivost/Sborniky/CSJ_OSS_SBORNIK_2015_final.pdf*, accessed on 2020-10-06.

[28] Coneva, I. (2012). Solving leakages of dangerous substances at traffic accidents with sorbent usage. Protection of the living conditions of the population. Environmental protection of population: 7th Scientific International Conference. VŠKE, Brno, p. 57–68.

[29] International Atomic Energy Agency (2012). Control of Orphan Sources and Other Radioactive Material in the Metal Recycling and Production Industries. Specific Safety Guide. No. SSG–17. International Atomic Energy Agency, Vienna.

Paper submitted: 25.01.2022.

Paper accepted: 18.06.2022.