https://doi.org/10.15407/scine22.01.107

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ANALYSIS OF THE CAUSES AND CONSEQUENCES OF RESONANCE ACCIDENTS IN BLAST FURNACES

Introduction. *The blast furnace, together with hot-blast stoves and gas-cleaning equipment, remains one of the most hazardous systems in the metallurgical industry. Accidents with catastrophic consequences for both equipment and personnel require special attention. Such events have no statute of limitations and shall be thoroughly analyzed to eliminate their root causes and to ensure safe future operation.*

Problem Statement. *The technical literature has offered insufficient or even contradictory coverage of particularly severe accidents — especially furnace explosions — which hinders the improvement and development of safe blast furnace operating technologies. Therefore, the identification of effective methods for preventing and mitigating such emergencies is of critical importance.*

Purpose. *To determine the actual mechanism of the explosive destruction of Blast Furnace No. 7 at the Dniprovsky Metallurgical Plant (DMP) on September 7, 1993, taking into account both objective and subjective contributing factors.*

Materials and Methods. *The analysis is based on archival materials presenting the furnace operating parameters on paper records, photographic documentation, reports and conclusions of expert commissions, as well as relevant publications on the subject.*

Results. *The mechanism of the explosive destruction of BF No. 7 at DMP (Ukraine) has been reconstructed, and the contributing factors have been systematized. A comparative analysis of this accident and the incident at BF No. 5 at the Port Talbot plant (UK) has been performed. Both incidents were triggered by the same catastrophic mechanism: the uncontrolled entry of a critical amount of water into the furnace working space.*

Conclusions. *It has been established that the large-scale destruction of BF No. 7 at DMP with multiple human casualties resulted from two explosions of different intensities rather tham from a single*

Citation: Kryachko, G. Yu., Sigarev, Ye. M., Pokhvalityi, A. A., Rudenko, M. R., and Yeskov, D. V. (2026). Analysis of the Causes and Consequences of Resonance Accidents in Blast Furnaces. *Sci. innov.*, 22(1), 107—122. https://doi.org/10.15407/scine22.01.107

explosion, as previously assumed. The dynamics of the changes in the blast furnace gas-blowing regime during the blow-in period have been demonstrated. It has been shown how, in the absence of burden descent at the furnace top, they led to an explosive accident. The study has emphasized the critical importance of adhering to established recommendations for preventing steam explosions in blast furnaces. The findings have represented a valuable contribution to the development of regulatory documents aimed at ensuring the safe operation of blast furnaces.

Keywords: blast furnace, accident, steam explosion, destruction mechanism, causes, consequences, compliance, recommendations.

Despite certain environmental restrictions, more than 85% of the world's iron is produced in blast furnaces (BF). The advantages of the blast furnace process compared to alternative ferrous metal production technologies include relatively low energy consumption for pig iron production, high utilization of furnace gas energy, and large unit capacity, which meets the needs of steel production [1].

However, BF and their auxiliary equipment belong to the category of explosion-hazardous production systems, where explosive and flammable substances — liquids, gases, dust, as well as molten iron and slag at temperatures of 1400—1500 °C — are used, generated, and transported. The study of industrial gas explosions at ferrous metallurgy enterprises shows that 28% of all explosions occur in blast furnace process units, which include hot stoves, dust catchers, and scrubbers with adjacent gas pipelines. Moreover, about 90% of these explosions take place during start-up and shutdown operations, with up to 60% occurring during start-up procedures and approximately 40% during furnace shutdown operations [2].

Blast furnace explosions are a relatively rare phenomenon, but they are highly resonant, as they are typically accompanied by human casualties and a significant number of injuries. According to the estimate [1], one BF explodes annually worldwide. Here is the r"recent" sad statistics of the last few years: on July 16, 2020, an explosion occurred at the BF in Burns Harbor (USA) [3]; on June 13, 2023, an explosion destroyed the BF of *Tata Steel* at the plant in Odisha (India), with 19 injured; on June 23, 2023, an explosion occurred at the BF of *Yingron Iron* & *Steel* (China), resulting in 4 fatalities and 5 injuries [5]; on April 29, 2024, an explosion took place at BF No. 6 of *EVRAZ NTMK* (Russia) [6] due to an uncontrolled cast iron release.

Unfortunately, blast furnace operations in Ukraine also suffer from explosive destructions. For instance, uncontrolled cast iron emissions occurred on July 27, 2015, at BF No. 1M of the Dniprovsky Metallurgical Plant (DMP) [7], and on April 29, 2018, during the blowing period at BF No. 9 of *ArcelorMittal Kriviy Rih* [8].

Accidents with catastrophic consequences, both for equipment and for the technological personnel, require special attention. Accidents with severe consequences are not subject to a statute of limitations; they shall be thoroughly studied to eliminate the causes of their occurrence. For example, in the monograph [1], the BF explosion on March 24, 1900, at the Henrichshutte plant in Germany is discussed. From global sources, analytical materials from 2008 [9], 2011 [10], and 2023 [11] can be cited, which cover the circumstances of the explosion at BF No. 5 of the CORUS plant in Port Talbot (UK) on November 8, 2001.

THE MATERIALS FOR ANALYZING THE CAUSES AND CONSEQUENCES OF THE EXPLOSION AT BLAST FURNACE No. 7 OF THE DNIPROVSKY METALLURGICAL PLANT (DMP)

The explosion of BF No. 7 at the Dniprovsky Metallurgical Plant on September 7, 1993, during the blowing period, has no analogs in global blast furnace practice, either in terms of the scale of the destruction or the number of human casualties. The damage to the furnace was so extensive that the expert commission involved in the investigation of the accident deemed it unfeasible to restore the furnace. Only later was a virtually new BF No. 1M built in its place.

Given the importance of learning from the lessons of this high-profile accident, publications [1, 12] have appeared at various times after the incident, in which the causes and consequences were analyzed based on the work of governmental and professional commissions. To investigate the accident, employees from four research institutes, four leading metallurgical enterprises of Ukraine, UkrDipromez, and the trusts *Dniprodomremont* and *Kryvbassvybukhprom* were involved. The professional expert commission (hereafter referred to as Commission 1), which worked from September 8 to 14, 1993, was chaired by S.T. Pliskanovsky — Professor of the Department of Cast Iron at DMetI, Doctor of Technical Sciences, a specialist with extensive production and administrative experience.

Later, in accordance with the decision of the Prosecutor's Office of the city of Dniprodzerzhynsk dated December 5, 1993, the Ministry of Industry of Ukraine, by order of January 31, 1994, established another expert commission (hereafter referred to as Commission 2). The commission included employees from the Ministry of Industry of Ukraine, DonNDIchermet, IChM, Dniprostalconstructions, and the heads of the blast furnace shops of the Mariupol Metallurgical Plant and Yenakiieve Metallurgical Plant. The commission was headed by the chief blast furnace operator of the *Zaporizhstal* Metallurgical Plant, V.I. Naboka.

The working conditions of the commissions varied significantly. During the work of Commission 1, the collapse of the furnace's metal structures prevented an assessment of the condition of the deck node. During the dismantling of the furnace, however, an opportunity arose to take metal samples for analysis of its condition, which was taken into account by the subsequent commission.

The authors of the article presented below do not question the high professional level of the participants in the aforementioned commissions investigating the accident at BF No. 7 of DMP. However, considering the authors' involvement in this investigation from September 8, 1993, to July 1994, they consider it their duty to add some materials that were unknown to the scientific and technical community and present their perspective on the events of September 7, 1993, in Ukraine, and November 8, 2001, in the United Kingdom.

Since the accident at BF No. 7 of the DMP occurred as a result of the layering of both objective and subjective factors, it is necessary to distinguish between the influence of blast furnace conditions on the event and human activities.

CHARACTERISTICS OF BLAST FURNACE No. 7 OF THE DNIPROVSKY METALLURGICAL PLANT

Blast Furnace No. 7 was built according to the first standard project in 1932. The volume of the furnace was 930 m³, and together with Blast Furnace No. 8, it was arranged in a block layout. In 1964, a reconstruction of BF No. 7 was carried out, increasing the useful volume to 1719 m³ by the method of overbuilding onto the prepared foundation. The furnace had 18 air tuyeres and one cast iron tap hole. During the major overhaul of the first category (MO-I) from December 1983 to February 1984, the furnace shell was replaced, a new charging device was erected, two cast iron tap holes were installed, and a second casting yard was arranged. The last major overhaul — MO-II was carried out in January-February 1990. The shell of the tuyere zone was partially replaced, and 24 tuyere devices were installed. Due to the increase in the number of tuyere devices, a new ring air duct was installed. Additionally, a full replacement of the cooling devices was carried out, except for the cooling devices of the bosh and charging device. From February 1990 to September 1993, three MO-III overhauls were carried out, replacing the charging equipment.

At the time of the accident, Commission 1 established the absence of a device for registering the water level in the scrubber and a design flaw in the equalizing gas pipeline between the scrubber and the interconical space of the furnace, which contributed to the accumulation of water in the gas pipeline. The technological condition of the furnace (cooling system, charging device, casing, metal structures) was satisfactory.

Throughout the entire period of the furnace shutdown and after the blowing, the steam consumption at the tuyere area was 4 tons per hour (including 3 tons per hour in the inter-conical space). The steam pressure was 196 kPa, and the temperature was 140—160°C, which did not meet the requirements of the technological instructions (pressure not lower than 392 kPa, temperature not lower than 250 °C).

CONDITIONS AND MODE OF BLAST FURNACE OPERATION

Prior to the accident, the iron ore materials consisted of sinter from the local plant, which accounted for 70—80% of the total charge, sinter from the Southern GOK (0—20%), and pellets from the Central GOK (8—20%). A day before the incident, poor-quality coke from the Bahlijski KHz was delivered to BF No. 7 due to the deterioration of the coal grade and long coking periods of 32—42 hours (Commission 1). Commission 2 clarified that the coke was made from a charge that did not contain *K* grade coal. The share of this coke in the charge was approximately 70%.

Unfortunately, the commission materials did not address the mechanism of the formation of the lower cavity in the charge column. The first and significant consequence of using substitute coke was the loss of gas permeability of the coke "windows" in the cohesion zone due to clogging with coke fines. As a result, the heating and melting of the solidified layers of iron ore materials during the downtime while blowing the furnace significantly slowed down, contributing to the sintering of the materials and the formation of a cavity at the interface between the bosh and the belly.

Table 1. **Gas-Blowing Parameters of the Furnace**

Indicators	Design Values	Actual Values (September 1—4)
Blast rate, nm^3/min	3400	1800—1900
Excess blast pressure at tuyeres, kPa	390	275—280
Blast temperature, °C	1200	960—980
Oxygen content, %	28.2	20.8—21.7
Excess pressure of tuyere gas, kPa	260	180—200

The second consequence of using substitute coke was the deterioration of the drainage and gas permeability of the coke bed, an issue pointed out by the authors [1].

As a result of the prolonged use of low-quality coke and its shortage, the gas-blowing mode in early September 1993 significantly differed from the design parameters (Table 1).

The technology provided for the use of combined blowing with oxygen enrichment and the injection of natural gas in an amount of 4—7% of the blast.

The thermal condition of the furnace, due to sharp fluctuations in coke quality, its shortage, and low smelting intensity based on blast consumption, was extremely unstable. The silicon content in the pig iron during the four-day period leading up to the accident varied from 0.23% on September 5, 1993, to 2.03% on September 1, 1993. On the last cast on September 5, 1993, the silicon content reached 1.11%.

The sharp fluctuation in the hearth heating before the furnace shutdown was caused by water entering through the burnt cooling system of the bosh, which was discovered during the dismantling in the year following the accident. The technological personnel could have detected this deterioration during the blowing period if they had paid attention to the high hydrogen content in the tuyere gas, which fluctuated between 4—6% from the moment of the furnace startup until 11:45 AM. And only later, likely due to the slippage of the hearth, the flow was eliminated with the decrease in the H_2 content to 1.5%.

CIRCUMSTANCES OF THE ACCIDENT

BF No. 7 at DMP was shut down on September 5, 1993, at 11:50 AM due to a lack of coke, with a burden level of 1.75 m, without gas ignition, and with steam supplied to the interbell and underbell space while the working burden was loaded onto the large bell. After a 45-hour idle period, blast air was introduced into the furnace at 8:50 AM on September 7, and by 10:00 AM, its flow rate reached 1000 m^3/min (Fig. 1, *a*) at an overpressure of 110 kPa and a temperature of 800 °C. The top gas overpressure was 30 kPa at a temperature of 200 °C.

Subsequently, without any signs of burden descent observed on the probe rods, the technologists increased the blast air flow rate in two stages to 1100 m^3/min, leading to a rise in the hot blast overpressure (Fig. 1, *b*) and the lower pressure drop (Fig. 2, *b*). Later, to reduce this pressure drop, the blast air flow rate was decreased by approximately 350 m^3/min. As a result of this reduction and the opening of the tap hole at 11:00 AM, the lower pressure drop decreased. Reasonably, Commission 2 interpreted this reduction as an indication of burden settlement in the lower part of the furnace. In our opinion, this settlement, along with the degradation of the coke "windows" above the settlement level and burden sintering, led to the formation of the first cavity (Fig. 3, item 7), which should have been immediately eliminated through a controlled burden settlement.

Instead of addressing the issue, the personnel, despite the absence of burden descent at the fur-

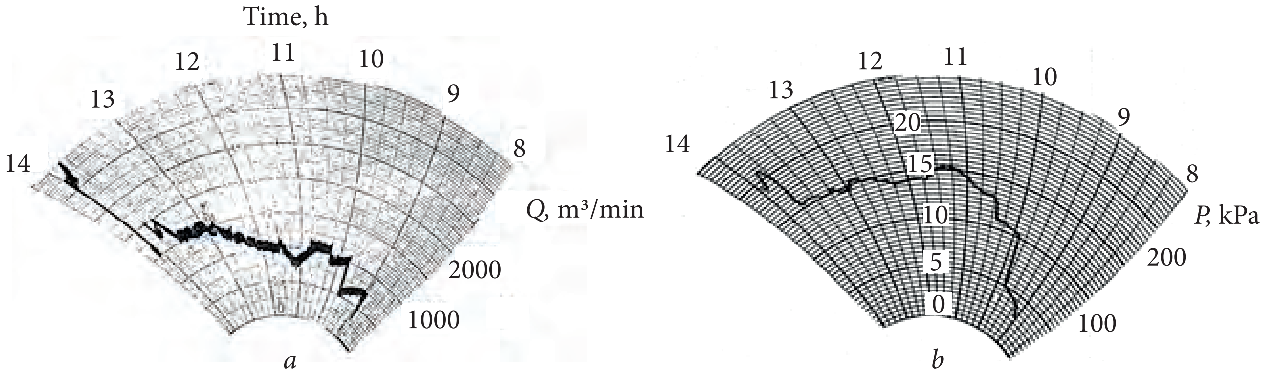

Fig. 1. Fragments of circular diagrams showing the cold blast flow rate after the snort valve (*a*) and the hot blast overpressure (*b*) during the blow-in period of BF No. 7 at DMP on 07.09.1993

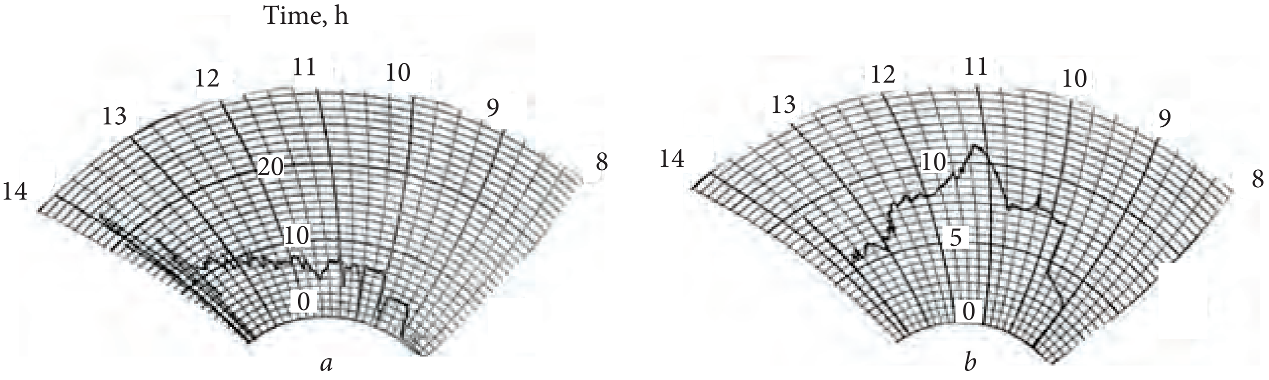

Fig. 2. Fragments of circular diagrams of the upper (*a*) and lower (*b*) gas pressure drops during the blow-in period of BF No. 7 at DMP on 07.09.1993

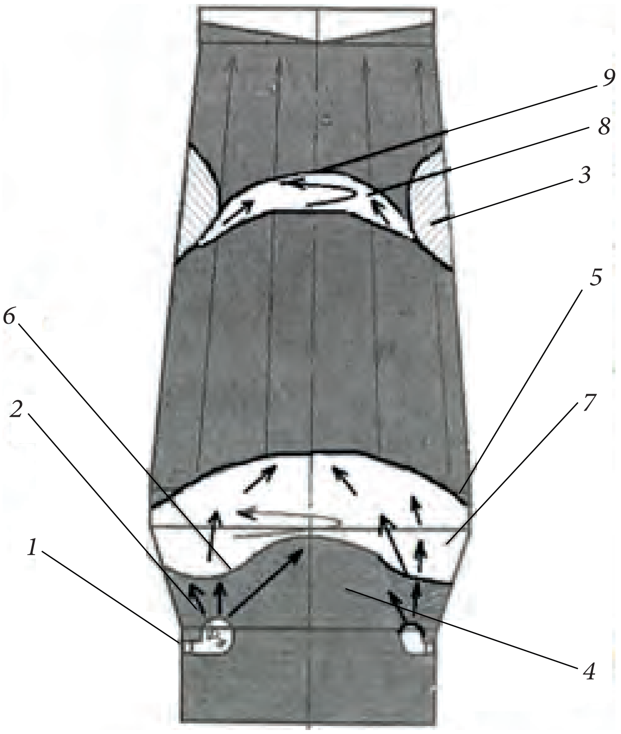

Fig. 3. Scheme of cavity formation in the column of burden materials during the first hours of the blow-in period of BF No. 7 at DMP on 07.09.1993: *1* — tuyeres; *2* — tuyere raceways; *3* — cooling zone; *4* — coke packing; *5* — upper boundary of the lower cavity; *6* — lower boundary of the lower cavity; *7* — lower burden cavity; *8* — upper burden cavity; *9* — upper boundary of the lower cavity

nace top and the increase in the upper pressure drop (Fig. 2, *a*), initiated blast rate intensification (Fig. 1, *a*). As a result, by 1:30 PM, the blast air flow rate reached 1500 m^3/min.

It should be acknowledged that the technologists' desire to avoid an unfavorable event, which often occurs during forced burden settlement — namely, the flooding of tuyères with slag — led to an unjustified risk. The loss of a single day of furnace operation for tuyère clearing is incomparable to its complete destruction.

A separate analysis is required to determine the causes of the increase in the upper pressure drop (shaft–throat). According to Commission 2, the upper layer of the burden at the furnace throat was in an overmoistened sintering state. It is well known that moistened burden, especially fine sinter in a cold state, has a higher bulk density and does not undergo sintering in a furnace with a throat diameter of 6.9 m.

Indeed, the fact of burden moisture accumulation under the large bell (LB) was confirmed, but its effect was different. With a steam consumption of 1 t/h under the LB, a total of 45 t of steam was supplied during the furnace downtime. Given the substandard quality of the steam, as mentioned above, and the fact that the materials in the furnace cool down by approximately 50 °C per day [13], it can be assumed that a significant portion of the 45 t of moisture contributed to the formation of an upper annular accretion in the upper part of the shaft.

In addition to the sharp increase in the upper pressure drop (Fig. 2, *a*), the presence of the accretion was indicated by the temperature dynamics of the top gas when the working burden, moistened by 9 t of condensate (according to IChM calculations), was released from the large bell (LB) at 1:40 PM. After the bell was lowered, the temperature dropped from 500 °C to 250 °C and then rose to 475 °C within 12 minutes.

Since the accretion contributed to the sintering of the materials beneath it, a cavity also formed (Fig. 3, item 8) due to the settlement of the burden column as coke and iron ore materials were consumed. Thus, by 1:30 PM on 07.09.1993, two critical zones had formed in BF No. 7 — one in the lower part and another in the upper part — without any measures being taken to settle the burden.

The tragic consequences were caused by the technological personnel's misunderstanding of the paradoxical situation in which the furnace receives a sufficiently high-temperature (800 °C) and high-flow blast, while the burden at the throat remains stationary. If the coke at the tuyeres burns, thereby freeing up a certain volume, and the hot reducing gas formed as a result of coke combustion heats, reduces, and melts the iron ore materials, then an additional volume is released in the working space of the furnace due to the burden descending over a certain height of the furnace.

Noteworthy is the sharp decrease in CO_2 concentration, as well as an increase in CO in the top gas at 12:00. Commission 2 noted that the resulting gas, except for CO_2, was practically indistinguishable from the hearth gas — the CO content in it exceeded 30%. According to the commission, this indicated either the presence of a channeling phenomenon in the furnace or that the entire iron ore mass of the burden had fully reduced during the downtime.

The assessment of changes in the degree of carbon monoxide utilization (η_{CO}) showed that the reduction processes continued up until the explosion. At 11:30, η_{CO} was 45%, while at 13:30, it had decreased to 36%. This indicates only an increase in the proportion of reduced iron. However, one should not disregard the possibility that a higher degree of iron ore material reduction, due to the degradation of the cohesive zone, could have contributed to the formation of an iron framework in the vault of the lower cavity.

At 13:50, natural gas injection began at a rate of 1,500 m^3/h, and by the time of the accident, a total of 375 m^3 of gas had been injected.

Due to the slow filling of the interbell space with gas during pressure equalization, a decision was made to purge the equalizing gas pipeline with a diameter of 600 mm. The purging was carried out by increasing the blast flow rate through the closure of the snort valve to 2,000 m^3/min without prior notification of the blast furnace compressor operator. The top gas pressure was raised to an excessive 155 kPa, and under these blast flow and pressure conditions, at 14:05, when the large bell — free of burden but not of water — descended, an explosive destruction of the furnace occurred.

In the investigation of the accident causes, Commission 1 identified the purging of the equalizing gas pipeline with semi-clean gas as a contributing factor. This led to moisture accumulation on the large bell, and upon its subsequent descent into the furnace, the release of intense steam was triggered, initiating the collapse of the moistened burden and its subsequent entry into the high-temperature zone (Section 3 of the Conclusion [12]). Given the scale of the destruction, the term "moisture accumulation" does not accurately reflect the reality.

According to our investigation, it was not moisture that accumulated on the large bell (LB), but rather water from the equalizing gas pipeline and the scrubber. A professionally trained eyewitness who was at a distance before the explosion of BF No. 7 observed water columns approximately 2 meters high above the exhaust gas pipelines of the interbell space. Since these pipelines, along with the corresponding valves, are welded into the gas seal cone of the charging unit, it is possible to roughly estimate the volume of water that entered the interbell space at approximately 90 m^3, which was subsequently discharged into the working space of the furnace when the LB was lowered. Commission 2 also identified water drainage from the large bell as the cause of intensive steam generation, without specifying the exact volume of this water.

MECHANISM OF THE EXPLOSIVE DESTRUCTION OF BLAST FURNACE No. 7 OF THE DNIPROVSKY METALLURGICAL PLANT

The necessity of addressing this important issue arises from the conclusion presented in a monograph dedicated to the analysis of gas explosions in blast furnace operations [1]. The authors of the monograph believed that the explosion at BF No. 7 of the Dniprovsky Metallurgical Plant (DMP) resulted from prolonged burden hanging, and its mechanism coincides with that of explosions in blast furnaces following extended hanging periods during operation. The same study [1] emphasizes that hanging refers to the complete cessation of burden descent in a blast furnace while blast air continues to be supplied through the tuyeres. During furnace startup, the absence of burden descent from the very beginning of the process is not considered hanging but is instead referred to as choking — a state in which the burden column remains stationary at the top, despite the operation of the tuyeres. Unfortunately, in domestic literature, the concepts of choking and hanging are often conflated [14], which hinders an objective assessment of influencing factors.

The technologists, who were found guilty of the accident by the government commission — except for the acting foreman — completely denied the possibility of an explosion, instead attributing the destruction of the furnace shell to structural aging. Eyewitnesses of the accident reported varying numbers of explosions, ranging from one to three. Particularly important is the testimony of the senior cast house operator of BF No. 7, who was at the furnace control panel (in a room adjacent to the furnace) at the moment of the explosion. He reported hearing two explosions — the first, weaker "pop"), followed by noise, and then a second, much more powerful explosion.

The nature and sequence of the furnace and its structural destruction fully align with the cast house operator's report.

The first medium-strength explosion occurred during the lowering of the large bell (LB) and the explosive steam generation in the upper furnace cavity (Fig. 3, item 8) as a result of the interaction of water drained from the cone with furnace gases and heated materials. The force of the first explosion, directed upwards, caused the opening of the atmospheric valves on the furnace gas ducts, ripped open the hatches on the inclined gas ducts, and destroyed the dust catcher dome, ejecting the shutoff valve over a considerable distance.

The destructive force of the explosions is significantly amplified by detonation — a phenomenon that occurs when the explosive shockwave of gas meets the reflected wave from the walls and barriers [1]. It was precisely due to detonation that the mounting hatches on the inclined gas ducts were torn off and the dust catcher was destroyed.

The force of the first explosion, directed downwards, caused a deep rupture of the charge along with the cooling material, moistened with water from the intercone space. In the short interval between the "pop" and the powerful explosion, eyewitnesses heard noise and shocks caused by local intense steam generation and a whistling sound, the origin of which can be explained by the existence of blowouts on the shaft casing (the presence of small blowouts was confirmed in the materials of Commission 2).

The rupture of the charge, initiated by the first explosion, led to a powerful "lower" explosion in the cumulative cavity (Fig. 3, item 7). The second explosion was much more powerful than the first due to the interaction of larger amounts of water with heated materials and gases, higher temperatures, and the existence of a large cumulative chamber (up to 250 m^3) in the area of the softening zone, which resulted in detonation.

The force of the second explosion, directed sideways, tore the shaft casing off the deck ring, while the upward force lifted the casing along with the charge and charge material to a height of at least 1 meter. The ejection of heated materials and gases during this process led to numerous accidents.

During the second explosion, 17 deck coolers were ejected from the furnace at a distance of 40 meters. The explosion destroyed the metal structures of the hoist, the inclined bridge, and the gas duct system — the frame was torn off from the western side, the descending gas pipelines fell onto the platform, and the ring air duct was knocked down. After the fall, the shaft casing shifted with a tilt in the southern direction. Photodocuments that provide insight into the scale of the destruction are presented in [1, 12].

ANALYSIS OF THE DESTRUCTION PATTERN OF BF No. 7

During the investigation, the blast furnace technicians insisted that the cause of the explosion was the use of the old section of the marathon ring left from the 1964 reconstruction (Fig. 4, *a*). To verify the adequacy of this version, the laboratories of the Dniprovsky Metallurgical Plant conducted research on samples of the deck ring and the adjacent shaft casing. Samples for the study (Fig. 4, *b*) were cut from different parts of the marathon ring and the shaft casing. The sample shown in Fig. 4, *b*

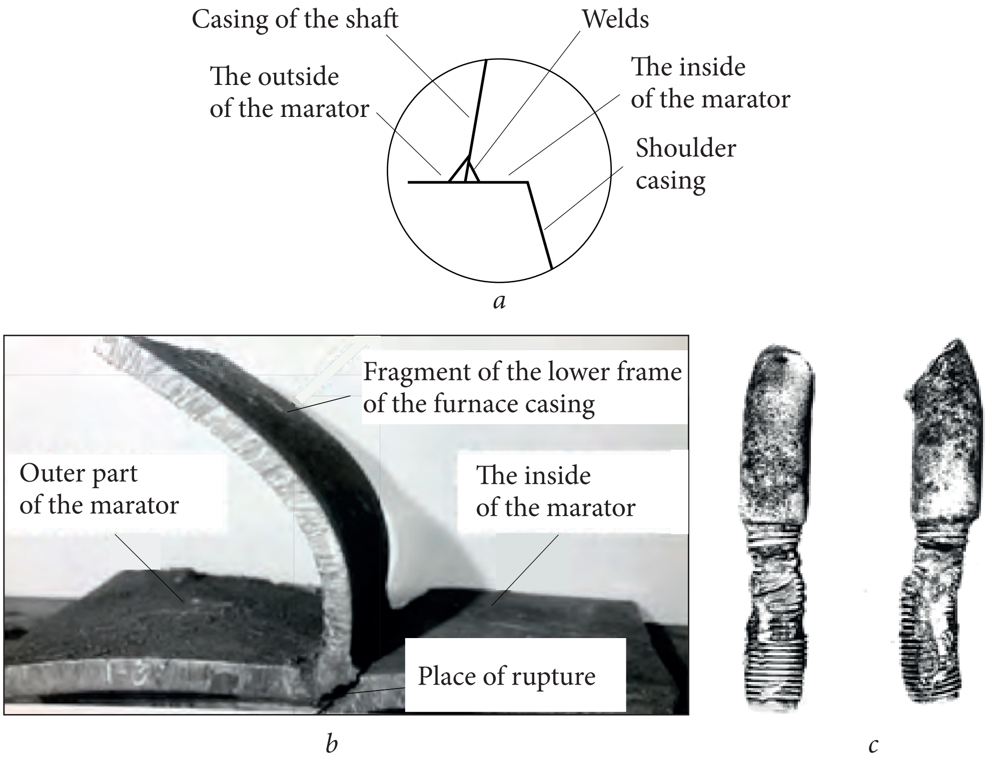

Fig. 4. Scheme of the deck ring assembly (*a*), sample for the study of the condition of the deck ring (marator) and shaft casing (*b*), taken at BF No. 7 DMP during disassembly, and the nature of the bolt destruction connecting the deck ring with the blast furnace column head (*c*). Samples were taken at BF No. 7 DMP during the disassembly of metal structures

contains two fragments with a gap between them — on the left, an intact outer part of the deck ring and shaft casing, and on the right, the inner (furnace) part of the marathon ring. The study showed that the deck ring was made of steel grade 09Г2С, according to the requirements of GOST 19281-89, and the casing was made of steel grade 15Х-20Х, according to GOST 4543-71.

It was established that the macrostructure and microstructure of the deck ring metal and the furnace casing at BF No. 7 were of satisfactory quality, and the weld seam connecting the ring with the casing was not destroyed.

A bolt that connected the deck ring with the column head was also taken for examination. It was determined that the bolt material corresponded to steel grade 3 according to GOST 380-71 and steel grade 20 according to GOST 1050-74. At the time of the deck ring failure, the bolt was subjected to both stretching and twisting (Fig. 4, *c*). Since the bolt head is welded to the outer surface of the marator, the stretching effect of the bolts occurred due to the lifting of the ring above the column head during the explosion (Fig. 5).

In the conclusions of Commission 1, it was noted that the shaft casing shifted with a tilt in the southeast direction (towards the dust catcher of BF No. 8). No explanation for the cause of this displacement was provided, presumably due to the lack of necessary data. During the disassembly of the metal structures of the destroyed furnace and its equipment, evidence of the causes of this displacement emerged.

As seen in Fig. 6, the aforementioned displacement of the shaft relative to the axis of the blast furnace occurred as a result of the shaft falling from a certain height due to the force of the explosion. The photo clearly shows the areas where

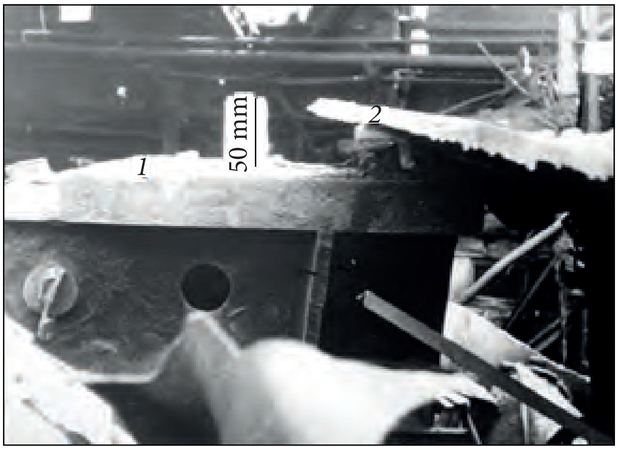

Fig. 5. Character of deformation of the inner part of the deck ring (marator) in the section not deformed by the shaft's fall: *1* — furnace column head; *2* — fragment of the inner part of the deck ring (marator) lifted above the column head

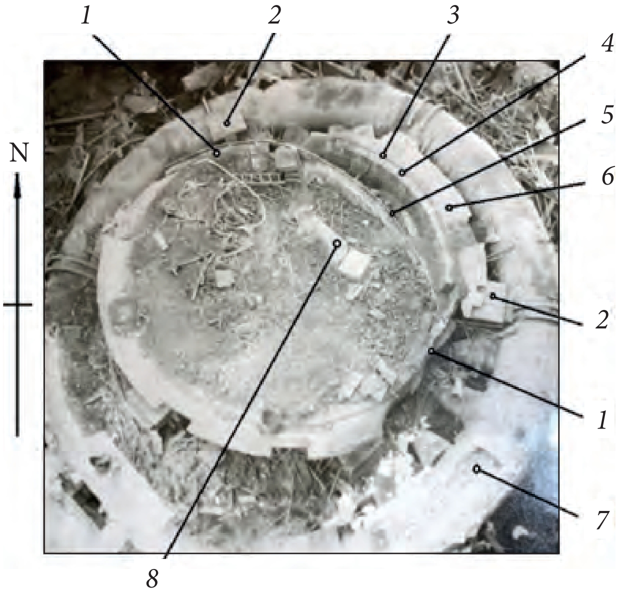

Fig. 6. General view of the metal structures of BF No. 7 during the dismantling of the lower part of the furnace: *1* — location of the boshes destruction due to the falling of the stamp; *2* — furnace column heads; *3* — boshes casing; *4* — boshes coolers; *5* — shaft casing; *6* — remnants of the internal part of the deck ring (marator) with cutouts for metal condition analysis; *7* — ring air duct; *8* — small cone, removed during furnace dismantling

the falling shaft cut through the inner part of the marator. Figure 7 shows the scale of the damage to the boshes and the shaft itself during its fall.

The nature of the damage to the inclined bridge of the skip hoist also indicates significant movement of the blast furnace structure during the explosion upwards. Earlier (M.S. Shchyrenko, *Mechanical Equipment of Blast Furnace Shops*, 1962), three-support bridges were built, where the upper support was placed on the furnace bosh, the middle support on the frame column (pylon), and the lower support on the skip pit wall. The pylon was made in the form of a flat truss that had flexibility along the longitudinal axis of the bridge. Three-support bridges were affected by the deformation of the blast furnace casing, which is why modern furnaces are equipped with two-support bridges (Fig. 8, *a*): the upper support is placed on the pylon, and the lower support is placed on the skip pit wall [15]. Due to the lack of a rigid connection between the console and the metal structures of the furnace shell, minor deformations of the furnace casing, such as those caused by gas explosions during blowouts, did not result in damage to the inclined bridge.

During the powerful explosion, the movement of the furnace along with the stamp upwards caused a violent impact that lifted the bridge console, which, when falling onto the pylon, bent it in the direction of the blast furnace. As a result, the inclined bridge was destroyed at the assembly joint (Fig. 8, *b*) [1, 12]. The rupture of the assembly joint was facilitated by the destruction of the stamp and the bosh platform, on which the console was supported. It is likely that the tilt of the furnace casing in the southeast direction at the moment of the explosion caused the shock from the destruction of the inclined bridge, and the existence of a temporary connection between the tuyere gas ducts and the dust collector through the descending gas ducts.

In conclusion, it should be noted that the large scale of the destruction of BF No. 7 was not caused by the appearance of cracks or the widening of the gap between the furnace casing and the

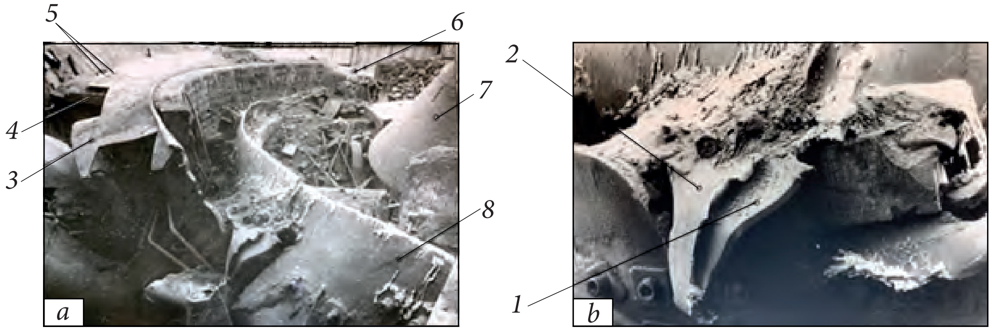

Fig. 7. General view of the destruction site of the boshes of BF No. 7 by the falling shaft (*a*) and a close-up fragment of this site (*b*): *1* — fragment of the crushed inner part of the deck ring; *2* — casing of the lower part of the shaft; *3* — inner part of the deck ring (marator) with cut-outs for research; *4* — head of the furnace column; *5* — bolt heads fastening the deck ring (marator) to the columns; *6* — place of destruction of the top of the boshes by the falling shaft from the southeast side; *7* — small cone of the charging device; *8* — remains of the casing of the shaft during disassembly

boshes, but by the explosion lifting the furnace casing with the metal structures to a certain height, resulting in the loss of the casing's function as the core of the structural rigidity of the central furnace unit [16, 17].

The extremely negative aspect of the block layout of the furnaces cannot be overlooked. The explosion wave from BF No. 7 demolished a simple wall made of corrugated steel sheet that separated the common casting yard into two sections, BF No. 7 and BF No. 8. It threw the overhead crane from BF No. 8 onto the yard and buried the yard with materials ejected from BF No. 7. The high-temperature steam-gas explosion wave from the damaged furnace fatally injured two workers who were in the gas-dynamic "shadow" of the wave behind the casing of BF No. 8. Therefore, it should be understood that during the reconstruction of furnaces, there is no alternative to the island layout.

COMPARISON OF THE ACCIDENT AT BLAST FURNACE No. 7 OF DMP WITH THE ACCIDENT AT BLAST FURNACE No. 5 OF CORUS

Eight years after the accident at BF No. 7 at DMP, on November 8, 2001, an accident occurred at BF No. 5 of CORUS at the Port Talbot plant (United Kingdom). The accident was similar in terms of the physical nature of the explosion to the accident at BF No. 7, also resulting in significant damage, human casualties, and injuries.

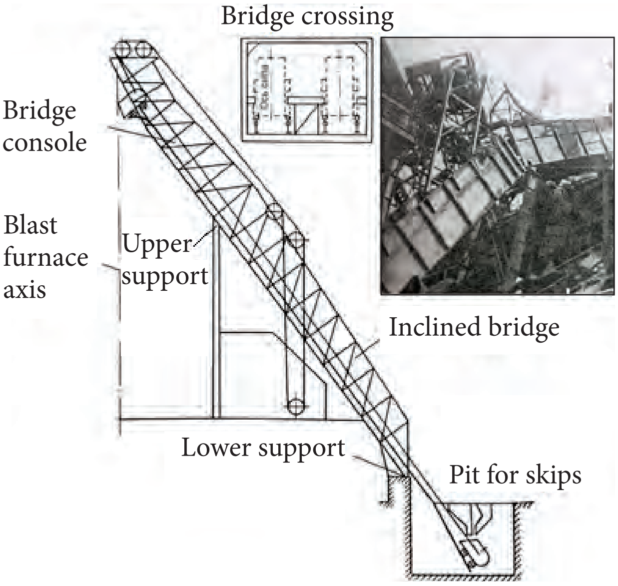

Fig. 8. Scheme of a two-support inclined bridge skip hoist (*a*) and the inclined bridge destroyed during the explosion of Blast Furnace No. 7 (*b*): photo from [12]

The approach of CORUS to the investigation of the accident deserves attention. Unlike the investigation of the accident at BF No. 7 DMP, where only two commissions were involved — the government commission and the one related to the criminal case — expert work at BF No. 5 CORUS involved not only specialists from the United Kingdom but also experts from abroad. As noted by the authors [10], the main source of difficulties in gathering evidence was the quantity of material evidence (70—90 tons), thousands of photographs, and 18 expert conclusions of varying levels of complexity.

In a relatively brief summary, the circumstances of the steam explosion at BF No. 5 CORUS were as follows. A failure of the electric pumps in the cooling system occurred due to a malfunction of the electrical equipment at the power station. Due to the lack of alternative means and the lack of response from the technological personnel, the furnace continued operation at full blast with only 55% of the necessary cooling capacity. As a result, some of the coolers burned out. Due to the delay in locating the leaking coolers, other coolers failed, and approximately 80 tons of water entered the furnace's working space. The amount of water that entered the furnace was determined experimentally after the accident: first, they measured how much water passed through the burnt cooler, and then, taking into account the number of burnt coolers and the duration of the leak through them, they calculated the total volume of water.

For the prevention of furnace cooling, technologists attempted to restore its operation using oxygen lances. At this time, water that entered the working space of the furnace came into contact with the heated materials and melts, leading to critical steam formation and pressure buildup. As a result of the steam explosion, the casings of the staves and bosh were torn at the point of the coupling connection. This caused the casing of the shaft, along with the metal structures and charge weighing approximately 5000 tons, to be lifted to a height of about 0.75 meters. Through the temporarily formed annular gap, molten materials, melts, and steam were ejected into the casting yard, leading to the deaths of three workers and injuring others.

After the explosion, the casing of the shaft fell onto the column heads. Authors [10] believe that most of the bolts connecting the deck with the bosh columns failed and could not limit the upward movement of the casing. In the case of BF №7 DMP, despite the longer operational period, the bolt connections were in satisfactory condition, but they did not serve as a limiting factor due to the powerful explosive force.

Based on our own research and publicly available materials from the Internet, we have compared some quantitative and qualitative characteristics of critical events in the studied furnaces (Table 2). The comparison shows that, despite different sources and rates of water ingress into the furnace, as well as different operational phases, the consequence was the destruction of the units due to explosive steam formation. It should also be noted that the most significant damage occurred due to a single lower explosion in the lower part of the furnaces, as this was where high material and gas temperatures were concentrated, along with an artificial emergency burden cavity (BF No. 7 DMP) and the normal tuyere-level cavities required for the blast furnace process (BF No. 5 CORUS).

Other explosions of significantly lower intensity, recorded by eyewitnesses of the accidents, should be attributed to the formation of the upper cavity (BF No. 7 DMP) and to possible localized explosions occurring when ejected hot materials from the furnace workspace came into contact with water from cooling system pipelines destroyed by the blast. In some locations, small explosions could also have occurred due to the depressurization of gas pipelines, where released process gas mixed with air.

In contrast to BF No. 7 DMP, the proximity of the explosion environment in BF No. 5 CORUS led to the burnout of six tuyeres, blockage of eight tuyere stocks by molten materials, and obstruction of nine more stocks along with their connection points to the bustle pipe.

If an audible and visual alarm had been activated on the furnace control panel when the water pressure in the cooling system of BF No. 5 CORUS dropped, and the personnel had immediately switched the furnace to a reduced blast mode, the catastrophe could have been avoided. In reduced blast mode, or preferably with the furnace shut down, it would have been possible to locate and disable the burnt-through coolers. It is surprising that in a country with a high level of technological development, such a basic procedure to prevent an accident related to a reduction or interruption in water supply was not implemented.

In the former USSR, according to the recommendations of the Iron and Steel Institute (E. E. Gavrilov and co-authors, *Blast Furnace Gas Operator*, 1986), when the water pressure in the cooling system dropped, operation at reduced blast was allowed for no more than 2 hours, after which the furnace had to be shut down. A condition for short-term operation at reduced blast was maintaining a water pressure at the tuyeres at least 50 kPa higher than the hot blast pressure. At the same time, water had to be supplied to the ring sprays for external cooling of the furnace shell. It is known [12] that even in cases of complete cessation of cooling water supply, timely actions by the process personnel made it possible to avoid severe

Table 2. **Comparison of Circumstances and Consequences of Blast Furnace Accidents with Steam Explosion Formation**

Country, City	Ukraine, Dniprodzerzhynsk (now Kamianske)	United Kingdom, Port Talbot
Plant, Furnace Number	Dniprovsky Metallurgical Plant, BF No. 7	CORUS, BF No. 5
Structural Parameters of the Furnace and Equipment:		
Useful volume, m^3	1719	~1700
Shell type	With deck	With deck, hearth, and bosh shell connected with an overlap
Number of hearth columns	6	8
Number of tuyeres	24	24
Cooler type	Cast iron, vertical plate coolers with embedded bricks	Horizontal copper box coolers
Charging device type	Double-bell	Chute-type
Burden hoisting system	Skip hoist	Skip hoist
Operating mode	Blow-in period	Normal stationary
Source of water ingress into the furnace	Equalizing gas pipeline and scrubber	Burned-out coolers
Approximate amount of water entering the working space of the furnace, m^3 and fraction of useful volume	~90 (~0.05V_useful)	~80 (0.047V_useful)
Characteristics of water ingress	Sudden from above through the top cone space	Gradual as the number of burned-out coolers increased along the furnace walls
Number of explosions	2—3	3
Location of the destructive explosion	Upper part of the bosh and belly	Lower part of the bosh
Technical consequences	Destruction of the furnace and part of the central unit equipment	Destruction of the furnace

accidents, limiting the damage to burning tuyeres and some tuyere coolers.

An intermediate cause of many accidents in blast furnace operations, both in Ukraine and internationally, is the insufficient attention given to improving the qualifications of process personnel. Training should be continuous and systematic rather than periodic and infrequent, as is often practiced. A central focus of such training should be the study of lessons learned from previous accidents to prevent similar incidents in the future.

The infiltration of a substantial amount of water — approximately 0.05 of the furnace's working volume — into the blast furnace during blowing after a hot standstill and during stationary (normal) operating conditions is typically accompanied by catastrophic consequences for both the furnace and the operating personnel. Accidents arising from explosive steam formation in the furnace working space cause significantly greater destruction than gas explosions.

The underlying causes of the analyzed accidents include the unreliability of the blast furnace cooling system (BF No. 5, CORUS) and the gas-cleaning system for blast furnace gas (BF No. 7, DMP). The absence of essential control and measuring equipment to monitor cooler burnout (BF No. 5, CORUS), the condition of the equalizing gas pipeline, and the high-pressure scrubber (BF No. 7, DMP) further contributed to the incidents. Experience demonstrates that cost-cutting measures in the technical maintenance of blast furnaces are incomparable to the losses resulting from accidents. During the construction or reconstruction of blast furnaces, it is therefore advisable to avoid, whenever possible, combined methods of blast-furnace gas purification. Under conditions of insufficient measurement technology, the need to apply artificial intelligence tools for monitoring furnace conditions has become evident.

In the examined cases, the immediate causes of the accidents stemmed from improper actions by process/operating personnel. These included attempts to accelerate furnace operation during a five-hour absence of burden descent after blowing-in (BF No. 7, DMP) and the continued use of a forced (normal) gas-blowing mode despite a 50% reduction in pressure and water flow in the cooling system (BF No. 5, CORUS).

Two primary directions appear essential for improving the qualifications of blast-furnace operators. First, accessible analytical information is needed regarding the circumstances, causes, and prevention of blast-furnace explosions not only nationally but also internationally, at least within the EU. Second, the qualification-improvement process for operators and auxiliary-service technologists should be continuous and strictly regulated rather than periodic, as it is today.

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Received 24.04.2025
Revised 09.08.2025
Accepted 19.09.2025

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АНАЛІЗ ПРИЧИН ТА НАСЛІДКІВ РЕЗОНАНСНИХ АВАРІЙ ДОМЕННИХ ПЕЧЕЙ

Вступ. Доменна піч, разом з повітронагрівальною і газоочисною технікою, залишається однією з найнебезпечних металургійних систем. Особливої уваги потребують аварії з катастрофічними наслідками як для обладнання, так і для техперсоналу. Вони не мають терміну давності й повинні ретельно вивчатися задля усунення причин їх виникнення та безпечного функціонування.

Проблематика. Недостатнє, а іноді й протирічне, висвітлення у технічній літературі інформації про особливо важкі аварії, зокрема вибухи печей, є перепоною для подальшого удосконалення та розробки безпечної технології ведення доменного процесу, тому пошук засобів запобігання та уникнення аварійних ситуацій є актуальним.

Мета. Встановити дійсний механізм вибухового руйнування доменної печі №7 Дніпровського металургійного комбінату (ДМК) 07.09.1993 р. з розглядом факторів об'єктивного та суб'єктивного впливів.

Матеріали й методи. Для аналізу використано архівні матеріали візуалізації параметрів роботи печі на паперових носіях, фотодокументи, акти й висновки експертних комісій, а також публікації з досліджуваного питання.

Результати. Відтворено механізм вибухового руйнування ДП №7 ДМК (Україна). Систематизовано фактори, що спричинили аварійну ситуацію. Виконано порівняння причин і наслідків аварій на досліджуваній печі і ДП №5 заводу в Port Talbot (Великобританія), що мали однаковий механізм катастрофічного руйнування агрегатів через неконтрольоване потрапляння критичної маси води в робочий простір печі.

Висновки. Встановлено, що на ДП №7 ДМК значний масштаб руйнувань з численними людськими жертвами був обумовлений не одним, як вважалося раніше, а двома вибухами різної потужності. Показано динаміку зміни газодуттьового режиму задувального періоду, що призвело при відсутності сходу шихти на колошнику до вибухової аварії. Охарактеризовано важливість дотримання рекомендацій для недопущення парових вибухів у доменних печах. Результати дослідження є важливим доповненням до створення нормативних документів для забезпечення безаварійної експлуатації доменних печей.

Ключові слова: доменна піч, аварія, паровий вибух, механізм руйнування, причини, наслідки, дотримання, рекомендації.