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COMPUTATIONAL MODEL OF THE BASIC EFFICIENCY PARAMETERS OF THE BUCKET WHEEL EXCAVATOR WORKING IN A BLOCK WITH A VERTICAL OBSTACLE

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Abstract: The article presents the results of the numerical experiments designed to determine the effect of obstacles in the form of the drainage wells/piezometer on the basic efficiency parameters of the excavator's work. Simulation research on built model included defining the basic parameters of the excavator working in the front block on stabile front (as a comparison) and on the non-stable front for two variants of drainage infrastructure exposing.

***Keywords*:** *bucket wheel excavator, efficiency, computational model, open cast mining*

1. INTRODUCTION

The main task performed by bucket wheel excavators is the process of generating a stream of excavated material. During the excavators' operation, productive states can be distinguished, when a stream of excavated material is generated, and unproductive states related to manoeuvring movements necessary to maintain the continuity of work. The condition for a productive state is the simultaneous occurrence of the main working movement (rotation of the bucket wheel) and the lateral movement of the boom (rotation of the excavator body). Nowadays, the speed of wheel rotation in excavators is usually unregulated, i.e., it has a constant value. The rotation speed of the excavator's

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body (swing mechanism) is controlled manually or automatically, according to a specific program and its value is limited by the maximum design value, given in the technical machine data. Unproductive states occur immediately after the completion of full cutting with a given working range of the cutting wheel, at its specific location in relation to the excavator's body, and at a given excavator site, in the excavated shortwall. The required manoeuvring activities to obtain the re-contact of the wheel with working face: the infeed movement, performed after each slice has been cut, the change of the terrace to a lower one, performed after excavating the slices in a given terrace, and lifting the boom with the cutting wheel to the height of the first terrace and thus, starting the mining of a new block advance.

In the BWE working process, stable and non-stable operations are distinguished. The states of stable work are achieved in the working front with constant parameters of a block in a quasi homogeneous soil medium. They are characterized by the fact that the stream intensity of the bulk material over a longer period of time oscillates close to its average value. The share of unproductive states during such work is the smallest. Non-stable operation states occur in the excavator's working process at the irregular front, forcing changes in the parameters of the excavator's working and manoeuvring movements.

Examples of non-stable work states are:

- work at the end of the working front (at the drive and return station) – the irregularity of the front is mainly caused by cutting slices of variable width while making an *s*-indentation into a new block,
- starting block cutting below work level – the irregularity of the front is caused by the cutting of slices of variable height,
- selective operation – also involves the operation of variable heights as well as forced breaks in the continuity of the stream, due to the time needed to change conveyors on the switch,
- work near obstacles, i.e., boulders, wells or piezometers – is caused by the increased number of manoeuvring movements needed to exploit the block in which the obstacle occurred.

1. COMPUTATIONAL MODELS OF A BUCKET WHEEL EXCAVATOR WORK

Mining companies strive to reduce the energy used at each stage of the mine's production value chain, thanks to which it is possible to both, reduce costs and carbon footprint (Kawalec et al. 2021; Kawalec, Król 2021, Suchorab, 2019). The computerization of mining works allows for the collection and analysis of more information about the mining activity and thus, the identification of the key parameters of the mine's value chain (Pactwa, Woźniak, 2015). The literature mentions many simulation and identification programs related to bucket wheel excavators. The scope of dependencies included in them is varied and depends on the objectives of the author's research. They concern the efficiency of the working process, the use of the excavators' potential (Nan et al. 2008; Rašić et al. 2016; Zhao-xue, Yan-long 2014; Galetakis, Roumpos 2015), maintaining the required safety as well as the reliability conditions of the machine (Daničić et al. 2016; Ilić 2021). Most of the research related to the technology of wheel excavators' work focuses on determining the efficiency in a single slice, with constant geometric parameters of the block, i.e., a constant height and width of the haul itself and individual terrace (Kressner 2006; Kołkiewicz, Szatan 1993; Brînaş 2021). Their common feature is the strictly deterministic character, as they are based on functional dependencies between the parameters of the working front's geometrical structures, the ranges and kinematics of the excavator's working units, as well as geotechnical and operational constraints.

As part of the implementation of the development project entitled: *Mechatronic system of control, diagnostics and security in opencast mining machines* identification and simulation software for bucket wheel excavators was prepared (Wygoda et al. 2013). It allows for the identification of a working front structure with a sublevel block as well as calculating the basic efficiency parameters of excavators. Supplementary data is available, containing information on the courses of individual phases calculated in the program, including the angular ranges of the cycle states and the time of their implementation. They can be used to program the manoeuvring movements of the machine for its autonomous operation (Poltegor-Instytut 2013). The created models do not allow for the simulation and determination of the excavator's work effects with an unstablized front, forcing changes in the parameters of the excavator's working and manoeuvring movements, as is the case with unconventional shapes of the excavator, e.g., in the case of an obstacle in the form of a boulder or a drainage well (Nowak-Szpak 2016).

Designing deeper and deeper open cast mines is associated with the need to protect them against additional groundwater resources that may be activated from the increase of effective infiltration in the area of the lowered water table (Szczepiński 2018). The forecasting size of the mine water inflow, and thus, the scale of the drainage problem, the hydrostructural system and the conditions for groundwater supply are the most important. This is especially visible in the case of the largest lignite open cast mine in Poland, Bełchatów. The depth of the mining pits is 200 m in the Bełchatów Field and 280 m in the Szczerców Field respectively (for which the planned maximum depth is 330 m). The large-diameter pumping well system covers the area of several thousand hectares. At the end of 2017, there were 819 drainage wells in operation (253 Bełchatów Field; 566 Szczerców Field) and 969 piezometers (Bełchatów Field – 339; Szczerców Field – 630) (Stobiecki, Pierzchała 2018). Their number significantly affects the work efficiency of bucket wheel excavators. Figure 1 shows the work plan of the K45 excavator operating in the second overburden floor in the Szczerców Field. There are over 30 wells/piezometers in the 3 km long and 100 m wide mining front.

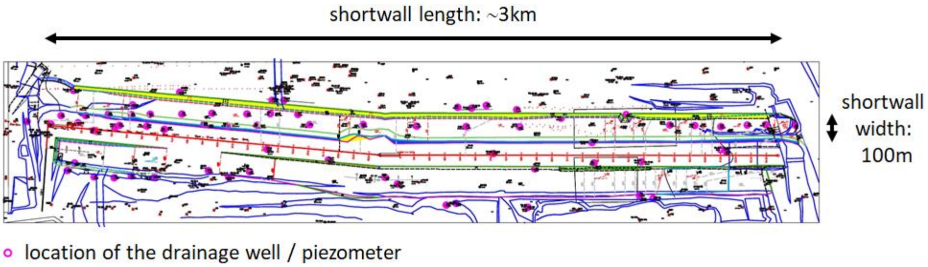


Fig. 1. Work plan of the bucket wheel excavator SchRs 4000.50 in the second overburden floor of the Bełchatów lignite mine, Szczerców exploitation field

The article presents the results of simulation tests performed on an extensive computational model developed by the author. The introduced changes to the algorithms took into account the increased number of unproductive states caused by the increased sequence of movements in a single block advance forcing the exposure of the vertical obstacle.

2. COMPUTATIONAL MODEL OF THE BASIC PARAMETERS OF AN EXCAVATOR'S WORK ON A NON-STABLE FRONT WITH A VERTICAL OBSTACLE

The extensive computational model describes, in a mathematical manner, the technological operation consisting of selecting the masses in such a way as to reveal the obstacle, enabling its elimination by appropriate mining services, while ensuring the safety of people and machines. The excavator's work in the vicinity of a drainage well can be carried out in various ways and depends on the existing conditions, but most of all – the subjectivism of operation control. Therefore, the mathematical model includes only the technically justified components of the operation, necessary to achieve the goal.

In order to correctly define possible technological operations in a single block advance with an obstacle, it is necessary to define the limits of the manoeuvring movements' path performed by the excavator. Since the computational model is to determine the difference in the achieved efficiency parameters during stable and non-stable work, it was assumed that the external boundaries of the single block, in which the obstacle occurred, will be the same as the single block in which there is no obstacle. Thus, the operation begins at the end of the work cycle on a block where the excavator's work is stable and ends at the beginning of the stable work cycle on a new block advance.

The boundaries of the manoeuvring path inside the block are determined by the location of the obstacle. The following parameters were adopted to identify it in a three-dimensional space:

- the boom deflection angle at which the obstacle is located at the moment the excavator starts cutting (*Ψprz0*),
- the distance of the excavator's axis from the obstacle's axis at the moment the excavator starts cutting (*Lprz_0*),
- The parameter supplementing the information about the obstacle is its diameter (*dp*).

Taking the aforementioned information into account, algorithms that allow for the precise determination of the obstacle's location were built and thus, the internal boundaries of the operation of exposing the wells in each of the strips are able to be calculated. Based on the observations as well as consultations with excavator operators, two variants of the excavator's operation were developed in a carrier with an obstacle.

Variant I call for the vertical obstacle in the form of a well to be removed (cut off) separately in each terrace. Thus, in the horizontal structure of the terrace, the phases of the technological process implementation have been identified (Fig. 2). In the first phase, the excavator works as in the case of a stable operation, i.e., it selects successive slices with the full width of the block. The boundary of phase I is the unveiling of the well to the extent sufficient to be mined. As the obstacle divides the terrace into two parts, the slices on the outer (phase 2) and then the inner (phase 3) side of the block are selected in the next stages of the process. The number of slices processed in these phases is determined by the necessity to fully expose it in the analysed stage and to keep the advance between the phases. Such preparation of the obstacle allows it to be safely accessed from the side of the front block and cut by a section corresponding to the height of the terrace, by authorized services. After removing the obstacle, the excavator continues to select the

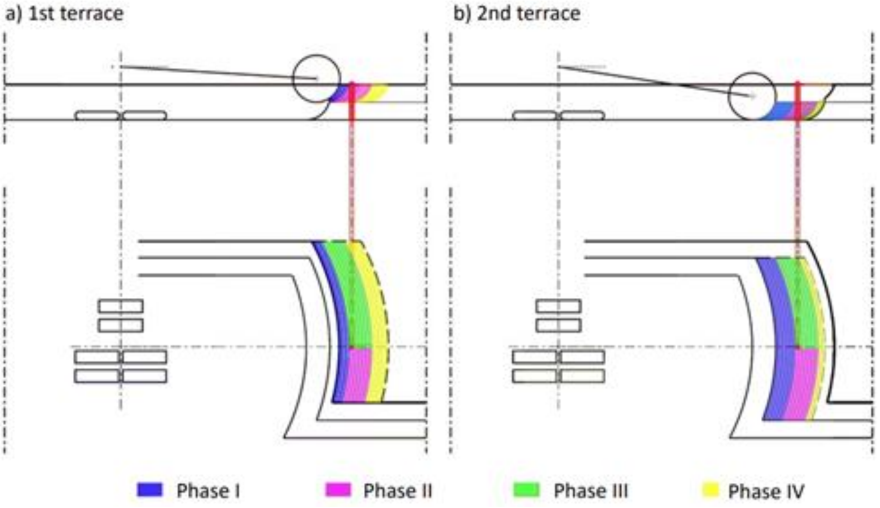


Fig. 2. Technological operation phases of the excavator's work on the single block advance with an obstacle in variant 1

masses in the terrace (phase 4). The sample diagram of the technological process developed according to the assumptions of variant I is shown in the figure (Fig. 2).

In Variant II, four phases were also separated in the horizontal structure of a single block, but a different sequence of their selection is assumed, so that they are characterized by a geometry different than in variant I. The work in the first phase proceeds as in the case of a stable operation, i.e., the width of the block. The sequence calls for that the first phase slices to be excavated in all terraces (Fig. 3). After the obstacle is exposed (in the section corresponding to the height of the upper step), strips are selected in all steps between the outer border of the block and the obstacle (phase 2) next, between the inside of the block and the obstacle (phase 3), and in the last stage, the remaining part of the block with obstacle is selected (phase 4).

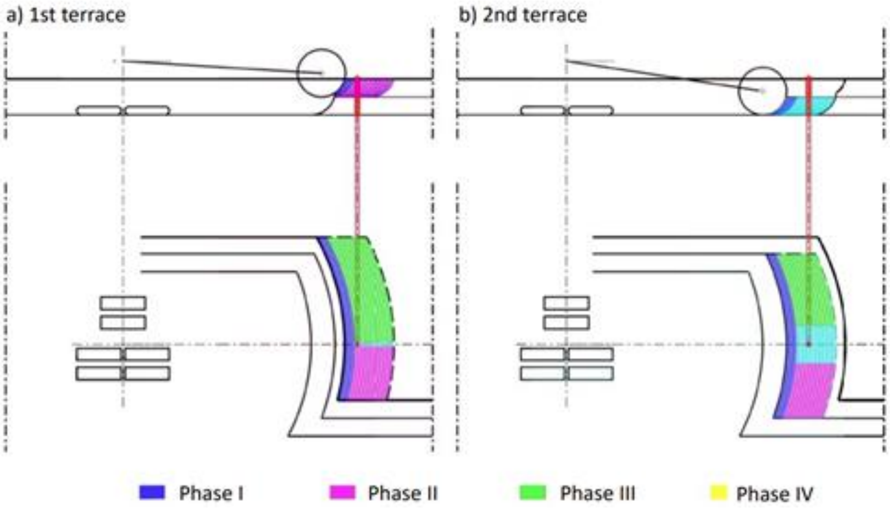


Fig. 3. Technological operation phases of the excavator's work on the single block advance with an obstacle in variant 2

3. SIMULATION TESTS OF EXCAVATOR WORK IN A SINGLE BLOCK ADVANCE WITH AN OBSTACLE

In this chapter, simulation studies were carried out as an example of the created model's practical application. The conducted numerical experiments were aimed at determining the impact of the occurrence of an vertical obstacle in the form of a drainage well/ piezometer of the excavator's work achieved basic parameters.

The simulation tests were carried out for the following geological and mining conditions of the SchRs 4000.50 bucket wheel excavator:

• Parameters of the excavated material:	overburden, workability class II/III, group 4;
• Block parameters:	
– number of terraces (bands)	*s* = 3 szt.,
– block height	*HZ* = 15 m,
– block width	*BZ* = 100 m,
– height of individual terraces (bands)	*hs*1 = 4 m, *hs*2 = 6 m, *hs*3 = 5 m,
– the length of a single excavator ride	*wdp* = 1.0 m,
– number of slices	*np* = 15,

– turning angle of rotor boom in a sublevel towards the inside lateral slope

$\Psi kw = 80^{\circ}$,

  - front slope angle $\alpha c = 60^{\circ}$,
  - side slope angle $\alpha b = 45^{\circ}$,
  - inside wedge band angle $\alpha 0z = 30^{\circ}$,
  - outside wedge band angle $\alpha 0w = 90^{\circ}$;
- the time needed to cut and remove the obstacle $Tup = 45$ min.

Assumed parameters for the location of the obstacle, at the moment of starting the mining of a single block:

- obstacle diameter $dp = 0.711$ m.
- the boom swing angle at which the obstacle is located $\Psi p\_0 = 0^{\circ}$,
- distance of the excavator's axis from the axis of the obstacle $Lprz\_0 = 86$ m.

The method adopted to determine the impact of a vertical obstacle is to compare the obtained effects of such work with the effects of work on the stable front. Therefore, in the first stage, a simulation was carried out on the work in which there was no obstacle. The computational model specifies the geometrical parameters according to which the uninterrupted operation of the excavator will take place. Since the work on the stable front is characterized by constant geometrical parameters, each of the 15 slices will have the same parameters of the technological model, i.e., widths (*BZi*, *Bwi*, *Bzi*), turning angle of rotor boom in a sublevel towards the inside and outside lateral slope (Ψwi, Ψzi) and cutting radius (*PUi*).

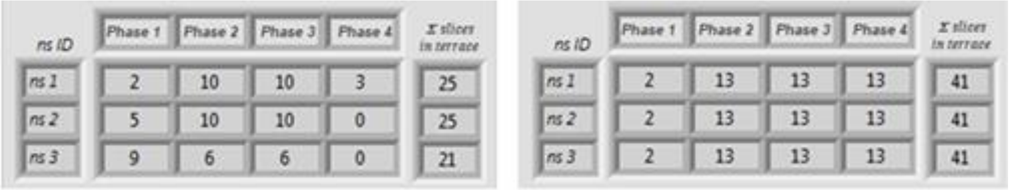
The total time needed for such work was estimated at 4 hours 18 minutes and 31 seconds (Table 1). The productive time during which the output stream is generated is 88% (03:47:42). The total unproductive time, which includes the time needed to perform manoeuvring and steering activities, is 12% (00:30:49). The effective capacity was determined at the level of 7,427 m^3/h.

Calculations for a single block advance according to the assumed variants of work in a carrier with a vertical obstacle showed that the number of slices to be selected in single terrace will increase from 15 to 25 in variant I and 41 in variant II (Fig. 4).

Table 1. Summary of the basic parameters of the excavator's work in the single block advance on the stable front

Basic parameters	Symbol	Unit	Value
Volume of the excavating block	*Vz*	[m^3]	32 000.95
Total operating time	*Tz*	[s] [hh:mm:ss]	15 511 04:18:31
– productive time	*Tp*	[s] [hh:mm:ss]	13 662 03:47:42
– unproductive time	*Tu*	[s] [hh:mm:ss]	1 849 00:30:49
Efficiency values			
– effective	*Qe*	[m^3/h]	7 427

– technical – theoretical	Qt $Q0$	[m^3/h] [m^3/h]	8 301 11 040
Performance indicators: – technical utilization rate – theoretical utilization rate	 $\eta 0$ ηe	 [–] [–]	 0.89 0.67



ns ID	Phase 1	Phase 2	Phase 3	Phase 4	Σ slices in terrace
ns 1	2	10	10	3	25
ns 2	5	10	10	0	25
ns 3	9	6	6	0	21

ns ID	Phase 1	Phase 2	Phase 3	Phase 4	Σ slices in terrace
ns 1	2	13	13	13	41
ns 2	2	13	13	13	41
ns 3	2	13	13	13	41

Fig. 4. The number of slices in successive phases of operations in individual terraces according to variant I (left) and variant II (right)

For such defined conditions for the implementation of technological operations, the basic parameters of the mining process were simulated (Table 2). The values show that working in a single block advance with an obstacle will reduce the effective efficiency to 80% in variant I and 76% in variant II. The total operating time will be extended by 3813 seconds (1 hour 3 minutes and 33 seconds) and 4982 seconds (1 hour 23 minutes and 2 seconds), respectively. The largest share in the extension of working time are periods of unproductive states, which in both variants increased almost threefold (variant I – 296%, variant II – 351%).

Based on the conducted estimates, the precise time after which subsequent sections of the drainage well are uncovered (in each terrace) was also determined. In the case of variant I, it is 01:14:07 (episode in 1st terrace), 03:24:44 (episode in 2d terrace) and 05:03:44 (episode in 3rd terrace). In variant II, this time is more concentrated because the expected moments of unveiling the next episodes occur after 4:32:58 (episode in 1st terrace), 4:56:38 (episode in 2nd terrace) and 5:20:39 (episode in 3rd terrace).

Table 2. Summary of the basic parameters of the excavator's work in the single block advance on the unstabile front according to variant I and variant II

Basic parameters	Symbol	Unit	Variant I	Variant II
Volume of the excavating block	Vz	[m^3]	31 995	31 995
Total operating time – productive time – unproductive time	Tz Tp Tu	[s] [hh:mm:ss] [s] [hh:mm:ss] [s] [hh:mm:ss]	19 324 05:22:04 13 846 03:50:45 5478*) 01:31:18*)	20 493 05:41:33 14 003 03:53:22 6490*) 01:48:10*)

Efficiency values				
– effective	*Qe*	[m^3/h]	5961	5620
– technical	*Qt*	[m^3/h]	8301	8301
– theoretical	*Q0*	[m^3/h]	11 040	11 040
Performance indicators:				
– technical utilization rate	$\eta 0$	[–]	0.72	0.68
– theoretical utilization rate	ηe	[–]	0.54	0.49

*) The unproductive time includes 45 minutes (2700 seconds) needed for the liquidation (cut-off) of a fragment of the drainage well.

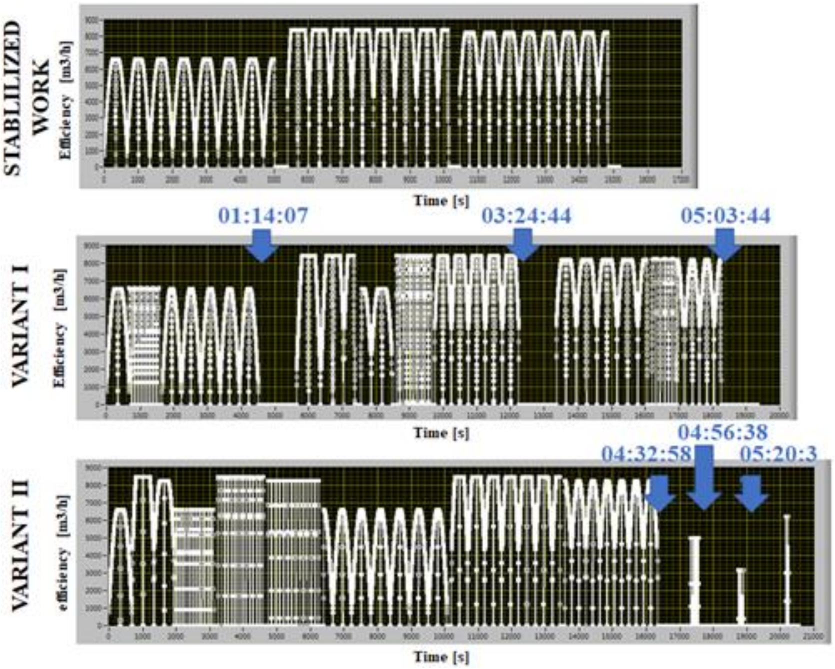


Fig. 5. Instantaneous efficiency of the bucket wheel excavator (time series) in single block advance:
a) stabile front, b) unstabile front according to variant I, c) unstabiled front according to variant II

Anticipating such information allows for the prior planning of the necessary auxiliary works and the organization of relevant mine services for the removal of drainage infrastructure. The parameterized models of the exploitation technology thus make it possible to consider many possible variants, compare them and decide which of the working scenario is the most appropriate in terms of the availability of these services.

In order to perform a more detailed analysis, a simulation was carried out, in which it was assumed that the time needed to cut and remove the obstacle (*Tup*) was 0 seconds. Such an assumption made it possible to estimate the actual differences resulting from the increased number of manoeuvring movements performed by the excavator.

In both variants, there are significant differences in the obtained operating parameters. The estimated time of unproductive states significantly reduced the total cutting time to 16 624 seconds (4 hours 37 minutes and 4 seconds) in variant I and 17 793 seconds (4 hours 56 minutes and 33 seconds) in variant II.

The change in the time of excavation of the single block advance significantly influenced the obtained effective work efficiency, which was determined at the level of 6872 m^3/h (variant I) and 6473 m^3/h (variant II). This means that the efficiency of the excavator's work caused by additional manoeuvring movements resulted in a decrease in efficiency to 93% and 87%, respectively.

The energy consumption to excavate single block advance while working on the stable front (estimated on the basis of active power) is 15.08 MWh. Extending the selection time of all slices while working on non-stable front with an obstacle results in increased energy consumption, which according to variants I and II is 16.16 MWh and 17.30 MWh, respectively.

4. CONCLUSIONS

The existing bucket wheel excavator simulation software allows only the programming of stabilized work – i.e., the working front with constant parameters of a block. The article proposes an innovative approach to the preparation of short-term work plans for a bucket wheel excavator operating on an unstable front, forcing changes in the parameters of the excavator's working and manoeuvring movements.

Thanks to the developed algorithms, it is possible to analyse variant manoeuvring movements to exploit the block in which the obstacle occurred. Based on the results obtained, the most appropriate scenario of carrying out this process may be selected. This decision is now left to the machine operator, and is solely based on his subjective decisions.

The use of the developed models allows a rational evaluation of the variant, based on the obtained performance parameters and the energy consumption needed to select a given block. It also provides the operator with a choice, due to the availability of the necessary auxiliary works. The simulations of the manoeuvring movements performed allow for the determination of the exact times in which their participation is necessary. Anticipating such information makes prior planning and the organization of relevant mine services for the removal of drainage infrastructure possible.

Further development of the presented method will consist of testing the developed model in real mine conditions. This requires an earlier compilation of the developed software with a GPS system installed on a bucket-wheel excavator as well as its control systems.

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