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STUDY OF THE EFFECTIVENESS OF METHODS FOR INCREASING THE PRODUCTIVITY OF URANIUM THROUGH PRELIMINARY FORECASTING

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Abstract. A study was conducted of the effectiveness of methods for increasing the productivity of uranium through preliminary forecasting. The objective of this study is to analyze and optimized the technological block currently in production. To analyze the performance of a block or cell different performance indexes are used: Tracer cut, Tracer in Place, Acid in place. Several scenarios of optimization have been tested using the HYTEC reactive transport program and modeling the uranium mining process. These scenarios involved new wells and the impact of "chemical well treatment" that increases the productivity of well. This work focused on improving the production of block. Three different scenarios were performed. Among the three scenarios, the third produced the highest amount of uranium 133 tons out of 154 tons of reserves. During optimization it is better to get the right efficiency value for each well's last trend in the cleaning action excel file. After chemical treatment of the well it was possible to increase the area where $pH < 1.85$. This shows the importance of optimization and chemical treatment of the well.

Keywords: uranium mining, in-situ recovery, reactive transport, hytec, forecast, acid in place, tracer in place, tracer cut, chemical treatment of the well

1. Introduction

About 10% of the world's electricity is generated from uranium in nuclear reactors. This amounts to over 2500 TWh each year. France gets about 70% of its electricity from uranium [1]. About two-thirds of the world's production of uranium from mines is from Kazakhstan, Canada and Australia. An increasing amount of uranium, now over 60%, is produced by ISR (In situ recovery). In 2021, Kazakhstan produced the largest share of uranium from mines (45% of world supply) [2]. In situ recovery mining has been steadily increasing its share of the total, mainly due to Kazakhstan, and in 2021 accounted for over 60% of production (32088 tonnes U) [2]. In situ recovery uses a chemical technique to separate the uranium in the Earth's crust from the surrounding rock, making it a different mining approach from traditional ones. It is possible to employ the ISR approach without engaging in extensive rock mining. Additionally, ISR costs less and has less of an impact on the environment and health than the standard way. The movement of liquid as opposed to rock minimizes surface disturbance [3].

The KATCO mining company is a joint venture between Orano Mining (51%) and Kazakhstan national mining company Kazatomprom which are the Kazakh and French national nuclear fuel cycle companies, respectively. It specializes in the in-situ recovery of uranium, in roll-front type formations, with a 4.000 tons uranium yearly capacity. The mine, located in the Shu Saryssu Bassin - Kazakhstan, exploits the Tortkuduk

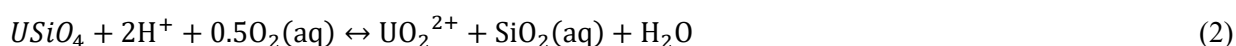
and Moiyunkum deposits along a southwest-northeast axis over 40 km in length. It currently operates this large territory in an acidic way with processing plants connected to the deposit by a well field [4]. ISR requires modeling because it enables the forecasting of crucial variables and the reservoir's behavior during the recovery process. This is crucial for weighing the possible risks and rewards of various strategies as well as for making well-informed decisions concerning the design and implementation of ISR programs. Without modeling, there is a higher chance of unforeseen results and time and resource waste. Reactive transport models are built at the block scale using a mix of hydrogeochemical reservoir description and process identification [5].

2. Theoretical part

2.1 Chemical process

Uranium dissolution during acidic leaching is dominated by the oxidation of U(IV) minerals (e.g., uraninite UO_2 , coffinite $USiO_4$) by Fe^{3+} in the bearing solution. The origin of ferric iron is multiple: local dissolution of gangue minerals (goethite, beidellite), recirculation of Fe^{3+} from the well field, or surface active regeneration of Fe^{3+} using peroxide or other oxidants. Low pH (typically < 2) is required to allow for ferric iron mobility [4].

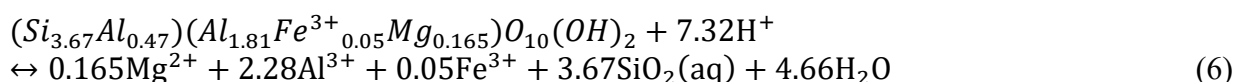
Oxidizing conditions (under acidic conditions) are necessary to dissolved [4]:



No dioxygen in the reservoir but Fe^{3+} reacts as a good oxidizer and is naturally present [4]:



Acid consumption: the reaction is controlled by the availability of ferric iron, solubility of uranium (in which complexation, notably with, SO_4^{2-} can play an important role) and kinetics. Reactions with gangue minerals are also key, since they can control pH or local sources of ferric iron [6]:



2.2 Porous media flow

The solution flow in porous media is governed by the basic law of underground hydrodynamics, Darcy's law:

$$Q = K_{cond}A \frac{\Delta h}{L} \quad (7)$$

Q is the flow rate; A is the cross-section area;; Δh is the pressure drop across length L ; $K_{cond} = K \frac{\rho g}{\mu}$ is the permeability (hydraulic conductivity);

According to Darcy's equation, the physical properties of during the ISR process considerable changes to the TDS (total dissolved solids) take place. This is particularly true at the beginning of leaching when the pore water is replaced by the reactant (acid) solution. Therefore, the physical properties of fluid are variable [3].

Darcy velocity is written as follows:

$$u = \frac{Q}{A} = K_{cond} \frac{\Delta h}{L} = -K_{cond} \nabla h \quad (8)$$

Continuity equation for non-stationary flow:

$$\frac{\partial(\rho\omega)}{\partial t} + \nabla \cdot (\rho\mathbf{u}) = 0 \quad (9)$$

Compressible-transient flow:

$$S_s \frac{\partial h}{\partial t} - \nabla \cdot (K_{\text{cond}} \nabla h) = q \quad (10)$$

Density-driven flow:

$$S_s \frac{\partial p}{\partial t} - \nabla \cdot \left(\frac{\rho}{\rho_0} K_{\text{cond}} \nabla (p + \rho g z) \right) = \rho g q \quad (11)$$

$S_s = \rho g \omega \left(\beta_1 - \beta_s + \frac{\alpha}{\omega} \right)$ is the storage coefficient; ω is the porosity; β_1 and β_s are water and matrix compressibilities; α is the elasticity; q is the source.

2.3 Reactive transport equation

Transport equation:

$$\frac{\partial \omega c}{\partial t} = \nabla \cdot (\mathbf{D}(\omega, D) \nabla c - c\mathbf{u}) \quad (12)$$

The solute transport mechanisms considered in the formulation are:

- Advection (due to water phase movement): advection is the transfer of dissolved substances by the flow of a liquid. The actual filtration velocity is higher than the filtration velocity determined by Darcy's law.

- Molecular diffusion; in a porous medium, diffusion processes slow down, because the path of molecules and ions in the liquid phase increases as a result of their movement through tortuous pore channels, around individual particles. Molecular diffusion of a dissolved substance in water is described by Fick's law:

$$\mathbf{J} = -D \nabla c \quad (13)$$

$$\frac{\partial c}{\partial t} = D \nabla^2 c \quad (14)$$

- Mechanical dispersion: dispersion is a mixture of two substances. Mechanical dispersion of a substance is explained by two effects. Molecules or ions of a dissolved substance in a porous medium follow path of different lengths, due to the structure of the pore space structure, local variability of the filtration velocity field. Molecular diffusion in the direction of decreasing concentration of the dissolved substance, branching of motion trajectories.

Diffusion-dispersion equation:

$$\mathbf{D}(\omega, D) = D_{\text{diff}} + \alpha_{L,T} \|\mathbf{u}\| \quad (15)$$

D is a diffusion coefficient; D_{diff} is a tensor with the diagonal coefficients α_L, α_T ; α_L and α_T are longitudinal and transverse dispersivities, usually $\alpha_L > \alpha_T$.

The dispersion coefficients allow to quantify the phenomenon of dispersion. It is assumed that they are proportional to the actual speed of water, such that:

Longitudinal dispersion coefficient:

$$D_L [\text{m}^2/\text{s}] = \alpha_L [\text{m}] \cdot u [\text{m}/\text{s}] \quad (16)$$

Transverse dispersion coefficient:

$$D_T [\text{m}^2/\text{s}] = \alpha_T [\text{m}] \cdot u [\text{m}/\text{s}] \quad (17)$$

2.4 Geochemistry

2.4.1 Reactions at equilibrium. Thermodynamic equilibrium

In an in situ leaching operation, the recovery of uranium is determined by the often very complex interaction of the physico-chemical, hydro-geological and mineralogical characteristics of the mineralized level and the chemical kinetics of the leaching solutions used [7].

Chemical reactions are characterized by the global notion of chemical potential μ_A [9]:

$$\mu_A = \left(\frac{\partial G}{\partial n_a} \right)_{P,T,n_i} \quad (18)$$

$$\mu_A = \mu^0(p, T) + RT \ln(A) \quad (19)$$

$\mu^0(p, T)$ is the standart potential;

A is an activity.

pH is the main indicator for determining the oxidation state. (H^+) is the hydrogen ion activity [9]

$$pH = -\log_{10}(H^+) \quad (20)$$

Oxydation - loss of e^- :



Reduction - gain of e^- :



Mass action law (solubility product):



Saturation Index (SI) of a fluid in relation to a mineral:

$$SI = \log \left(\frac{(A^{2+})(B^-)^2}{K_s} \right) \quad (24)$$

Precipitation if $SI > 0$ and dissolution if $SI < 0$.

2.4.2. Kinetic control

Dissolution/precipitation of mineral M:

$$\frac{d[M]}{dt} = kA_v \prod_i (A_i)^{a_i} \left(\left(\frac{Q}{K_s} \right)^p - 1 \right) \quad (25)$$

$A_v = A_s[M]$ is the specific surface, $[m^2/kg]$ and $\prod_i (A_i)^{a_i}$, (A_i) is the catalyst if $a_i > 0$ or inhibitor if $a_i < 0$.

Arrhenius law [10]:

$$k = A \exp \left(\frac{-E_A}{RT} \right) \quad (26)$$

E_A is an apparent activation energy, $[J/mol]$;

3. Method of research: Performance indicators

The indicator Tracer in Place (TIP) translates the process of invasion by the VR (leaching solution) fluid. The VR tracer is set-up to be non-reactive with the others elements and has a constant concentration. Once it is injected, the VR will propagate inside the reservoir and behave like a non-reactive tracer. By looking at the concentration of VR one can have an idea of where the injection fluid is going. The objective is that this VR invade all mineralization, in hope that the oxidizer will oxidize the uranium. A high TIP means a good invasion of the reservoir. This indicator TIP has its limits. Indeed, once the VR is injected it will replace the water in place from the aquifer. Once this water is removed and replaced by the VR, the TIP will remain high. The TIP is mainly useful during the acidification process and the first year of production. After, another indicator called Acid in Place (AIP) will be used. With the TIP you can quickly observe the problem of injectivity, balance and wrong screen position. The Tracer Cut (TC) is the percent of VR produced compared to what is injected. This indicator is showing the recovery of the VR fluid and is indicating whether the well is producing water from the aquifer or VR from the injector. This indicator is close to the pH but do not consider any geochemical process that may arise on its way.

The Acid in Place (AIP) can observe similar invasion as TIP, but considering the acidification process. Both injectivity problem and acidification problems can be observed with this indicator. The optimal condition for dissolution of uranium minerals is under acidic conditions ($\text{pH} < 1.85$). Initially, the pH of the reservoirs mostly more than 1.85 on block (red zone of the AIP evolution graphs Fig. 1(c), Fig. 3, Fig. 4(c), Fig. 6(c), Fig. 8). As the acid is injected in the reservoir, pH start decreasing. Over time, part of the reservoir with a pH less than 1.85 increases. This corresponds to the green zone of the AIP evolution graph. The yellow zone indicates the percentage of dissolved uranium (Fig. 1(c), Fig. 3, Fig. 4(c), Fig. 6(c), Fig. 8).

Thus, on the AIP evolution graph, the volume of uranium (in red) decreases as the uranium is dissolved, and the volume of this uranium itself is invaded by the acid (the $\text{pH} < 1.85$ region in green of the graphs Fig. 1(c), Fig. 3, Fig. 4(c), Fig. 6(c), Fig. 8). The volume of uranium is interpreted as follows (red zone of the graphs Fig. 1(c), Fig. 3, Fig. 4(c), Fig. 6(c), Fig. 8):

$$\text{Mineralization } \text{pH} > 1.85 = \frac{(\text{Volume U} > 100\text{ppm})_i [\text{m}^3]}{(\text{Volume U} > 100\text{ppm})_{i=1} [\text{m}^3]}, \quad i = 1, 2, 3, \dots \quad (28)$$

$(\text{Volume U} > 100\text{ppm})_i$ is the volume of uranium on i^{th} day; $(\text{Volume U} > 100\text{ppm})_{i=1}$ is the initial volume of uranium on 1st day.

The volume of this uranium itself is invaded by the acid is interpreted as follows (green zone of the graph):

$$\text{Mineralization } \text{pH} < 1.85 = \frac{(\text{Invasion } \text{pH} < 1.85)_i [\text{m}^3]}{(\text{Volume U} > 100\text{ppm})_{i=1} [\text{m}^3]}, \quad i = 1, 2, 3, \dots \quad (29)$$

$(\text{Invasion } \text{pH} < 1.85)_i$ is the invasion of acid on i^{th} day; The AIP is interpreted as follows (green curve of the graph):

$$\text{AIP} = \frac{\text{Value of green zone}}{\text{Value of red zone}} = \frac{(\text{Invasion } \text{pH} < 1.85)_i [\text{m}^3]}{(\text{Volume U} > 100\text{ppm})_i [\text{m}^3]}, \quad i = 1, 2, 3, \dots \quad (30)$$

4. Results and discussions

4.1 Scenario-1: Forecast with last trend

Forecast is long-term planning, one of the main applications of HYTEC [8]. The long-term production plan's objectives are to balance production by year and disperse production throughout the blocks. The sum of the active production blocks is used to determine global production. Each block includes a production curve for the amount of flow and acid. Flowrate options is creating flowrate for forecast by wells. The "last trend" for the flowrate option was chosen in this research work. Forecast scenario's data is given in the Table 1.

Table 1. Forecast scenarios information

Historical Data	15/03/22-27/06/23 (470 days)	837 days
Forecasting Data	28/06/23-28/06/24 (367 days)	

In the Fig.1. (a) shows a Tracer Cut plotted over time. A higher percentage indicates more solution is being recovered from the well, and lower indicates more solution is leaving the well through the aquifer. The historical data shows a steady TC around 79%. The forecast predicts the TC will slowly rise to 92.6% over time. This data suggests that the well is currently recovering about 79% of the leaching solution injected. Over time, the model predicts the well will recover more and more of the solution, reaching up to 92.6%.

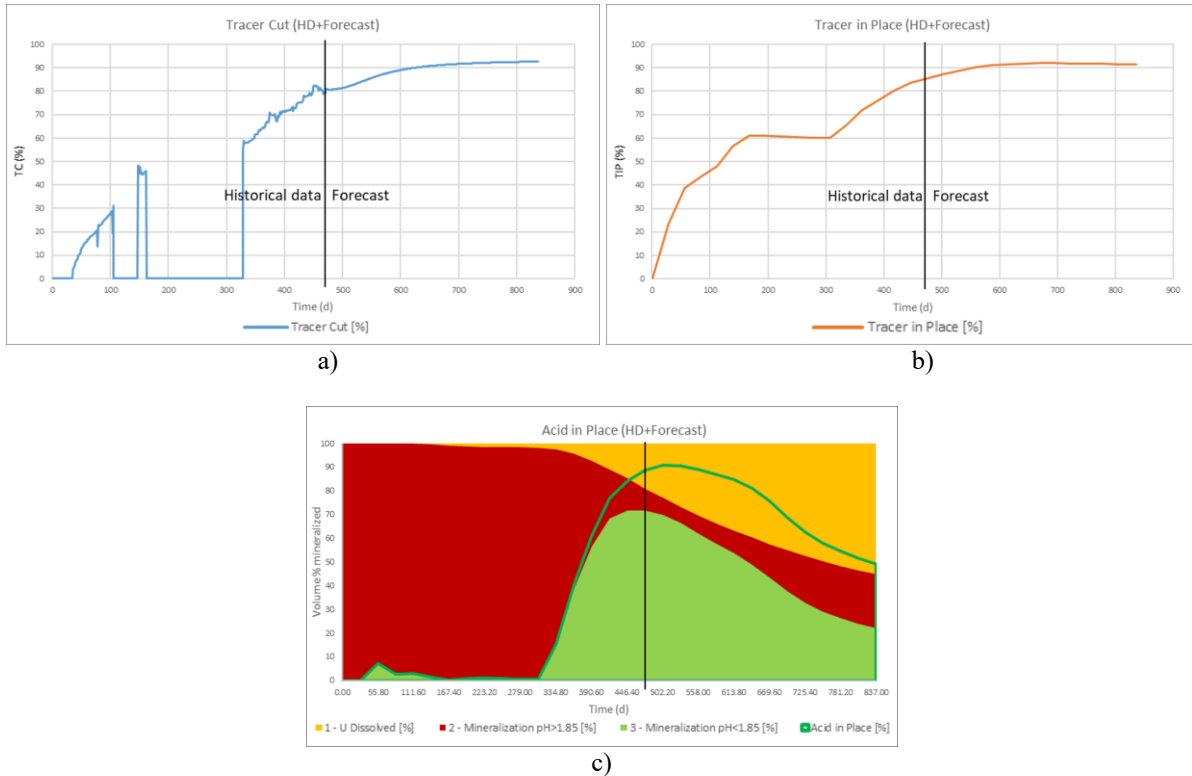


Fig.1. Forecast with last trend performance indicators

Fig.1. (b) shows Tracer in Place plotted over time. A higher TIP value means more of the reservoir has been reached by the solution. The historical data shows a TIP that steadily increases to about 85%. The forecast predicts the TIP will continue to increase to 91.4%. This data suggests that leaching solution has reached a large portion of the reservoir according to the model. Over time, the model predicts an even greater portion of the reservoir will be contacted by the solution. Fig.1. (c) shows AIP evolution.

AIP for the forecast of the block, the red part is 49%. And the green part, ready for production, is 27%. 105.5 tons (Fig.2 (a)) of uranium were produced in 837 days. This is equivalent to 68.5 percent of the 154 tons of initial uranium reserve (Fig.2 (b)).

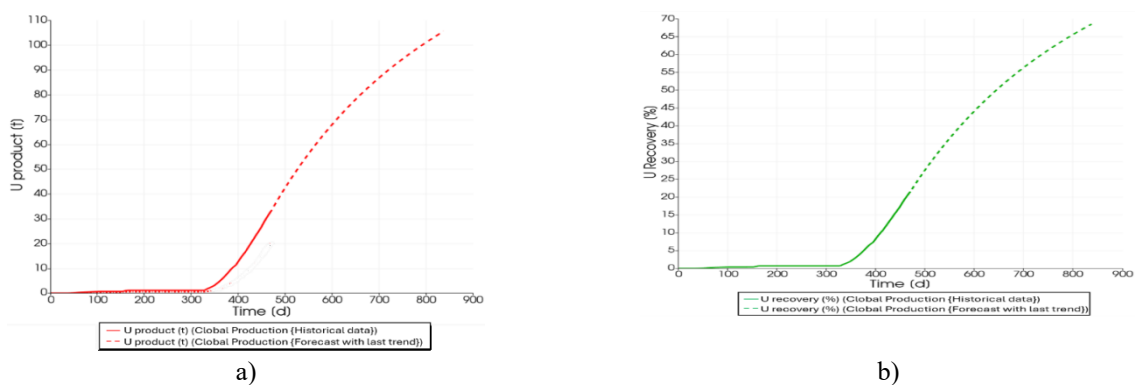


Fig.2. Forecast with last trend variables

5. Optimization

AIP considering the reaction of acid within the reservoir and the acidification process. Both injectivity problem and acidification problems can be observed with this indicator. The cells Cell_02, Cell_03, Cell_04, Cell_06, Cell_09, Cell_15, Cell_16, Cell_17 did not show a good AIP evolution.

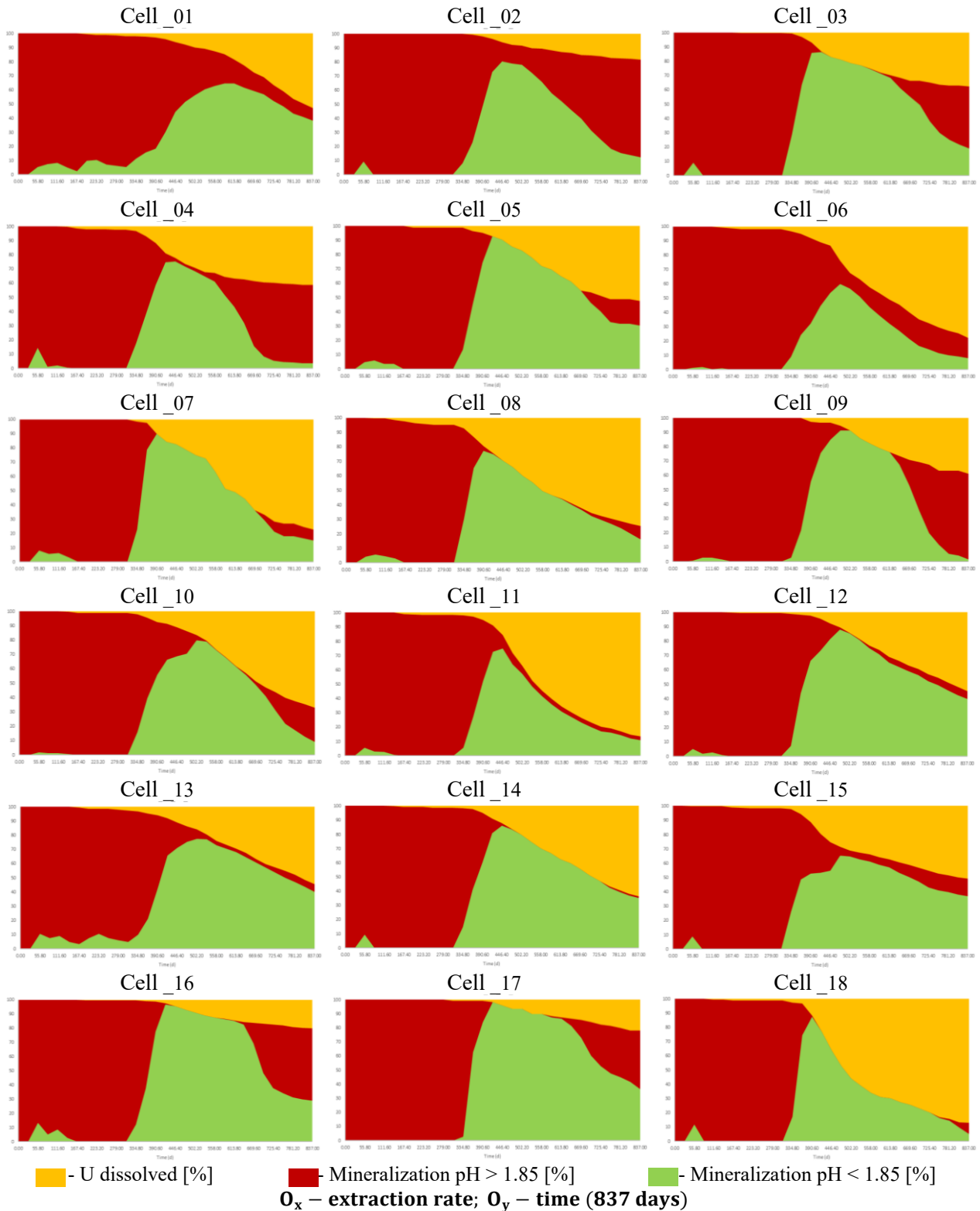


Fig.3. The AIP evolution of each cell

There's less green zone and that means less material we can mine (because the green zones have a good acidity level for mining, below 1.85 pH). If look at Fig. 1(c), you'll see a lot of red in the middle of the green and yellow zones. This red zone is uranium that hasn't been mined yet (because it's not acidic enough, with a pH higher than 1.85). So, to improve the mining process, we should focus on these zones with the most red. We need to improve well productivity by correcting flowrates and by cleaning actions on the well ABF. The list of cells with low performance and the necessary works to optimize these cells are shown in the Table 2.

Table 2. Table of cells problem cells and required works

Cells	Required works
Cell _02; Cell _03; Cell _04; Cell _06; Cell _09; Cell _15; Cell _16; Cell _17	- To increase flowrates for producer and injector wells; - ABF - Connect the well Producer Cell _15 to work.

5.1 Scenario-2: Forecast with ABF-1

Well filters get filled with clogging product this affects the performance of the well. The flowrate variation is able to the cleaning actions on the well. 3 types are possible: ABF (chemical treatment of the well); RVR (mechanical cleaning); Redrilling (additional wells). Every three months, the ABF procedure was carried out. At the end of the simulation the percentage the tracer cut rate following ABF is 91.6% (Fig.4 (a)). This is slightly lower than for the scenario-1 (92.6%). Fig.4 (b) shows that TIP reached after ABF 94% for forecast, 2.6% better than for the trend scenario-1. After ABF, AIP for the scenario-2 of the block, the red part is 43.2%. And the green part, ready for production, is 27% (Fig.4 (c)). For good results, the values of the red and green parts should be close to each other.

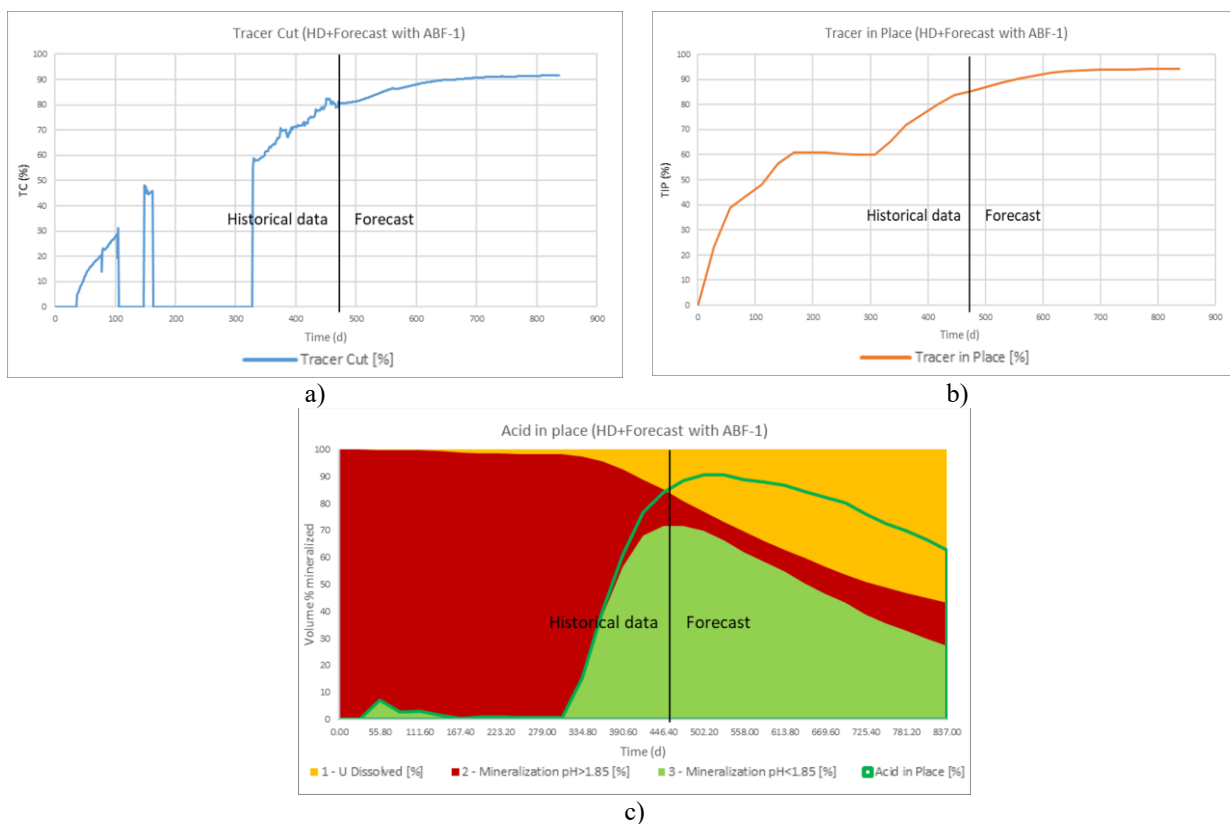


Fig.4. Forecast with ABF-1 performance indicators

In 837 days, 110 tons (Fig.5) of uranium were mined. The outcomes are 5.5 tons better than before ABF. The first 154 tons of uranium reserve are comparable to 71.6 percent of this.

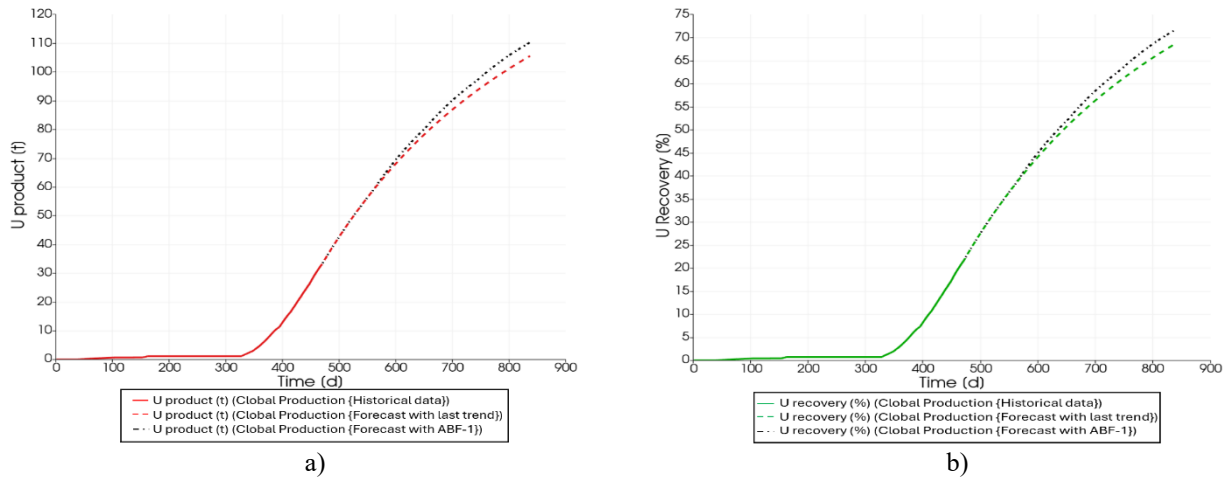


Fig.5. Forecast with ABF-1 variables

5.2 Scenario-3: Forecast with ABF-2

A chemical treatment of the well (ABF) was performed with other new data. For each cell, an efficiency value (flow rate) that closely matched the last trend line was chosen. The planning well Cell_15 was connected to the work. At the end of the simulation the percentage the tracer cut rate following ABF is 94% (Fig.6 (a)). Fig.6 (b) shows that TIP reached after ABF-2 94% for forecast. After ABF-2, AIP for the forecast of the block, the red part is 32%. And the green part, ready for production, is 29% (Fig.6 (c)).

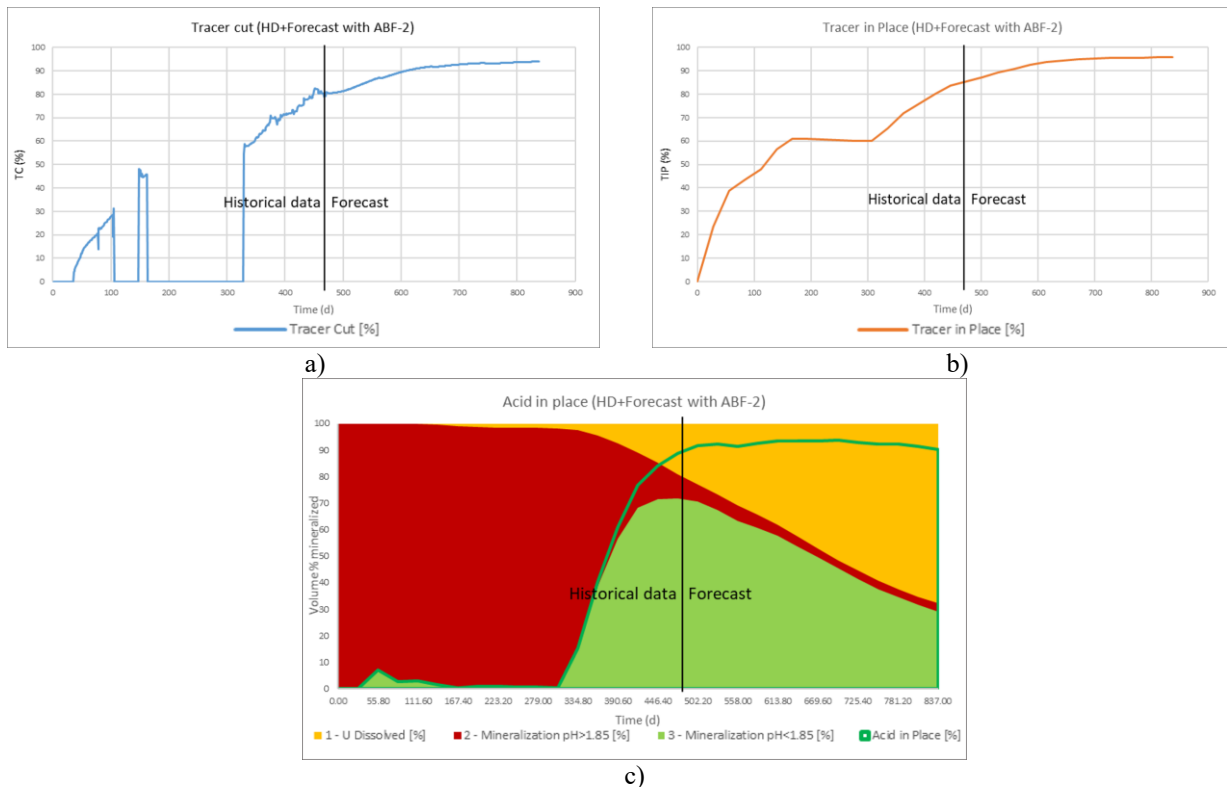


Fig.6. Forecast with ABF-1 performance indicators.

In 837 days, 133.3 tons (Fig.7 (a)) of uranium were mined. The result is 29 tons better than before ABF. By operating well Cell_15 and changing the efficiency of each well it was possible to increase production by 86.5% (Fig.7 (b)).

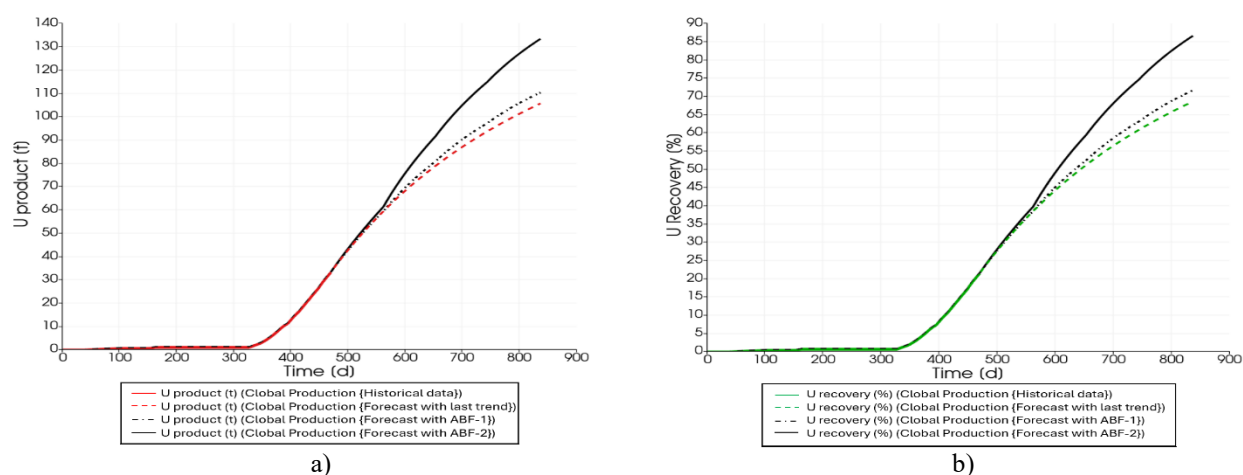


Fig.7. Forecast with ABF-2 variables

After chemical treatment of the well with ABF-2 it was possible to recover U from all the cells even those that were identified as problematic in the forecast scenario (Fig.A1, Appendix). This shows the importance of optimization. In long-term planning, flow rates forecasting is very important. When using build-in tools to forecast flowrate based on historical data, a manual verification has to be done to be sure that the results are in line with last trends. The volume of uranium production and the recovery percentage in the block of all three scenarios are shown in the Table 3. Among the three scenarios, the third produced the highest amount of uranium 133 tons out of 154 tons of reserves. During optimization it is better to get the right efficiency value for each well's last trend in the cleaning action excel file.

Table 3. Variables of three scenarios

	Historical data	Scenario-1	Scenario-2	Scenario-3
U _{product} , [t]	32.7 t	105.5 t	110 t	133.3 t
U _{recovery} , [%]	21%	68.5%	71.6%	86.5%

6. Conclusion

This study investigated methods to improve uranium production from block using in-situ recovery. Three forecast scenarios were evaluated. The results obtained will certainly be of value for future uranium mining in the technical block (Tortkuduk, KATCO). Thanks to the forecast, we can optimise production, plan a long-term strategy, reduce risks, and increase efficiency. Predicting potential problems, such as depletion or declining uranium quality, will help you take steps to minimise them in advance. By optimising production and planning, it is possible to improve the overall efficiency of uranium exploitation in the block. The long-term forecast provided in this paper will shorten the operating time of the block. Chemical treatment (ABF) is crucial for improving uranium recovery. Treatment significantly increased the area with a favorable pH level (below 1.85) in problematic wells. Flow rate forecasting requires careful consideration. While historical data provides a basis, manual verification is essential to ensure alignment with recent trends. Optimization is vital for maximizing production. Selecting the appropriate efficiency values for each well during cleaning actions significantly enhances uranium output. Overall, this study demonstrates that a combination of forecasting, well cleaning (ABF), and optimization can substantially increase uranium production in ISR mining.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRedit author statement

Kachkinova A.K.: Investigation, Formal analysis, Writing- Reviewing and Editing; Turalina D.E.: Supervision, Validation; Nurmakhanov N.U.: Conceptualization, Methodology. The final manuscript was read and approved by all authors.

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Appendix A

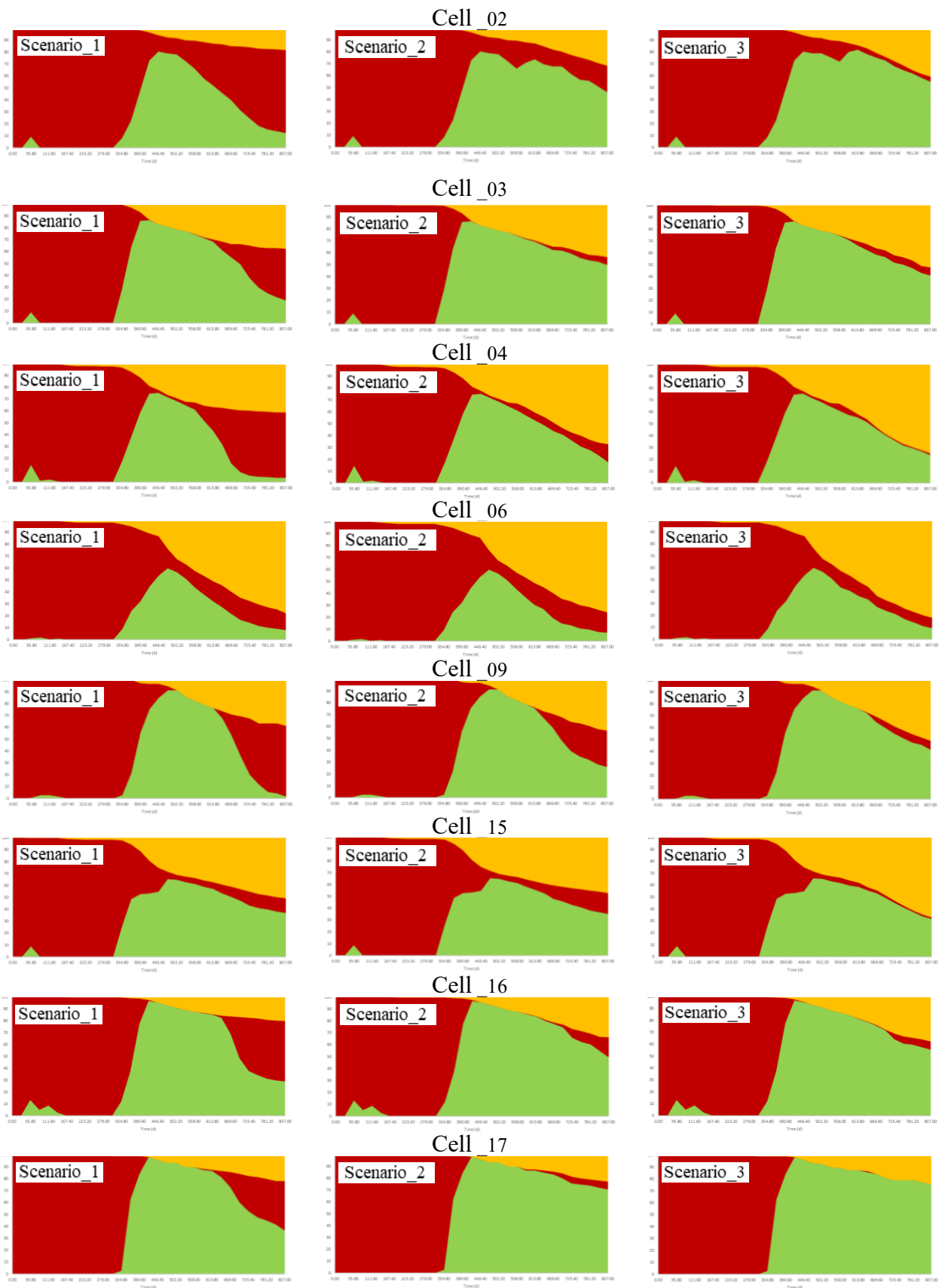


Fig.A1. Comparison of AIP evolutions of three different scenarios