CO_2 storage risk assessment: feasibility study of the systemic method MOSAR

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Abstract

The current environmental background is modifying human behaviour in every society. Indeed, one of the main causes of global warming is the emission of greenhouse gases, including mainly CO_2. Several ways have been found to gradually reduce the CO_2 emissions, among them the Carbon Capture and Storage (CCS) process. This is a technique which extends the use of fossil energies while giving necessary time for renewable energies to develop on a large scale. The CO_2 is captured, brought to the storage site, and injected either into dried up oil and gas deposits or into unworkable coal seams or into deep saline aquifers. Long-term monitoring of the storage site is maintained afterward. The question pending, and a source of controversy, relates to the underground evolution of the CO_2 in the medium- and long-term. The aim is to lead preliminary determination of risks on a generic basis. Projects are managed and storage installations built on a global scale. Depending on the country, the risk approach is not the same. Mostly, only the FEP method is used – accident scenarios are built up based on several events and cumulated processes. This study develops the MOSAR method (Organized and Systemic Method of Risk Analysis) to analyse the technical risks of a human plant and to identify the prevention means to neutralize them. The innovative side of this work is that we have created a typology grid of under-systems hazard sources adapted to a CO_2 geological storage site. Risk scenarios can then be built and organized hierarchically in a grid by means of gravity based on probability. Once this is done, this study leads to the identification of prevention and protection means. Similar to most systemic methods for risk analysis, this MOSAR method is time consuming in order to define all risks and scenarios. However, the software tool facilitates this work and we show in this paper that the method is efficient.

Keywords: scenario, typology of hazard sources, gravity, probability, barrier, prevention, protection, systemic.

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1 Introduction

Carbon storage is considered one of the main solutions to reduce greenhouse gas emissions. Injecting the CO_2 either into dried up oil and gas deposits or into unworkable coal seams or into deep saline aquifers seems to be a handy and efficient solution which requires relatively inexpensive and feasible implementation. The difficulty is not in the technical process, but rather in the assessment of the risks involved. How can one be sure of having foreseen each possible accident scenario? As in every new technological installation, there are intrinsic risks that we have to bring under control in order to make this technique acceptable to society. To do so, we have applied the systemic method MOSAR, a method used in industrial risks, on a Carbon Storage site to analyse risks and determine the prevention means.

In this paper, we first set out the topical stakes linked to Carbon Storage, then we give a concise view of the main characteristics of the Carbon Capture and Storage process. Finally, we dwell on the MOSAR application method and its way of evaluating the risks.

2 A common objective: to reduce the CO_2 emissions

In order to protect the environment, societies have to reduce greenhouse gas emissions. The solution is not easy to find because energy needs are continually increasing and renewable energies are not sufficiently developed and used.

However, the situation has to be settled quickly. The main greenhouse gas is CO_2. If the current trends remain the same, CO_2 emissions will double by 2050 and they will reach 1,000 ppm by the end of the XXIst century [3]. Obviously, the climatic and social consequences would be dramatic. Indeed, according to climatologists, to maintain global warming under 2 degrees Celsius we have to stabilize the CO_2 content to 450 ppm. This aim of 450 ppm implies a reduction in CO_2 emissions by half regarding those current between now and 2050. If we look at the CO_2 emissions per inhabitant, to reduce the emissions by half on a worldwide level is like dividing industrial countries' emissions by four. So, important changes have to be planned in the way of generating and consuming energy, one of the first areas responsible for Carbon emissions.

At present, three solutions are envisaged:

- To reduce energy consumption thanks to changes in consumption habits or thanks to an improvement in energy outputs.
- To implement fuels emitting less CO_2: the substitution of coal by natural gas, the massive use of nuclear and renewable energies, the production of biomass.
- The Carbon Capture and Storage (CCS): this choice is applicable to fixed installations which produce much CO_2 like industries of electricity, steel or cement productions.

So, it seems adapted to set out this process in detail, analyzing the various steps of CCS and afterwards the risks which we have to foresee.

3 CCS: definition and risks assessment

3.1 CCS characteristics

The first step is to capture the CO_2 at the factory exit. It is unthinkable to want to compress the CO_2 with other gases present in fumes (such as oxygen, steam, or nitrogen) due to the lack of space and the energy that would be required. Three separation methods have been developed to capture only the CO_2: post-combustion, oxy-combustion, and pre-combustion capture [1].

Then, the CO_2 is compressed or condensed to be transported by pipeline, ship, or truck to a storage area where it will be injected. The supercritical CO_2 – P>73,8 bar, T>31,1° Celsius – behaves like a gas which occupies the whole volume but with a liquid density. It is immiscible in water. The CO_2 injectivity study is of utmost importance because the aim is to determine what the rate of flow would be if the CO_2 is injected.

Lastly, the storage step is carried out. One storage type can be considered: geological storage.

Three geological storage sites exist [3]:

- Oil and gas dried up deposit storage: the CO_2 injection takes advantage of this situation to do the assisted salvage of oil. Although these reservoirs are unequally distributed around the world, their impermeability is proven.
- Unworkable coal seams storage: coal has the capacity to primarily absorb CO_2 that presents methane. When the CO_2 is injected into the seams, the coal discharges the methane which can be recuperated by wells, such as natural gas.
- Deep saline aquifers storage: these underground water reservoirs are present here and there in the world but their high salt content makes them unsuited as resources in drinking water or in water irrigation. The main trapping mechanism here is the gas dissolution in water.

These geological formations offer a huge potential thanks to their worldwide distribution and their big storage capacity. However, they are relatively unknown as they have not yet been studied because there is no economic interest in doing so.

We, therefore, need to estimate the interaction phenomena between the CO_2, the existing fluids, and the rocks. The aim is to simulate the CO_2 medium and long-term evolution underground in order to judge if it is a safe method and to understand the possible risks.

3.2 Risks assessment

Like with every new installation, it is necessary to evaluate the potential risks. The major problem is there is no feedback from past experience of any accident which could happen on an installation. The only one is listed as a natural disaster which concerns a limnic eruption which took place in 1986 in Cameroon. There was a CO_2 natural reservoir situated under lake Nyos, a mountain lake on the inactive side of the volcano [4]. On 21st August 1986, it exploded and discharged around one cubic kilometre of CO_2, causing the death of more than 1,700 persons and numerous animals.

Although this was an extreme case, we can imagine that a simple gas leak, colourless and odourless, can have dramatic consequences on every life form.

In consequence, it seems unavoidable to develop a general risks assessment and control method along with adapted emergency procedures.

Two different approaches exist. The first aim is to identify the installation advantages and disadvantages [6]. This causes tension between the pros and cons because they are not based on an approved risks study [10]. The second is the FEPs (Features, Events, and Processes) approach ([7–9]). This method consists in systematically developing a limited number of scenarios which describe the possible future state or the evolution of a storage site. To build these scenarios, we use the FEPs as basic elements, one scenario is an interdependent FEP joining. Then, mathematical models are selected or developed in order to determine the consequences of possible scenarios, quantify these consequences, and assess the risks.

This method is used for current CO_2 storage in Canada, Australia, and Germany. It gives interesting results, and is judged as satisfactory to begin the site injections.

However, we can quote some limitations:

- Scenario building is based on a blend of events and processes. It seems more rigorous to determine an events sequence according to individual processes.
- The consequences of possible scenarios are built thanks to complicated mathematical models — the implementation is long, tedious and full of uncertainties.
- A new site doesn't have an effect on the method.
- The FEP number is limited. Can we be absolutely sure that all scenarios are listed?

We suggest here to study the MOSAR method contribution due to these limitations. We have applied it to a storage site.

4 MOSAR method application to a CO_2 storage site

MOSAR (Organized and Systemic Method of Risk Analysis) [5] allows the analysis of the technical risks of a human installation and then identifies the prevention means in order to neutralize them. This method applies not only to a new installation, but also to an existing installation diagnosis. Two steps form this method (Fig. 1).

The first step, named A, allows the realisation of an analysis of major risk. From an installation change to under-systems, we identify systematically how each under-system can be a danger source. To do so, we use a typology of a danger sources system and a method which connects danger sources and targets. The use of a black box technique produces risks scenarios between the under-systems which, when gathered on a same event, form an event tree. The research of prevention means, which are necessary to neutralize the scenarios, insures the risks prevention.

The second step, step B, makes a detailed analysis of an installation and specifically implements the safety tools relating to the technical dysfunction of machines and devices. All dysfunctions are also found with this step.

MOSAR is a method which is built level by level, and each level gives information so it is possible to stop at a chosen level.

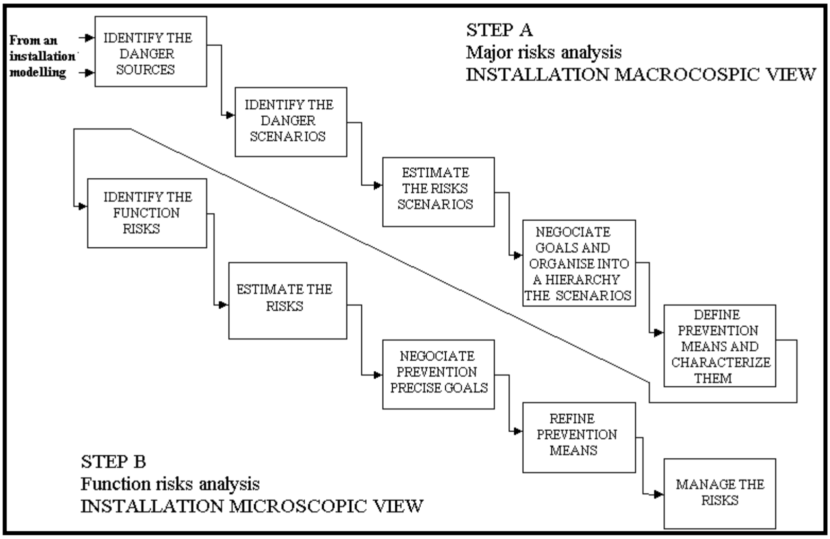


Figure 1: MOSAR: Steps A and B.

We have set out step A in detail in a general context. To apply the second step, B, we must have further information on a particular installation.

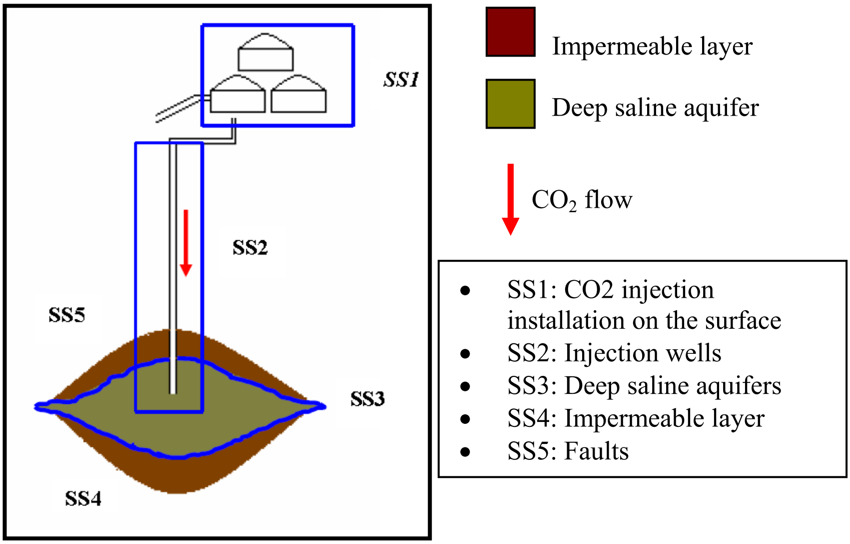
4.1 Unexpected events

First of all, it is important to define the unexpected events — all accidents which could cause unpleasant effects on individuals, the population, the ecosystem, and/or an installation. This accidents list is made with the different, involved parties. Here, we can suggest some unexpected events:

- Physical harm: poisoning, asphyxiation, death.
- Material damage: cracks, breaks, collapse.
- Fauna, flora and ground damage [2]: water, air, and ground pollution, decrease in micro-organisms, changes in physical characteristics of ground.
- Economic damage: increase in insurance premiums, compensation costs.
- Damage to population: evacuation, population internment if there is a leak.

4.2 Modelisation: system and under-systems

We have to draw up boundaries for the system which we want to study, but also split it into under-systems. The global system is the storage. Capture and transport parts will be studied in the future. The storage system is divided into five under-systems (Fig. 2).



- SS1: CO2 injection installation on the surface
- SS2: Injection wells
- SS3: Deep saline aquifers
- SS4: Impermeable layer
- SS5: Faults

Figure 2: System and under-system definition.

We have also considered the temporal aspect of the installation. Indeed, the time factor influences the evolution of the installation. We have three stages: building, injection, and long-term storage.

4.3 Hazard sources and processes

Once the under-systems have been chosen, we identify how each can be a source of hazard by considering several categories (i.e. of mechanic origin, of chemical origin, of biological origin, of socio-economical origin, etc.).

We then combine an originator of events (the cause of the problem), original events (the first consequences), and main events (the most blatant consequences) to each danger source and to the under-system. We put these elements in a chart, called the typology grid of under-systems danger sources (Fig. 3). Building this grid requires a great deal of time. With only five under-systems and the 21 hazard sources found, we obtain 105 possibilities – without counting the life stages, which increase the possibilities. However, this step is indispensable to build the scenarios.

Hazard source under-systems	Life Stages	Originator events		Original events		Main events
		Outside	Inside	Linked to container	Linked to content	

Figure 3: Typology grid of under-systems hazard sources.

4.4 Scenarios building and organisation into a hierarchy

The under-systems are visualised as black boxes with inputs and outputs. The inputs are the originator events and the outputs are the main events. We can thus build scenarios around an under-system (Fig. 4). However, we quickly realize that some outputs of one under-system correspond to some inputs of another under-system. The result is the building of more complex scenarios (Fig. 5).

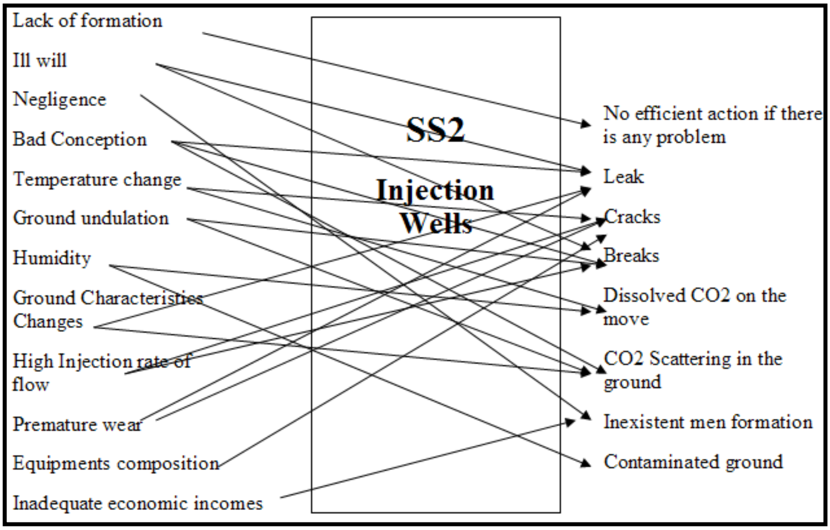


Figure 4: Example of simple scenarios with under-system 2.

Then, each scenario is put in a “Gravity times Probability” grid in order to organise it into a hierarchy (Fig. 6). Gravity is defined as the negative, direct and indirect consequences linked to risks. Probability represents the dangerous event occurrence. The aim of this schedule is to locate the border between what is acceptable and what is unacceptable. This work is carried out by all consultation actors, including operators, populates, politicians, economic associates, etc.

For instance, the scenario considered above is in an unacceptable area. To become acceptable we have to determine the prevention and protection means.

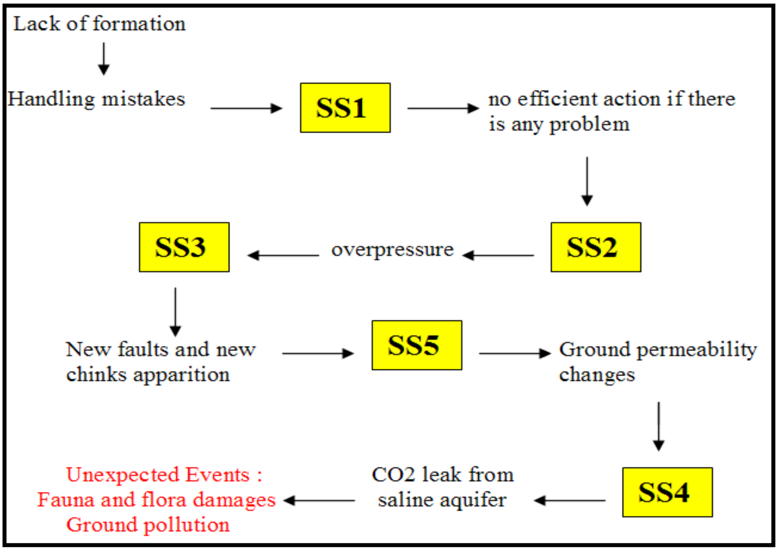


Figure 5: Example of a complex scenario.

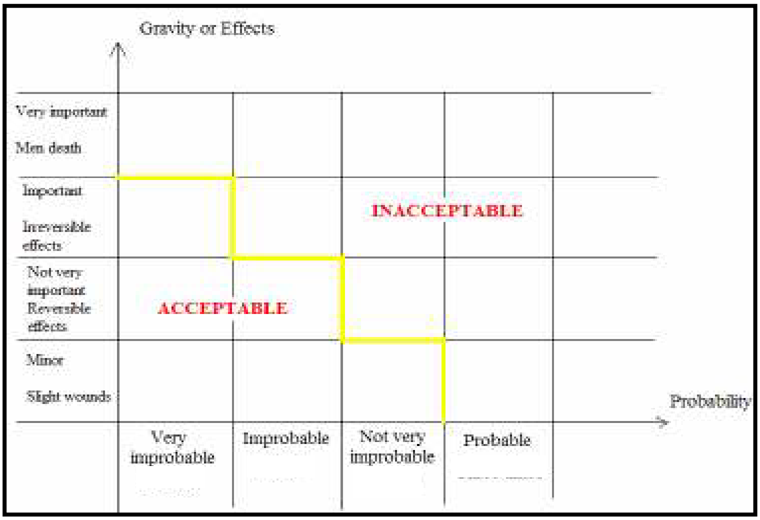


Figure 6: “Gravity times Probability” Grid.

4.5 Prevention and protection means

It is here that risk control begins. The work in the shape of a grid allows quick visualisation of the sort of action that we will take to make a scenario acceptable. The prevention barriers, all the means necessary to avoid a dangerous situation or a worsening situation, allow the probability to decrease. The protection barriers, all the means that will be used when an unexpected event happens, reduce the gravity of the situation.

We can distinguish two sorts among these barriers:

- Technological Barriers (BT): elements which are integrated members of the installation – they oppose the apparition of an event which is prejudicial to safety, they can't be cancelled by human intervention (an automatic ventilation system, for instance).
- Operating or User Barriers (BU): actions which need human intervention – based on precise orders.

The BU are weaker than the BT because they are dependent on operators, human mistakes, etc. Obviously, these barriers must not produce a new risk. In the case of CO_2, we have found several barriers (Fig. 7).

BT	BU
Emergency valves	Formation period for all the operators
Alarm activated if there is a CO_2 leak	Practice exercises with all the actors
Injection automated stopping if leak (air, ground, water)	Shift of 2 operators/ break every 2 hours
Resistant and accurate measuring device	Comprehensible and accessible risk specifications
Emergency circuit	Sufficient economic incomes otherwise project stopping
Badge for keeping watch on inputs and outputs	Common information delivered
Barriers around factory	Evacuation plans
Infrastructures reinforcement	Available oxygen masks for each
Important ventilation	Guards 24h/24
CO_2 measured everywhere in the factory with an alarm if a threshold is exceeded	Scheduled maintenance

Figure 7: Technological and user barriers linked with CO_2 storage.

By applying these barriers to each scenario, we can reduce the probability, or the gravity, not to say both. The scenarios are graded back in a "gravity times probability" grid (Fig. 8). It is possible that some scenarios remain in the unacceptable field — they form the residual risk. In this case, either the various actors accept the risk, or they put in place other barriers or decide not to build the installation. This analysis can allow us to define a "good storage site," one which provides the most safety. Our conclusion is that a storage site has to present at least the following characteristics:

- site not near water table which is used for drinking water or farming activities
- appropriate geological formations: no fault, far from seismic areas, proved site impermeability, etc.
- easy access area where surveillance can be done
- site far from housing areas
- several small storage sites rather than only one big site
- well-informed and cooperating population near the site
- sufficient budget in order to neglect nothing

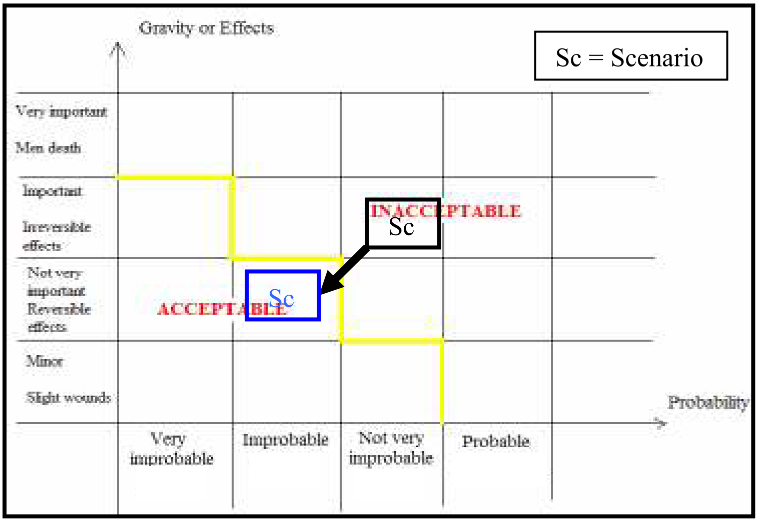


Figure 8: Change of scenario position in “gravity times probability” Grid when we apply barriers.

4.6 MOSAR method contribution

The MOSAR Method, when applied to this kind of installation, is very productive.

First, it is a systematic method which relies on a step by step approach, no step can be neglected. This fact does not prevent flexibility. If an unexpected event arises or a new danger source appears, it is possible to include it at the beginning of the method without calling all the rest into question. We just have to deduce new scenarios and barriers which will allow mitigation.

Then, although the analysis basis is valid for all installations, MOSAR is applicable to a specific installation because it takes technical aspects, site morphology and geology, politics, and economic and social aspects into account.

One other strong point is that it is based on site observations and facts and not just on complicated mathematical models. This is a systemic method which has the advantage of creating improbable and unforeseeable risk scenarios with a first analysis, but whose implementation can be extremely beneficial.

Finally, MOSAR can always be supplemented, for instance, on a protection and prevention barriers level. The aim will be to concentrate all the scenarios in an acceptable area in order to reduce, as much as possible, the residual risk. So, the technical and user barriers can be improved and new ones can be built. This work will depend, to some extent, on the experience feedback produced by simulation exercises and regular consultation with actors.

However, we notice the important subjectivity of MOSAR, either the delimitation step of systems and under-systems, or when we organize the scenarios into a hierarchy. Indeed, all these parameters are going to be dreaded differently by the different actors (operators, the company management, bankers, local authorities, populates, politicians, etc.). However, these different points of view will not be problematic if we set up real consultation and dialogue.

The MOSAR method is undeniably relevant in the case of CO_2 storage. We should just underline that its implementation is not easy and it needs true cooperation between actors, an efficient and frank dialogue, and applicable and implemented means.

5 Conclusion

Thanks to this study, we have shown first, the importance of the risk measurement for all new installations, even if it is built to confront an urgent problem. It is obvious that the current risk description, in the shape of an advantages and disadvantages list, is not sufficient. In order to make the CO_2 storage technique valid, a consistent and rigorous risk study has to be carried out. As such, the MOSAR method can be used. Its systemic and systematic approach, its possible adaptation to a specific site, and its potential evolution in its applications makes it efficient in determining relevant scenarios and in integrating expert advice. Subsequently, the use of software, which automates the scenarios implementation, can be useful if this method is chosen.

We can add that MOSAR subjectivity should be viewed as a strong point and not as a hindrance. The various judgements and possible opinions on the gravity and probability of scenarios must lead to the making of concrete decisions. The actors should not fall into a trap of endless, ineffectual deliberation.

This study suffers from a lack of experienced feedback. So, it seems judicious to use storage sites like the Ketzin site (Germany, CO_2SINK project) in order to complete the building of the typology grid of under-systems danger sources.

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