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Water distribution and risk governance: data issues in view of development of risk-informed decision-making approach

Keywords

water distribution system, failure analysis, supply water safety, water network, risk

Abstract

The issues of failure risk assessment in water distribution systems are presented. Water supply network failure constitute a crucial issue in water distribution sector. Attention has been paid to the problem of risk assessment considering risk acceptance criteria. Besides, the water network failure indicators were assessed. The presented methods can be used to describe the general characteristics and the technical conditions of the water distribution system. The chapter is intended to draw the attention to the need for further technical and organisational improvement and for the standardization of the failure risk assessment in the water distribution systems.

1. Introduction

The task of water supply systems is to provide consumers with the required amount of water having proper quality and necessary pressure, according to the valid standards, at an acceptable price and at the convenient time for the consumer.

The water supply and distribution subject receives the highest attention of regulating bodies (Directive 2020/2184; EN 15975-1, 2011; EN 15975-1, 2013; WHO, 2011) as well as the water science and engineering researchers (Kulicz-kowska et al., 2020; Kwietniewski et al., 1993; Pietrucha-Urbanik & Tchórzewska-Cieślak, 2017; Sadiq, et al., 2004).

Besides, many researchers from industry and from academy develop methods and tools to enhance our capacities in risk management. Some propose methods for risk management driven by life cycle management including adoptative and advanced maintenance strategies others suggest the use of predictive techniques to prevent, eliminate or mitigate failures and their consequences (Barton, 2019; Economou et al., 2009; Eisenbeis et al., 1999; Kerwin et al. 2020; Kleiner & Rajani, 2000). At present, the main concerns in developed countries is to upgrade the management of the water supply and distribution safety in compliance with modern standards and regulations and the renewal of the aged water distribution networks. The operation of aged water networks with pipe ages varying from 50 to even 100 years is characterized by a high failure frequency and criticality. That impacts on the water losses, as well as on the system operational safety and reliability (Mays, 2005; Engelhardt et al., 2003; Pietrucha-Urbanik & Tchórzewska-Cieślak, 2018; Robles-Velasco et al., 2020).

Another important problem with aged networks is the oversized diameters of water-pipes. That decreases the water flow rate and subsequently in-

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creases the risk of water quality deterioration (Domon et al., 2018; Park & Kim, 2017; Rak et al., 2019; Tchórzewska-Cieślak et al., 2017).

Assessing technical performance of the aged distribution networks requires failure databases of high statistical quality. A crucial task in the failure analysis is gathering the proper failure records, as well as experts' technical assessments (e.g. operators) and specialists (e.g. researchers) (Eid, 2010; Motiee & Ghasemnejad, 2019; Tchórzewska-Cieślak, B. et al., 2021).

Based on data with high statistical quality, different issues in water supply and distribution can be effectively assessed such as; reliability and safety, supplied water pricing, natural water sources security, and conformity with standards and regulations (Pietrucha-Urbanik & Rak, 2020; Pietrucha-Urbanik & Tchórzewska-Cieślak, 2021; Rak, 2007; Tchórzewska-Cieślak et al., 2019, Papciak et al., 2019; Rak, 2009; Rak & Pietrucha-Urbanik, 2019).

All the previously mentioned issues should be effectively assessed at the earliest stage of the system design, construction, renovation, and throughout the whole operational life, aiming at (Fuchs-Hanusch et al., 2008; Tchorzewska-Cieslak et al., 2021; Pietrucha-Urbanik et al., 2020; Eid et al., 2015; Kakoudakis, 2018; Tang et al., 2019; Winkler et al., 2018; Chen, et al. 2019):

- best specification of water supply system,
- determining the critical value of the failure rate of the water supply network,
- specifying the type of safety procedures associated with the operation of the water supply network,
- determining the critical value of risk levels.

Regarding renovation issue, Failure analysis constitutes the main source of information needed to perform the water network modernization (Asnaashari et al., 2009; Barton et al., 2022).

In 2004, the third edition of the Guidelines for Drinking Water Quality (Guidelines for Drinking-Water Quality) published by the World Health Organization provided guidance for the development of the so-called Water Safety Plan, whose aim is to establish the requirements concerning critical infrastructure protection (WHO, 2005). The water safety plans should also be included in the standards. WHO standards recommends to perform failure risk analysis of the water distribution network in order to fulfil the safety and reliability requirements for the water supply system (Salehi et al., 2021; Snider & McBean, 2019).

The proposed analysis should provide the basis for a comprehensive risk management of to be implemented in the water safety plans as well as in decision-making processes. The aim of this chapter is to propose a scheme for operational assessment.

2. Failures occurring in water distribution systems

The water network consists of mains, distributional pipes and water supply connections together with particular fittings such as check valves, hydrants, flow meters, etc.

Failures which occur in water pipe network and fittings have random character and can be caused by the events connected with groundwork, water pipe technical state, errors at mounting, or sudden temperature changes. Such situations cause the difficulty in performing the analysis (Bruaset & Sægrov, 2018; Christodoulou, 2010; Xu et al., 2022).

During the operation of the water supply system functioning, various failures can occur causing water losses and they can be a reason for the secondary contamination of water in the water network, which is a serious threat to consumer safety (Lin et al., 2022; Mathye et al., 2022).

Very often, such situations cause high failure frequency in the network according to (De Oliveira et al., 2011; Giraldo-González & Rodríguez, 2020; Jafar, 2010; Teichmann et al. 2020):

- incorrectly assumed concept of network structure (network in open or mixed system),
- wrongly chosen network operating hydraulic conditions,
- too high working pressure,
- lack of cut-off and control fittings that protect against water hammer.

Frequently the failures in the water network concern:

- pipes, e.g. cracks, corrosion,
- loose connections, e.g. leaks,
- fittings, e.g. damage of hydrants.

Proper operation of water network consists of its constant control, which includes (Tchórzewska-Cieślak, 2009):

- pressure measurement in water pipe network, inspection of water pipe network fittings (maintenance or removal), expansion of water

network and construction of new connections, repairs to water pipe network failure,
- pipes renovation (the interior surface is covered with cement mortar or epoxide mortar, flexible lining),
- pipes reconstruction (pipes relining, compact pipe (U-liner), plastic pipes put into pipe being repaired),
- renewal of pipes (using the trench and trenchless method, removing or leaving the old pipe).

3. Data collection

A significant problem is gathering and archiving statistical data of failures (Asnaashari et al., 2009; Barton et al., 2022; Kleiner & Rajani 2000; Snider & McBean, 2020). To perform this activity, the modern Supervisory Control And Data Acquisition (SCADA) systems should be used (Choi, 2021; Xiong et al., 2020).
The input data can be distinguished in two classes: network descriptive characteristics and operational feedback failure frequency and recovery time data (Yamijala et al., 2009).
The descriptive characteristics of the network cover the following groups (Pietrucha-Urbanik et al., 2021; Tchórzewska-Cieślak & Pietrucha-Urbanik, 2018):
- general information about the objects (locations, ages, etc.),
- technical data about the objects (types of objects considering their functionality, geometry, materials, technology, operational conditions, etc.),
- data on failure (type of event, cause, mechanisms, etc.),
- data on the effects and consequences of failure (type, damage severity, extensions, etc.),
- additional information (report date, environmental data, cost).

4. Determining failure rate and availability

Failure rate is used in the analysis and assessment of the water supply system failure and is calculated as the average value of the damage intensity of pipes, connectors, and fittings.
A failure occurrence rate λ is calculated using the following equation (Kwietniewski et al., 1993):

$$\lambda(t) = \frac{n(\Delta t)}{\Delta L \cdot \Delta t} \tag{1}$$

where $n(\Delta t)$ represents the number of failures observed during the time duration Δt and along a pipe of length ΔL.
The criteria and categories presented are developed on the basis of waterworks practice and failure analysis performed in different water supply systems.
Criteria regarding failure rate were proposed in the following works (Kwietniewski, 2011; Rak, 2005). The former criteria (Rak, 2005) provide that failure rates should not exceed criterion values, as follows. In the case of mains λ_{Mcrit} is less than 0.3 $km^{-1}\cdot year^{-1}$, compared to less than 0.5 for the distribution pipe λ_{Dcrit}, and $\leq 1.0\ km^{-1}\cdot year^{-1}$ for service connections λ_{SCcrit}. In (Kwietniewski, 2011), proposals for the classification of failure rate criteria for the entire water distribution network were presented and classified in terms of reliability, with a high failure rate concerning low reliability when $\lambda_{lr\_crit} \geq 0.5\ km^{-1}\cdot year^{-1}$, high reliability when $\lambda_{hr\_crit} \leq 0.1\ km^{-1}\cdot year^{-1}$, and average reliability between the criteria values mentioned $0.1 < \lambda_{ar\_crit} < 0.5\ km^{-1}\cdot year^{-1}$.
The criteria should primarily take account of aspects related to the safety of water consumers, and technical or technical/economic analysis. Such criteria are used for decisions that are made about running the system (e.g., regarding renovation, modernisation, and authorisation for use) (Taeho et al., 2014).
Mean Time to Repair MTTR [h] considers the time from the moment of failure declaration until re-establishing of the water flow in the damaged section of the water supply network:

$$MTTR = \frac{1}{n}\sum_{i=1}^{n}(T_{et} + T_r)_i \tag{2}$$

where T_{et} is the administrative time for repair [h] and T_r is the real time of repair [h].
The precise definition of operating states of the water supply system has a significant impact on the analysis of the reliability and safety of the system (Rak & Tchórzewska-Cieślak, 2013).
The following values are proposed, which defines the operating conditions in the water supply system taking into account the category of the water supply system (Pietrucha-Urbanik & Tchórzewska-Cieślak, 2018; Rak, 2005).
In case of failure rate:

- water network supplying less than 2000 recipients: tolerable ≤ 0.9 $km^{-1}\cdot year^{-1}$, controlled from 0.9 to 2.0 $km^{-1}\cdot year^{-1}$, unacceptable ≥ 2.0 $km^{-1}\cdot year^{-1}$,
- water network supplying the settlement units of more than 2000 and less than 200 000 recipients: tolerable ≤ 0.5 $km^{-1}\cdot year^{-1}$, controlled from 0.5 to 1.5 $km^{-1}\cdot year^{-1}$, unacceptable ≥ 1.5 $km^{-1}\cdot year^{-1}$,
- large water network that supplies more than 200,000 recipients: tolerable ≤ 0.5 $km^{-1}\cdot year^{-1}$, controlled from 0.5 to 1.0 $km^{-1}\cdot year^{-1}$, unacceptable ≥ 1.0 $km^{-1}\cdot year^{-1}$,
- particularly important industrial plants, hospitals: determined on the basis of a detailed analysis.

In case of MTTR:

- water network supplying less than 2000 recipients: tolerable ≤ 3 h, controlled from 3 to 24 h, unacceptable ≥ 24 h,
- water network supplying the settlement units of more than 2000 and less than 200 000 recipients: tolerable ≤ 2 h, controlled from 2 to 18 h, unacceptable ≥ 18 h,
- large water network that supplies more than 200,000 recipients: tolerable ≤ 2 h, controlled from 2 to 12 h, unacceptable ≥ 12 h,
- particularly important industrial plants, hospitals: determined on the basis of a detailed analysis.

In case of the tolerable category, the system can be operated under no special conditions, the operators should perform inspections and conduct failure analysis. In comparison, when the unacceptable category of water supply system occurs, the system should not be operated and immediate action should be initiated.

The level of water losses can be distinguished as indicators of service quality level and water network conditions and can be distinguished in the following way:

- water loss rate per unit for the entire length of the line,
- Unavoidable Annual Real Losses (UARL) is the annual volume loss, which is considered to be inevitable and economically viable. This means that the removal of small leaks does not cause significant water losses and damages in the vicinity of the water supply and greatly exceeds the material damage caused by these leaks,
- Infrastructure Leakage Index (ILI) is the ratio of the annual volume ratio of losses to UARL,
- Real Loss Benchmark (RLB) calculated as the annual volume of unsold water per length of water pipeline.

5. Estimation of failure cost of water pipelines

Prior to an analysis of the effect of an undesirable event *C*, components of the cost of liquidating a single failure were determined as c_{fi}.

This cost consists of components as follows and can be expressed as (Urbanik et al., 2019):

$$c_{fi} = c_{lab} + c_{tran} + c_{mat} + c_{mes} + c_{pm} \tag{3}$$

where c_{lab} represents labour costs, c_{tran} transport costs, c_{mat} material costs, c_{mes} mark-up expenses supply, and c_{pm} is mark-up profit and tax.

In turn, costs due to water losses in the course of a failure c_{gl} are estimated according to the formula:

$$c_{gl} = \Delta V \cdot c_{gp} \tag{4}$$

where ΔV is the amount of water lost, in m^3, and c_{gp} is the price of water in EUR/m^3.

Other costs associated with failure repairs concern the cost of restoring the failure place to the state before failure, as well as costs of preliminary works including the separation of the failure place, location of water pipe failure, industry supervision, approval and acceptance inspection, marking place in the case of traffic organization change.

Labour costs are calculated on the basis of reports on water supply failures and labour sheets of employees taking part in the removal of these failures. The costs for the course of the vehicles owned by the municipal enterprise associated with failure repairs of the water network were calculated on the basis of the failure report attached to the road cards of the cars.

Additional costs related to the unreliability of the water supply system are the costs of maintenance brigades. In addition to water loss costs other than the unreliability of the system, so-called unavoidable water loss occurring on the water network or during rinsing the network.

It is worth mentioning that the research-based method of analysing the acceptance by water

consumers of the costs incurred by enterprises in risk reduction should be part of an appropriate policy that an enterprise pursues in the context of consultation with the local community (Tchórzewska-Cieślak et al., 2020). It can also constitute an important step towards ensuring the safety of water consumers and should therefore be a fundamental element in the strategy pursued by water utilities. Detailed procedures should be consulted with a wide range of experts from various fields. The costs of changes and improvements should be taken into account, but priority should always be given to providing consumers with water that is safe for their health (Tchorzewska-Cieslak, 2007).
An important element of failure risk-informed management in a water supply company should be the analysis of consumer acceptance of the actions taken to reduce failures, as these influence the price of water. On this basis, water utilities can implement information management procedures.

6. Failure-effect analyses in water distribution system

The effects can involve both a lack of income for the water company due to the fact that the water goes undelivered and possible compensation to recipients deprived of water (Tchórzewska-Cieślak, 2018).
The estimation of losses, which are often random in nature, is not simple in practice.
Losses increase expenses and are associated with costs, with the result that profit is reduced. This justifies an interest, on the part of water companies, in an assessment of risk that is as accurate as possible. In general, the principle that small losses occur at relatively high levels of probability is proven in practice (Farmani et al., 2005; Fuchs-Hanusch, 2012; Giustolisi, et al. 2006).
As risk-level calculations can be performed for several thresholds that are adapted to expected water shortages or possible costs, it is necessary to determine the risks of unreliability of functioning and safety unreliability (Haffejee & Brent, 2008; Tchórzewska-Cieślak, 2011).
The direct risk assessment method is based itself on historical data, with no analysis of the causes of losses being carried out (Brandowski, 2005; Walski & Pelliccia, 1982).

Risk can be defined as the probability that a specified value of financial losses will be exceeded (Tchórzewska-Cieślak, 2018):

$$r = P\{C \geq C_{boundary}\} \quad (5)$$

and

$$r = E(C)/profit \quad (6)$$

where r is the risk of losses and $E(C)$ is the value of an expected loss, in calculations based on the formula (Tchórzewska-Cieślak, 2018):

$$E(C) = \sum_i P_i \cdot C_i \quad (7)$$

where P_i is the probability of an undesirable event causing losses, and C_i is the absolute value of losses expressed as financial costs resulting from the occurrence of a single undesirable event and the expected financial profit.
If there is no appropriate database from which appropriate probabilities can be determined, the risk can be derived from the following formula:

$$r = C_{avg}/profit \quad (8)$$

where C_{avg} is the average annual size of losses and profits that are expected in the given year. This measure is an indicator of financial losses.

7. Methods of failure risk analysis of water distribution system

7.1. Risk prioritizing in water supply network

The method of risk prioritizing involves selecting the level of factors that affect the risk of failure in the water supply network. The proposed method is based on the classification of risk factors for failure of the water supply network and assigning them points values – functional criteria (FC_i) and point weights – assessment criteria (AC_i), and then calculating the index of risk prioritizing (*IRP*).
In this way, a value of the risk prioritization index – IRP – is calculated according to the formula (Tchórzewska-Cieślak, 2011):

$$IRP = \sum_{i=1}^{n} FC_i \cdot AC_i \quad (9)$$

where ***IRP*** is the index of failure vulnerability, FC_i means functional criteria, AC_i means assessment criteria and n is the number of criteria taken into account in the considered method. Each functional criterium, depending on the degree of influence of the factor on the risk prioritizing index, has assigned a point value in the following way as shown: from 0 to 1 – neglected, from 2 to 3 – unimportant, from 4 to 6 – the average important, 7 and 8 – important, from 9 to 10 – very important. The values of assessment criteria AC_i are adopted depending on the importance of the damaged pipe, according to the following scale: 1 – low, 2 – medium, 3 – high, or 4 – very high.

The value of the ***IRP*** obtained through performed analysis helps to make decisions concerning the operation or modernization of the system. Neglected risk (IRP < 70 points) - no further action is required and system operates in proper and reliable way. In case of obtaining tolerable risk preventive action in the system is not needed (from 70 to 100 points). Controlled risk means that the system is allowed to operate but under the condition that modernization or repair will be undertaken (from 100 to 170). If unacceptable level occurs an immediate action should be taken to reduce the IRP (> 170 points).

The following factors can be considered in the analysis: water network age and material, hydrogeological conditions, network monitoring, corrosion protection, the density of underground infrastructure in the area where the network is located, dynamic loads, including the difficulty of repairs in the area where the network is situated, failure rate, size of possible losses resulting from failure occurrence, the difficulty to repair damages (Rak & Tchórzewska-Cieslak, 2006; Tchórzewska-Cieślak, 2018).

7.2. Multi-criteria decision analysis for risk assessment as regards failures in water distribution system

Multi-criteria decision analysis entails a choice of criteria influencing the risk of failure in a water distribution network, and the future occurrence thereof. The method suggested is based on risk-criteria grouping as regards failure in a water distribution network, with assessment then carried out by reference to determined point values under the Analytic Hierarchy Process method (Saaty, 1977). As well as approaches to incorporating data uncertainty into multi-criteria decision making models (Ezbakhe & Pérez-Foguet, 2018; Lienert & Scheidegger, 2014). It is assumed that risk means a measure by which to assess a hazard or threat resulting either from probable events beyond our control or from the possible consequences of a decision. Impacts are distinguished through the additive value of risk, which includes the category criterion of the size of possible financial losses resulting where failures arise. Evaluation criteria weights, as a criterion of financial losses. The risk is interpreted in terms of expected losses (Pietrucha-Urbanik & Tchórzewska-Cieślak, 2018).

The procedure for using this method involves definition and analysis of the decision problem and goal setting decisions. The final decision is based on a synthesis of partial evaluation and selection of the best variant, through the creation of overall assessment scales using criteria and partial evaluation of alternatives.

7.3. Application of Dempster Shafer evidence theory in analysis of failure risk of water distribution systems

The Dempster Shafer theory (DST) is treated as a generalization of Bayesian probability theory. For different hypotheses or evidences, the probabilities are assigned using the belief function referred to as BPA (Basic Probability Assignment) or *m* (Dempster, 1967; Shafer, 1976, Tchórzewska-Cieślak, 2011). The DST also provides the possibility of combining different hypotheses and, on that basis, determining the baseline probability (Kacprzyk, & Fedrizzi, 1991). The main difference between the probabilities lies in the fact that the m function does not need to be specified for all elements of the event and only for some of the subsets (Demotier, 2006; Yager, 1987).

The DST gives the possibility to combine the opinions of various experts and consequently the risk assessment of failure in the water distribution systems. The theory of mathematical evidence allows assigning each premise not one but two values (Alim, 1988; Tchórzewska-Cieślak, 2011).

Apart from modelling the uncertainty it makes possible to obtain a numerical value (Luo & Caselton, 1997). The proposed method can be used when operating data are not sufficient for statistical and probabilistic analysis, but can be the basis (together with the experience and

knowledge) for expert opinion regarding the level of failure risk (Tchórzewska-Cieślak, 2011).
The combining of the information contained in the two sets of experts opinions through two hypotheses gives the opportunity to update their knowledge, which has a beneficial effect on decision-making and failure risk management. The result is a new subset of possible hypotheses with the new values characterizing the possibility of individual risk categories. This process can be continued as long as the information is coming from the experts, as to obtain the most reliable results.
Application of the theory of mathematical evidence to failure risk analysis of water supply network should be used in the process of risk management, in particular based on the collection, verification and grouping data and hypotheses (Tchórzewska-Cieślak, 2011).
Only hypotheses that are not in conflict are considered, and contradictory hypotheses are ignored by standardization.
Analysis of the failure risk with the use of the DST is based on the analysis of opinions of experts, who assess (giving hypothesis and values of the belief function) the possibility of risk level (Tchórzewska-Cieślak, 2011).

7.4. Failure risk analysis of water distributions systems using hydraulic models

To help minimize the consequences of the failure of the water supply pipeline and hence range, duration, and size of interruptions in water supply, the hydraulic models are developed in EPANET 2, mapping the network operation. It allows to simulate failure of individual network sections defining the scope of the impact of the section exclusion on the network operation.
It should be noted that the water supply system constitutes a set of interrelated elements which work affects other elements. The parameters which describe the operation of these elements are, among others, the flow rate, pressure, and flow resistance. The consequence of such structure is the need for modelling the entire water supply system (Pietrucha-Urbanik & Studziński, 2020).
Before performing the simulation, the water demand is updated for each node of the model. The pipes of the model are assigned to the individual streets along which they are laid, according to the updated map obtained from the water company. In the model, the number of water meters in the street and the number of inhabitants supplied from the given pipe are determined. The value of the individual water demand is established after taking into account the work of tanks, reservoirs, and therefore cooperation with the pumping station, readings of water meters, and water level fluctuations in the expansion tanks. This allows determining the daily and hourly water demand (Pietrucha-Urbanik & Studziński, 2017).
A major limitation of the method is to have the revised hydraulic model of water supply network, the construction of which is time-consuming, requires a series of data, which many water-supply companies do not possess, such as diameter and absolute roughness of pipes built in the first half of the twentieth century, and finally the need to calibrate the model. In practice, only a few waterworks have verified the hydraulic models that can be used in the presented method (Studziński & Pietrucha-Urbanik, 2019).

8. Conclusion

The water supply system is characterized by a continuous operation, its reliable and safe operation has a direct impact on the quality of life of water consumers.
The reliability analysis of the water network, as well as a precise database of operational information of the system have a significant impact on the correctness of performed analysis and the final result of the reliability analysis. Therefore, to perform the proper analysis, the failure database consisting of the failure protocol should be developed.
Failures in the water supply system do not occur without a cause, often appear in a chain of undesirable events, they are also a result of making wrong decisions and poor management, resulting in a negative impact on the water supply system operation. To improve the current situation of the water supply system and reduce or regulate the pressure in the water supply network, monitoring of the water network should be provided. Additionally, modernization of the valves in the distributional pipe and modernization of the existing water supply system, including Active Leak Detection, should be implemented.
Risk and failure analyses in the water supply system should be standardized during system operation and may be considered as a tool to support

decisions made in the proper risk-informed management process.

The analysis of the water network failures can contribute to the assessment of the technical state of networks, which can help in planning potential repairs and, consequently, contribute to prevention and reduction in the number of failures, as well as minimize their consequences. The development of appropriate failure assessment methods contributes to reducing the possible consequences of disasters; helps engineers, designers, or government officials to make correct decisions regarding the selection of the optimal solution for technical facilities; and provides means for securing their users and the surrounding environment. In the world today, the development of technology has brought many benefits, but it has also contributed to the emergence of many threats. Through such techniques, terrorists have access to chemical-biological-radiological-nuclear hazard vectors (CBRN) and modern information and communication technologies (ICT). Therefore, failure analysis related to the operation of all technical systems should now be a priority action undertaken by the appropriate stakeholders.

Water networks are continuing to increase in length, what leaves fully justified efforts to develop new research methods that will allow for determinations of potential risks. Developed studies supported by the experience and expert knowledge constitute more-effective methods of monitoring water networks, and seeking to protect them against failure.

The considerations presented here may constitute a basis for further research, proving helpful in a process of risk management that should start by determining priority problems, with the next step then being the formulation of management principles. Technical solutions adopted should then be optimized from the point of view of effects anticipated and sums invested. The chosen solution should be implemented, and its functioning monitored to provide for verification of the method, as well as the determination of limitations on risk that have been achieved.

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