Journal of Polish Safety and Reliability Association
Summer Safety and Reliability Seminars, Volume 9, Number 3, 2018

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Proposal of a R&D frame to develop resilience models for services supply continuity in view of crisis situations

Keywords

resilience, modelling, critical, infrastructure, crisis, management

Abstract

The authors propose a frame to develop mathematical models describing the resilience of the service(s) supply processes and the associated critical-infrastructure(s), in crisis situation. The paper is intended to contribute in developing the paradigm of resilience and appropriate metrics. It describes briefly the paradigm of resilience used in some scientific disciplines, especially: the physical-mechanical resilience (material sciences), the ecological resilience and the psychological resilience. Presently, the use of resilience is very loos, especially, in analysing vital service supply continuity and in crisis management, as far as we are concerned. An advanced resilience concept should encompass: temporality, stochasticity and measurability. The authors propose an R&D frame to develop such formal models in order to help in resilience analysis and decision making for crisis management. Formal models are necessary to rationalise analyses, normalise best practices and build decision making processes. The proposed R&D frame integrates: vulnerability and dependency/interdependency.

1. Introduction

The concept of “resilience” has been showing a persistent rapid emergence in critical infrastructure protection and in crisis management, during these last decades. But, the present paradigms of resilience need to be revisited, [1]. The concept itself is not a recent one. Many scientific disciplines make frequent use of it. However, the concept of resilience is still fuzzy. Besides, its use in risk assessment and system operability-failure analysis is recent and not well-established yet.

Engineers and risk analysts find great difficulties to come up not only with a universal unique view of resilience but also even a sectorial view limited to circumstantial engineering applications, needs and/or operational environment.

Developing “*the concept*” or “*concepts*” of resilience requires the establishment of an R&D frame of work that can continuously be reviewed and improved. This R&D frame can’t but be conceived on a multidisciplinary bases. As, the concept of *resilience* gained a growing interest in relation with the growing complexity of the studied systems. Noting that the most complex systems created by Nature are the living beings and their ecosystems.

An exhaustive treatment of the subject of Resilience & Complexity is beyond the scope of this paper. But the dialectic Resilience-Complexity should be present in mind while examining the resilience concept.

This preceding points explains the necessity that classical risk management should integrate in some way the concept of resilience. As, modern systems are more and more complex, in the sense that they are: distributed, dependent/interdependent, smart, active and proactive.

The paper is structured as following.

Chapter 1 is this introduction.

Chapter 2 presents a brief overview of the proven use of the concept “resilience” in other disciplines in order to identify any potential generic parcel of knowledge that could help in sculpting a resilience concept appropriate for risk-engineering disciplines.

In chapter 3, the features of the resilience concept, models and the corresponding metrics are presented, in a wide generic sense.

In chapter 4, the paper focuses on the notion of crisis and scenarios and proposes mathematical models for scenarios composed of n-sequential events integrating vulnerability and dependency/interdependency (D/I).

Chapter 5 lay down a proposal of some dynamic models to describe and measure the resilience with the help of different measurable and their associated metrics.

Finally in chapter 6, we conclude by underlining the most marking features and aspects of the proposed R&D frame, in view of the analysis of the resilience of vital services supply and of the corresponding critical infrastructures, to help in crisis management.

2. Resilience – overview

In crisis management, one may come over the use of the term "resilience" within different disciplines: physical-mechanical resilience (material sciences), ecological resilience and psychological resilience.

Historically, the first use of the term "resilience" was in mechanics and material sciences. In mechanics and material sciences, "resilience" is very well-defined and well-measured. Notably, *Resilience* is the ability of a material to absorb and release energy within the elastic range, [2]. Tow metrics are used to measure *Resilience*, in that sense. The "proof resilience" which is defined as "the maximum elastic energy absorbed by a given body, measured in Joule (J). Besides, the "resilience modulus" which is defined as "the maximum elastic energy absorbed per unit volume of a given body [2][3] measured in Joule per cubic meter (J/m3). In material sciences, it is just a matter of restoring the initial state once the stressing phase is off. The resilient material should then become "as good as before stressing". However, there is no concerns about "how long the healing would take". In material since, two different materials are identical from material resilience stand point if their "proof resilience" values are identical, even if one can be restored in 10 seconds while the other needs 10 minutes. For this "material resilience", characteristic mathematical models and precise metrics exist. In fact, this is the simplest concept of resilience for the simplest category of systems, in sciences.

As for the *Ecological Resilience*, it has been introduced into the ecological sciences in 1973 by C. S. Holling, [4]. He writes: "If we are examining a particular device designed by the engineers to perform specific tasks under a rather narrow range of predictable external conditions, we are likely to be more concerned with consistent invariable performance in which slight departures from the performance goal are immediately counteracted. A quantitative view of the behaviour of the system is, therefore, essential. With attention focused upon achieving constancy, the critical events seem to be the amplitude and frequency of oscillations. But if we are dealing with a system profoundly affected by changes external to it, and continually confronted by the unexpected, the constancy of its behaviour becomes less important than the persistence of the relationships. Attention shifts, therefore, to the qualitative and to questions of existence or not.", [4].

Holling does clearly focus on the system "being" not on the system "doing/behaviour", in presence of an extreme external and existential aggression. Subsequently, qualitative measure receives the highest intention. But, Holling recognises also that if the menace is not existential then "A quantitative view of the behaviour of the system is, therefore, essential." One may argue differently on Holling's point of view. However, discussing the foundations of this point is out of our scope. We offered this ecological resilience point of view in order to assess the multiplicity of the views about resilience. Also, we believe that engineering science have much to inspire from ecological and psychological science, as far as resilience concept is examined.

Finally and regarding the *Psychological Resilience* in crisis management field, it switches to *societal (community) resilience*. It is viewed as a process where communication plays the major role. Researchers distinguish, then, two kinds of resilience: individual resilience (microscopic) and community one (macroscopic). All the basic tools and models used in societal resilience find their roots in the psychological resilience. For example, Hyvärinen J. and Vos M. propose a conceptual framework that can act as a starting point for further investigations on how communication can strengthen community resilience and include citizens in the response network, [5]. Their paper contains a very interesting rich list of references that focus on communication in crises in order to enhance community resilience. However, the concept of "societal resilience" that they seek to enhance is not defined in the paper.

As, our paper is designed within the context of crisis management, we will opt for the communication-oriented resilience concept. Therefore, we will rather look in the direction of the psychological resilience. Psychological resilience seeks to understand why some individuals are able to withstand – or even thrive on – the pressure they experience in their lives while some others are not, [6].

In psychological and behavioural sciences, specialists will rather describe "resilience" not as a "quality/ability" but as a process. They may describe resilience as: "as the process of effectively negotiating, adapting to, or managing significant sources of stress or trauma", [7]. Luthar et al., [8], referred to it as a "dynamic process encompassing positive adaptation within the context of significant adversity". We may notice also from Luthar et al. [8][9], that this dynamic process has a non-deterministic quality. That means: the dynamic process does not encompass the same adaptive pattern in response to a repetitive action of the same stressing vector on the same individual. The absence of the "deterministic" quality, lets us suppose that it is a "stochastic" process.

We share G. Windle's, [7], on the use of an "operational definition of resilience". We add then that this operational definition should cover these qualities: elasticity, dynamic and stochastic.

By elasticity, we refer to the quality of being "as good as before", after stressing. Dynamic is evidently being time-dependent. While "stochastic" refers to the probabilistic inherent characters of the dynamic response of the individual under stress.

These are the three qualities that we will be considering when developing the resilience models.

As for metrics and considering that resilience should be expressed mathematically as a measurable quality, then quantitative measures will receive the highest priority.

We believe these are the minimum common features for all resilience models describing services supply continuity and helping in decision making in crisis situations.

3. Features of the required models

The previous short survey illustrated how the concept of resilience is described, measured and applied in three scientific disciplines: materials mechanic, ecological sciences and psychological sciences. These are the disciplines that make the most advanced use of the concept of resilience. Although, the description, the measure and the operational practices are not identical in the three disciplines. Still, we may be able to identify some common and even generic features of an advanced paradigm of resilience. From our stand point, the features to be retained are embeded in the following definition of the concept: "*resilience*" describes the process of aggression-recuperation of a given (complex) system under the action(s) of a threat (stressing vector).

We use the term "process" vs "aptitude" to integrate two features: temporality and randomness.

The features of the resilience concept are explicitly:

- Descriptive process of aggression-recuperation (/elasticity),
- Dynamic (/temporality), and
- Stochastic (Randomness /probabilistic models and metrics)

In the following chapters, we also use the terms:

- Crisis: to refer to "the active phase of stress",
- Threat: to refer to the "stressing vector".

4. Crisis & scenarios

A crisis is declared once the continuity of supply of a vital service (or many vital services) is potentially or effectively menaced. Each vital service supply is dependent on the operability of a set of well-identified CIs and/or processes. These CIs and processes may to some extend be dependent and interdependent. The dependency/interdependency (D/I) would propagate the loss of operability from one CI to another and may even amplify it.

These CIs and processes may, also, be vulnerable to the threat in action.

4.1. Dependency/interdependency (D/I)

The D/I between CIs may be described is two disjoint ways: either through the operability loss rate or operability loss probability.

As for the work reported here, we are proposing to describe D/I through the operability loss rate. As it is fully described it in, [10][11].

We use a 1st order approximating model to describe the D/I as follows:

$$\lambda_i^* = \lambda_i \left[\prod_{\substack{j=1 \\ j\neq i}}^{N} (1+\varepsilon_{ij}) \right] \tag{1}$$

Where,

λ_i^* : The operability loss stressed rate of the i^{th} CI,

λ_i : The operability loss unstressed (nominal) rate of the i^{th} CI, and

ε_{ij} : The dependency strain factor of the i^{th} CI due to its dependency on the j^{th} CI

Obviously, on may propose more elaborated and non-linear models. But, we recall that this is not the scope of the present paper that focus on the features of the R&D frame work rather than on the details of R&D work itself.

We admit four classes of D/I as described by Rinaldi et al. in, [14], such as: physical, cyber, geographical and logical.

However, we partially admit Rinaldi et al definition of "interdependency" as: a "bidirectional relationship between two infrastructures". The "Bidirectional" interdependency is only one mode that we admit and we classify it as a "1st order interdependency mode". Then, we identify other higher order modes of interdependency. It is the case with the following mono-directional dependencies: A impacts (partially or fully) on B, B impacts (partially or fully) on C and C impacts (partially or fully) on A.

Whatever the class of D/I, we would like to consider also the temporal dimension. That means that the propagation of the "loss of operability" from on CI to the others takes time. Generally, the propagation is not instantaneous. This "propagation time" depends on the "loss of operability" mode and the concerned couple of the CIs.

The D/I between a set of CIs can then be described through the dependency strain matrix ε_{ij} that describes the dependence of the i^{th} CI on the j^{th} one. We note that ε_{ij} is generally not symmetric.

We, equally, note that ε_{ij} is always positive in order to guarantee the "coherency" of the system-of-systems.

The "coherency" condition requires that the "loss of operability" of a CI does not improve the global operability of the set of the concerned CIs, and the "recuperation" of a CI does not degrade the global operability of the set of the concerned CIs.

4.2.Vulnerability

The CIs vulnerability to threats may be described is two disjoint ways, as above: either through the operability loss rate or operability loss probability.

CIs loss of operability is also dependent on the type of the threat. That is to say the CIs are differently vulnerable to different threats.

As far as our work reported here, we are proposing to describe vulnerability through the operability loss rate. As it is fully described it in, [10][11],

We use a 1st order approximating model to describe the D/I as follows:

$$\lambda_i^* = \lambda_i \left[\prod_{j=1}^{N}(1+\nu_{ij})\right] \tag{2}$$

Where,

λ_i^* : The operability loss stressed rate of the i^{th} CI,

λ_i : The operability loss unstressed rate of the i^{th} CI, and

ν_{ij} : The vulnerability strain factor of the i^{th} CI to the j^{th} threat.

The vulnerability strain matric ν_{ij} describes the vulnerability of the i^{th} CI to the j^{th} threat. The element ν_{ij} can be positive or negative but always higher than -1, $[\nu_{ij} \geq -1]$. That is to describe two classes of events. The 1st class contains the events where occurrence rates increase under stress. The 2nd class contains those where occurrence rates decrease under stress. This can be illustrated in the following two examples:

5. A pipe rupture; the pipe rupture stressed rate during the active phase of a quake can't be but higher than the unstressed rate. Then ν_{ij} can't be but positive, $(\nu_{ij} > 0)$,
6. A broken pipe repair; the stressed repair rate during the active phase of a quake can't be but lesser than the unstressed rate. Then ε_{ij} can't be but negative and higher than -1, $(\nu_{ij} \in [-1,0])$.

Both situations are functionally identical indeed and guarantee the coherence of the system-of-system, as explained in the preceding section.

4.3. Scenarios

In the scope of crisis management activities, experts determine the significant (plausible) scenarios. Significant scenarios result from the combination of the actions of some active threats and the (partial or full) loss of operability of a set of impacted CIs and processes. Very often, the occurrence order of the preceding events determines a specific scenario associated to a specific set of hazardous outcomes that may be more or less of different severity.

Accordingly, an effective crisis management process should consider the plausible set of well-identified scenarios of events. The occurrence probability $P_n(t)$ of a given scenario of n-ordered events can then be described by the following model:

$$P_{n+1}(t) = \int_0^t \rho_1(\xi_1)d\xi_1 \int_{\xi_1}^t \rho_2(\xi_2)d\xi_2 \dots \int_{\xi_n}^t \rho_{n+1}(\xi_{n+1})d\xi_{n+1} \tag{3}$$

Equation (3) can also be rewritten using its differential form:

$$\frac{d}{dt}P_{n+1}(t) = \rho_{n+1}(t) * P_n(t) \tag{4}$$

where,

$\rho_i(t)$: is the occurrence density function of the i^{th} event (in the order).

If the ordered events follow a Poisson's stochastic process, an analytical solution exist, [15].

It is obvious that each scenario of events leads to a well-defined set of hazardous outcomes. However, the same well-identified set of hazardous outcomes may be the results of different possible scenarios. The mapping between the set of the plausible scenarios $E(S)$ and the set of potential outcomes $E(C(S))$ is not then bijective.

4.4. Required data

The proposed approach requires three distinguished species of datasets:

7. The CI unstressed (nominal) loss of operability probability density functions.
8. The vulnerability strain factors describing the vulnerability of a given CI to a set of well-defined threats.
9. The D/I strain factors describing the directional dependency between the concerned CI.

The unstressed loss of operability characteristics are in principal available for most of the critical infrastructures and their internal components and subsystems. These data are effectively imbedded in the daily operational histograms of each CI.

However, these data has a sectorial nature: energy, gas, transport, health …

Many imbedded disruption data exist in databases as insurance companies such as: Energy Losses Database of Willis, [16], March's Energy Database, [17], and Sigma database of Swiss Re, [18]. Sectorial CI's disruptions are also embedded in accident databases such as: the Worldwide Offshore Accident Databank (WOAD) of DNV, the Energy-Related Severe Accident Database (ENSAD) of PSI and the OECD Databases for Chemicals and Biosafety, [19]. A good collection of data on manmade accidents are referenced in [20].

However, there are many other private databases used by national industries that map and monitor the operations of the nation's systems of electric grids, ICT networks, processing plants, gas pipelines, … etc. Most of these information are proprietary.

Regarding vulnerability of CIs to threats, some databases exist. However, it is not exactly in the suitable form to be directly exploited by the proposed approach. As in the previous paragraph, many data are embedded in some databases, such as: EM-DAT of the International Emergency Disasters Database of the Centre for Research on the Epidemiology of Disasters (CRED), NatCat: Natural Catastrophes Service (Munich Re).

But, as far as we can assert there is no a specific vulnerability database. We believe this is mainly due to:

10. The loose definition of the concept of vulnerability,
11. The proliferation of vulnerability models and indices, with no convergence towards a standard set of models.

One may also add the vulnerability is a so local quality, e.g.: the vulnerability of two identical buildings to the same quake would be do so different if the soil is rocky or sandy. The vulnerability of a structure/procedure/organisation to a given threat integrates all the elements of its ecosystem. And this seems to be true whatever the definition of the vulnerability is.

As for the D/I data required by the proposed approach, they are also not presently available in the required form. Several R&D programs are conducted in order to develop D/I databases. In Argonne National Laboratory (ANL), a team is developing data collection tools and models in order to allow for a more detailed analysis of critical infrastructure dependencies and interdependencies. Data collection and analyses start to address physical, cyber, and geographic dependencies and initiate the anticipation and visualization of first-order cascading failures, [21]. However, most of the existing tools and models operate in silos and have little interaction with complementary tools and models. Understanding logical dependencies and escalating failures is obviously a complex task.

We may then conclude that only disruption data exist for CIs. Although, it is not always explicitly available, it is always embed in the operational histograms of the CI. Still, the proposed approach requires data to be able to work out both the strain D/I matrix ε_{ij} and the strain vulnerability matrix ν_{ij}.

We admit how serious are the issue of the adequate data and data-sources. Developing data models and collecting data require long term efforts, generous resources and adequate standards underlays.

5. Resilience measure & metrics

The proposed approach disposes different measures for the resilience. All of them use as a basic break the occurrence probability function of a given sequence of events, such as the one described in Eq.(3) and Eq.(4).

A sequence is initiated by the action of a well-defined threat followed by a mixed sequence of CI disruptions and actions of the same threat and/or other different existing threats, in a given order. Each event is identified by its occurrence order i and its occurrence probability density function, $\rho_i(t)$. These two preceding inputs are enough to determine the occurrence probability of the sequence as described by Eq.(3) or Eq.(4).

However, there is two possible ways to conceptualise the evolution of a running crisis, such as:

12. A threat action(s) followed by CI disruptions that ends by services supply disruption, or
13. A threat action(s) followed by CI disruptions but ends by establishing the service(s) supply

If one considers the 1st way, Eq.(3) and Eq.(4) will be describing the $P_n(t)$ as the probability of the loss of supply within a time interval t, where t is measured from the moment of the threat activation.

If one considers the 2nd way, Eq.(3) and Eq.(4) will be describing the $P_n(t)$ as the probability of establishing the supply within a time interval t, where t is measured from the moment of the threat activation.

Both points of views can be used to help in resilience analysis and crisis management decision making.

Actually, both points of view are developed by the proposed approach. We recommend the parallel use of both.

However, for the purpose of this section, we will use the 2nd point of view, i.e., where $P_n(t)$ is the probability of establishing the supply within a time interval t.

The purpose of this chapter is to propose measures of resilience using the appropriate metrics. We propose some of measures and associated metrics, in the following section.

NB: the curves that are given in the following sections are used as illustrative means. They are from an analysis of the resilience of a water supply network, [22]. In that work, a cascade of 4 elementary CI disruptions are considered. The disruptions admit some degree of D/I and the corresponding CIs are vulnerable to a threat (quake). The elementary disruptions follow a Poisson's stochastic process in both situations: nominal and stressed. Both D/I and vulnerability strain factors are constant. The numerical details can be found in, [22].

5.1. Recover probability function

The 1st and the most immediate proposed measure is the recovery probability function, $P_n(t)$. We recall its definition: "the probability to recover from the crisis with the interval t. Given that $P_n(t)$ is a cumulative function, it starts at zero-value at $t = 0$ to attend an asymptotic value when $t \to \infty$.

The $P_n(t)$ time-profile is certainly a pertinent measure that can be useful to help in measuring the resilience of a given CI or a set of CIs associated to the supply of a given service.

Certainly, the comparison between the $P_n(t)$ time-profiles in stressed and unstressed situation is informative, as well. The comparison between the stressed and the unstressed $P_n(t)$ may be direct as in Figure 1, from reference [22].

This measure is then dimensionless.

Comparison may also be through the determination of an incremental loss of resilience, such as in the next section.

5.2. Incremental loss of resilience

We propose an incremental loss of resilience, Δ_{res} defined by:

$$\Delta_{res} = [\Delta P_n^*(\Delta T) - \Delta P_n(\Delta T)] * \Delta T \tag{5}$$

where, $\Delta P_n^*(\Delta T)$ and $\Delta P_n(\Delta T)$ are the stressed and the unstressed differences in recovery probabilities, respectively over the given interval ΔT, an ΔT is the interval $[T_1, T_2]$.

This incremental loss occurs with a probability given by: $P_n^*(T_2) - P_n^*(T_1)$, over the interval $[T_1, T_2]$.

This indicator allows to determine how much the recovery of the system evolves in stressed situation compared to unstressed one. It is then a direct relative measure.

The used metric is Time t.

5.3. Probability density functions

The probability density function $\rho_n(t)$ is also a good measure of resilience, recalling that:

$$\rho_n(t) = \frac{d}{dt} P_n(t) \tag{6}$$

In fact, this would specially be recommended if an analytical expression of $P_n(t)$ exist. This is the case of the example presented in Figure 2 showing a comparison between the stressed and unstressed cases, from reference [22].

The metric used here is t^{-1}.

5.4. Entropic recovery rate

Finally, on may propose the entropic recovery rate $\kappa(t)$ which is defined as:

$$\kappa(t) = -\frac{d}{dt}\left(ln \frac{P_n(\infty)}{P_n(t)}\right) = \frac{\rho_n(t)}{P_n(t)} \tag{7}$$

Notice that $P_n(t)$ is a cumulative probability such that:

$$\lim_{t \to 0} P_n(t) \to 0, \quad \text{and} \quad \lim_{t \to \infty} P_n(t) \to P_n(\infty) \tag{8}$$

So that :

$$\lim_{t \to 0} \left(ln \frac{P_n(\infty)}{P_n(t)} \right) \to \infty \text{ , and}$$

$$\lim_{t \to \infty} \left(ln \frac{P_n(\infty)}{P_n(t)} \right) \to 0 \qquad (9)$$

The entropic recovery rate $\kappa(t)$ measures how close the recovery is to its asymptotic situation.
It is simply the ratio between the density probability function and the probability function, Eq.(7).
We underline this measure because it is very discriminating between stressed and unstressed situations. It is also as discriminating between different stressing situations.
This measure is dimensionless.

6. Conclusions

This paper is intended to propose an R&D frame to develop resilience models in view of assessing the risk of loss of supply of vital services due to the loss of operability of some CIs, in crisis situations.
The R&D frame covers:

14. A definition of the concept “resilience”
15. An identification of its features
16. A proposal of mathematical model of a resilience measurable and some of its derivatives
17. A brief example as proof of applicability

We observe that the concept of resilience is still loos in engineering risk analysis not to say fuzzy. Thus, the paper perform a brief overview on the advanced use of the concept resilience practiced in other disciplines than system engineering. The overview, led us to identify the principal features of an advanced concept of resilience such as:

18. Descriptive process of aggression-recuperation,
19. Dynamic, and
20. Stochastic

The paper proposes also a model to describe the resilience in terms of a *dynamic stochastic process*. The model integrates simplified models in order to integrate both: vulnerability and dependency/ interdependency.
The simplified model of vulnerability uses a linear strain factor, ν_{ij}, to describe the vulnerability of a system/process/organisation i to a given threat j, given that $[\nu_{ij} \geq -1]$.
The simplified model of dependency/interdependency uses a linear strain factor, ε_{ij}, to describe the vulnerability of a system/process/organisation i to a given threat j, given that $[\varepsilon_{ij} \geq 0]$.
The proposed model allows to use different metrics to measure resilience: the recovery probability function within a given interval of time, the incremental loss of resilience, the recovery density probability function and the entropic recovery rate.
Both the proposed R&D frame and models are obviously subject to continuous reviewing and improvements until the resilience modelling and analysis issue find satisfaction.
The scope of this work is to contribute into assessing the vital services supply continuity and decision making, in crisis management. This is through structuring the suitable R&D frame work to review and develop the necessary paradigm of resilience.

Acknowledge

Thanks to all those are contributing directly and indirectly in elaborating this view of resilience. I would like specifically to mention these communities: EU Project CIPRNet, EU Project PREDICT, SSARS meetings and ESReDA Project Group CI-R&P.

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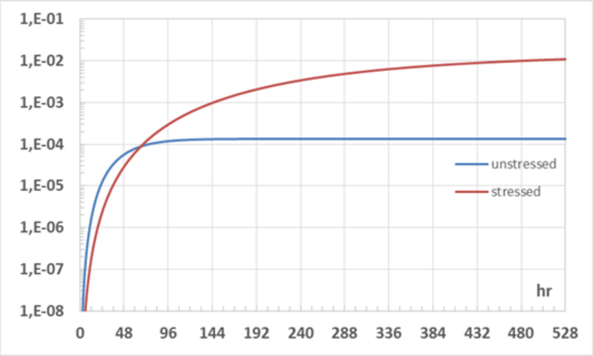

Figure 1. Recovery probability time-profile

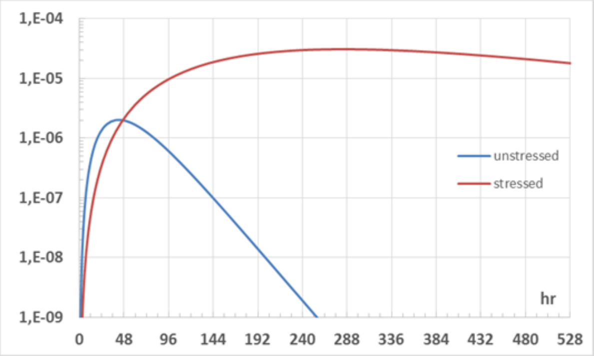

Figure 2. Recovery density function time-profile

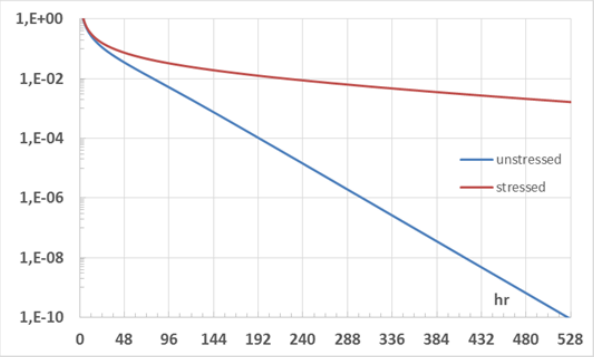

Figure 3. Entropic recovery rate time-profile