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## General Comment

The white paper focuses on defense in depth (DiD) as potentially a key basis for an NRC policy for nuclear safety. In my comments, I propose using resilience as the key basis for such a policy. Such a basis meets a set of requirements that are necessary for making appropriate decisions (Ayyub 2003, 2013 and 2014).

The NRC web site <http://www.nrc.gov/reading-rm/basic-ref/glossary/defense-in-depth.html> defines DiD as an approach to designing and operating nuclear facilities that prevents and mitigates accidents that release radiation or hazardous materials. The key is creating multiple independent and redundant layers of defense to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon. Defense-in-depth includes the use of access controls, physical barriers, redundant and diverse key safety functions, and emergency response measures. For further information, see Speech No. S-04-009, "The Very Best-Laid Plans (the NRC's Defense-in Depth Philosophy)."

Resilience (Ayyub 2013, PPD 21) on the other hand "means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."

Comparing these definitions, it is evident that the DiD definition does not include designing for recovery. From historical perspectives, engineers dealt with safety by initially using factors of safety and allowable stresses in order to produce acceptable safety margins. Then these margins were treated probabilistically in reliability-

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based design. This advancement was followed by considering failure consequences in risk-informed design. The risk-informed practices explicitly identify failures as potential outcomes without explicitly designing for the aftermath of such failures for the purpose of recovery of the performance of the systems and affected things. Designing for recovery, i.e., designing for resilience, is the next logical step.

Resilience can be considered as an overarching concept for a "nuclear safety construct." It offers two primary benefits: (1) linking any future NRC policy to the Presidential Policy Directive on Critical Infrastructure Security and Resilience (PPD21), and (2) adding an important consideration of performance recovery through design, not as a post-disaster reaction. We should not wait until after a disaster in order to advance our design practices to include designing for recovery.

Another consideration is its impact on any liability limitations offered by the Price-Anderson Act (see Ayyub 2012).

I am attaching three files for additional information on resilience and financing nuclear liability.

#### References:

1. PPD21, Presidential Policy Directive -- Critical Infrastructure Security and Resilience, <http://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil>
2. Ayyub 2013 resilience paper attached.
3. Ayyub, 2003, Risk Analysis in Engineering and Economics, Chapman Hall/CRC Press. <http://www.amazon.com/Analysis-Engineering-Economics-Bilal-Ayyub/dp/1584883952>
4. Ayyub, 2014, Risk Analysis in Engineering and Economics, Second edition, forthcoming in April 2014, Chapman Hall/CRC Press. [http://www.amazon.com/Analysis-Engineering-Economics-Second-Edition/dp/1466518251/ref=dp\\_ob\\_title\\_bk](http://www.amazon.com/Analysis-Engineering-Economics-Second-Edition/dp/1466518251/ref=dp_ob_title_bk)

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<http://www.amazon.com/Bilal-M.-Ayyub/e/B001HCXYMQ>

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## Attachments

AyyubResilience-\_NRCPublicHearing20140130

Ayyub-Resilience-JRA\_DOI 10.1111/risa.12093

Science 1494.2Ayyub-Parker

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## Designing for Resilience as a New Nuclear Safety Construct

Bilal M. Ayyub, PhD, PE

Professor and Director

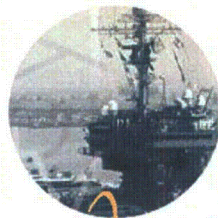
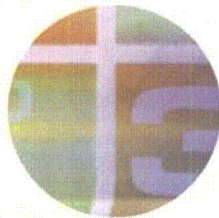
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# U.S.NRC

Public Meeting to Discuss the Draft White Paper of a  
Conceptual Example of a Proposed Risk Management  
Regulatory Framework

January 30, 2014



UNIVERSITY OF MARYLAND





## Outline

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- Background
- Resilience
  - Definition
  - Metrics
  - Valuation
  - Aggregation
- Concluding Remarks



## Background: Sandy and Nuclear Power Plans

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- **Indian Point** – Automatic shutdown of a reactor unit due damage to electrical connection
- **Oyster Creek** – Issuance of an alert since water level were higher then usual for the intake. it also lost power
- **Limerick** – Reduction of power to 91% since the storm damaged a condenser
- **Salem** – Shutdown, when 4 out of 6 pumps stopped working
- **Nine Mile Point** – Automatic shutdown of a reactor unit and another lost power when there was an electrical fault, unclear if storm related



## Background: Recovery after Shutdown

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- Many Japanese nuclear plants shutdown after the March 2011 earthquake without appropriate regulatory restart criteria
- In 2002 there was a major event at the Davis-Besse leading to difficulties with restart criteria (see NUREG/BR-0353)
- Fort Calhoun plant shutdown after a flooding event taking several years to restart
- The 2011 earthquake resulting in the shutdown of the North Anna plants for 3 months



## Background: Nuclear Safety

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- Factors of safety and allowable stresses
  - Acceptable safety margin
- Reliability-based design
  - Acceptable (average safety margin)/(standard deviation of the safety margin)
- Risk-informed design
  - Safety acceptance by also considering failure consequences
- What is next?
  - Designing for recovery? Designing for resilience?



## Resilience Definitions

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- **Psychology** – Resilience is an individual's tendency to cope with stress and adversity
- **Material science** – It is the capacity of material to absorb energy when it is elastically deformed
- **Engineering** – Many definitions exist and a succinct definition is the ability of the system to return to a stable state after a perturbation
- **Systems science** – A resilient system returns to an equilibrium state after perturbation, with more resilient systems having multiple equilibrium points
- **Other uses** – Ecological, infrastructure, neuroscience, economic and community systems



## Resilience Definitions

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- Presidential Policy Directive (PPD-21, 2013) on Critical Infrastructure Security and Resilience
  - The “term resilience means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.”



## Resilience Definitions

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- A Summary by Attoh-Okine (2009)
  - Holling (1973 in ecology)  
Resilience determines the persistence of relationships within a system, and is a measure of the ability of these systems to absorb change state variable, driving variables, and parameters and still persist
  - Lebel (2001)  
Resilience is the potential of a particular configuration of a system to maintain its structure/function in the face of disturbance, and the ability of the system to re-organize following disturbance-driven change



## Definition Requirements

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- Requirements for an operational definition that lends itself to measurement or metrics:
  - Considering initial capacity or strength, and residual capacity or strength after a disturbance, i.e., robustness
  - Accounting for abilities to prepare and plan for, absorb, recover from or more successfully adapt to adverse events as provided in the NRC (2013) definition
  - Treating disturbances as events with occurrence rates and demand intensity, i.e., modeling them as stochastic processes
  - Treating different performances based on corresponding failure modes for various things at risk, such as people, physical infrastructure, economy, key government services, social networks and systems, and environment





## Definition Requirements

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- Requirements for an operational definition to support metrics(cont.):
  - Accounting for systems changes over time, in some cases being improved, in other cases growing more fragile or aging
  - Considering full or partial recovery and times to recovery
  - Considering potential enhancements to system performance after recovery
  - Relatable to other familiar notions such as reliability and risk, i.e., building on the relevant metrics of reliability and risk
  - Enabling the development of resilience metrics with meaningful units



## Proposed Definition

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### Building on Notional Definition per PPD-21 2013

#### **Resilience Measurement**

The resilience of a system's function can be measured based on the persistence of a corresponding functional performance under uncertainty in the face of disturbances

#### **ISO (2009) Risk Definition**

Risk is the effect of uncertainty on objectives



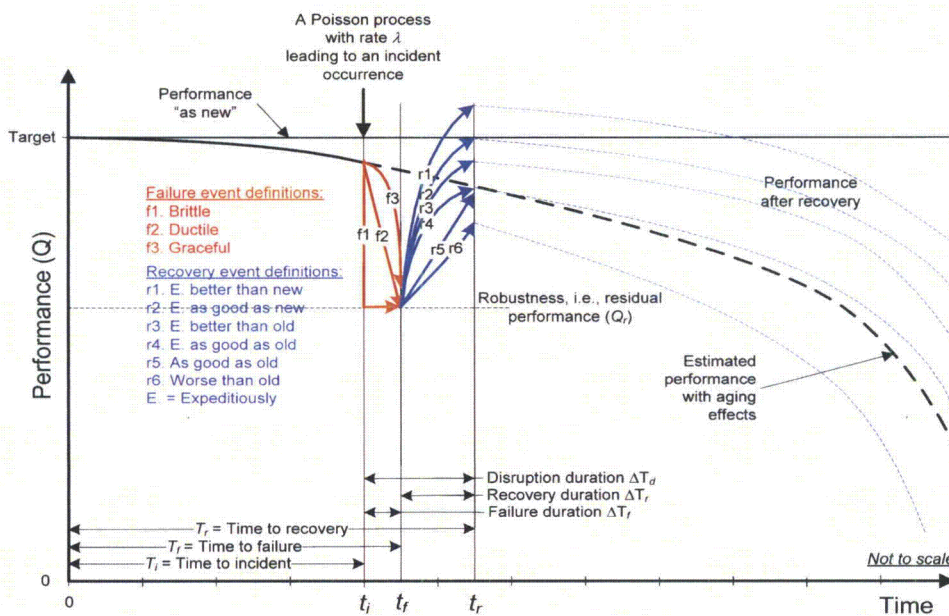
## Steps Towards Quantification

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- **The key words in the definition are listed in a suggested order for their analysis as follows:**
  - System's performance defined in terms of requirements or objectives, and examined in the form of functions: output, throughput, structural integrity, lifecycle cost, etc.
  - Uncertainty relating to events such as storms, disturbance, conditions, system states, etc.
  - Persistence examined in terms of enduring the events, recovery, continuance and/or resumption of functional performance



# Measuring Resilience (Persistence)



$$\text{Failure (F)} = \frac{\int_{t_i}^{t_f} f dt}{\int_{t_i}^{t_f} Q dt}$$

$$\text{Recovery (R)} = \frac{\int_{t_f}^{t_r} r dt}{\int_{t_f}^{t_r} Q dt}$$

$$\text{Resilience (R}_e\text{)} = \frac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r} \quad R_e \geq 0$$



## Valuation of Resilience

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- Anthropocentric in nature based on utilitarian principles
- Consideration of all instrumental values, including existence value
- Permitting the potential for substitution among different sources of value for human welfare
- Individual's preferences or marginal willingness to trade one good or service for another that can be influenced by culture, income level and information making it time- and context-specific
- Societal values as the aggregation of values by individual



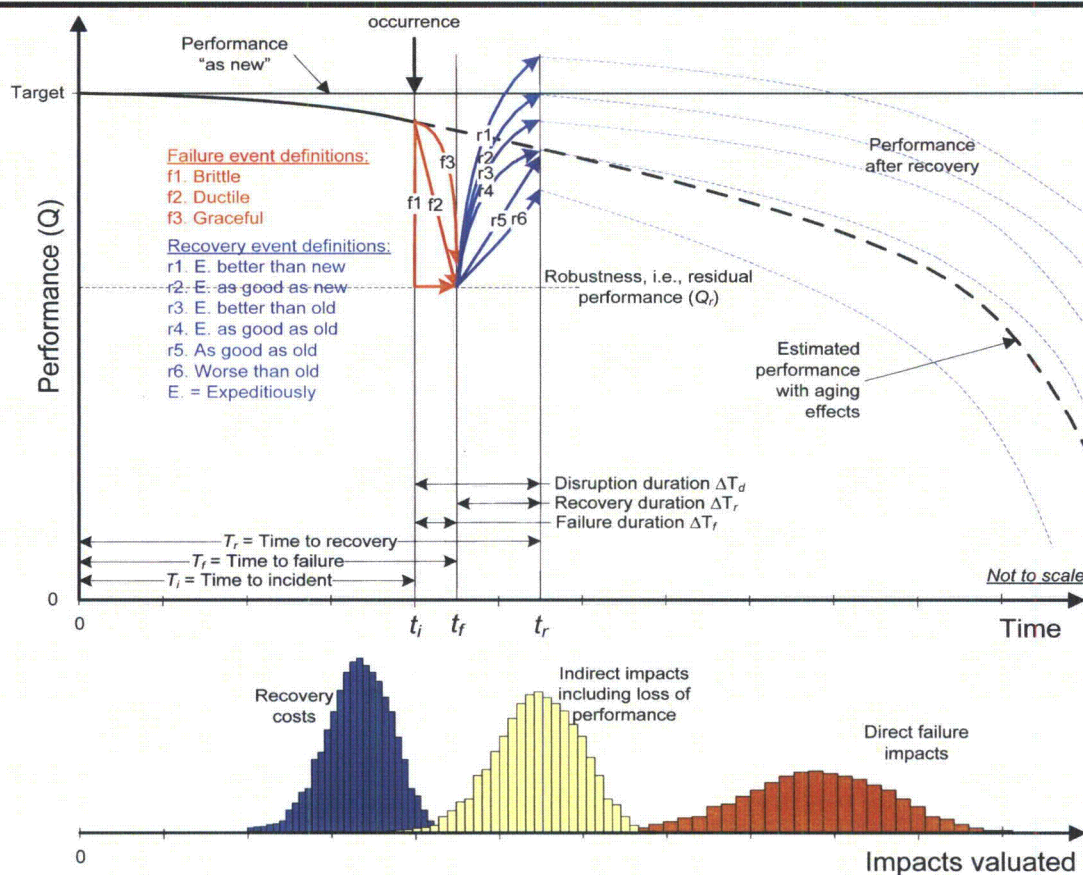
## Measuring Performance

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Systems	Performance	Units
Buildings	Space availability	Area per day
Other structures: Highway bridges	Throughput traffic	Count per day
Facilities: Water treatment plants	Water production capacity	Volume per day
Infrastructure: Water delivery	Water available for consumption	Volume
Network: Electric power distribution	Power delivered	Power per day
Communities	Economic output	Dollars
	Quality of life (consumption)	Dollars



# Economic Valuation of Resilience







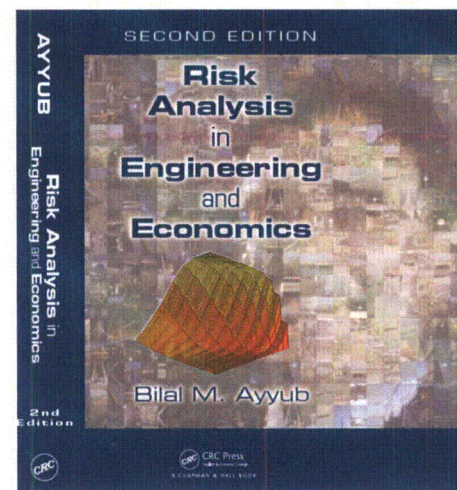
# Decision Analysis

- Identify alternatives (strategies)
- Assess benefits and costs of each
- Assess impacts of strategy on future options

Benefit = Valuation Differential  
due to an Action

$$\text{B/C Ratio} = \frac{\text{Benefit}}{\text{Cost}} \quad \beta_{B/C} = \frac{\mu_B - \mu_C}{\sqrt{\sigma_B^2 + \sigma_C^2}}$$

$$P\left(\frac{\text{Benefit}}{\text{Cost}} \geq 1\right) = 1 - P(\text{Benefit} - \text{Cost} \leq 0)$$





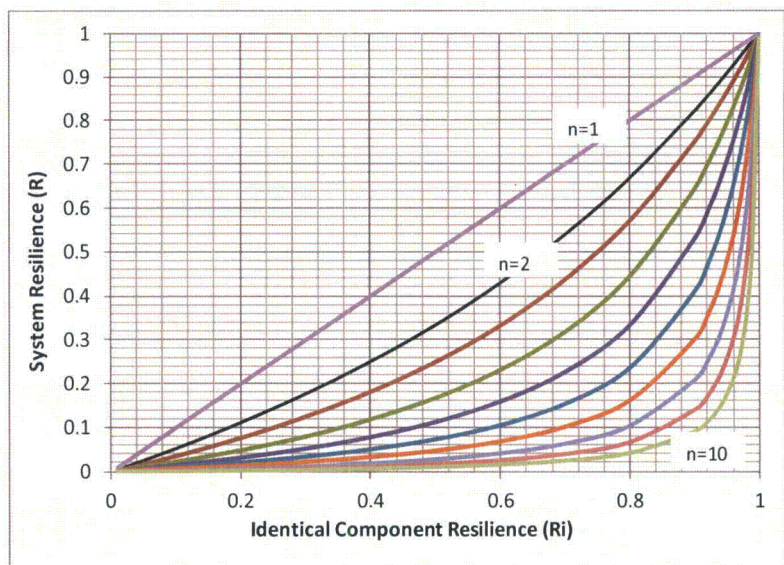


## Resilience Segregation & Aggregation

For  $0 \leq R_i \leq 1$ , (MCEER 2010) defines

$$\text{Resilience}(R_{12}) = \frac{R_1 \cdot R_2}{R_1 + R_2 - R_1 \cdot R_2}$$

For identical components using the independence assumption





## **Concluding Remarks**

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- **Resilience metrics**
- **System analysis (interdependence)**
- **Resilience aggregation**
- **Announcements**
  - **ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems**
  - **Proposed ASME CRTD workshop on Resilience and Nuclear Facilities**

**Thank you**

# Systems Resilience for Multihazard Environments: Definition, Metrics, and Valuation for Decision Making

Bilal M. Ayyub\*

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The United Nations Office for Disaster Risk Reduction reported that the 2011 natural disasters, including the earthquake and tsunami that struck Japan, resulted in \$366 billion in direct damages and 29,782 fatalities worldwide. Storms and floods accounted for up to 70% of the 302 natural disasters worldwide in 2011, with earthquakes producing the greatest number of fatalities. Average annual losses in the United States amount to about \$55 billion. Enhancing community and system resilience could lead to massive savings through risk reduction and expeditious recovery. The rational management of such reduction and recovery is facilitated by an appropriate definition of resilience and associated metrics. In this article, a resilience definition is provided that meets a set of requirements with clear relationships to the metrics of the relevant abstract notions of reliability and risk. Those metrics also meet logically consistent requirements drawn from measure theory, and provide a sound basis for the development of effective decision-making tools for multihazard environments. Improving the resiliency of a system to meet target levels requires the examination of system enhancement alternatives in economic terms, within a decision-making framework. Relevant decision analysis methods would typically require the examination of resilience based on its valuation by society at large. The article provides methods for valuation and benefit-cost analysis based on concepts from risk analysis and management.

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**KEY WORDS:** Community; consequence; infrastructure; measure; measurement; metrics; recovery; resilience; risk; robustness

## 1. BACKGROUND

The United Nations Office for Disaster Risk Reduction (UNISDR) reported that half of the world's inhabitants, expected by 2025 to increase to roughly two-thirds, and the vast majority of property and wealth are concentrated in urban centers situated in locations already prone to major disasters, such as earthquakes and severe droughts, and along flood-prone coastlines.<sup>(1)</sup> UNISDR<sup>(1)</sup> also reported that

the 2011 natural disasters, including the earthquake and tsunami that struck Japan, resulted in \$366 billion in direct damages and 29,782 fatalities worldwide. Storms and floods accounted for up to 70% of the 302 natural disasters worldwide in 2011, with earthquakes producing the greatest number of fatalities. Average annual losses in the United States amount to about \$55 billion. It is anticipated that such disasters would occur in increasing trends of storm rates and disaster impacts because of a combined effect of climate change and increased coastal inventory of assets.<sup>(2)</sup> Although no population center or a geographic area can ever be risk free from natural or human-caused hazards, communities should strive to enhance resilience to the destructive forces or the impacts of resulting events that may claim lives and damage property. Gilbert<sup>(3)</sup> provided

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population-and-wealth-adjusted loss and fatality count trends from 1960 to 2009 to demonstrate that both are about flat without significant slopes; however, it is noted that the United States is becoming more vulnerable to disaster because of increased population concentration in areas prone to natural disasters<sup>(4,5)</sup> and persisting inadequate condition of infrastructure.<sup>(6)</sup>

Enhancing system resilience at the structure, network, community, etc. levels could lead to massive savings through risk reduction and expeditious recovery. The rational management of such reduction and recovery is facilitated by an appropriate definition of resilience and associated metrics. Current definitions do not always lend themselves naturally and intuitively to the development of consistent resilience metrics with clear relationships to metrics of the relevant abstract notions of reliability and risk. The objective of this article is to review existing definitions and metrics, and to propose ones that meet logically consistent requirements drawn partly from measure theory. These metrics would provide a sound basis for the development of effective decision-making tools for multihazard environments. Appendix A lists selected urban areas, their respective population sizes, location attributes, and hazards as a summary of the data reported by UNISDR.<sup>(1)</sup> This summary demonstrates at a global level the extent of exposure to various hazards. The hazard most often listed is flooding, including coastal, and earthquakes.

Resilient systems should be developed to meet sustainability requirements defined by the three pillars of sustainability by reconciling environmental, social equity, and economic demands. These three pillars of sustainability are not mutually exclusive and can be mutually reinforcing. Similar to the long-lived and healthy wetlands and forests, as sustainable biological systems, humans should sustain their long-term well-being in the environmental, economic, and social dimensions and achieve resiliency.

## 2. RESILIENCE DEFINED

The concept of resilience appears in different domains ranging from ecology to child psychology and psychiatry to infrastructure systems. It was formally introduced in ecology, defined as the persistence of relationships within a system,<sup>(7)</sup> and measured by the system's ability to absorb change-state variables, driving variables, and parameters and still persist. In discussing the philosophical basis of risk analysis,

Starr *et al.*<sup>(8)</sup> characterized the resilience of a system in agreement with the *Webster's New World Dictionary & Thesaurus*<sup>(9)</sup> as its ability to bounce or spring back into shape or position, or to recover strength or spirits quickly. The common usage, including technical ones, of the word *resilience* permits some elasticity in its placement in declarative statements, for example, the following are meaningful forms that are structurally identical: (1) infrastructure resilience is desirable and (2) storm resilience is desirable. In the former statement, resilience is an explicit quality of infrastructure, whereas in the latter resilience is an implicit quality of whatever is affected by a storm. Generalizing the latter form to "event resilience is desirable" might imply the event itself is the resilient one, not its subject. This ambiguity in usage is indicative of the elastic nature of the word, and perhaps this elasticity partly explains the confusion in its definition in the literature. Park *et al.*<sup>(10)</sup> tenuously described some aspects of this ambiguity by describing resilience as an emergent property of what an engineering system does, rather than a static property the system has; therefore, resilience is better understood as the outcome of a recursive process that includes sensing, anticipation, learning, and adaptation, making it complementary to risk analysis with important implications for the adaptive management of complex, coupled engineering systems.

In psychology, resilience is an individual's tendency to cope with stress and adversity. In material science, it is the capacity of material to absorb energy when it is elastically deformed. In engineering, many definitions exist and a succinct definition is the ability of the system to return to a stable state after a perturbation. In systems science, a resilient system returns to an equilibrium state after perturbation, with more resilient systems having multiple equilibrium points. The notion of resilience is used not only for ecological systems, infrastructure, and individuals, but also for economic systems and communities.<sup>(11–16)</sup>

The use of the term resilience with respect to hazards and disasters is a logical step, as discussed by White and Haas<sup>(17)</sup> and Mileti,<sup>(18)</sup> and was used in the 2005 Hyogo Framework for Action by 168 members of the United Nations to enhance its priority for governments and local communities.<sup>(19)</sup> A substantial number of studies focused on defining the notion of resiliency for infrastructures and the development of resiliency metrics. For example, Bruneau *et al.*<sup>(20)</sup> defined a resilient system to have reduced failure probability, reduced consequences from failure, and reduced time to recover. Little<sup>(21)</sup>

examined resilience in the context of infrastructure interdependencies in terms of how to react when a disruption occurs. Lebel *et al.*<sup>(22)</sup> defined resilience as the potential of a particular configuration of a system to maintain its structure and function in the face of disturbance, and the ability of the system to reorganize following disturbance-driven change. Walker *et al.*<sup>(23)</sup> defined it as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks. Holling and Gunderson<sup>(24)</sup> identified the rate and speed of return to preexisting conditions after disturbance as key elements for measuring resilience. Fiksel<sup>(25)</sup> examined resilience relating to infrastructure systems that have rigid operating parameters with intrinsic resistance to stress in some narrow bounds and with vulnerability to small, unforeseen perturbations. He conceptually extended the resilience concept from a process to an enterprise. Hollnagel *et al.*<sup>(26)</sup> examined resilience in the context of anticipating the changing potential for failure on the basis of plans and procedures. Norris *et al.*<sup>(27)</sup> and Sherrieb *et al.*<sup>(28)</sup> described disaster resilience as a process, whereas Kahan *et al.*<sup>(29)</sup> described it as an outcome. Cutter *et al.*<sup>(30)</sup> described it as a process and outcome. Colten *et al.*<sup>(31)</sup> defined it to embrace inputs from the engineering, physical, social, and economic sciences. Gilbert<sup>(3)</sup> defined it from the perspective of economics as the ability to minimize the costs of a disaster, to return to a state as good as or better than the *status quo ante*, and to do so in the shortest feasible time. He also classified definitions reported in the literature as process-oriented or outcome oriented. This classification appropriately covers and is consistent with the definitions provided in this section.

Several reputable entities defined resilience in their high-impact documents, most notably:

- In the Presidential Policy Directive (PPD-21)<sup>(32)</sup> on Critical Infrastructure Security and Resilience, the “term *resilience* means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.”
- The National Research Council<sup>(33)</sup> defined resilience as the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events as

a consistent definition with U.S. governmental agency definitions (SDR,<sup>(34)</sup> DHS,<sup>(35)</sup> and PPD-8<sup>(36)</sup>) and NRC.<sup>(37)</sup>

- The ASCE Committee on Critical Infrastructure<sup>(38)</sup> states that resilience refers to the capability to mitigate against significant all-hazards risks and incidents, and to expeditiously recover and reconstitute critical services with minimum damage to public safety and health, the economy, and national security.
- The National Infrastructure Advisory Council defines infrastructure resilience as the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient system depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.
- The Multidisciplinary Center for Earthquake Engineering Research (MCEER)<sup>(39)</sup> of the State University of New York at Buffalo lists characteristics of resilience to include robustness, redundancy, resourcefulness, and rapidity.
- UNISDR<sup>(19)</sup> characterized a resilient city by its capacity to withstand or absorb the impact of a hazard through resistance or adaptation, which enable it to maintain certain basic functions and structures during a crisis, and bounce back or recover from an event.
- The Civil Contingencies Secretariat of the Cabinet Office, London, United Kingdom<sup>(40)</sup> defined resilience as the ability of a system or organization to withstand and recover from adversity.

Based on these definitions and an understanding of the needs of its broad use ranging from buildings to other structures to infrastructures to networks to communities, an operational definition of resilience should enable its measurement by meeting the following requirements for which metrics are either available or needed:

- (1) Building on previous notional definitions and particularly presidential policy directives (PPDs<sup>(32,36)</sup>);
- (2) Considering initial capacity or strength, and residual capacity or strength after a disturbance, i.e., robustness;
- (3) Accounting for abilities to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events as provided in the NRC<sup>(33)</sup> definition;

- (4) Treating disturbances as events with occurrence rates and demand intensity, i.e., modeling them as stochastic processes;
- (5) Enabling the inclusion of different performances based on corresponding failure modes for various things at risk, such as people, physical infrastructure, economy, key government services, social networks and systems, and environment (MCEER,<sup>(39)</sup> Gilbert<sup>(3)</sup>);
- (6) Accounting for systems changes over time, in some cases being improved, in other cases growing more fragile or aging;
- (7) Considering full or partial recovery and times to recovery;
- (8) Considering potential enhancements to system performance after recovery;
- (9) Relatable to other familiar notions such as reliability and risk, i.e., building on the relevant metrics of reliability and risk; and
- (10) Enabling the development of resilience metrics with meaningful units.

A proposed resilience definition that builds on the PPD-21<sup>(32)</sup> and lends itself for measurement by meeting the above requirements is as follows:

Resilience notionally means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from disturbances of the deliberate attack types, accidents, or naturally occurring threats or incidents. The resilience of a system's function can be measured based on the persistence of a corresponding functional performance under uncertainty in the face of disturbances.

This definition is consistent with the ISO<sup>(41)</sup> risk definition of the "effect of uncertainty on objectives." The proposed measure includes three key words that offer a basis for quantification. These words are listed in a suggested order for their analysis as follows:

- System's performance defined in terms of requirements or objectives, and examined in the form of output, throughput, structural integrity, lifecycle cost, etc.;
- Uncertainty relating to events such as storms, disturbance, conditions, and system states;
- Persistence examined in terms of enduring the events, recovery, continuance, and/or resumption of performance.

Most resilience definitions do not always lend themselves naturally and intuitively to the development of consistent resilience metrics with clear re-

lationships to the most relevant metrics of the abstract notions of reliability and risk. The use of the operative word of *ability* sometimes has resulted in setting the measurement process on tracks that focus on the abilities rather than the outcomes of these abilities. The primary outcome of these abilities is the continuance of performance of a system, including bouncing back, a characteristic that could be appropriately termed as performance persistence for a particular function of the system. Performance persistence would naturally set measurement in terms of availability of the performance or continuance of system's states of normalcy. Subsequent sections of this article provide metrics based on this definition that meet logically consistent requirements drawn partly from measure theory, and provide a sound basis for the development of effective decision-making tools for multihazard environments.

### 3. MONOTONE MEASURES FOR RESILIENCE

According to Ayyub and Kilr,<sup>(42)</sup> a *measure* in the context of mathematics is a function that assigns a number to quantify a *notion* as a *metric* representing a subset of a given set, e.g., size, volume, or probability. Some notions are abstract in nature, such as probability and resilience, whereas others are not, such as distance and volume. Measures, in general, build on the concepts of a universal set ( $X$ ), a nonempty family  $C$  of subsets of  $X$  with an appropriate algebraic structure, sets (such as  $A$ ), and the power set ( $P_A$ ) to establish a logical measure that can be used to characterize some system attributes of interest, i.e., resilience, probability, uncertainty, belief, etc. Classical measures formulated for a universal set  $X$  and a family of subsets  $C$  such that if  $A_i \in C$ , it leads to  $A_i \subset X$ . The family  $C$  is called an *algebra*, if the following conditions are met:

$$C \text{ contain the empty set, i.e., } \phi \in C, \quad (1)$$

$$C \text{ contains the entire set } X, \text{ i.e., } X \in C, \quad (2)$$

$$\text{For any } A_i \in C, \text{ the complementary set } \bar{A}_i \in C, \quad (3)$$

where  $\phi$  is the empty set,  $\in$  means belonging, and the  $\subset$  means subethood. The family is called a  $\sigma$ -algebra if it has the following additional property:

$$\text{For } A_i \in C, i = 1, 2, \dots, \bigcup_{\text{all } i} A_i \in C, \quad (4)$$



where  $\bigcup$  means the union over all  $i$ . In other words, Equation (4) states that the countable union of any family of subsets in  $C$  belongs to  $C$ .<sup>(43,44)</sup>

A measure  $\mu$  can be defined in its broadest form as a function that maps  $C$  on to the real line ( $R$ ). This function can be defined mathematically as follows:

$$\mu : C \rightarrow R. \quad (5)$$

Of special interest for the purposes of this article is a function that is limited to nonnegative real values ( $R_+$ ). In probability theory, the probability measure imposes additional requirements on  $\mu$  consisting of the following:

$$\mu : C \rightarrow [0, 1], \quad (6)$$

$$\mu(\phi) = 0, \quad (7)$$

for disjoint  $A_j \in C$ ,

$$i = 1, 2, \dots, \mu \left( \bigcup_{all i} A_i \right) = \sum_{all i} \mu(A_i), \quad (8)$$

where any events  $A_i$  and  $A_j$  meet the following condition:

$$A_i \cap A_j = \phi. \quad (9)$$

Equation (6) limits the mapping to the closed interval of  $[0,1]$  with the measure for the null set being zero according to Equation (7). Equation (8) states that the function  $\mu$  for the union of several disjoint subsets, i.e., with null intersections, is the sum of the measures (i.e.,  $\mu$  values) of these subsets. This *additive property* is unique to this *classical measure of probability*. Although the development and evolution of probability theory was based more on intuition rather than mathematical axioms during its early development, an axiomatic basis for probability theory was established and it is now universally accepted.

Generalized measures are employed for representing other than likelihood notions where it makes sense to require that the additivity property of classical measures used in probability theory be replaced with a weaker property of monotonicity with respect to the subethood relationship. Such measures are called *monotone measures*. Their range is usually the unit interval  $[0,1]$ , as in probability measures, and it is required that the measure of the universal set be 1. Such measures are called *regular monotone measures*.

A *regular monotone measure* can be defined based on a nonempty family  $C$  of subsets from  $P_X$

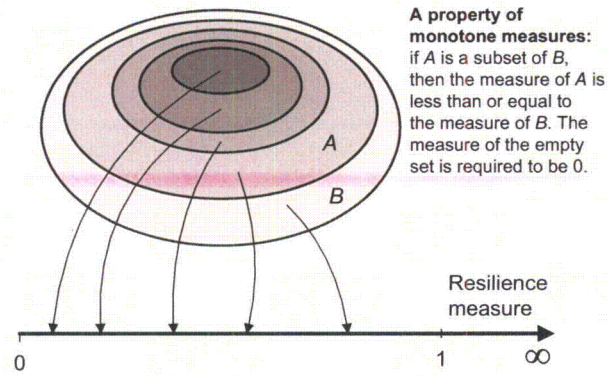


Fig. 1. A monotone measure for resilience.

(i.e., the power set of  $X$ ) for a given universal set  $X$ , which contains  $\phi$  and  $X$ , with an appropriate algebraic structure as a mapping from  $C$  to  $[0,1]$ . A monotone measure must satisfy the following conditions:

- (1) Boundary condition: The monotone measure must meet the following *boundary conditions*:

$$\mu(\phi) = 0 \quad \text{and} \quad \mu(X) = 1. \quad (10)$$

- (2) Monotonicity: This property is illustrated in Fig. 1.

For all  $A_i$  and  $A_j \in C$ , if  $A_i \subseteq A_j$ ,

$$\text{then } \mu(A_i) \leq \mu(A_j). \quad (11)$$

- (3) Continuity from below:

For any increasing sequence  $A_1 \subseteq A_2 \subseteq \dots$

of sets in  $C$ , if  $\bigcup_{all i} A_i \in C$ ,

$$\text{then } \lim_{i \rightarrow \infty} \mu(A_i) = \mu \left( \bigcup_{all i} A_i \right). \quad (12)$$

- (4) Continuity from above:

For any decreasing sequence  $A_1 \supseteq A_2 \supseteq \dots$

of sets in  $C$ , if  $\bigcap_{all i} A_i \in C$ ,

$$\text{then } \lim_{i \rightarrow \infty} \mu(A_i) = \mu \left( \bigcap_{all i} A_i \right). \quad (13)$$

Functions  $\mu$  that satisfy Equations (10), (11), and either Equations (12) or (13) are called *semicontinuous from below and from above*, respectively.



For any pair  $A_1$  and  $A_2 \in C$  such that  $A_1 \cap A_2 = \phi$ , a monotone measure  $\mu$  is capable of capturing any of the following situations:<sup>(42,45,46)</sup>

$$\mu(A_1 \cup A_2) > \mu(A_1) + \mu(A_2), \quad (14)$$

called *superadditivity*, which expresses a cooperative action or synergy between  $A_1$  and  $A_2$  in terms of the measured property,

$$\mu(A_1 \cup A_2) = \mu(A_1) + \mu(A_2), \quad (15)$$

called *additivity*, which expresses the fact that  $A_1$  and  $A_2$  are *noninteractive* with respect to the measured property, and

$$\mu(A_1 \cup A_2) < \mu(A_1) + \mu(A_2), \quad (16)$$

called *subadditivity*, which expresses some sort of inhibitory effect or incompatibility between  $A_1$  and  $A_2$  as far as the measured property is concerned.

Probability theory, which is based on the classical measure theory, is capable of capturing only the situation of Equation (15). This demonstrates that the theory of monotone measures provides us with a considerably broader framework than probability theory for formalizing a measure for resilience. The metric for resilience should be consistent with the way mathematical measures are developed by (1) having a state space defined by the desired performances, (2) using real lines for the performance metrics to define appropriate sigma algebra over the state space, and (3) meeting the monotonic property.

#### 4. RESILIENCE MEASUREMENT AND METRICS

In previous sections, a resilience definition of “the persistence of a system’s performance under uncertainty in disturbances and its states” is proposed to be consistent with the ISO<sup>(41)</sup> risk definition of the “effect of uncertainty on objectives.” Before proposing metrics for resilience, the article examines other models found in the literature and discusses their purposes and limitations. It should be noted that some of the limitations stem from not only the resilience notion’s ambiguous nature but also from its ambiguous definition as an abstract notion. In this section, available metrics are summarized followed by a proposed model.

##### 4.1. Available Resilience Metrics

Bruneau and Reinhorn<sup>(20)</sup> proposed metrics for measuring resiliency based on the size of expected

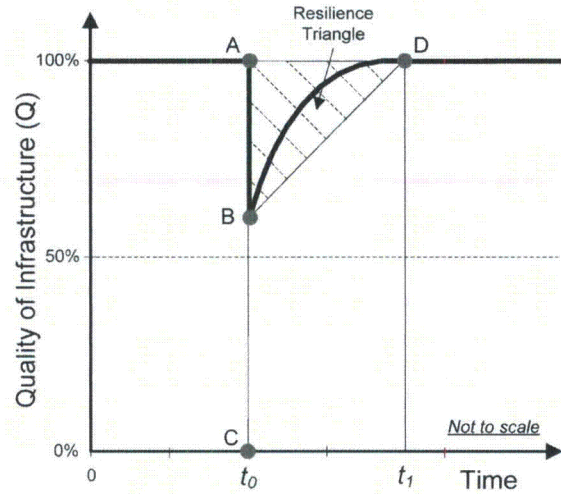


Fig. 2. The resilience properties and triangle.

degradation in the quality of an infrastructure by quantifying robustness, redundancy, resourcefulness, and rapidity to recovery. Garbin and Shortle<sup>(47)</sup> outline an approach to quantitatively measure the resilience of a network as the percentage of links damaged versus the network performance and the percentage of nodes damaged versus the network performance. Tierney and Bruneau<sup>(48)</sup> suggested measuring resilience based on observing that resilient systems reduce the probabilities of failure and enhance recovery, and therefore resilience can be measured by the functionality of an infrastructure system after an external shock including the time it takes to return to initial level of performance. They illustrated the concept as shown in Fig. 2 calling it the resilience triangle. Attoh-Okine *et al.*<sup>(49)</sup> used several potential paths of infrastructure performance during normal operation and cases of unexpected events, for example, a path demonstrating sudden failure as shown in Fig. 2, a path demonstrating decrease in service life, and a path for the normal operation of the system. They used the concept of resilience as illustrated in Fig. 2 to define a resilience index as follows:

$$\text{Resilience} = \frac{\int_{t_0}^{t_1} Q(t) dt}{100(t_0 - t_1)}, \quad (17)$$

where  $Q$  is the infrastructure quality, or the performance of a system,  $t_0$  is the time of incident or disturbance occurrence, and  $t_1$  is the time to full recovery. According to this model, the units of resilience are performance per unit time, where performance can be measured in percent according to



**Table I.** Definition of Resilience Properties

Property	Models (Points A, B, C, and D per Fig. 2)	Units	
Robustness	Robustness = B – C	Percentage	(18)
Redundancy	Not defined		
Resourcefulness	Not defined		
Rapidity	Rapidity = $\frac{A-B}{t_0-t_1}$	Average recovery rate in percentage per time	(19)

Equation (17). Equation (17) was also used by the earthquake community<sup>(48)</sup> with a suggested framework of resilience, called the four “Rs,” as follows:

- Robustness as the ability of the system and system elements to withstand external shocks without significant loss of performance;
- Redundancy as the extent to which the system and other elements satisfy and sustain functional requirements in the event of disturbance;
- Resourcefulness as the ability to diagnose and prioritize problems and to initiate solutions by identifying and monitoring all resources, including economic, technical, and social information; and
- Rapidity as the ability to recover and contain losses and avoid future disruptions.

These properties are defined in Table I with reference to Fig. 2 based on models provided by Shinzuka *et al.*<sup>(50)</sup>

Li and Lence<sup>(51)</sup> refined the resilience index developed by Hashimoto *et al.*<sup>(52)</sup> by using the performance ratio over two different time periods. Omer *et al.*<sup>(53)</sup> measure resilience for Internet infrastructure systems as the ratio of the difference in information transmission before, i.e., initial, and after an event divided by the initial information transmission. Attoh-Okine *et al.*<sup>(49)</sup> also provided formulation of a resilience index of urban infrastructure using belief functions. McGill and Ayyub<sup>(54)</sup> related resilience concepts to regional capabilities performance assessment for human-caused hazards in homeland security.

Gilbert<sup>(3)</sup> provides extensive coverage of and mathematical models for recovery after a storm in the context of a disaster cycle consisting of response, recovery, mitigation, and preparedness. He includes in his discussion partial recovery and full recovery including instant urban renewal of population recovery, physical infrastructure, econ-

omy, social networks, government services, and environments. He also develops simulation models of recovery and provides validation examples for the Kobe Earthquake.<sup>(55)</sup> Generally, the recovery trends shown have decreasing slopes as shown in Fig. 2.

#### 4.2. Proposed Resilience Model

Fig. 3 provides a schematic representation of a system performance ( $Q$ ) with aging effects and an incident occurrence with a rate ( $\lambda$ ) according to a Poisson process. At time  $t_i$ , it might lead to a failure event with a duration  $\Delta T_f$ . The failure event concludes at time  $t_f$ . The failure event is followed by a recovery event with a duration  $\Delta T_r$ . The recovery event concludes at time  $t_r$ . The total disruption ( $D$ ) has a duration of  $\Delta T_d = \Delta T_f + \Delta T_r$ . The figure shows for illustration purposes three failure events: brittle ( $f1$ ), ductile ( $f2$ ), and graceful ( $f3$ ), and six recovery events: expeditious recovery to better than new ( $r1$ ), expeditious recovery to as good as new ( $r2$ ), expeditious recovery to better than old ( $r3$ ), expeditious recovery to as good as old ( $r4$ ), recovery to as good as old ( $r5$ ), and recovery to worse than old ( $r6$ ). These events define various rates of change of performance of the system. The figure also shows the aging performance trajectory and the estimated trajectory after recovery. The proposed model to measure resilience is:

$$\text{Resilience } (R_e) = \frac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r}, \quad (20)$$

where for any failure event ( $f$ ) as illustrated in Fig. 3, the corresponding *failure profile*  $F$  is measured as follows:

$$\text{Failure } (F) = \frac{\int_{t_i}^{t_f} f dt}{\int_{t_i}^{t_f} Q dt}. \quad (21)$$

Similarly for any recovery event ( $r$ ) as illustrated in Fig. 3, the corresponding *recovery profile*  $R$  is measured as follows:

$$\text{Recovery } (R) = \frac{\int_{t_f}^{t_r} r dt}{\int_{t_f}^{t_r} Q dt}. \quad (22)$$

The failure-profile value ( $F$ ) can be considered as a measure of robustness and redundancy, and is proposed to address the notion offered by Equation (18), whereas the recovery-profile value ( $R$ ) can be considered as a measure of resourcefulness and rapidity, and is proposed to address the notion offered by Equation (19). The time to failure ( $T_f$ ) can be

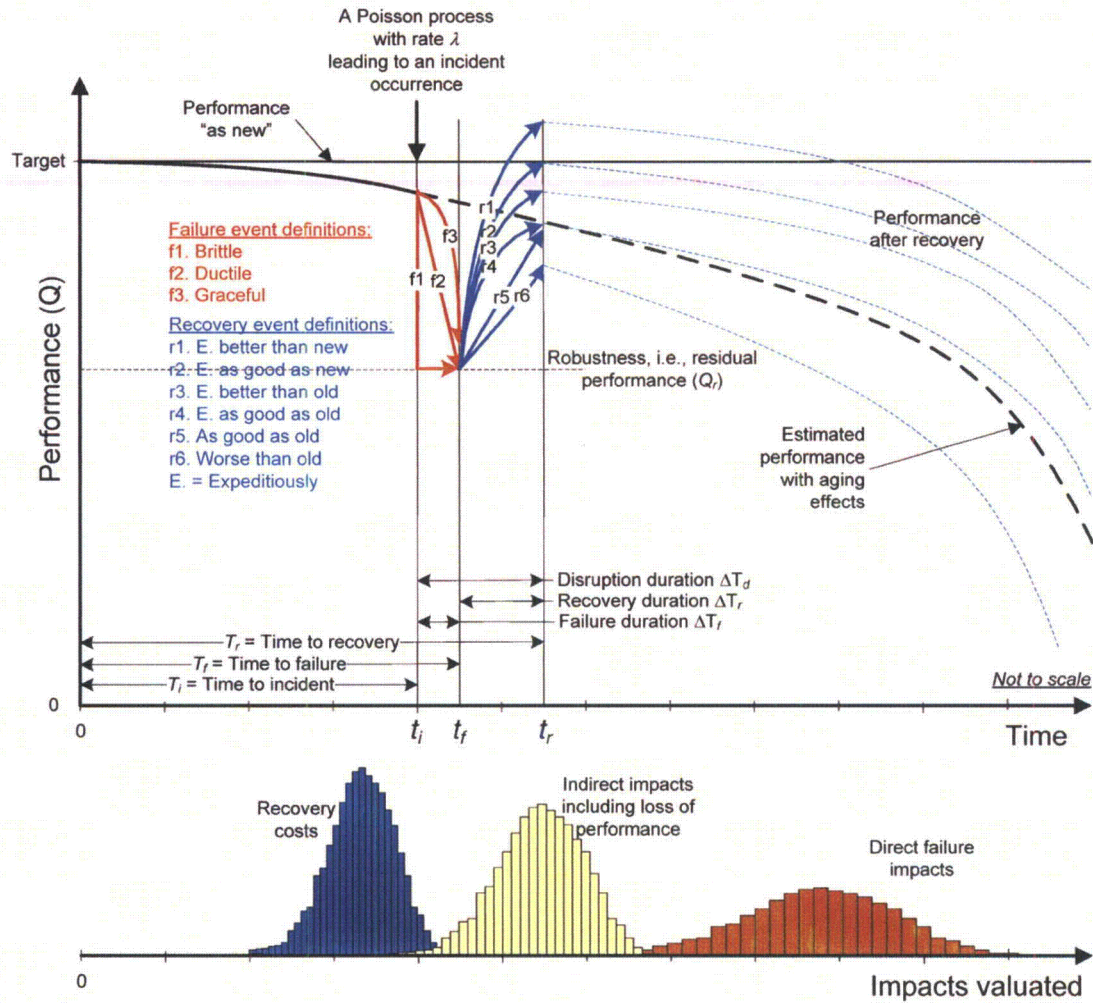


Fig. 3. Proposed definitions of resilience metrics.

characterized by its probability density function computed as follows:

$$-\frac{d}{dt} \int_{s=0}^{\infty} \exp \left[ -\lambda t \left( 1 - \frac{1}{t} \int_{\tau=0}^t F_L(\alpha(\tau)s) d\tau \right) \right] f_{S_0}(s) ds, \quad (23)$$

where  $Q$  is defined as the system's performance in terms of its strength ( $S$ ) minus the corresponding load effect ( $L$ ) in consistent units, i.e.,  $Q = S - L$ . Both  $L$  and  $S$  are treated as random variables, with  $F_L$  = the cumulative probability distribution function of  $L$ , and  $f_S$  = the probability density function of  $S$ . The aging effects are considered in this model by the term  $\alpha(t)$  representing a degradation mechanism as a function of time  $t$ . It should be noted that the term  $\alpha(t)$  can also represent improvement to the system.

Equation (23) is based on a Poisson process with an incident occurrence, such as loading, rate of  $\lambda$ , and is based on Ellingwood and Mori.<sup>(56)</sup> The probability density function of  $T_f$  as shown in Equation (23) is the negative of the derivative of the reliability function.

The proposed model of Equation (20) for measuring resilience meets the set of requirements described in the section on the resilience definition according to the following list of respective items:

- (1) The model is consistent with the PPD-21<sup>(32)</sup> definition.
- (2) The model accounts for the initial and residual capacities as noted in Fig. 3 with the performance "as new" and the robustness.

- (3) The use of the time to failure and time to recovery accounts for the abilities to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events as provided in the NRC<sup>(33)</sup> definition.
- (4) The disturbances are treated as events with occurrence rates and demand intensity, i.e., modeling them as stochastic processes.
- (5) The model permits the use of different performances based on corresponding failure modes for various things at risk, such as people, physical infrastructure, economy, key government services, social networks and systems, and environment.
- (6) The model accounts for systems changes over time, in some cases being improved, in other cases growing more fragile or aging.
- (7) The model accounts full or partial recovery and times to recovery as illustrated in Fig. 3.
- (8) The model accounts for potential enhancements to system performance after recovery.
- (9) The model can be related to other familiar notions such as reliability and risk according to Equation (23).
- (10) The model requires input with meaningful units, is unit-consistent, and produces results with meaningful units.

The model of Equation (20) also meets the monotone conditions of Equations (6)–(13) by having the following attributes:

$$R_e : (f \cap r) \in C \rightarrow [0, \infty), \quad (24)$$

$$R_e(\phi) = 0. \quad (25)$$

For disjoint  $A_i \in C$ ,  $i = 1, 2, \dots$ ,

$$R_e \left( \bigcup_{all\ i} A_i \right) = \sum_{all\ i} R_e(A_i). \quad (26)$$

It should be noted that  $F:f \rightarrow [0, 1]$  and  $R:r \rightarrow [0, \infty)$ . The times  $T_i$ ,  $T_f$ , and  $T_r$  are random variables as shown in Fig. 3, and are related to durations as follows:

$$\Delta T_f = T_f - T_i, \quad (27)$$

$$\Delta T_r = T_r - T_f. \quad (28)$$

The disruption duration is given by:

$$\Delta T_D = \Delta T_f + \Delta T_r. \quad (29)$$

#### 4.3. Performance Measurement for Resilience Metrics

The resilience model of Equation (20) can be used for systems, such as buildings, other structures, facilities, infrastructure, networks, and communities. The primary basis for evaluating Equation (20) is the definition of performance ( $Q$ ) at the system level with meaningful and appropriate units, followed by the development of an appropriate breakdown for this performance, using what is termed herein as performance segregation. The performance segregation should be based on some system-level logic that relates the components of the performance breakdown to the overall performance at the system level as the basis for a system model. This model can be used to aggregate the performance of components to assess system-level performance. Such performance segregation and aggregation analysis is essential for examining the resilience of systems for buildings, other structures, facilities, infrastructure, networks, and communities. The uncertainties associated with the performance components can be modeled as random variables with any necessary performance events to use Boolean algebra and the mathematics of probability to characterize the performance  $Q$  in Equation (20).

MCEER<sup>(39)</sup> proposed the use of resilience index ( $R_i$ ) in the range  $[0, 1]$  for each (the  $i$ th) quality of service, and an aggregation model for these resilience indices using an independence assumption. For example, in the case of two indices, the aggregated index is as follows:

$$\text{Resilience } (R_{12}) = \frac{R_1 \cdot R_2}{R_1 + R_2 - R_1 \cdot R_2}. \quad (30)$$

Fig. 4 shows a plot of Equation (30) for the case of two identical indices, i.e., resilience components, for the entire range of values of  $R_i$ . The figure also shows the effect of increasing the number of components from one to ten. The downward intensification is attributed to the independence assumptions.

The development of such a system-level model relating components' performances to a system performance is beyond the scope of this article. Such a model is domain specific; however, future studies should set meta-methodological requirements for the development of such models. Anthony<sup>(57)</sup> discussed challenges associated with the treatment of system-level resilience, such as communities, and provided illustrations.



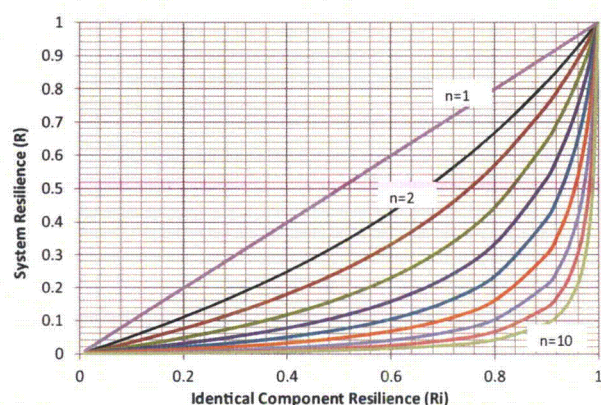


Fig. 4. System resilience aggregate based on two identical resilience components.

Table II. Systems and Performance Measurements

Systems	Performance	Units
Buildings	Space availability	Area per day
Other structures:	Throughput traffic	Count per day
Highway bridges		
Facilities: Water treatment plants	Water production capacity	Volume per day
Infrastructure: Water delivery	Water available for consumption	Volume
Network: Electric power distribution	Power delivered	Power per day
Communities	Economic output	Dollars
Communities	Quality of life (consumption)	Dollars

The units of performance at the system level vary depending on the system type and the objectives of the analysis. Table II shows examples of performance types and units of measurement for selected systems for demonstration purposes.

## 5. ECONOMIC VALUATION AND BENEFIT-COST ANALYSIS

Improving the resiliency of a system to meet target levels requires the examination of system enhancement alternatives in economic terms, within a decision-making framework. Relevant decision analysis methods would typically require the examination of resilience based on its valuation by society at large. Methods for the total economic valuation of resilience are needed, and should satisfy the essential requirement of consistency with respect to the definition and metrics of resilience. Concepts from

risk analysis and management can be used for this purpose.<sup>(58)</sup>

Valuation can be approached broadly from philosophy and particularly from ethics to make distinctions among values such as (1) instrumental and intrinsic values, (2) anthropocentric and biocentric (or ecocentric) values, (3) existence value, and (4) utilitarian and deontological values.<sup>(59,60)</sup> The focus of this section is on economic valuation; however, it is necessary to introduce and discuss these distinctions. An ecosystem is used as an example to discuss these distinctions.

For an ecosystem, the instrumental value is derived from its role as a means toward an end other than itself, i.e., its value is derived from its usefulness in achieving a goal. In contrast, intrinsic value, also called noninstrumental value, is its existence independently of any such contribution defined by usefulness. For example, if an animal population provides a source of food for either humans or other species, it has instrumental value that stems from its contribution or usefulness to the goal of sustaining the consuming population. If it continues to have value even if it were no longer useful to these populations, e.g., if an alternative, preferred food source were discovered, such a remaining value would be its intrinsic value. For example, a national park, such as the Grand Canyon, has an intrinsic value component that exists unrelated or independent of direct or indirect use by humans for recreation or investigation. Such an intrinsic value can also stem from cultural sources, such as monuments and burial grounds.<sup>(60)</sup>

An anthropocentric value system considers humankind as the central focus or final goal of the universe, human beings as the only thing with intrinsic value, and the instrumental value of everything else is derived from its usefulness in meeting human goals. On the other hand, a biocentric value system, i.e., nonanthropocentric, assigns intrinsic value to all individual living systems, including but not limited to humans, and assumes that all living systems have value even if their usefulness to human beings cannot be determined or can be harmful to human beings.

Existence value reflects the desire of human beings to preserve and ensure the continued existence of certain species or environments to provide for humankind welfare, making it an anthropocentric and utilitarian concept of value and within the domain of instrumental value system. Therefore, utilitarian values are instrumental in that they are viewed as a means toward the end result of increased human

welfare as defined by human preferences, without any value judgment about these preferences. The value of particular species or environments comes from generating welfare to human beings, rather than from the intrinsic value of these nonhuman species. This definition permits the potential for substitution or replacement of this source of welfare with an alternative source, i.e., the possibility of a welfare-neutral tradeoff between continued existence of species or environments and other things that also provide the same utility.

The deontological value system is based on an ethical doctrine for assigning worth for an action by its conformity to some binding rule rather than by its consequences. In this case, a deontological value system implies a set of rights that include the right of existence. Something with intrinsic value is irreplaceable and its loss cannot be offset by having more of something else. For example, the death of person is a loss of an intrinsic value because it cannot be offset or compensated by that person having more of something else. The contentious issue is whether this concept should be extended to nonhuman species, for example, animals, either individual animals or species, or all biological creatures, i.e., all plant and animal life, collectively called the biota. In the context of ecosystem valuation, the modern notion of intrinsic value extends the rights beyond human beings. On the other hand, utilitarian values are based on providing utilities.

In this article, the use of a valuation approach with the following characteristics is proposed:

- Anthropocentric in nature based on utilitarian principles.
- Consideration of all instrumental values, including existence value.
- Its utilitarian basis to permit the potential for substitution among different sources of value that contribute to human welfare.
- Individuals' preferences or marginal willingness to trade one good or service for another that can be influenced by culture, income level, and information, making it time and context specific
- Societal values as the aggregation of individual values.

This approach is consistent with NRC<sup>(60)</sup> and does not capture nonanthropocentric values, e.g., biocentric values and intrinsic values as related to rights. In some decisions, including environmental policy and law, biocentric intrinsic values should be

included in agreement with previous practices, e.g., the Endangered Species Act of 1973.

A total economic value (TEV) framework can be constructed based on the above characteristics and using individual preferences and values. The TEV framework is necessary to ensure that all components of value are recognized and included while avoiding double counting of values.<sup>(61,62)</sup>

Economic valuation, as commonly used in decision analysis, is defined as the worth of a good or service as determined by the market. Economists have dealt with this concept initially by estimating the value of a good to an individual alone, and then extend it broadly as it relates to markets for exchange between buyers and sellers for wealth maximization.

Traditionally, the value of a good or service is linked to its price in an open and competitive market determined primarily by the demand relative to supply. Therefore, goods, property, assets, safety of people, service, etc. are treated as commodities, and if there is no market to set the price of a commodity then it has no economic value. Therefore, the value refers to the market worth of a commodity, which is determined by the equilibrium at which two commodities are exchanged. The limitation herein is in its inability to set a value to things that are not exchanged in markets.

In the labor theory of value, a good or service is associated with the amount of discomfort or labor saved through the consumption or use of it. According to this theory, the exchange value is recognized without recognizing its equivalence to an economic value, i.e., price and value are considered as two different concepts. Accordingly, a value is determined based on the exchange price, which does not necessarily represent its true economic value.

An economic measure of the value of a good or the benefit from a service can be defined as the maximum amount a person is willing to pay for this good or service. The concept of willingness to pay (WTP) is central to economic valuation. An alternate measure is the willingness to accept (WTA) of an amount by the person to forgo taking possession of the good or receiving the service. WTP and WTA produce amounts that are expected to be close; however, generally WTA generated amounts are greater than WTP generated amounts due primarily to income levels and affordability factors.

The economic concept of value, including its exchange value, can be criticized as being stripped from moral and ethical considerations. For example, having an exchange value for a good or a service that

is harmful in nature, e.g., markets of illegal drugs or gambling or prostitution or weaponry, have value in some open markets, in some underground markets, and no value in others. Contrarily, not having an exchange value for a good or a service that is good in nature, e.g., volunteer work, might not have a market value but this does not necessarily make it without any value. Accounting for such moral and ethical considerations in economic models can be contentious, and commonly such goods or services are ignored. To perform tradeoff analysis, resilience should be treated in these economic terms.

The valuation of resilience can be based on the savings in potential direct and indirect losses, and cost of recovery as illustrated in Fig. 3. Alternatives for enhancing resilience that can reduce these potential losses can be analyzed using models for benefit-cost analysis, where the benefit ( $B$ ) is the potential savings in losses and recovery costs because of the implementation of an alternative and the cost ( $C$ ) is the cost of the alternative. The benefit and costs are treated as random variables.<sup>(58)</sup> Assuming  $B$  and  $C$  to be normally distributed, a benefit-cost index ( $\beta_{B/C}$ ) can be defined as follows:

$$\beta_{B/C} = \frac{\mu_B - \mu_C}{\sqrt{\sigma_B^2 + \sigma_C^2}}, \quad (31)$$

where  $\mu$  and  $\sigma$  are the mean and standard deviation. The probability of cost exceeding benefit can be computed as:

$$P_{f,B/C} = P(C > B) = 1 - \Phi(\beta), \quad (32)$$

where  $\Phi$  is the standard normal cumulative distribution function. In the case of lognormally distributed  $B$  and  $C$ , the benefit-cost index ( $\beta_{B/C}$ ) can be computed as:

$$\beta_{B/C} = \frac{\ln\left(\frac{\mu_B}{\mu_C} \sqrt{\frac{\delta_C^2 + 1}{\delta_B^2 + 1}}\right)}{\sqrt{\ln[(\delta_B^2 + 1)(\delta_C^2 + 1)]}}. \quad (33)$$

where  $\delta$  is the coefficient of variation. In the case of mixed distributions or cases involving basic random variables of  $B$  and  $C$ , other reliability methods can be used as described by Ayyub.<sup>(58)</sup>

## 6. CONCLUSIONS

Enhancing the resilience of a system, including buildings, infrastructure, network, and communities, could lead to massive savings through risk reduction and expeditious recovery. In this article, a resilience

definition is provided that meets a set of requirements with clear relationships to metrics of the relevant abstract notions of reliability and risk. Those metrics also meet logically consistent requirements drawn from measure theory, and provide a sound basis for the development of effective decision-making tools for multihazard environments. The proposed metrics provide a strong basis for the rational management of such reduction and recovery facilitated by an appropriate definition of resilience and associated metrics. Also, the article provides a framework for the valuation of resilience by society at large, methods for benefit-cost analysis based on concepts from risk analysis and management. Although resilience valuation is in its infancy and additional work is necessary along with case studies, this article offers a basis for such efforts.

## ACKNOWLEDGMENTS

The author would like to acknowledge the discussion and insights provided by the University of Delaware Professor Nii Attoh-Okine, and Dr. Emil Simiu of the National Institute of Standards and Technology (NIST). Initial versions of this work were presented at a panel discussion on resilience engineering at the sixth Congress on Forensic Engineering, San Francisco, CA, on November 1, 2012, and NIST's Engineering Laboratory on December 19, 2012, and the article benefited from the comments received. On April 11, 2013, the University of Maryland, the National Academy of Engineering and the State of Maryland, in cooperation with the National Science Foundation, Virginia Tech, the University of Delaware, the University of the District of Columbia, and the University of Virginia hosted a by-invitation symposium to examine the state of knowledge with respect to the development of infrastructure, regional, and community resilience to natural and human-caused disasters, and to discuss actions that might be taken by governments, academe, and the public and private sectors to achieve resilience. Symposium participants represented federal, state, and local governments from Delaware, Maryland, Virginia, and the District of Columbia, and businesses and universities with interests and expertise in infrastructure and community resilience. The author would also like to thank his co-chair of this symposium, Professor Gerry Galloway of the University of Maryland, and the participants at this symposium for comments received based on his presentation of some aspects of this article.

## APPENDIX A: SELECTED URBAN AREAS AND HAZARDS

**Table A1.** Selected Urban Areas, Their Respective Population Sizes, Location Attributes, and Hazards as a Summary of the Data Reported by UNISDR<sup>(1)</sup>

Urban Area and Population	Location Attributes	Hazards
Santa Fe, Argentina 400,000	The flood plain of the Parana and Salada Rivers	Flooding and intense rainfall
Cairns, Australia 164,356	A coastal town in the wet tropics, northern Queensland	Cyclones, flooding, storm surge, and tsunamis
Tyrol Province, Austria 712,077	Western Austria, consisting of nine districts	Flooding and landslides
Thimphu, Bhutan 79,185	Landlocked state in South Asia, east of the Himalayas	Prone to earthquakes, landslides, cyclones, and flooding
North Vancouver, Canada 82,000	Coastal municipality in southwest British Columbia on the mountainsides	Landslides, flooding, and wildfire
Valle de Itata, Chile 80,762	Northwest of the bio region of Chile	Flooding, extreme wind and rain, wildfire, and earthquakes
Baofeng, China 498,000	Henan Province	Drought, flooding, wind, snowstorms, and earthquakes
Siquirres, Costa Rica 59,000	Limon Province, in the plane of the Talamanca mountains	Flooding, landslides
Copenhagen, Denmark 1,213,822	Eastern shore of the island of Zealand, partly on the island of Amager and on a number of natural and artificial islets	Flooding and landslides
Dubai, United Arab Emirates 2,200,000	Southeast of the Persian Gulf on the Arabian Peninsula	Drought, heat waves, sand storms
Quito, Ecuador 2,197,698	Northeast of the country at 2,800 m above sea level	Volcanic hazards, earthquakes, landslides, and flooding
Santa Tecla, El Salvador 200,000	Part of the metropolitan area of the country's capital, San Salvador	Earthquakes, landslide, and flooding risks
Bonn, Germany 300,000	About 25 km south of Cologne on the river Rhine	Flooding from the Rhine and recently extreme heat waves during summer
Bhubaneswar, India 1,000,000	In the Khurda District, Orissa	Earthquakes, flooding, cyclones, heat waves
Pune, India 5,000,000	At the confluence of three rivers: the Mutha, Mula, and Pavana at 560 m above sea level	Flooding
Mumbai, India 19,700,000	A coastal megacity built on what used to be a group of seven islands, many areas are only 5 m above low tide level	Coastal flooding
Makassar, Indonesia 1,400,000	Southwest coast of the island of Sulawesi, facing the Makassar Strait	Tsunamis and flooding
Jakarta, Indonesia 9,800,000	Situated in the northwest coast of Java, at the mouth of the Ciliwung River on Jakarta Bay, which is an inlet of the Java Sea	Earthquakes and flooding
Mashhad, Iran 2,420,000	850 km east of Tehran at 950 m elevation in the valley of the Kashaf River between two mountain ranges	Flooding, cyclones, earthquakes, and drought
Venice, Italy 263,996	On a group of 118 islands in the Venice Lagoon	Flooding as a result of low (and falling) elevation
Ancona, Italy 100,000	Adriatic coast, south of Venice	Most significant hazard is landslides
Saijo, Japan 114,625	Mountainous terrain in Ehime Prefecture	Extreme rainfall, typhoons, mudslides, landslides, and flooding
Aqaba, Jordan 108,500	Coastal city situated at the northeastern tip of the Red Sea	Drought, heat waves
Narok, Kenya 60,000	Southern side of the Rift Valley and has varied topography, with a predominantly agricultural economy base	Flooding and drought

(Continued)



Table A1. Continued

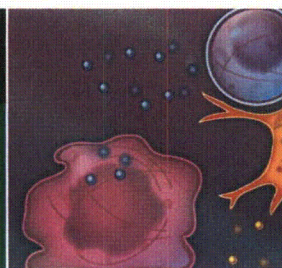
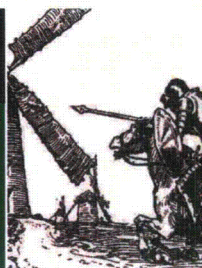
Urban Area and Population	Location Attributes	Hazards
Kisumu, Kenya 200,000	Port city in western Kenya	Flooding
Beirut, Lebanon 1,500,000	On a peninsula at the midpoint of Lebanon's Mediterranean coast	Earthquakes, flooding, wildfires, and landslides
Kathmandu, Nepal 1,000,000	Situated in central Nepal bowl-shaped valley between four major mountains, at high elevation	Earthquakes and landslides
Telica, Quezalguaque and Larreynaga-Malpasillo, Nicaragua 71,000	Basin of the Leon	Volcanic, seismic, hurricanes, flooding, epidemics, environmental risks linked to gold mining, and monoagriculture
Pakistan 30 cities	Varies	Landslides, flooding, storms, cyclones, earthquake, drought, fire, epidemics, riots, and conflicts
Chincha, Pisco, Cañete, and Ica, Peru 536,000	Peru's Pacific coast	Earthquakes and flooding
Albay, Philippines 1,000,000	Albay Province	Typhoons, storm surge, volcanoes, landslides, tsunamis, and flooding
Amadora, Portugal 175,135	Northwest of the Lisbon metropolitan area	Earthquake, flood, heat wave, land slide, technological disasters
Makati, Philippines 510,383 to 3,700,000 (daytime)	West valley fault system	Earthquakes, flooding, and landslides
San Francisco, Philippines 48,834	Small island within the Camotes Island group and part of the province of Cebu	Flooding and landslide
Quezon City, Philippines 1,700,000	Largest and most populous	Flooding, earthquakes, fire, and epidemic
Cape Town, South Africa 3,700,000	Coastal area	Storm surge, heat wave, flooding, fires, and drought
Johannesburg, South Africa 3,500,000	In the eastern plateau area of South Africa known as the Highveld, at an elevation of 1,753 m	Intense rainfall and flooding
Overstrand, South Africa 76,000	Situated in the Western Cape Province of South Africa	Drought, flooding, and fire
Batticaloa, Sri Lanka 515,857	Situated in the East Province, and the administrative capital of the Batticaloa	Civil unrest in the area (ended in 2009), Indian Ocean tsunami
Colombo, Sri Lanka 647,100	On the west coast of the island and adjacent to Sri Jayawardenapura Kotte	Flooding, typhoons, earthquakes, landslides, fires, and tsunami
Moshi, Tanzania 150,000	A market hub town in northeastern Tanzania at the foot of Mount Kilimanjaro	Drought and flooding
Bangkok, Thailand 9,700,000	Coastal in Southeast Asia	Flooding
Istanbul, Turkey 13,000,000	In northwestern Turkey within the Marmara Region on a total area of 5,343 km <sup>2</sup>	Earthquakes
San Francisco, California, USA 805,235	West coast of the United States, at the tip of the San Francisco Peninsula including significant stretches of the Pacific Ocean	Wild fire, tsunami, landslide, heat wave, flooding, earthquake, drought
Chacao, Venezuela 71,000	Mideastern portion of the Caracas Valley, north of the Guaire River	Earthquake and flooding

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## LETTERS

edited by Jennifer Sills

## Financing Nuclear Liability

IN LIGHT OF THE 2011 FUKUSHIMA DISASTER, recent discussion has focused on finding the best nuclear storage options (1) and maximizing the oversight power of global institutions (2). However, even with the best risk-informed planning and guidelines, accidents at nuclear power plants (NPPs) could still occur (3). The 1990 report from a U.S. presidential commission estimates that the catastrophic nuclear accident probability in the United States (about 100 nuclear reactors) in the remaining lifetime of 40 years per plant is one accident in 250 thousand years (4). There are currently 438 NPP units worldwide (predicted to increase to 500) (5); extrapolating the U.S. figure with some uncertainty considerations to obtain the worldwide average time to an accident yields an estimate of one accident in 5 thousand to 50 thousand years for remaining lifetimes. Given the possibility of another accident, in addition to strengthening safety measures, we should develop dependable liability coverage that can be tapped in an emergency.

In 1957, the United States enacted the Price-Anderson nuclear liability regime for managing the risk of nuclear accidents. The legislation aimed to establish a mechanism for compensating the public for losses and to encourage the private development of nuclear power. With 104 operating reactors, the United States has a total of \$11.975 billion in coverage (as of 2011) (6) before congressional authorization for additional funding. The U.S. Department of Energy provides similar liability coverage for its activities.

Internationally, three conventions are available with similar goals (7): the 1968 Convention on Third Party Liability in the Field of Nuclear Energy, called the Paris Convention; the 1977 Vienna Convention on Civil Liability for Nuclear Damage; and the Convention on Supplementary Compensation for Nuclear Damage (CSC), which will enter into force when ratified by at least five countries with at least 400 GW of installed nuclear capacity.

Estimates of the damage due to a catastrophic accident range from \$110 billion to as much as \$7 trillion (8). Accidents do not recognize political borders and could lead to disputes.

Achieving adequate nuclear liability coverage requires an efficient and cost-effective system with adequate funds to pay damages. Starting with the premise of a worldwide need to mitigate the consequences of one catastrophic nuclear accident, each NPP unit can be assessed for a cost share secured by international legal instruments, subject to adjustments based on, among other metrics,

a safety rating system to create the incentive to reduce accident rates. To succeed, financing will be essential, perhaps via securities and hedge funds.

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## The Future of Coral Reefs

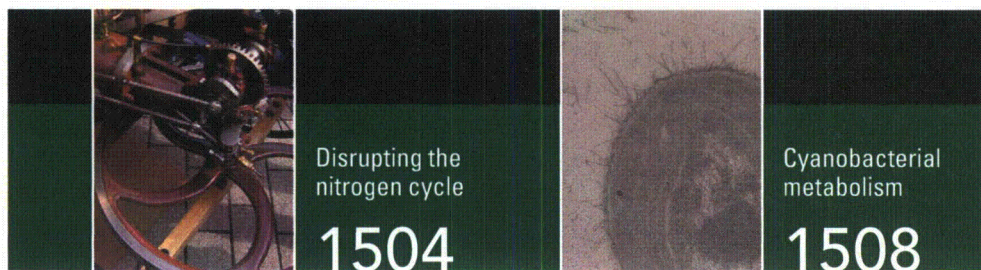
IN THEIR REVIEW "PROJECTING CORAL REEF futures under global warming and ocean acidification" (22 July, p. 418), J. M. Pandolfi *et al.* argue that the threat of climate change for corals has been exaggerated by pointing to variability in coral heat tolerance, adaptation potential, and the recent fossil record. In doing so, they fail to consider the full range of model assumptions and the precision of the fossil record.

Under the section "Projecting coral reef futures," Pandolfi *et al.* predict that adaptation of the dinoflagellate symbionts that provide the host with energy is likely to help coral reefs maintain their structure in the near future. The argument is based on an untested model of symbiont population dynam-

## Letters to the Editor

Letters (~300 words) discuss material published in *Science* in the past 3 months or matters of general interest. Letters are not acknowledged upon receipt. Whether published in full or in part, Letters are subject to editing for clarity and space. Letters submitted, published, or posted elsewhere, in print or online, will be disqualified. To submit a Letter, go to [www.submit2science.org](http://www.submit2science.org).





ics (1). This model incorporates tradeoffs between symbionts' thermal tolerance and symbiont population growth, but it ignores tradeoffs that involve essential properties of coral reefs (such as documented reductions in calcification of corals harboring thermally tolerant symbionts). For symbiont adaptation to ensure the future of coral reefs, they would have to simultaneously evolve the following characteristics: (i) thermal tolerance to the synergistic effects of increased atmospheric  $pCO_2$  on sea water; (ii) capability to maintain metabolic exchange in energy and nutrients between themselves and their coral hosts; and (iii) compatibility across a broad range of available coral hosts and environments. Each of these adaptations is unlikely on its own, and there is little evidence that any have occurred to date (2), making the probability of the simultaneous evolution of all these traits in the near future highly improbable. Even if these adaptations were to evolve simultaneously, coral reef structure would only be sustained if the intrinsic capability of corals to maintain high rates of calcification, above the rates of erosion, were preserved.

Despite acknowledging the absence of analogous periods that match the current rate of change in ocean acidity and temperature, Pandolfi *et al.* draw on the fossil record for insights into past coral reef response to climate change. However, the precision of these records over ecologically relevant time scales (decadal to centennial) is inherently problematic because of the low resolution of radiocarbon aging and the uncertainty associated with the order in which reefs devel-

oped and the dating results (3, 4). In the example presented by Pandolfi *et al.*, proxy records of temperature from sediment cores were sampled on average every  $133 \pm 7$  years, whereas radiocarbon ages were sampled every  $1321 \pm 329$  years; accurate comparison of rates of change that differ over decadal to centennial scales is consequently highly problematic. Conversely, the proxy temperature records from the same core record (5) indicate remarkably stable conditions during the past 10,000 years ( $25.9^\circ$  to  $27.7^\circ C$ ). Consequently, most paleoecological perspectives are limited in their usefulness for interpreting the rapid trends and impacts that are occurring today.

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#### Response

HOEGH-GULDBERG *ET AL.* ASSERT THAT EVOLUTIONARY responses to climate change in corals are highly improbable in the near future, citing tradeoffs between tolerance to warming and acidification, and two factors

related to the integrity of the coral-symbiont partnership. In support, they cite an earlier paper making similar claims (1), but this reference presents no empirical or theoretical evidence for this thesis.

In fact, the hypothesis that adaptation cannot occur over decadal time scales has been shown repeatedly to be incorrect: Numerous and complex physiological, metabolic, and morphological changes can occur rapidly and repeatedly among independently evolving lineages (2–5). Specifically, tradeoffs are ubiquitous in nature, and, although they influence the rate and direction of evolution (as emphasized in our Review), they do not prevent any evolution from happening. Moreover, contrary to Hoegh-Guldberg *et al.*'s assertions that characteristics of endosymbiosis will impede adaptation in corals, studies of other organisms have found that endosymbionts and hosts, if anything, evolve more rapidly than their free-living counterparts (6, 7).

In our projections section, we discuss Baskett *et al.* (8) because it is the only study that attempts to rigorously determine the potential effects of thermal adaptation on coral cover. Moreover, Baskett *et al.* (8) explicitly include feedbacks of symbiont thermal tolerance on coral colony growth. More broadly, the fact that the model in (8) has important limitations does not justify eschewing attempts to model evolutionary dynamics entirely.

Our Review presented fossil evidence for varying sensitivity of coral reefs to climate change over multiple temporal scales. Hoegh-Guldberg *et al.* argue that the geological record lacks resolution to detect such changes, such as during the well-known and accepted periods of Abrupt Climate Change (ACC) during the early to mid-Holocene (9). However, the decadal- to centennial-scale chronology and paleoclimate from the Cariaco Basin study (10) shows substantial fidelity to high-precision Greenland ice-core records and adheres to all of the best practices recommended in the relevant paper cited by Hoegh-Guldberg *et al.* (11). The Cariaco Basin sediments record continuous annual episodes of sedimentation that generally lack the bioturbation and time-averaging typical of reef deposits, so the concerns with using radiometric dating to study the fine-scale chronology of reef accretion cited by Hoegh-Guldberg *et al.* (12) are irrelevant.

Our Review is emphatic that "coral reefs are indeed threatened by climate change" (Pandolfi *et al.*). However, we believe that the best way for coral reef scientists to inform policy responses to this threat is to do our best to comprehensively and rigorously account for all the processes likely to deter-



mine reefs' responses to climate change—physiological, ecological, biogeographical, and evolutionary.

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#### CORRECTIONS AND CLARIFICATIONS

**News & Analysis:** "8.7 million: A new estimate for all the complex species on Earth" by D. Strain (26 August, p. 1083). The article noted that Nigel Stork of Griffith University in Queensland, Australia, and colleagues published a paper estimating that there are some 3.7 million arthropod species on Earth. This figure was based on a calculation error and was subsequently revised in a corrigendum. Their median estimate, depending on the model, was revised to 6.1 million or 7.8 million species.

**Technical Comments:** Response to Comments on "Drought-induced reduction in global terrestrial net primary production from 2000 through 2009" by M. Zhao and S. W. Running (26 August, p. 1093; [www.sciencemag.org/cgi/content/full/333/6046/1093-e](http://www.sciencemag.org/cgi/content/full/333/6046/1093-e)). The sentence "the reduction of NPP in the 2005 drought of the Amazon is 5.56% of the mean NPP from 2000 to 2004" was incorrect. The reduction was 9.28%, not 5.56%.

**Research Articles:** "Local and long-range reciprocal regulation of cAMP and cGMP in axon/dendrite formation" by M. Shelly *et al.* (29 January 2010, p. 547). The paper included a misleading description of the method of FRET imaging. The last sentence on p. 547 (beginning eight lines from the bottom of the page) should read, "Bath application of the membrane-permeant cAMP analog Sp-8-Br-cAMPS (20  $\mu$ M) or the AC activator forskolin (20  $\mu$ M) resulted in a

global increase of cAMP and PKA signals in ICUE- and AKAR-expressing cells, respectively, as measured by the increase in the ratio of yellow fluorescent protein (YFP) to cyan fluorescent protein (CFP) fluorescence at the neurite (Fig. 2, A, B, D, E, and G) for AKAR, and the ratio of CFP to YFP fluorescence for ICUE." In addition, there was a mistake in the name of a FRET probe used in Fig. 2B and Fig. 4. The label on the left in Fig. 2B should be "AKAR (PKA)," not "ICUE (cAMP)." In the Fig. 2 legend, the first sentence describing panels B and C should read, "FRET signals observed at the neurite tip of 16-hours neurons expressing AKAR or cGEC-DE5." In the Fig. 4 legend, the first sentence describing panel A should begin, "YFP fluorescence and FRET signals for PKA-activity in an AKAR-expressing hippocampal neuron at 16 hours...."

**Reports:** "Label-free, single-molecule detection with optical microcavities" by A. M. Armani *et al.* (10 August 2007, p. 783). The authors reported the use of optical microresonators immersed in aqueous solutions and functionalized with antibodies to detect small concentrations of the analytes recognized by the antibodies. The Report presented discontinuities in the resonant response, which the authors took to represent the responses from binding individual analyte molecules. The amplitude of these discontinuities was too large to be caused by the direct effect of the analyte binding; to explain their large size, the authors proposed a thermo-optic effect, in which local heating of the resonator surface from light-analyte interaction amplified the effects of analyte binding. However, as noted by Arnold *et al.* [*Optics Express* **18**, 281 (2010)], the thermo-optic effect cannot account for the size of the discontinuities. The origin of the large wavelength discontinuities is being investigated by several independent efforts.

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