I T H E A

International Journal

INFORMATION THEORIES & APPLICATIONS

2009 Volume 16 Number 1

International Journal
INFORMATION THEORIES & APPLICATIONS
Volume 16 / 2009, Number 1

IJ ITA is official publisher of the scientific papers of the members of the ITHEA® International Scientific Society

IJ ITA welcomes scientific papers connected with any information theory or its application.
IJ ITA rules for preparing the manuscripts are compulsory.
The **rules for the papers** for IJ ITA as well as the **subscription fees** are given on *www.ithea.org* .
The camera-ready copy of the paper should be received by http://ij.ithea.org.
Responsibility for papers published in IJ ITA belongs to authors.
General Sponsor of IJ ITA is the **Consortium FOI Bulgaria** (www.foibg.com).

International Journal "INFORMATION THEORIES & APPLICATIONS" Vol.16, Number 1, 2009

Printed in Bulgaria

Edited by the **Institute of Information Theories and Applications FOI ITHEA®**, Bulgaria,
in collaboration with the V.M.Glushkov Institute of Cybernetics of NAS, Ukraine,
and the Institute of Mathematics and Informatics, BAS, Bulgaria.

Publisher: **ITHEA®**
Sofia, 1000, P.O.B. 775, Bulgaria. www.ithea.org, e-mail: info@foibg.com

ISSN 1310-0513 (printed) **ISSN 1313-0463 (online)** **ISSN 1313-0498 (CD/DVD)**

APPLICATION OF INFORMATION THEORIES TO SAFETY OF NUCLEAR POWER PLANTS

Elena Ilina

Abstract: *To this date, strategies aiming at a safe operation of nuclear power plants focused mainly on the prevention of technological breakdowns and, more recently, on the human attitudes and behaviors. New incidents and challenges to safety, however, motivated the nuclear community to look for a new safety approach. The solution became a strong focus on knowledge management and associated theories and sciences as information theories, artificial intelligence, informatics, etc. In all of these, the fundamental role is played by a category of information. This work reviews a number of information interpretations and theories, among which of great relevance are those capturing the fundamental role information plays as a mean to exercise control on the state of a system, those analyzing information communication between agents involved in safety-related activities, and, finally, those which explore the link between information and the limits of our knowledge. Quantitative measures of information content and value are introduced. Completeness, accuracy, and clarity are presented as attributes of information acquired by the receiver. To conclude, suggestions are offered on how to use interpretations and mathematical tools developed within the information theories to maintain and improve safety of nuclear power plants.*

Introduction

It is widely recognized that safety of nuclear power plants is a problem of great relevance for society. If it is not properly managed, the increase in power and complexity of the plants can lead to a catastrophic release of energy and dangerous materials and pollute the environment. To prevent this to happen, the nuclear community always put significant efforts into finding new ways to improve safety.

As a matter of fact, the nuclear accidents in Chernobyl and in Three Mile Island lead to initiation of extensive research activities within the nuclear society. A consensus quickly emerged that the breakdowns could not be explained exclusively from the perspective of technological failures but indeed required new, holistic views on safety. A solution seemed to be a strong focus on human attitudes and behaviors. The concept of safety culture, first introduced by the International Atomic Energy Agency (IAEA), rapidly became increasingly popular [1].

These efforts notwithstanding, incidents continued to occur indicating that important aspects of plants' safety remain unsolved. In fact,

- In 2000, at the Davis Besse nuclear power plant, an extensive material degradation was detected in an area around a nozzle of the reactor pressure vessel. Commentators have suggested that a minor additional propagation of the crack would have lead to the rupture of the pressure vessel. Obviously, the plant owners did not possess accurate and updated information of current condition of the reactor pressure vessel [2].
- In 2006, at the Forsmark nuclear power plant, a sudden disruption from an external power supply lead to the failure of the house turbine operation, the internal battery secured power supply, and of 2 of the 4 emergency diesel generators. Luckily, the 2 diesel generators that started were able to supply sufficient power to the cooling system of the reactor core, and, thus, were able to maintain the whole system in functioning conditions. This dangerous incident has resulted from errors in modifications of old components, caused by insufficient understanding of the consequences of introduced changes [3].

These examples indicated that the established safety frameworks were in need of further improvement if the occurrence of severe accidents is to be prevented. Recognizing this need of further improvement, the IAEA has recently declared a strong focus on knowledge management and built a new knowledge management group for assisting member states in associated questions [4, 5].

However, the scope of knowledge management is known to be broad and overlap, for instance, information management, information theories, artificial intelligence, systems theories, synergetic, informatics, etc. What all of these theories and sciences have in common is the information orientation. With other words, the category of information plays the fundamental role here whilst other categories as data, knowledge, intelligence, etc. can be derived from the category of information. Therefore, a review of main information theories and interpretations seems to be a reasonable start.

Review of main information theories and interpretations

The concept of information acquires meaning only with respect to the context within which it is used. Specifically, different definitions of information can be provided depending on whether information is:

1. Used as a mean for regulation and control.
2. *Transferred* (communication).
3. Or *generated* (acquisition).

(1) Information as a tool for regulating (controlling, steering) activities was emphasized first within the science of cybernetics. This perspective is often denoted as *functional* (also known as cybernetic, external, active, or relation-based). Norbert Wiener, who may be considered as the father of cybernetics, claimed that all goal-oriented actions of human beings are based on information [6]. An opposite, *structural* (also known as attributive, or internal) perspective believes that information mirrors an objectively existing diversity in the reality [7,8,9]. The structural perspective emphasizes that information is an overall property of the reality from its simplest forms to the human brain or complex engineered facilities.

That is to say, the concept of information is the bi-polar concept that arrives into two shapes: a functional perspective and a structural perspective. Both perspectives are necessary for an effective and rigorous management of safety. From the functional point of view, all decisions on safety must to be based on accurate and updated information. From the structural point of view, safety of an engineered facility is determined by its structural organization, i.e. its components, subsystems, systems, and connections between them.

A measure of regulation of complex systems was proposed by another prominent figure in the field of cybernetics, Ross Ashby, who stated that “only variety can destroy variety” [8,9]. The meaning of this statement, which is also known as the *Law of requisite variety*, is that the survival of a system depends on the regulator’s ability to master the diversity of external impacts and to block the flow of information. When *essential variables* start going outside the acceptable range, the regulator must take actions until the essential variables are stabilized and the safe condition is reached. A notion of essential variables (also known as *order parameters* within the science of synergetic) denotes those variables that govern the entire system. Ashby’s view of information as the variety agrees with the *structural* perspective on information.

Information as an instruction (algorithm, program) is emphasized within a non-probabilistic approach, also known as *algorithmic information theory*, developed by Andrej Kolmogorov [10]. Kolmogorov considers information as an *instruction* that has to be executed in order to transform a system from state *A* into state *B*. The larger the difference between the states *A* and *B*, the longer (more complex) the transformation instruction.

Although an exact mathematical measure of Kolmogorov’s complexity has not yet been provided by the community of mathematicians, the idea itself allows fruitful discussions on how to manage instructional information, which is contained in norms, standards, instructions, and other types of documentation. Another insight that follows is that successful accomplishment of the goal is dependent on the quality in a program, which describes what measures need to be taken to achieve the goal.

(2) Information is regarded *as a transferred message* within a *communication model*, which was proposed by Claude Shannon [11]. This model includes at least the following elements: a source (a sender), a channel, and a receiver. The channel is always *noisy*, and noise leads to the loss or misinterpretation of information. Ashby [8,9] was first to point out that the distinction between message and noise depends on what the receiver regards as important. The receiver tends to ignore information that does not promote the achievement of his *goals and objectives.* Furthermore, the receiver cannot understand information that considerably exceeds his *background knowledge*. For this reason, all concepts involving information communication should be formulated accounting first and foremost the information acquired by the receiver, while the information sent by the source should play a lesser role, as pointed out by David Harrah in his *model of rational communication* [12,13].

Illustrativeness of Shannon's and Harrah's communication models helps to understand the role of individual objectives, values and knowledge for information perception and making choices. It is therefore increasingly important for top managers to clarify for all the employees the overall goal and values of the entire organisation. In case of conflicts between the subjective objectives of the individual employees and the overall goal and values of the entire organization, the latter have precedence.

As mentioned above, Shannon's *communication model* [11], considers information as a *message* that is transferred from a source to a receiver via a channel. The *information content* of that message was defined by Hartley [14], Shannon [11], and Wiener [6] as the *uncertainty* that can be eliminated upon reception of the message. Ralph Hartley [13] appears to be first with providing an explicit mathematical way to determine the information content of an event in the simplest case in which an event has *N* possible outcomes with equal probability of occurrence $p = (1/N)$:

$$I = -\log p = \log N$$

Note that according to this interpretation, it is possible to speak about information only when *several alternatives are available*. For situations of certainty (determinism) a number of available alternatives shrinks to 1 and information content shrinks to 0. For situation of complete randomness all alternatives have equal probability and information content goes to maximum. The smaller probability of a chosen alternative to happen, the larger the uncertainty it removes and thus the larger amount of information it *generates*.

The great advance of information theories lies in highlighting relationships between information, uncertainty, presence of alternatives, choice, and, in the end, decision making. A decision, i.e. a choice of one among available alternatives, may need to be made although the available information is insufficient. Each choice is thus associated with a risk of making wrong decision and resulting unwanted consequences. Looking from that perspective, insufficient information can be interpreted in terms of the existence of several alternatives to act. In case of decision making by a group of people, a lack of consensus indicates that more information is needed in order to clarify the best choice.

Hartley's equation was limited to the simplest case of complete randomness and later Shannon proposed a more general equation [11]. The following mathematical expression gives the average information which is available when the knowledge about an alternative is expressed by the probabilities p_i. Information content is then measured by averaging over *n* groups:

$$I = -\sum_{i=1}^{n} p_i \log p_i$$

This mathematical expression is identical to that of entropy, as it is defined in statistical mechanics, and plays a fundamental role in several applications of information theories. Of interest to this review, Jaynes [15] suggested the information content as a fundamental quantity from which the probability values, p_i, weighting the possible outcomes of that event, could be recovered. To this end, the values p_i must be chosen so that information content has a maximum constrained by the available knowledge about a given event. This procedure is known as *a principle of maximum entropy*.

Prescription that follows from the principle of maximum entropy is to use the probability distribution, which maximizes the information content with respect to the available knowledge. This procedure allows making the least biased conclusions under situations, when available information is not sufficient for making certain conclusions. Figuratively speaking, one needs to choose a broad probability distribution that comprises all known events.

(3) Information generation is addressed by a *dynamical information theory* [16], which has recently being developed within the frame of science of synergetic. A central notion of *information value* estimates to what extend the information helps to accomplish *goals and objectives* of the user.

Information without a *meaning* has certainly no *value*. Therefore, it is in many cases convenient to study information value and meaning at the same time, using semantic-pragmatic information theories. The fundamental works of Bar-Hillel and Carnap [17] suggested using logic probability to measure semantic information. Logic probability describes to which degree a hypothesis has been confirmed and, from the practical point of view, resembles probabilistic equations of Shannon and Wiener.

The equation for estimate of information value, *V,* was proposed in an early work of Alexander Harkevich [18]:

$$V = \log \frac{p_1}{p_0} = \log p_1 - \log p_0$$

where p_0 and p_1 - are probabilities of goal accomplishment before (a priori) and after (a posteriori) the information has been acquired.

Disinformation leads to decrease in probability of goal accomplishment and information value becomes negative. In the opposite situation, when the goal has actually been accomplished, the value of information becomes equal maximal information content for the system:

$$V = \log \frac{p_1}{p_0} = \log p_1 - \log p_0 = \log 1 - \log \frac{1}{N} = 0 - (-\log N) = \log N = I$$

In the above equation the posteriori probability p_1 is equal 1 because the goal has been accomplished. The a priori probability p_0 is equal *1/N* because under the conditions of limited knowledge all alternatives are considered being equally probable.

A proposal on how some information theories and interpretations can be applied to safety of nuclear plants

It needs to be emphasized that the nuclear community including the nuclear operators, the government regulators, the international organizations such as the IAEA, and other involved actors, has always had a strong focus on safety and a strive for continuous improvement. However, the nuclear power plants belong to a class of complex dynamic systems, which can be difficult to fully overview, understand and control. This work suggests to use information theories and interpretations to solve some safety issues of nuclear plants, in particular those associated with nuclear containments, maintenance schedule, configuration management, and incident explanation.

Configuration management

As a matter of fact, the amount of information that is handled at nuclear power plants increases steadily with time. The amount of information at the operational start was quite limited and well-structured as so called safety analysis reports (SAR). With time, the plants undergo modifications and the old components and systems are being replaced by new items. Changes in technological processes, variations in environmental parameters, new-employments, and other factors contribute to the need to update the information.

The vital role of information for safety management of nuclear power plants was recognized by the IAEA [19] within the concept of configuration management. The IAEA structures the information into following categories:

- The documentation of the entire life-time of the nuclear power plant comprising its design, manufacturing, construction, pre-operational testing, operation, maintenance, testing, and further modification.
- The information contained in safety standards, codes, norms, etc.
- The personnel files and work instructions.

In all three cases, the IAEA requires information to be *complete* and *accurate*. However, measures of information completeness and accuracy are not discussed. Similarly, potential problems arising from excess of information are not addressed, disregarding the fact that extraction of relevant information from abundant sources is as problematic as the lack of information. Crucial issues connected with quantifying the amount of transferred information and assessing the impact of the receiver's background knowledge on the successful completion of this process do not receive the much needed attention. Finally, the need for time optimization of information generation is mentioned in wordings like "right information at right time", but no indication is offered on appropriate strategies to achieve this objective. An additional remark, which demands consideration by any satisfactory approach to safety management but is not addressed adequately by the IAEA's document, concerns the IAEA's requirement for information be clear. It should be stressed that, although *clarity* is a necessary requirement for achieving safety, it does not suffice. In fact, clear information is not necessarily true, or, alternatively, disinformation can also be clearly communicated.

It is to be noted that according to the communication theories of Shannon and Harrah the information that is received by the receiver is not the same information that has been sent by the source. Information acquired by the receiver is conditioned to the receiver's background knowledge as well as subjective goals, objectives and values. That is why all measures (such as information completeness, accuracy, clarity) must be estimated from the perspective of receivers (users) of information.

Degradation of nuclear containments

It is known that containments in nuclear power plants constitute the last barrier between the dangerous radiation and the environment. In case of a nuclear accident, the containment is supposed to confine the radiation and, by doing so, to protect people and the environment. However, containments were constructed for decades ago and are subject to a long-term ageing deterioration. The original design lifetime of containments has been exceeded in many cases [20]. At the same time, the established testing and inspection practices are limited mostly to visual inspections of containments' accessible surfaces and pressure tests, and are not capable of providing needed information about the state and safety of containments.

From the informational-functional point of view, all conclusions on containments' safety must be based on the accurate and updated information. In this regard, two major questions must be answered: "What material parameters are needed to be measured to assess the state and safety of containments?" and "What methods shall be used to perform needed measurements?"

Here, the earlier mentioned concept of "essential variables" by Ashby (corresponds to a more recent term is "order parameters" in the science of synergetic) is useful. Though the containments are complex structures, composed of a reinforced and prestressed concrete and a steel liner vessel, it might be sufficient to use a few essential variables that govern the state and safety of the entire structure. The previous study [20] has indicated that measurements of four major variables as concrete strength, concrete fracture toughness, prestressing force, and corrosion of steel members provides a solid ground for overall assessment of containments state and safety.

Once essential variables have been identified, one needs to decide what method to use for the measurements. It is known that concrete structures may be tested by means of various methods such as taking cores, Schmidt hummer, visual inspections, radar, radiography, fiber-optical method, acoustic emission, and other destructive and non-destructive (NDT) testing methods. The information approach offers an appropriate tool for choosing the best method with regard to methods' informativeness. According to the previous study [20] the best (the most informative) method seems to be a quantitative acoustic emission (QAE) NDT method. The QAE method can reliably and independently:

- Monitor the entire reinforced concrete structure under the specific conditions of nuclear power plants.
- Reveal specific defects or combination of defects in the entire structure and differentiate between undamaged and damaged parts of the structure.
- Distinguish between different types of defects.
- Assess flaws in terms acceptable for fracture mechanics analysis. Particularly, the real stress state in the prestressed concrete structure.

An additional remark concerns the algorithmic information and its impact on containments' safety. The first generation of containments in the Swedish nuclear power plants was designed and constructed in 60s and 70s, when there were no specific standards or norms available for the task. The second generation of containments was designed and constructed in 80s after the American standards were developed and published. Because of the insufficient instructional (algorithmic) information at the time of design and construction, the old containments are very probably not as strong as the new containments [20].

Optimization of maintenance schedule

Each nuclear power plant contains several thousands of components, most of which are needed to be maintained over time. A question that arises is: "How to determine an optimal time point for maintenance activities?" Support for the optimization of maintenance schedule is provided by the dynamical information theory. As previously discussed, the information theories highlight the intimate relationship between decision making and information.

In case of maintenance, a maintenance engineer must choose (decide) when to perform maintenance activities. The overall goal of the maintenance is to find defects, if any, and to repair them in order to restore the state of the facility. If maintenance activities are scheduled too late, a defect will likely cause failure of the component. Then the decision to repair becomes obvious, the posterior probability p_1 goes to 1, and the information value *V* goes to maximum:

$$V = \log(p_1 / p_0) = \log(1 / p_0) = V_{max}$$

At the same time, the information content *I* goes to zero. Once the component has broken down, the choice becomes obvious. That is it to say, this is the situation of certainty with one outcome:

$$I = \log N = \log 1 = 0$$

If maintenance activities are scheduled too early, the defect will very probably not be detected, which means that available alternatives of the component's state (the presence of defect alternatively the absence of defect) have equal probabilities. In this situation of uncertainty the information content *I* goes to maximum:

$$I = \log N = I_{\max}$$

At the same time, the information value *V* goes to zero because the maintenance actions do not increase probability of goal-achievement:

$$V = \log(p_1 / p_0) = \log 1 = 0$$

To sum up, when choosing an optimal time point for maintenance, one needs to consider and maximize both information content and value. In many cases, the optimal time point for maintenance will lie close to the end of the life-time, when the defect if large enough to be reliably detected, but is not so large that it can cause a sudden failure.

Incident explanation

It has almost become a common practice for nuclear regulators to blame poor safety culture each time a degradation is observed in a nuclear plant. For instance, after the well known incident in Forsmark in July 2006 [3], the regulator explained the incident by deficiencies in the plants' safety culture. As a result, the following programme of corrective measures had a strong focus on safety culture and associated questions as attitudes to safety, existence of written instructions, etc.

This work believes that the focus on safety culture is necessary but not sufficient for explanation of occurred incidents and prevention of new incidents to happen. Indeed, one needs to take a look from the information perspective and to identify and correct deficiencies in information acquisition, information communication, knowledge creation, decision making, and other stages in information processes.

In case of the Forsmark incident, it is known that the incident was initiated by a severe distortion in the external power grid. This distortion propagated far into the plant and lead to the failure of several power supply systems and safety systems. As a matter of fact, the employees of the plant lacked experiences of similar distortions and could not foresee possibility of such distortions to happen. Furthermore, the incident revealed that the employees of the plant did not fully realize that recently performed modifications of old electrical equipments have changed systemic interactions of the plant. In particular, the sensitivity to distortions increased or with other words, vulnerability of the plant degraded.

As a matter of fact, modification works and exchange of old equipments take place in several operating nuclear plants. As a result, the nuclear community may face situations when decisions need to be taken when the available information is not sufficient to take certain decisions. Therefore, it is important to highlight the role of information aggregation and the need to consider all types of knowledge including practical experiences, modeling results, expert judgments, calculations, tests, etc. for making plausible decisions under conditions of uncertainty.

Conclusions

From the review of main information theories and perspectives, it emerges that information can be understood

- As a *message* which is transferred from a source to a receiver via a communication channel.
- As an *instruction* (program, algorithm) which, once it is carried out, allows the transformation of a system from state *A* to state *B*.
- As *uncertainty* regarding the present state or evolution of a system, which can be reduced upon reception of the message.
- To mirror the diversity of reality (*structural* perspective).
- To provide the ground for regulation, control, steering, and other goal-directed activities (*functional* perspective).

Furthermore, information can be *quantified*, and therefore *measured*. The relevance of its potentially fundamental role as a tool to verify whether transfer of crucial knowledge has properly occurred cannot be overestimated. In addition, as it is emphasized in the communication models, issues concerning completeness, accuracy, and clarity of information should mainly concern the information *acquired by the receiver*. The role of background knowledge, objectives and values of the receiver is an additional point of concern which emerges from this review. Finally, a mathematical model has been developed which allow for current information to be updated without running the risk of unjustified bias in favour of a particular alternative/outcome.

The diversity in interpretations of the concept of information mirrors potential instances in which problems for the safe operation of nuclear plants may arise. The promotion of a proper understanding this concept within the specific context in which it is used, and of the mathematical tools developed within information theories, will hopefully help preventing accidents to occur in the future.

References

[1] “Safety culture in nuclear installations. Guidance for use in the enhancement of safety culture.” IAEA, Vienna, 2002.

[2] “Davis Besse reactor pressure vessel head degradation.” US NRC, NUREG/BR-0353, rev 1, August 2008.

[3] Wikdahl CE. “Forsmark incident on the 25th of July 2006.” Analysis group at KSU, N 4, Sweden, 2006.

[4] 2002 IAEA General Conference, IAEA, Vienna, 2004.

[5] “Knowledge management now seen as a priority.” IAEA, Nuclear news, Vienna, September 2007.

[6] Wiener N. “Cybernetics: control and communication in the animal and the machine.” New York, 1948.

[7] Ursul A. “Information: a philosophical study.” Berlin, Dietz, 1970.

[8] Ashby R. “An introduction to cybernetics.” J Wiley, New York, 1956.

[9] Ashby R. “Design for a brain.” Chapman and Hall, London, 1952.

[10] Kolmogorov A. “Three approaches to the definition of information content.” Problems of information communication, N 1, pages 3-11, Moscow, 1965.

[11] Shannon C. “A mathematical theory of communication.” The Bell system technical journal, N 27, pages 379-423 and 623-656, 1948.

[12] Harrah D. “The psychological concept of information.” Philosophy and Phenomenological Research, Vol 18, N 2, pages 242-249; December 1957.

[13] Harrah D. “A model of communication.” Philosophy of science, Vol 23, N 4, pages 333-342, October 1956.

[14] Hartley RVL. “Transmission of information.” Bell system technical journal, N 7, pages 335-363, 1928.

[15] Jaynes E. "Information theory and statistical mechanics." Physical review, Volume 106, N4, pages 620-630, May 1957.

[16] Chernavsky D. "Synergetic and information." URSS, Moscow, 2004.

[17] Bar-Hillel Y., Carnap R. "Semantic information." British Journal of science, N 4, pages 147-157.

[18] Harkevich A. "On information value." Cybernetics problems, N 4, Physmathgiz, Moscow, 1960.

[19] "Configuration management in nuclear power plants." IAEA-TECDOC-1335, Wien, 2003.

[20] Österberg E. (changed name to Ilina E.). "Revealing of age-related deterioration of reinforced concrete containments in nuclear power plants – Requirements and NDT methods." The licentiate research thesis, The royal institute of technology, Stockholm, 2004.

Author information

Elena Ilina*- Present employment 1:System analyst at the Swedish radiation safety authority, Department of nuclear plants safety, System assessments, Solna Strandväg 122, 17 154 Solna, Sweden, email: elena.ilina@ssm.se*

Present employment 2: PhD student at the Royal institute of technology, Department of structural engineering, Brinellvägen 34, 100 44 Stockholm, Sweden, email: elena.ilina@byv.kth.se

Major fields of scientific research: Application of information and knowledge theories to the safety assessments of complex technologies