3 Introductory Human Factors, Reliability, and Error Concepts

3.1 INTRODUCTION

Over the years considerable new developments have taken place in the areas of human factors, reliability, and error. Human factors, reliability, and error have become recognizable disciplines in the industrial sector in many parts of the world. There are many standard documents on human factors that directly or indirectly cover human reliability and error as well. These standard documents are often cited in the design specification of complex engineering systems [1].

More specifically, the new system design must satisfy requirements specified in these documents. Thus, nowadays it is not uncommon to come across human factors specialists (who cover human reliability and error as well) working alongside design engineers during the design and development of engineering systems, for use in areas such as nuclear power generation and aviation. These specialists use various human factors, reliability, and error-related concepts to produce effective systems with respect to humans [2, 3].

This chapter presents various introductory human factors, reliability, and error concepts considered useful for application in the areas of engineering maintenance, taken from published literature.

3.2 HUMAN FACTORS OBJECTIVES AND MAN–MACHINE SYSTEM TYPES AND COMPARISONS

There are many objectives of human factors. They may be categorized under four distinct classifications as follows [4]:

- **Classification I: Fundamental Operational Objectives.** These are basically concerned with improving system performance, increasing safety, and reducing human errors.
- **Classification II: Objectives Affecting Operators and Users.** These are concerned with improving the work environment, increasing aesthetic appearance, increasing user acceptance and ease of use, and reducing fatigue, physical stress, boredom, and monotony.
- **Classification III: Objectives Affecting Reliability and Maintainability.** These are concerned with improving reliability, increasing maintainability, reducing the manpower need, and reducing training requirements.

- **Classification IV: Miscellaneous Objectives.** These are concerned with items such as reducing equipment and time losses and increasing production economy.

Although there are many types of man-machine systems, they may be grouped under the following three categories [5]:

- **Category I: Automated Systems.** These systems carry out operation-related functions including processing, sensing, decision making, and action. The majority of these systems are of the closed-loop type and normally the basic human functions associated with such systems are monitoring, maintenance, and programming.
- **Category II: Mechanical or Semiautomatic Systems.** These systems contain well-integrated parts, such as various types of powered machine tools. Normally, in these systems the machines provide the power and the humans typically carry out the control function.
- **Category III: Manual Systems.** These systems contain hand tools and other aids along with the human operator who controls the overall operation. The operator makes use of his or her own physical energy as a power source, and then transmits/receives from the tools a significant amount of information.

Some of the important comparisons between humans and machines (in parentheses) are as follows [6]:

- Humans have excellent memory (machines are remarkably costly to have the same capability).
- Humans have relatively easy maintenance needs (machines' maintenance problems become serious with the increase in complexity).
- Humans are subjected to social environments of all kinds (machines are independent of social environments of all types).
- Humans' performance efficiency is affected by anxiety (machines are quite independent of this shortcoming).
- Humans are very flexible with respect to task performance (machines are relatively inflexible).
- Humans have high tolerance for factors such as ambiguity, vagueness, and uncertainty (machines are quite limited in tolerance in regard to factors such as these).
- Humans are limited to a certain degree in channel capacity (machines have unlimited channel capacities).
- Humans are poor monitors of events that do not occur frequently (machines possess options to be designed to reliably detect infrequently occurring events.
- Humans are subjected to stress because of interpersonal or other difficulties (machines are completely free of such difficulties).

- Humans are unsuitable for performing tasks such as amplification, data coding, or transformation (machines are extremely useful for performing tasks such as these).
- Humans have rather restricted short-term memory for factual matters (machines can have unlimited short-term memory but its affordability is a limiting factor).
- Humans are subjected to factors such as motion sickness, disorientation, and Coriolis effects (machines are completely free of such effects).
- Humans are often subjected to departure from following an optimum strategy (machines always follow the design strategy).
- Humans are subjected to deterioration in performance because of boredom and fatigue (machines are not affected by factors such as these, but their performance is subjected to deterioration because of wear or lack of calibration).
- Humans are very capable of making inductive decisions under novel conditions (machines possess very little or no induction capabilities at all).

3.3 HUMAN SENSORY CAPACITIES AND TYPICAL HUMAN BEHAVIORS AND THEIR CORRESPONDING DESIGN CONSIDERATIONS

Humans possess many useful sensors: touch, sight, taste, hearing, and smell. A clear understanding of their sensory capacities can be quite useful in reducing the occurrence of human errors in engineering maintenance. Thus, some of the human sensory-related capacities are described below [3, 7].

3.3.1 Touch

The sense of touch is related to humans' ability in interpreting visual and auditory stimuli. The sensory cues received by muscles and the skin can be used for sending messages to the brain, thus relieving the ears and the eyes of the workload, to a certain degree.

3.3.2 Sight

This is stimulated by the electromagnetic radiation of certain wavelengths, often referred to as the visible portion of the electromagnetic spectrum. The spectrum's various areas, as seen by the human eyes, appear to vary in brightness. For example, in the day light, the human eyes are very sensitive to greenish-yellow light with a wavelength of about 5500 Angstrom units [7].

Moreover, the human eyes perceive all colors when they are looking straight ahead but as the viewing angle increases, the color perception begins to decrease. Also, the human eyes see differently from different angles.

3.3.3 Vibration

Past experiences indicate that the presence of vibration could be quite detrimental to the performance of mental and physical tasks by humans such as maintenance personnel. There are numerous vibration parameters including frequency, velocity, acceleration, and amplitude. More specifically, large amplitude and low frequency vibrations contribute to various problems including headaches, eyestrain, fatigue, motion sickness, and interference with the ability to read and interpret instruments properly [7].

Furthermore, high frequency and low amplitude vibrations can also cause fatigue to a certain degree.

3.3.4 Noise

Noise may simply be described as sounds that lack coherence and human reactions to noise extend beyond the auditory systems (e.g., irritability, fatigue, or boredom). Excessive noise can lead to problems such as adverse effects on tasks requiring a high degree of muscular coordination and precision or intense concentration, reduction in the workers' efficiency, and loss of hearing if exposed for long periods.

Over the years, various human behaviors have been observed by researchers in the field. Some of the typical human behaviors and their corresponding design considerations are presented in Table 3.1 [2].

TABLE 3.1
Typical Human Behaviors and Their Corresponding Design Considerations

No.	Typical Human Behavior	Corresponding Design Consideration
1	Humans often tend to hurry	Develop design such that it properly takes into consideration the element of human hurry
2	Humans get easily confused with unfamiliar items/things	Avoid designing totally unfamiliar items/things
3	Humans often use their sense of touch for exploring or testing the unknown	Give careful attention to this factor during design, particularly to the product/item handling aspect
4	Humans frequently regard manufactured items as being safe	Design products such that they become impossible to be used incorrectly
5	Humans have become accustomed to certain color meanings	During design strictly observe existing color coding standards
6	Humans normally expect to turn on the electrical power, the switches have to move upward, or to the right, etc.	Design such switches as per human expectations
7	Humans always expect that faucets/handles will rotate counter-clockwise for increasing the flow of gas, steam, or liquid	Design such items as per human expectations

3.4 HUMAN FACTORS–RELATED FORMULAS

Over the years, researchers have developed various types of mathematical formulas for estimating human factors–related information. Four of these formulas considered useful for application in engineering maintenance are presented below.

3.4.1 Formula for Estimating Inspector Performance

This formula is concerned with estimating inspector performance with respect to inspection tasks. Thus, the inspector performance is expressed by [3, 8]

$$\theta_i = \frac{T_{tr}}{n_p - n_{ie}} \tag{3.1}$$

where θ_i is the inspector performance expressed in minutes per correct inspection, n_p is the total number of patterns inspected, n_{ie} is the total number of inspector errors, and T_{tr} is the total reaction time expressed in minutes.

3.4.2 Formula for Estimating Rest Period

When humans perform lengthy or strenuous tasks, the incorporation of proper rest periods is considered essential. Thus, this formula is concerned with estimating the length of scheduled or unscheduled rest periods. The length of the required rest period is expressed by [9]

$$T_{rp} = \frac{T_w (E_a - E_s)}{(E_a - RL_a)} \tag{3.2}$$

where T_{tr} is the required length of the rest period expressed in minutes, T_w is the working time expressed in minutes, E_a is the average energy cost/expenditure expressed in kilocalories per minute of work, E_s is the kilocalories per minute adopted as standard, and RL_a is the approximate resting level expressed in kilocalories per minute (usually, the value of RL_a is taken as 1.5).

3.4.3 Formula for Estimating Character Height

As usually the instrument panels are located at a viewing distance of 28 inches for the comfortable performance and control of adjustment-oriented tasks, this formula is concerned with estimating the character height at the viewing distance of 28 inches. Thus, the character height is expressed by

$$C_h = \frac{C_s D_v}{28} \tag{3.3}$$

where D_v is the specified viewing distance expressed in inches, C_h is the character height at the specified viewing distance, D_v, expressed in inches, and C_s is the standard character height from a viewing distance of 28 inches.

Example 3.1

Assume that maintenance workers have to read a meter from a distance of 70 inches and the standard character height at a viewing distance of 28 inches is 0.50 inches. Estimate the height of numerals for the stated viewing distance.

By substituting the given data values into Equation (3.3), we get

$$C_h = \frac{(0.50)(70)}{28}$$
$$= 1.25 \text{ inches}$$

Thus, the height of numerals for the stated viewing distance of 70 inches is 1.25 inches.

3.4.4 Formula for Estimating Glare Constant

Various types of human errors can occur in maintenance work due to glare. The value of the glare constant can be estimated by using the following formula [9]:

$$\alpha = \frac{(\lambda^{0.8})(\beta^{1.6})}{L_g \, \mu^2} \tag{3.4}$$

where α is the glare constant, L_g is the general background luminance, λ is the solid angle subtended at the eye by the source, μ is the angle between the direction of the glare source and the viewing direction, and β is the source luminance.

3.5 USEFUL HUMAN FACTORS GUIDELINES AND DATA COLLECTION SOURCES

Over the years, researchers working in the area of human factors have developed many useful human factors-related guidelines for application in engineering system design. Some of these guidelines are as follows [2, 6]:

- Review system objectives with respect to human factors.
- Obtain all appropriate human factors-related design reference documents.
- Develop an effective human factors-related checklist for use during system design and operation phases.
- Use the services of human factors experts as considered appropriate.
- Conduct field tests of the system design prior to its approval for delivery to customers.
- Review final production drawings in regard to human factors.
- Make use of mock-ups for “testing” the effectiveness of user-hardware interface designs.

There are many sources for collecting human factors-related data. Some of the important ones are as follows [10, 11]:

- **Test reports.** These reports contain data obtained from testing manufactured items or goods.
- **User experience reports.** These reports contain data reflecting experiences of users with the system/equipment in the field use environment.
- **Published standards.** These documents are published by various organizations including professional societies and government agencies.
- **Published literature.** This includes items such as journals, technical reports, and conference proceedings.
- **System development phase.** This is a good source for collecting various types of human factors-related data.
- **Previous experience.** This is a quite good source for obtaining data from similar cases that have occurred in the past.

3.6 HUMAN PERFORMANCE EFFECTIVENESS AND OPERATOR STRESS CHARACTERISTICS

Over the years, various researchers have studied the relationship between human performance and stress. They conclude that such relationship basically follows the shape of the curve shown in Figure 3.1 [12, 13].

The curve shows that stress to a moderate level is necessary to achieve optimal human performance effectiveness. Otherwise, at a very low stress, the task will become dull and unchallenging, and consequently human performance effectiveness will not be at its highest point.

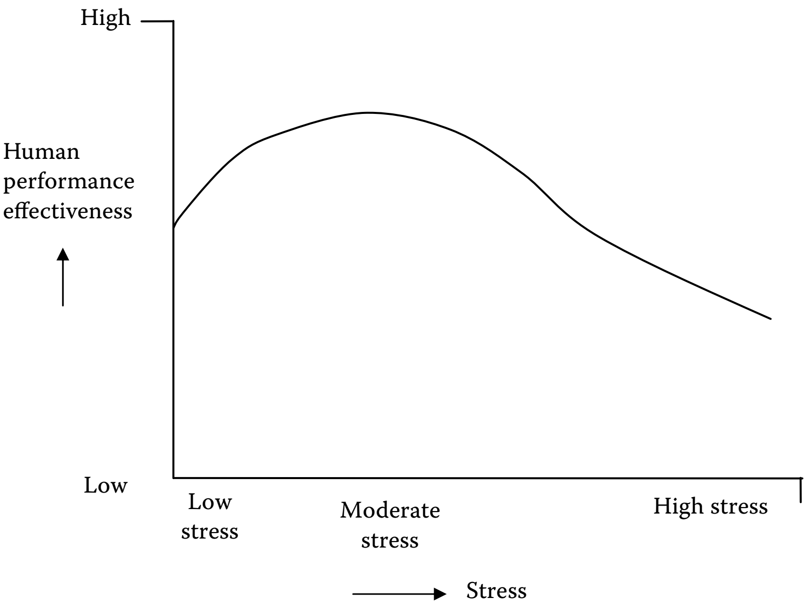

FIGURE 3.1 Human performance effectiveness versus stress curve.

In contrast, stress beyond a moderate level will cause deterioration in human performance because of factors such as fear, worry, or other kinds of psychological stress. It simply means that the probability of human error occurrence will be higher under high stress than under moderate stress.

Human operators perform various types of tasks in diverse engineering areas. In performing such tasks, they may have certain limitations. Past experiences indicate that when these limitations are violated, probability for the error increases quite significantly [14]. This probability can be reduced significantly by carefully considering operator limitations or characteristics during the system design. Some of these characteristics are as follows [14]:

- Performing task steps at high speed
- Poor feedback information in determining the correctness of actions taken
- The requirement for prolonged monitoring
- Having rather short decision-making time
- Performing tasks that require a very long sequence of steps
- Requirement to operate more than one control simultaneously at high speed
- Requirement to make quick comparisons of two or more displays
- Requirement to make decisions on the basis of data collected from diverse sources

3.7 OCCUPATIONAL STRESSORS AND GENERAL STRESS FACTORS

The occupational stressors may be classified under the following four categories [12]:

- **Category I: Workload-related stressors.** These stressors are concerned with work under load or work overload. In the case of work under load, the present duties being carried out by the individual fail to provide sufficient stimulation. Some examples of work under load are the lack of any intellectual input, task repetitiveness, and the lack of opportunity to use acquired expertise and skills of the individual. In contrast, in the case of work overload the job requirements exceed the ability of the individual to satisfy them in an effective manner.
- **Category II: Occupational change-related stressors.** These stressors are concerned with factors that disrupt cognitive, behavioral, and physiological patterns of functioning of the individual.
- **Category III: Occupational frustration-related stressors.** These stressors are concerned with the problems related to occupational frustration. The problems include the lack of proper communication, poor career development guidance, and the ambiguity of one's role.
- **Category IV: Miscellaneous stressors.** These stressors include all other stressors that are not incorporated into the above three categories. Some examples of the miscellaneous stressors are poor interpersonal relationships, too much or too little lighting, and too much noise.

Over the years, various researchers in the area of human engineering have pointed out that there are many general factors that considerably increase stress on an individual, in turn leading to a significant deterioration in his or her reliability. Some of these general factors are as follows [15]:

- Poor health
- Possibility of redundancy at work
- Having to work with individuals with unpredictable temperaments
- Serious financial difficulties
- Working under extremely tight time pressures
- Lacking the proper expertise to perform the ongoing job
- Experiencing difficulties with spouse or children or both
- Poor chances for promotion
- Excessive demands from superiors at work

3.8 HUMAN PERFORMANCE RELIABILITY AND CORRECTABILITY FUNCTIONS

Both these functions are derived below, separately.

3.8.1 Human Performance Reliability Function

Although all the tasks performed by humans are not in continuous time, from time to time humans do perform time-continuous tasks such as scope monitoring, missile countdown, and aircraft maneuvering. In situations such as these, human performance reliability is a very important parameter.

Thus, in time-continuous tasks the probability of occurrence of human error in the finite time interval Δt is expressed by [16–19]

$$P(B/A) = \lambda(t)\Delta t \tag{3.5}$$

where A is an errorless performance event of duration time t, B is an event in which the human error will occur in time interval $(t, t + \Delta t)$, and $\lambda(t)$ is the time-dependent error rate.

Thus, the joint probability of the errorless human performance may be expressed as follows:

$$P(\bar{B}/A)P(A) = P(A) - P(B/A)P(A) \tag{3.6}$$

where $P(A)$ is the probability of occurrence of event A, and $\bar{B}$ is the event that human error will not occur in time interval $[t, t + \Delta t]$.

Equation (3.6) may be rewritten as follows [16–19]:

$$HR(t) - HR(t)P(B/A) = HR(t + \Delta t) \tag{3.7}$$

where $HR(t)$ is the human reliability at time t and $HR(t + \Delta t)$ is the human reliability at time $t + \Delta t$.

It is to be noted that Equation (3.6) denotes an errorless human performance probability over time intervals [0, t] and [t, $t + \Delta t$].

By substituting Equation (3.5) into Equation (3.7), we obtain

$$\frac{HR(t+\Delta t)-HR(t)}{\Delta t}=-\lambda(t)\,HR(t) \tag{3.8}$$

In the limiting case, Equation (3.8) becomes

$$\frac{dHR(t)}{dt}=-\lambda(t)\,HR(t) \tag{3.9}$$

By rearranging Equation (3.9), we get

$$\frac{1}{HR(t)}\,dHR(t)=-\lambda(t)\,dt \tag{3.10}$$

By integrating both sides of Equation (3.10) over the time interval [0, t], we obtain

$$\int_{1}^{HR(t)}\frac{1}{HR(t)}\cdot dHR(t)=-\int_{0}^{t}\lambda(t)\,dt \tag{3.11}$$

because at $t = 0$, $HR(0) = 1$.

After evaluating the left-hand side of Equation (3.11), we get

$$ln\ HR(t)=-\int_{0}^{t}\lambda(t)\,dt \tag{3.12}$$

Thus, from Equation (3.12), we obtain

$$HR(t)=e^{-\int_0^t \lambda(t)dt} \tag{3.13}$$

Equation (3.13) is the general expression for computing human reliability, irrespective of whether the human error rate is constant or nonconstant. More specifically, it holds when time to human error is described by statistical distributions such as normal, gamma, exponential, Weibull, and Rayleigh.

Example 3.2

Assume that the time to human error of a maintenance worker follows Weibull distribution. Thus, his or her time-dependent error rate is expressed by

$$\lambda(t)=\frac{\beta\, t^{\beta-1}}{\theta^{\beta}} \tag{3.14}$$

where t is time, β is the distribution shape parameter, and θ is the distribution scale parameter. Obtain an expression for the maintenance worker's reliability.

By substituting Equation (3.14) into Equation (3.13), we get

$$\begin{aligned} HR(t) &= e^{-\int_0^t \left(\frac{\beta t^{\beta-1}}{\theta^\beta}\right)dt} \\ &= e^{-\left(t/\theta\right)^\beta} \end{aligned} \tag{3.15}$$

Thus, Equation (3.15) is the expression for the maintenance worker's reliability.

3.8.2 Human Performance Correctability Function

This is concerned with the human capacity to correct self-generated human errors and is defined as the probability that an error will be corrected in item t subject to stress constraint inherent in the nature of the task and its associated environment [18]. Mathematically, the correctability function is defined as follows [18, 19]:

$$CP(t) = 1 - e^{-\int_0^t \alpha(t)dt} \tag{3.16}$$

where $CP(t)$ is the probability that an error will be corrected in time t and $\alpha(t)$ is the time-dependent rate at which tasks are corrected.

It is to be noted that Equation (3.16) holds whether the task correction rate is constant or nonconstant. More specifically, it holds for any time to task correction probability distribution.

Example 3.3

Assume that the time to error correction of a maintenance worker follows exponential distribution. Thus, his or her error correction rate is defined by

$$\alpha(t) = \alpha \tag{3.17}$$

where α is the constant error correction rate of the maintenance worker. Obtain an expression for the maintenance worker's correctability function.

Substituting Equation (3.17) into Equation (3.16) yields

$$\begin{aligned} CP(t) &= 1 - e^{-\int_0^t \alpha dt} \\ &= 1 - e^{-\alpha t} \end{aligned} \tag{3.18}$$

Thus, Equation (3.18) is the expression for the maintenance worker's correctability function.

3.9 HUMAN ERROR OCCURRENCE REASONS, CONSEQUENCES, WAYS, AND CLASSIFICATIONS

Past experiences indicate that there are many reasons for the occurrence of human errors. Some of the important ones are poor training, poor equipment design, poor motivation, complex task, poorly written equipment operating and maintenance procedures, inadequate lighting in the work area, poor management, improper work

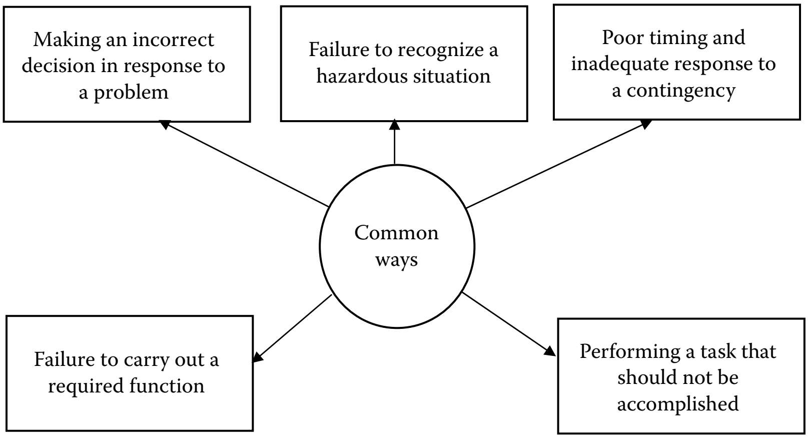

FIGURE 3.2 Common ways human error occurs.

tools, crowded workspace, poor work layout, poor verbal communication, and high noise and temperature in the work area [20].

The consequences of a human error can range from minor to very severe, for example, from insignificant delays in system performance to a very high loss of lives. Furthermore, they may vary from one situation to another, from one task to another, or from one piece of equipment to another. In particular, with respect to equipment, the human error consequences may be grouped under three classifications: equipment operation is stopped completely, equipment operation is delayed quite significantly but not stopped completely, and delay in equipment operation is insignificant.

There are many ways in which a human error can occur. The common ones are shown in Figure 3.2 [21].

Human errors in engineering may be grouped under various classifications. The seven commonly used classifications are as follows [20, 22–24]:

- Maintenance errors
- Operator errors
- Design errors
- Assembly errors
- Inspection errors
- Handling errors
- Contributory errors

Additional information on the above errors is available in Refs. [20, 22–24].

3.10 HUMAN RELIABILITY AND ERROR DATA COLLECTION SOURCES AND QUANTITATIVE DATA

Human reliability and error data are the backbone of any human reliability/error prediction. These data are collected through means such as expert judgments, experimental studies, field experiences, self-made error reports, and published literature [3, 25–26].

TABLE 3.2
Human Reliability and Error Data for Some Selective Tasks

No.	Error/Task Description	Performance Reliability	Error Rate per Million Operations
1	Turning rotary selector switch to certain position	0.9996	—
2	Finding maintenance (scheduled) approaches in maintenance manual	0.997	—
3	Failure to tighten nut and bolt	—	4800
4	Reading gauge incorrectly	—	5000
5	Installing o-ring incorrectly	—	66700
6	Closing valve incorrectly	—	1800
7	Connecting hose incorrectly	—	4700
8	Failure to install nut and bolt	—	600
9	Procedural error in reading instructions	—	64500
10	Incorrect adjustment of mechanical linkage	—	16700

There are many data banks for obtaining human reliability and error-related information [3, 26]. Some of these are Data Store [27], Nuclear Plant Reliability Data System [28], Safety Related Operator Action (SROA) Program [29], Aerojet General Method [30], Bunker-Ramo Tables [31], Air Force Inspection and Safety Center Life Sciences Accident and Incident Reporting System [32], and Aviation Safety Reporting System [33].

Human reliability and error data for some selective tasks, directly or indirectly related to engineering maintenance, are presented in Table 3.2 [3].

3.11 PROBLEMS

1. Discuss three types of man-machine systems.
2. Discuss at least ten comparisons between humans and machines.
3. What are the four main classifications of human factors objectives?
4. List at least six typical human behaviors.
5. Assume that maintenance workers have to read a meter from a distance of 60 inches and the standard character height at a viewing distance of 28 inches is 0.50 inches. Estimate the height of numerals for the stated viewing distance.
6. Discuss at least five sources for collecting human factors-related data.
7. Describe the human performance effectiveness versus stress curve.
8. What are the important reasons for the occurrences of human errors?
9. Discuss five common ways in which a human error can occur.
10. What are the common classifications of human errors in engineering?

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