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Five fatal flaws in API RP 581

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ABSTRACT

API RP 581: 'Risk-based Inspection Technology' gives a methodology to implement Risk-based Inspection or RBI programs on fixed equipment and piping in the hydrocarbon and chemical process industries. The theory of RBI is described in API RP 580, which comprehensively lists the elements of risk caused by degradation of material, and the numerous possibilities to deal with these risks. RP 581 takes this outline one step further and describes how to qualify and quantify risks and how to plan and execute the inspection program. This methodology, however, is based on several flawed concepts or assumptions, notably:

1. The concept of a generic failure frequency: probability of failure as an intrinsic property of all equipment.
2. The concept of a damage factor that multiplies the generic failure frequency, depending on configuration and conditions.
3. The concept to apply statistical theory as a prediction tool for failure.
4. The premise that certainty can rely on inspection alone.
5. The premise that a larger inspection program improves risk assessment.

As a result of these flawed concepts, ineffective and inefficient inspection programs have ensued. This paper will examine these flaws and their effects, and propose alternatives.

INTRODUCTION

Risk is a term with a multitude of meanings ranging from the subjective to the mathematically exact. The ISO 31000 / Guide 73 broad definition is 'effect of uncertainty on objectives' which may be both positive or negative. Quantifying risk, both in absolute or relative sense, relies on the relationship: "Risk is the product of the probability of an event times the consequence of the event". Used in an absolute sense this relationship produces a figure in the same units as those of the consequence -often a monetary unit - in the period of time considered, e.g. a year. In a relative sense, the equation can be used to judge the change of risk level. For instance, the effect of activities that change the probability of an event, or of measures that change the consequence of an event. In risk management relative risk is an important guide.

<u>Risk in technology and engineering.</u>

In the process industries, risk invariably applies to failure or loss of functionality and considers the probability of such failure or malfunction, and its consequences. These risks are generally complex due to interactions of human factors and numerous technical variables on the probability side of the equation and the very broad range of possible outcomes –involving health, environment and financial losses- on the consequence side. In some industrial environments semi- or fully quantitative methods, such as fault tree analysis or bowtie analysis are applied to determine risks. In these methods, every step of conceptual failure scenarios are analyzed from start to finish and the probability and consequence of each path is considered. Naturally, the quality of the outcome of such analyses depends on the quality of the input data. Think, for instance, of the recent nuclear catastrophe at Fukushima. Flawed data or an inadequate scenario are by no means unique in quantitative risk assessment and can work both ways: from a severe overestimation of an identified risk, to being oblivious of a risk.

The difficulty in assessing technological risks has created the concept of 'ALARP': As Low As Reasonably Practicable. A risk is ALARP at a point where the resources required to reduce the risk further are disproportionate to the benefit gained. The ALARP principle recognizes the fact that it is not fruitful, or can even be counterproductive, to spend infinite amounts of time and money trying to reduce a small risk further. Common sense and engineering judgment are the main tools to strike a balance between a residual risk reduction and the price that society has to pay for that reduction.

Probability of Failure

The concept of 'failure' in process units can have various meanings. From broad to narrow:

1. Failure by loss of integrity or compliance or fitness-for-purpose; when components lose legal or technical integrity, for instance due to cracking or loss of thickness.
2. Failure by loss of functionality; when a component in a unit no longer meets the performance standard.
3. Failure by loss of containment; when tanks or pressure containing parts are leaking or worse. This is in fact a special case of 2.

Probability of failure by loss-of-containment is a vital part of risk assessment. In order to estimate the risk of events with grave or catastrophic consequences a credible assessment of the probability of the event must be available. This proves to be rather elusive: when the degradation processes and its potential rates are known, the probability of failure is rather low since the safe-life of the equipment can be assessed and monitored with considerable accuracy. In the opposite case, when degradation processes are not known and incidents go unnoticed, the probability of failure can be higher. 'Vulnerability' or 'susceptibility' are concepts that can be used but need to be defined and quantified. These concepts often point to certain unintended dynamic aspects of the environment or the equipment, such as contaminations, starvation, enrichment processes, overheating, wear, unintended phase transformations or reactions, accumulation, overdosing, or fouling.

Therefore, the value of 'probability of failure' (PoF) is paradoxical and very difficult to quantify. Reason: the very moment one considers the issue for a given item, its value changes because causes, effects and remedies are being considered. Several methods to establish an objective value have been proposed:

1. A quantitative standard PoF-value based on broad statistics
2. A quantitative specific PoF-value based on narrow statistics
3. A 'high-medium-low-negligible' division based on a certain criteria. These criteria may:
    a. reflect the nominal corrosivity of the environment to the equipment

   b. assess the potential for extreme values of corrosivity. This approach includes off-design and what-if analysis.
4. Combinations of the above

Compliance

Corrosion engineering is a mature discipline. This means that the likely and the possible corrosion mechanisms in any given process environment are known. In the design of process plants these known threats are managed, which implies that integrity is assured in a process environment and equipment condition that are both compliant, i.e. meet the design and functional specifications. In case they are not compliant, departure from design degradation may occur.

In developed process systems the effect of a certain degree of non-compliance is generally known and manageable. The situation can be different when the operator is unfamiliar with the process and the fact of or level of non-compliance are not obvious. 'Developed' and 'compliant' are subjective; what is mature for one operator may still be unfamiliar for another; demarcation between non-critical and critical non-compliance may be clear to one operator and less so to the next. These challenges, however, are temporary and can be fixed as much insightful integrity information is available in the public domain [3-10].

The possibilities and the respective control strategies against potentially catastrophic degradation can be captured in a 2x2 matrix:

	Compliant equipment	**Non-compliant equipment**
Compliant process	Expect design corrosion and monitor multidisciplinary for deviating features and trends.	Assess the possibility of extreme degradation rates. Assess critical non-compliance levels.
Non-compliant process	Assess the possibility of extreme degradation rates. Monitor degradation-critical process parameters.	Combine all

Integrity assurance and inspection

To control potential integrity threats, plant owners use a range of integrity management methods. By decreasing effectiveness:

1. Degradation registers giving the nature, location, areas of vulnerability, materials factors and parameters, all based on theory and experience.
2. A register of degradation-critical process parameters and its safe limits.
3. Internal and external corrosion monitoring tools installed on selected locations.
4. Formation of multidisciplinary integrity-assurance teams that evaluate unusual occurrences and non-compliances in the plant.
5. Identified-threat-focused external inspection, primarily with ultrasonic thickness measurement or radiography.

6. Periodic internal inspection during planned or unplanned shutdown with the purpose to verify the predicted corrosion features and patterns.
7. Non-dedicated external inspection.

The purpose of activities 4-6 is basically to verify the predictions of the first three.

External onstream inspection can be an important tool to establish identified degradation threats. The limitations of the two common external inspection methods, ultrasonic thickness testing and radiography, are a relatively low resolution in the field and a high demand on resources. These methods should be applied sparingly and judiciously:

- The possibility of a detectable degradation must be established. Without the guidance of a credible degradation description, inspection programs are unfocused searches for unknown features.
- This identified potential degradation must not be reliably detectable through other, more effective means.
- The rate of degradation must be sufficiently low to allow detection at reasonable inspection intervals, unless permanent, continuous inspection devices can be effectively applied.
- The locations of degradation must be sufficiently predictable to enable focused inspection.

Large scale external inspection can be effective against an 'unknown' form of loss-of-thickness, which is, by any measure, an extremely remote risk. Surprisingly, broad, general inspection programs are commonly applied by plant owners; not only in dedicated, degradation-based inspection programs, but also in general surveys for unspecified degradation threats. The main reason for this is the emphasis that some Recommended Practices place on large-scale onstream inspection, notably API RP 581 [2].

API RP 581 : RISK-BASED INSPECTION TECHNOLOGY

An authorative guideline for RBI is API Recommended Practice 581 : Risk-Based Inspection Technology. This publication offers quantitative procedures to establish an inspection program using risk-based methods for pressurized fixed equipment in conjunction with API RP 580 [1]. RP 580 gives the main structure and minimum general guidelines for RBI, while API RP 581 provides calculation methods to determine a risk.
Some of the concepts that API RP 581 uses for quantification are misconceived; the risk assessments produced by these misconceptions are equally flawed. The gravest misconceptions in API RP 581 are the following:

1. The concept of a generic failure frequency: the likelihood of failure as an intrinsic property of all equipment .
2. The concept of a damage factor, a multiplier for the generic failure factor greater or equal 1.0..
3. The suggestion that statistical theory has predictive value for assessment of likelihood of failure.
4. The premise that assured integrity must rely on inspection.
5. The premise that a larger inspection program improves risk assessment.

Generic Failure Frequency

The average probability of failure in a large population of components is the 'generic failure frequency' *gff*. RP 581 gives the following description: *"The generic failure frequency for different component types was set at a value representative of the refining and petrochemical industry's failure data. The generic failure frequency is intended to be the failure frequency prior to any specific damage occurring from exposure to the operating environment, and are provided for several discrete hole sizes for various types of processing equipment".*

The failure data, being representative for the industry would consider the number of failures F of a specific equipment type, recorded by a number of statutory bodies in a given period and relate them to the total number of non-failures NF. The basic equation would be something like *gff* = F/((F+NF)*y).
This *gff* is used to calculate the probability of failure:

$$P\ f(t) = gff\ {*}D\ f(t)\ {*}F_{MS}$$

The probability of failure, *P f(t),* is determined as the product of *gff* , a damage factor, *D f(t),* and a management systems factor F_{MS}.

The management systems factor F_{MS} adjusts for the influence of the management system on the mechanical integrity of the plant, which is entirely valid. The F_{MS} evaluation method consists of answering numerous questions. Although the questions tend to address the level of bureaucracy of the organization rather than its vigilance, it does, by and large, reward having one's house in order. The answers produce a quantitative, reproducible score for the quality of the management system. The value of F_{MS} can lie between 0.1 for perfect management to 10 for very weak management. This means that the minimum of *P f(t)* for any individual item can be 10 times lower than the average failure rate in the data sample used to determine *gff*.

RP 581 lists the values of *gff* for various equipment: for heat exchangers, 3.06E-05 y^{-1}; pipe (length not specified), 3.06E-05 y^{-1}; tank bottoms, 7.2E-04 y^{-1}; tank courses 1.00E-04 y^{-1}. One should note:

- That *gff* is equal for the equipment type and that the maximum life of the various equipment types predicted by *gff* ranges from approx. 1000 to 30000 years. Since a meaningful sampling period cannot realistically exceed 10-20 years, to allow for maturity and technical progress, *gff* represents a linear extrapolation by a factor between 50 and 3000. This linear extrapolation is an unrealistic assumption : early failures are generally the result of design- and fabrication errors. Most equipment has –in a practical sense- infinite life.
- Therefore, the lowest possible value of $P\ f(t)= F_{MS}$ * *gff* is too high and the application of RP 581 will produce an average failure frequency that is much higher than for the original sample that *gff* was based on. This is unrealistic, and the total risk thus calculated is so much higher than a realistic failure frequency would show.

The approach could be valid in populations where life is relatively short, failure is sudden, and where the proportion of non-failures in the database is relatively small. For example, failure frequency of engines or rotating equipment. For static process equipment, though, this approach is invalid. Even if equipment will not live forever, the degradation rate is known and equipment life is usually many orders of magnitude larger than the economic life of the installation. This implies that 'probability of failure' equates to 'probability of something unexpected happening' which is –by its nature- very hard to quantify. 'Generic failure frequency' , therefore, may have a statistical meaning but has no practical significance in the field.

Damage Factor

A multiplier or damage factor applied to the generic failure frequency of a component takes the damage mechanisms that are active in that component into account. To do this, calculation protocols for a large number of damage factors have been included in API 581: for general and localized thinning, for cracking, for HIC/SOHIC cracking in sour environments, for carbonate, for polythionic acid cracking in austenitic stainless steel and non-ferrous alloy components, for chloride stress corrosion cracking, for hydrogen stress cracking in HF environments, for HIC/SOHIC cracking in HF environments, for external corrosion on ferritic components, for CUI on insulated ferritic components, for external chloride stress corrosion cracking on austenitic stainless steel components, for high temperature hydrogen, for various embrittlement processes and for mechanical fatigue.

Each damage factor is valued by the severity of potential damage-causing process- and materials conditions and D may range from a value of 1 up to 5000. Typically, D is composed with an equation: $D= D_0* (F_1…F_n) / F_{om}$, where D_0 is the basic damage factor and F are a number of adjustment factors, always >1, that account for the presence of unfavorable process conditions or equipment configurations. F_{om} represents a factor to account for online monitoring. Still, the minimum value of D = 1.0. This implies that even in the absence of any damage mechanism, say for a stainless line in clean dry hydrocarbon, all damage factors would be 1.0 and the PoF the same as for the average line in the database.

The notion that the PoF can be determined in this manner needs to be examined. The damage factor D is a multiplier for the probability of failure. RP 581 allocates a higher risk when more information is available. Moreover, RP 581 raises the risk through identified single factors. This approach is not realistic: threats from known single factors very rarely cause failures because they have been accounted for in the design and have been eliminated, for instance through material selection. Enhanced degradation by the synergy of multiple factors –of which at least one is a new, unknown or unrecognized factor- is the common cause of failures. Single factors are mainly irrelevant and will give useless PoF predictions.

Statistical theory cannot predict the likelihood of failure.

API RP 581 claims that certain failures can be predicted on the basis of a Weibull distribution. The two-parameter Weibull distribution for the cumulative failure density function, is expressed as:

$$F(t) = 1 - R(t) = 1 - \exp[-(t/\eta)^{\beta}]$$

Where β is the shape factor or slope-parameter and the η-parameter is the characteristic life (in years). *t* is the independent variable (years). The η-parameter is equivalent to the Mean Time Between Failure (MTBF) when β = 1.0.

The assumption that Weibull parameters are generic in a given service is made for several different equipment types: pressure relief valves (PRD) , rupture disks and heat exchanger tube bundles. The premise is that in similar services PRDs will have a similar probability of failure on demand (failure to lift when needed) and similar probability of leakage.

For tube bundles the concept is that a reliability database is useful to evaluate the risks associated with bundle failure. The database would be organized by gathering exchanger details for each bundle. Basic data required for the database include nearly 40 different –mainly mechanical- parameters of the bundle. Based on the assumption that similarly designed bundles in similar service will have the same failure mechanism, a Weibayes approach can be used. This approach assumes that the shape, or slope, of the Weibull curve for the cut-set of similar bundles will be identical to the bundle that is being evaluated. The Weibayes' approach would allow statistical failure prediction to be performed.

RP 581 cautions that if a Weibull curve is created from too many failure data, the data will not yield a proper Weibull plot. When this occurs, a likely reason is that multiple failure mechanisms are being plotted and a more specific list of matching criteria is required to isolate the failures to each individual mechanism. The benefit of this approach would be that the target date for the next inspection can be determined with the inspection adjusted failure rate curve, as defined by the new Weibull parameters. Also, that the statistics can be utilized to predict the optimal replacement frequency for a bundle. And it can answer the question as to whether it makes economic sense to inspect or replace a bundle at an upcoming shutdown.

The fallacy in this entire approach is threefold:

- Any failure process that consists of a distributed incubation time and a distributed degradation rate will show a cumulative failure density function that looks like a Weibull distribution.
- For any three sequential data points two Weibull parameters with a perfect fit can be found. For four or five points a reasonable fit is likely. This is a form of regression analysis with no physical significance and predictive relevance.
- Industrial failure processes are driven by rather different parameters than are listed in the RP 581. Realistic models for most failure processes primarily use chemical parameters and consist of multiple non-continuous stages and multiple interactions in which coincidental and off-design conditions are essential.

Therefore, the predictions based on statistics from similar plants or from earlier failures in the same plant have no physical basis and can equally over-predict or under-predict the probability of the next failure. The case to apply the failure statistics of process equipment to failure prediction is weak.

Another objection against the use of statistical analysis of failure phenomena in this manner is the suggestion of inevitability; that failures happened and will happen again, driven by the rigor of statistics, not by controllable process factors. Naturally, this is not a challenging approach. Every single failure holds the information, to be disclosed by failure analysis, about its causes and how it could have been prevented. There is nothing inevitable about this.

The premise that certainty can rely on inspection alone.

API RP 581 gives credit to the quality and frequency of inspection programs in the 'probability-of-failure' assessments. This factor is called the effectiveness of inspection. A number of shortcomings that may limit the effectiveness of an inspection program are listed:

a) Lack of coverage of an area subject to deterioration,
b) Inherent limitations of some inspection methods to detect and quantify certain types of deterioration,
c) Selection of inappropriate inspection methods and tools

d) Application of methods and tools by inadequately trained inspection personnel,
e) Inadequate inspection procedures,
f) The damage rate under some conditions (e.g. start-up, shut-down, or process upsets) may increase the likelihood or probability that failure may occur within a very short time.
g) Inaccurate analysis of results leading to inaccurate trending of individual components,
h) A low probability of detection by the applied NDE technique for a given component type, metallurgy, temperature and geometry .

These shortcomings have one thing in common, they are only recognizable after the fact (of failure). Unsurprisingly, the recommendation to prevent such shortcomings is through highly 'effective' inspection e.g. 50-100% ultrasonic scanning. If, however, I rewrite the list conversely, a different solution presents itself:

a) Assess the areas of vulnerability and its features of degradation.
b) Identify the suitable detection method for these features.
c) Select the appropriate detection tools.
d) Ensure execution by competent personnel,
e) Ensure that proper procedures and written schemes of examination are followed ,
f) Assess the effect of extraordinary conditions on the damage rate.
g) Do not consider trends for individual components conclusive, unless based on at least 4 readings at sufficient intervals.
h) When NDE techniques are potentially unsuitable for detection, complement with other methods.

Formulated in a proactive manner it is blindingly obvious that prior analysis by a competent specialist is essential to avoid the pitfalls mentioned. RP 581, however, recommends prior analysis by a competent corrosion engineer only for local thinning, online corrosion monitoring, tank-bottom corrosion and sulfuric acid corrosion. Compare the recommendations for effective non-intrusive inspection for general and local thinning:

Inspection Effectiveness Category	General Thinning	Local Thinning
A - Highly Effective	50 to 100% ultrasonic scanning coverage (automated or manual) or profile radiography	50 to 100% coverage using automated ultrasonic scanning, or profile radiography in areas specified by a corrosion engineer or other knowledgeable specialist.
B - Usually Effective	Nominally 20% ultrasonic scanning coverage (automated or manual), or profile radiography, or external spot thickness (statistically validated)	20% coverage using automated ultrasonic scanning, or 50% manual ultrasonic scanning, or 50% profile radiography in areas specified by a corrosion engineer or other knowledgeable specialist.
C - Fairly Effective	2 to 3% examination, spot external ultrasonic thickness measurements, and little or no internal visual examination	Nominally 20% coverage using automated or manual ultrasonic scanning, or profile radiography, and spot thickness measurements at areas specified by a corrosion engineer or other knowledgeable specialist.
D - Poorly Effective	Several thickness measurements, and a documented inspection planning system	Spot ultrasonic thickness measurements or profile radiography without areas being specified by a corrosion engineer or other knowledgeable specialist.
E - Ineffective	Several thickness measurements taken only externally, and a poorly documented inspection planning system	Spot ultrasonic thickness measurements without areas being specified by a corrosion engineer or other knowledgeable specialist.

The remarkable difference between general and local thinning is that, according to API RP 581, a corrosion engineer or knowledgeable specialist has something meaningful to say about local thinning but not about general thinning. Actually, corrosion engineering knowledge helps to understand every degradation process: why it occurs, where it will occur, what factors influence the rate and how it can be detected. Even general thinning is never uniform, and often it is so in a predictable way due to differences in temperature, phase, flow rate, etc. Prior analysis can contribute to a more effective and efficient inspection strategy.

The premise that a larger inspection program improves risk assessment.

Process installations are designed and build for an economically optimum lifetime. Normally, this lifetime is somewhere between 10 and 40 years and over the years the tendency has been to build the installations more robust. Therefore, design degradation rates are very low, typically less than 0.1 mm/y and often much less. Degradation modes and rates in compliant and non-compliant process environments are well known and have been described in numerous authoritative publications e.g. [3-10]. API RP 581 however, gives little credit for low or zero corrosion rates by the manner in which corrosion rates contribute to the multiplier D. To determine the multiplier for thinning the following procedure is recommended: For uncladded components use the equation below:

$$A_{rt} = \max[1-(t_{rd} - Cr * age)/ (t_{\min} + CA), 0.0]$$

Where t_{rd} =thickness reading, *age* = time since last inspection, C=corrosion rate and CA is corrosion allowance. You will note that A_{rt} does not address the actual loss of thickness, but represents an expected relative loss. Mechanically, a 10% loss of wall thickness may be roughly equivalent for all pipes; in corrosion terms an 0.6 mm loss is a very different case than a 2.0 mm loss, especially so when the inaccuracy of UT-testing is taken into account.
Secondly, the equation produces a small or zero value for A_{rt} when corrosion rate Cr is very low. This gives a multiplier or thinning damage factor D=1 and $P\ f(t) = gff\ *F_{MS}$. In other words, an established low corrosion rate is ignored and does not reduce $P\ f(t)$ or risk. This lack of distinction between degradation rates establishes and maintains large inspection programs, even on systems where corrosion is not expected or impossible.
Third, the resolution of UT-testing in the field is not very high. An error of ±0.5 mm may be used. Due to the inherent inaccuracy of UT-measurement, a low Cr cannot be established until a minimum of four or five corrosion readings have been made at intervals of at least one year for each measuring location; for high Cr this number is at least three. In other words, for non-corroding systems RP 581 requires four or five UT-measurements in as many years to confirm that the risk is negligible. This is not useful.

It is useful to recognize that the accuracy of fixed and permanent UT-measurement devices as well as corrosion monitoring probes is far superior to those of manual periodic UT-readings, especially for low Cr. When the critical locations are known, these instruments must be considered for integrity assurance.

Does this make the inspection of components that are subject to very low degradation rates entirely pointless? It depends on the perspective taken, since inspection can have three purposes. First, to verify the design corrosion rate; two, to safeguard against higher losses due to known extraordinary degradation caused by non-compliances; three, to safeguard against entirely unknown threats. Schematically:

	Compliant unit & process	**Non-compliant unit or process**
Known degradation	Design corrosion rates.	Potentially increased corrosion rate. Monitor critical non-compliance, then inspect.
Unknown degradation	Remote probability; detectability doubtful	Elusive

The normal approach in external onstream inspection is to address known and possible forms of degradation, both for compliant and non-compliant configurations. The matrix shows that to safeguard against all conceivable degradation risks, management of unknown degradation must be considered. This can be very difficult. In the last sixty years several new forms of degradation were discovered in process equipment on various processes and materials. All these discoveries were cracking processes, all were abruptly recognized after failures or during internal inspections:

- 1950 – SCC of Ni-base alloys in high purity water
- 1980 – HIC in special pipeline steels under sour conditions
- 1982 – SOHIC in common pressure vessel steel under sour conditions
- 1983 – Deaerator cracking in non-PWHT vessels
- 1990 – SCC of CS in fuel-grade ethanol
- 1990 – irradiation induced cracking of CS

Sometimes the insight grew gradually, such as the steady downward correction of the ½Mo-line in the Nelson curve for hot hydrogen attack.

All these failures were -even with the benefit of hindsight- very poorly detectable through onstream inspection. Inspecting for unknown threats in well developed process systems goes –in my opinion- beyond ALARP.

Conclusion

Integrity management of static equipment in process plant is a multi-disciplinary activity based on a wide range of interdependent methods and technologies. External on-stream or off-stream inspection is one of these methods and is not the most effective one. Still, API RP 581 advocates the management of risk by loss of containment predominantly by external inspection on a large scale. This approach is based on a number of flawed concepts.

1. The concept of a generic failure frequency which proposes that the likelihood of failure is a uniform intrinsic property of all similar equipment. This paper argues on logical and technical grounds, that *gff* is derived from baseless extrapolations and is internally inconsistent.
2. The concept of a damage factor, a factor that multiplies the generic failure frequency, depending on configuration. This paper argues that the fact of recognition of fail-factors already reduces the probability of failure, and does not raise it. Instead, unknown or unrecognized conditions tend to increase the probability of failure.
3. The concept to apply statistics to predict failure. This paper argues that failure processes in static process equipment are far too complex to systematically obey simple statistical relationships. An appearance of statistical order is coincidental.
4. The premise that certainty can rely on inspection alone. This paper argues that corrosion theory, process monitoring and assurance of compliance are more effective means to manage and assure integrity.
5. The premise that a larger inspection program improves risk assessment. This paper argues that larger inspection programs do not necessarily reduce risk and that targeted inspection is more efficient and effective.

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