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Introduction to API RP 78, *Wellbore Surveying and Positioning*

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Abstract

The American Petroleum Institute (API) recently undertook the development of a document called Recommended Practice 78, *Wellbore Surveying and Positioning*, (RP 78), a modern technical industry standard for wellbore placement that can be applied to all wellbore construction applications. The standard is intended to serve as the primary technical reference for proven engineering practices in the applications of oil and gas, geothermal, carbon sequestration, coalbed methane (CBM), horizontal directional drilling (HDD) trenchless boring, mineral ventilation and extraction, scientific coring, and all other subsurface borehole construction applications.

API RP 78's development was led by a group of independent consultants, industry experts, academics, and representatives from public and private energy operators. The Operator's Wellbore Survey Group (OWSG), which later became an official sub-committee of the Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA), initiated the project after a poll of operator members showed the need for a set of minimum industry requirements for wellbore construction, safe-separation, and positioning. The ISCWSA is equivalent to the Society of Petroleum Engineers (SPE) Wellbore Positioning Technical Section (WPTS). The establishment of this standard, made available through API's standards development process, will provide modern practices for all subsurface boring industries, beyond just oil and gas applications.

Introduction

In 2012, the OWSG was formed to bring oil and gas operators together for more frequent collaboration. The group aimed to prioritize operator needs and initially met monthly in Houston, Texas, with operators taking turns as hosts. The OWSG established a mission statement and an antitrust statement, which remain unchanged today.

The mission of the OWSG is to enhance confidence in wellbore positional accuracy by promoting best practices in directional surveying. This involves calculating wellbore positional uncertainty, also known as error models, using directional survey software programs.

To comply with anti-trust laws, the following anti-trust statement is read at the start of every OWSG meeting to ensure attendees understand the rules and regulations governing the meeting:

> *We are meeting to help develop and promote good practices in wellbore surveying necessary to support wellbore construction which enhance safety and competition. The meeting will be conducted in compliance with all laws including the antitrust laws, both state and federal. We will not discuss prices paid to suppliers or charged to customers nor will we endorse or disparage vendors or goods or services, divide markets, or discuss with whom we will or will not do business, nor other specific commercial terms, because these are matters for each company or individual to independently evaluate and determine.*

Virtual meetings are now held online every other month and are open to anyone, as opposed to previously being exclusive to oil and gas exploration and production operators. Presentations and past meeting minutes are posted on the ISCWSA website, and those interested in participating can request to be added to the distribution list through the website.

OWSG Focus Areas and Initiatives

The need for a standard set of position uncertainty models, also known as error models, became a priority at early meetings. Error models, also called instrument performance models (IPM), play a crucial role in the management of directional survey operations (Thorogood et al., 1990). Another common name for an error model is a positional uncertainty model (PUM). Examples of instruments that require error models include conventional legacy film-based instruments, modern electronic magnetic tools, and gyroscopic survey systems.

Some of these models serve only a utility purpose and are not based on survey instruments. These include:

- Inclination-Only Planning: a method for near-vertical wellbore paths based on departure trend analysis from field studies.
- Blind Model: a conservative model applied to long intervals without directional survey data.
- Unknown Model: a conservative instrument performance model used when data is available but key attributes are

missing.

- Zero-error Model: a utility commonly used for wellbore paths that need to avoid subsurface hazards or follow specific boundaries such as hardlines.

Separation Factor (SF) is a ratio of separation distance to the combined uncertainty of subsurface proximity analysis for drilling and planning. Error models generate ellipsoids and are included as the denominator of the SF calculation. The closest distance between wellbores is used as the SF numerator and is termed the center-to-center least-distance or closest approach. The WPTS Error Model Maintenance Sub-Committee previously maintained a set of error models based on the industry standard Accuracy Prediction for Directional MWD (Williamson et al., 1999).

In addition, another challenge presented itself because of unintentional reliance on invalid and inconsistent models from various sources. Before the MWD model, uncertainty calculations were based on the now-retired Wolff and de Wardt (WdW) systematic model (Wolff et al., 1981). Developed in the 1990s, the WdW systematic method was once used in the application of modern gyroscopes. However, these advanced gyros were different from the conventional film-based gyros covered in the systematic method. WdW continued to be used for modern gyro instruments like advanced inertial and true north-seeking earth-rate gyros until a new key industry paper was authored establishing a framework for all gyros (Torkildsen et al., 2004).

The elementary half-percent calculation method is another separation rule used in the industry. This method calculates the separation distance based on one-half percent of the measured depth (MD), resulting in a linear slope of five feet of separation per thousand feet of depth along the borehole. It does not consider wellbore position uncertainty and is based on practical experience rather than engineering theory or measurement. For example, at 10,000 ft MD, the separation distance would need to be at least 50 ft, while at 15,000 ft MD, it would need to be at least 75 ft. While still in use today, depth-based rules are secondary to SF rules and are mainly used to complement them.

Another important issue raised by operators focused on the improper application of the standard MWD model. It became apparent that because the industry had been using this model with low-resolution references, unrealistic position confidence was occurring, and a need existed to take advantage of the improved magnetic models. The MWD error model was modified to accommodate both the low-resolution (LRGM) and high-resolution (HRGM) geomagnetic models. The original MWD model assumes the use of a standard resolution geomagnetic model (SRGM). The common SRGM is the BGGM crustal field model developed by BGS, and it determines local magnetic reference values. Geomagnetic models are used to calculate the magnetic declination correction crucial for directional and horizontal well surveys and are the primary source of lateral uncertainty. The date-sensitive reference values, including magnetic dip angle and total magnetic field strength, are crucial for quality control and meeting field acceptance criteria.

The industry faced a new challenge with the need to adopt improved magnetic models such as NOAA's HDGM (Maus et al., 2012). This new model contains detailed information on the Earth's main magnetic and crustal fields derived from satellite and sea vessel measurements and is updated annually to correct for changes over time. However, at the time, the MWD model was not designed to accommodate a LRGM and HRGM such as WMM or IGRF and HDGM, respectively.

A vital need arose to adopt the improved magnetic models. Most operators relied on magnetic models supplied by vendors or software providers, leading to inconsistency between planning and drilling operations.

OWSG Error Models

The OWSG set of error models (Rev2) was developed to establish consistency among operators and service providers (Grindrod et al., 2016). The paper defines five primary sets:

Set A: Standard
Set B: Extended
Set C: Vendor-supplied
Set D: Gyro software validation
Set E: Prototypes in development

The OWSG models were updated in June 2015 with a model selection guide and a standardized naming structure. Meanwhile, the ISCWSA MWD models were updated to Rev4 from the original Rev0 in 1999 and were included in OWSG Rev2.

The OWSG models were handed over at the 50th ISCWSA meeting and are now stewarded by the Error Model Maintenance Sub-Committee (EMM_SC). The latest revision (updated September 2022) is referred to as ISCWSA Revision 5-1, and the OWSG is no longer used in the model naming. The latest ISCWSA generic tool codes are available on the ISCWSA website in Excel workbooks for easy download. The update includes generic reference names for low, standard, and high-resolution reference models, and details for five primary geomagnetic reference categories can be found on the ISCWSA EMM_SC website, including power spectrum degree and update rate requirements.

The OWSG meetings continued discussions related to the need for establishing standard engineering practices in survey data management, directional planning, collision avoidance, and drilling near offset wells. Conversations centered around the need for joint survey operating and reporting procedures (JSORP) to confirm calculated wellbore positions and estimate uncertainty. The requirement for raw sensor measurements (RSM) to be independently processed surveys was discussed because service providers were not commonly reporting RSM. This led to be improved survey reporting requirements with more reference information. Desired post-job reports included BHA details, steering reports, tool calibration, estimated uncertainty, and quality control plots. A final survey program with a specified error model was required for loading into a survey management database.

Immediately following the release of OWSG Rev2, the group shifted its focus to developing established engineering practices in wellbore positioning. After careful consideration, the group collectively decided to seek the formation of a technical workgroup under API and organize teams to start drafting what would become API RP 78. Recognizing the importance of wellbore surveys as a safety-critical aspect of wellbore assets and the legal and economic necessity of accurate wellbore positioning, the task group was established. The project's main objective and motivation were to explicitly state uncertainties in position as part of the wellbore record and to add key attributes to ensure final surveys are properly loaded into the survey management system for future safe separation planning.

Membership in API’s standards-writing committees is on a volunteer basis, free, and open to anyone with both a direct and material interest; corporate membership in API is not required to participate. API committees are comprised of various subcommittees and/or groups (i.e., task, resource, or work groups) whose members consist of industry professionals and subject matter experts who are appropriate to develop standards. The members include, mostly but not limited to, oil and gas companies, manufacturers and suppliers, contractors and consultants, and representatives from government authorities and academia. By API policy, all new projects sought must be justified by valid business and safety needs, and only after obtaining the appropriate approvals may activity commence to draft new standards, revise current standards, or develop some other technical publication or output (API et al., 2022).

API RP 78 Task Group (TG)

To streamline the authorship process, the task group was divided into various sections to address specific topics. Each section focused on a particular subject, and each group consisted of a section leader, a technical lead, and a team of volunteer contributors. The section leader was tasked with keeping the team on track and ensuring that deadlines were met. They were also responsible for maintaining consistency across all sections with respect to the API standard writing style guide. The technical lead ensured that all statements were technically accurate and reflected established engineering practices. The main sections of the workgroup held separate meetings throughout the duration of the document-drafting process. The key topical sections include:

- Purpose and Scope
- Terms and Definitions
- Measurement and Calculation
- Survey Mathematics
- Planning & Engineering
- Survey Program
- Quality Assurance / Quality Control (QAQC)
- Engr to Operation-Execution Handoff
- Directional Survey Records (originally called Post Survey Execution)
- Collision Avoidance
- Surface Location
- Software
- Positional Uncertainty Models
- Database
- Maps-Plots-Graphics

The TG began meeting in April 2016, where they worked diligently to draft comprehensive sections that required extensive refinement, particularly the QAQC section, which focused on the quality of depth, magnetic, and gyro instruments.

Once combined, the large body of text from these sections was distilled into a minimal set of requirements by the ISCWSA QAQC Sub-Committee (QAQC_SC); the purged text was saved for potential future use to develop an educational eBook. API RP 78 is intended to support industry practice through concise requirements and not replace previously published industry eBooks, textbooks, guidance documents, educational materials, and technical papers.

Additionally, simultaneous work by the ISCWSA Collision Avoidance Sub-Committee (CA_SC) led to the publication of two primary peer-reviewed journal articles, which served as the basis for the need of this new industry technical standard (Sawaryn et al., 2019). The first manuscript conference proceeding's paper focused on the key elements of collision avoidance management, while the second conference paper established the first agreed-upon industry-wide unified wellbore collision avoidance separation rule (Sawaryn et al., 2017). These two papers were significant contributions to the industry and provided the foundation and rationale for why API RP 78 was an essential industry standard.

The eight key management principles for determining the Minimum Allowable Separation Distance (MASD), as shown in Figure 1 (Sawaryn et al., 2017), are:

1. Data Structure Integrity
2. Position Uncertainty
3. Well Reference Point
4. Wellbore Survey Program
5. Collision Avoidance Management
6. Wellbore Survey Operations
7. Quality Assurance
8. Effective Communication

The management principles paper features the importance of API RP 78 by highlighting nineteen documented wellbore misplacement case studies resulting from gross errors caused by the absence of standard industry practices. To avoid similar incidents, API RP 78 aims to establish a uniform set of best practices to ensure safe and accurate wellbore positioning.

The eight key elements depicted in Figure 1 form the crucial components necessary for effective collision avoidance management. When combined, they enforce the requirement of maintaining the Minimum Acceptable Separation Distance

(MASD). This distance considers the positional uncertainties associated with both the wellbore and the offset wellbore directional trajectories, thus preventing well collisions and promoting subsurface safety.

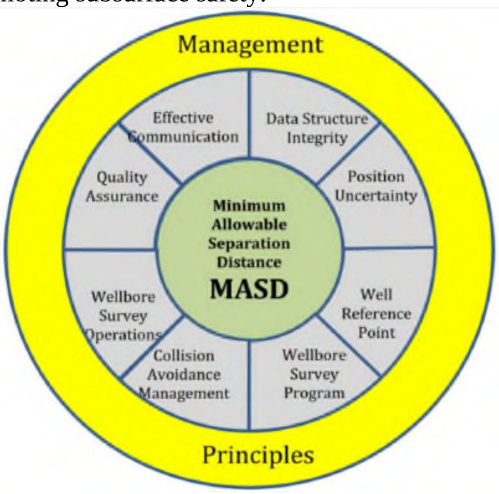

Figure 1 – Elements of a Collision Avoidance Systems (Sawaryn et al., 2017)

The MASD serves as the foundation for determining the acceptable deviation from the planned well construction process to ensure a safe separation distance is maintained.

Human Factors in Collision Avoidance Management

To achieve optimal results in collision avoidance, the following human factors must be given the utmost consideration:

- Taking a proactive approach to evaluating potential risks through comprehensive assessments always errs on the side of caution.
- Ensuring all involved in the collision avoidance process are properly trained, evaluated for competence, and audited by both the operator and the directional drilling service provider.
- Implementing a stringent STOP-WORK policy in cases where wellbore collision raises serious concerns about health, safety and environmental (HSE) risks.
- Recognizing that both dangerous actions and poor design and planning can create hazardous conditions.

Well Separation Rule

The SPE WPTS Separation Rule is a unified rule that calculates the probability of the reference well crossing into an unacceptable risk zone regarding a specific offset well (as shown in Figure 2). This section outlines the main equations and rules for safe separation calculation, collaboratively developed by operators and service providers within the CASC under the guidance of the primary author of key peer-reviewed journal papers (Sawaryn et al., 2017, 2018, 2019). This work marks a significant achievement for the industry.

Crossing the boundary plane depicted in the figure is considered a well collision and carries the risk of unknowingly steering into the offset well while attempting to steer away (Sawaryn et al., 2017). API RP 78 establishes the common engineering practices necessary to maintain system integrity when implementing well separation rules, equations, and related practices during the planning and execution of new wellbores (drilling and surveying operations).

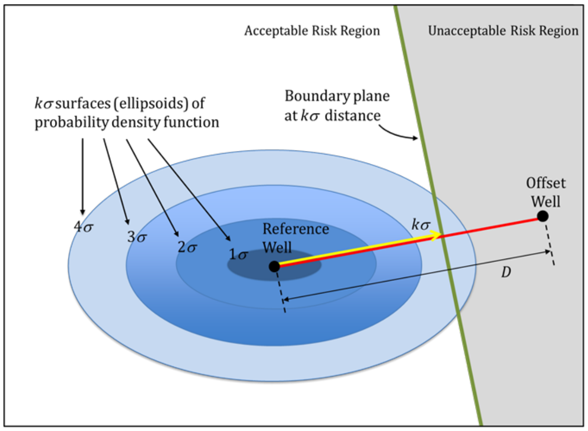

Figure 2 – This diagram shows the application of the SPE WPTS Separation Rule which defines the probability of the reference well crossing into the unacceptable risk region (shaded) relative to a specified offset well. The green line represents the boundary at a distance of kσ from the reference well separating the acceptable and unacceptable risk regions. The boundary is depicted as a plane in 3D (a straight line in 2D) and is perpendicular to the line connecting the points of interest of the two wells. (Sawaryn et al., 2017)

The separation rule defines a critical threshold for the allowable distance between two wells based on their relative positional uncertainty. It is expressed as a dimensionless number known as the separation factor (SF), which is calculated as the ratio of the adjusted center-to-center distance between the wells as a function of their relative positional uncertainty. When the SF value equals 1, it indicates a critical condition; drilling should stop for further evaluation by higher authority. The equation for calculating SF is provided in Equation 1, and its parameters are explained in Table 1.

$$SF = \frac{D - R_r - R_o - S_m}{k\sqrt{\sigma_s^2 + \sigma_{pa}^2}} \qquad \text{(Eq. 1)}$$

The term $k\sqrt{\sigma_s^2 + \sigma_{pa}^2}$ in Eq. 1 is equivalent to the distance from the reference well to the boundary plane.

Parameter	Description
D	The distance between two well centerlines is defined as the shortest distance from a specified point on the centerline of the reference well to the nearest point on the centerline of the offset well. The reference well's centerline point is specified first, and the offset well's

	closest point of approach is determined in three-dimensional space or in the plane normal to the reference well when cylindrical diagrams are utilized for collision monitoring.
R_r	The open hole radius of the reference borehole.
R_o	The open hole radius of the offset borehole.
S_m	The "surface margin" term serves to add an extra safety margin to the effective radius of the offset well. This accounts for potential small errors that may go unnoticed and addresses one of the limitations of the separation rule. By including this term, the minimum acceptable distance between the reference and offset wells is established during facility design, ensuring that the separation rule will prohibit any actions that would bring the wells into nominal contact even if the positional uncertainty is zero.
k	The dimensionless scaling factor that determines the probability of well crossing.
σ_{pa}	The project-ahead uncertainty quantifies the standard deviation of uncertainty in the projection of the wellbore path ahead of the current survey station. It is partially dependent on the projection distance, which is calculated as the sum of the current well depth and the next survey interval. The actual magnitude of the uncertainty is influenced by factors such as the planned curvature of the wellbore and the BHA performance in the current formation. However, this estimate is only an approximation, and for mathematical simplicity, the project-ahead uncertainty (σpa) is defined as the radius of a sphere oriented normal to the reference well.
σ_s	The relative uncertainty at one standard deviation between the two points of interest derived from their respective positional uncertainties σ_r and σ_o in the direction of D. Note that $\sigma_s = \sqrt{\sigma_r^2 + \sigma_o^2}$

Table 1 – Separation Factor Equation Parameters

The wellbore positioning standard surface margin is 0.3 meters with a risk assessment dimensionless scaling safety factor of 3.5. The project-ahead uncertainty may reach 0.5 meters if recommended survey intervals are not followed and does not account for routine drilling or other well objectives. To be considered valid, surveys must meet defined quality control criteria for the survey tools and positional uncertainty model used.

Survey frequency increases with higher dogleg severity (DLS) and decreased separation factor (SF) and may be adjusted for non-standard tool joints or stands according to API RP 7G-1 (17^{th} Edition, 2023). Survey intervals may also be extended if there is a clear deviation from HSE-classified offsets.

Table 2 indicates that the maximum survey intervals should decrease with lower separation factors (Sawaryn et al., 2017).

Maximum Survey Interval [ft]		DLS [deg/100 ft MD]		
		< 1	1 – 5	> 5
SF [-]	>2	200	100	33
	1.5 – 2	100	100	33
	<1.5	33	33	33

Table 2 – Recommended Maximum Survey Interval for Safe-Separation and Collision Avoidance (Sawaryn et al., 2017)

In formations where the behavior of the bottomhole assembly is difficult to predict, the project-ahead uncertainty should also be increased. When these values are plugged into Eq. 1, the simplified separation rule for HSE risk offset wells is obtained and is expressed in metric units (Equation 2).

$$SF = \frac{D - R_r - R_o - 0.3}{3.5\sqrt{\sigma_s^2 + 0.25}} \quad \text{(Eq. 2)}$$

The critical value for the separation factor (SF) is 1, indicating that acceptable well separation requires SF to be equal to or greater than 1; this value is mandatory for HSE risk wells. Other SF threshold values may be set as triggers for collision avoidance measures.

The minimum allowable separation distance changes with depth, considering the positional uncertainties of the well trajectories. The most stringent MASDs apply to offset wells that pose an HSE risk. The difference between the planned well path and the MASD (calculated using Equation 3) is called the allowable deviation from the plan (ADP). In practice, the ADP may be further limited to prevent future collision problems deeper in the well.

$$D_{MASD} = k\sqrt{\sigma_s^2 + \sigma_{pa}^2} + R_r + R_o + S_m \quad \text{(Eq. 3)}$$

If the distance *D* falls below D_{MASD}, then SF < 1. The difference between the planned distance D_{plan} and the D_{MASD} is the allowable deviation from the plan D_{ADP}, Equation 4.

$$D_{ADP} = D_{plan} - D_{MASD} \quad \text{(Eq. 4)}$$

Offset Well Status and Environment Classification

In the planning and drilling process, the assessment of offset well status and environment classification is crucial to ensuring safe drilling operations. The most concerning collision risk is a loss of well control, which can result in disastrous consequences. Additionally, other HSE collision hazards may include abandoned radioactive sources, platform piles, and subsurface mines.

Evaluating the reference well and offset well pressures is essential to minimize the risk of well control incidents, as they often pose an HSE risk. Accurately calculating the reference well pressure at the point of potential intersection requires an understanding of fluid parameters such as mud types, fluid density, and the true vertical depth (TVD) of the intersection. Consequence assessment is a critical consideration in the event of a collision that could cause a loss of well control (Sawaryn et al., 2017).

The Wellbore Positioning Standard

The recent QAQC_SC rewrite of depth, magnetic surveying, and gyro surveying has resulted in the completion of the primary document. An editorial review has been conducted to finalize the document for balloting, with the aim of releasing the final version by the end of Q2 2023 if approved. The document is now organized into six main categories:

1. *Scope*
2. *Normative References*
3. *Terms, Definitions, Symbols, and Abbreviations*
4. *Wellbore Positioning – Technical Requirements*
5. *Wellbore Positioning – Process*
6. *Data Transfer – Output, Deliverables, and Transfer Files*

API RP 78 includes coordinate references, illustrations, mathematical equations, nonmagnetic isolation, magnetic field predictions, target sizing, audits, and quality controls for various facets of the surveying process. These details are included in the three primary annex sections of the standard.

Conclusions

The API RP 78 (*Wellbore Surveying and Positioning*) standard will revolutionize the wellbore construction industry and serve as the gold standard for maintaining safe separation from subsurface hazards. This vital document is the result of the collective efforts of a dedicated group of industry volunteers and must be embraced by all wellbore construction participants. To ensure the standard remains relevant and up-to-date, a volunteer group will be tasked with performing periodic reviews with a minimum frequency of every five years. The standard will be reassessed to determine if it should be revised, extended, reaffirmed, or even withdrawn, reflecting the rapidly evolving technology and changing landscape of the industry. The hope is for industry-wide adoption.

Acknowledgments

The authors acknowledge the collective efforts of numerous industry volunteers and contributors who have been instrumental in the development of this standard. The authors would like to recognize and extend their gratitude to the OWSG founding members, API RP 78 task group section leaders, technical leads, and other significant contributors who selflessly supported this project and made its completion possible. Special recognition goes to Steven J. Sawaryn, Pete Clark, and Lisa Grant for their invaluable contributions.

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In Memoriam

The authors would like to recognize the significant contributions of Steven J. Sawaryn (1955–2021). Steven, a renowned petroleum engineer who earned his PhD in this field from Cambridge University, received numerous awards and honors, including the SPE Drilling Engineering Award at the 2019 SPE Annual Technical Conference and Exhibition and several SPE Service and Technical Editor Awards (JPT et al., 2021). Steven's leadership as the Collision Avoidance Sub-Committee Chair resulted in a collaborative industry effort and the establishment of a technical framework for the industry standard (Sawaryn, 2021). His last publication resulted in solving a directional drilling problem he had been working on for two decades, was a landmark solution to a technical problem, and is a testament to his brilliant career (Sawaryn, 2021).

Nomenclature

API = American Petroleum Institute
ISCWSA = Industry Steering Committee on Wellbore Survey Accuracy
HSE = Health, Safety and Environment
OWSG = Operator's Wellbore Survey Group
SPE = Society of Petroleum Engineers
WPTS = Wellbore Positioning Technical Section
IOGP = International Association of Oil and Gas Producers

IADD = International Association of Directional Drilling
IPM = Instrument Performance Model
IGRF = International Geomagnetic Reference Field
WMM = World Magnetic Model
LRGM = Low Resolution Geomagnetic Model
SRGM = Standard Resolution Geomagnetic Model
HRGM = High Resolution Geomagnetic Model
HDGM = High Definition Geomagnetic Model
BGS = British Geological Survey
BGGM = BGS Global Geomagnetic Model
PUM = Position Uncertainty Model or Error Model
NOAA = National Oceanic and Atmospheric Administration
QAQC = Quality Assurance / Quality Control
QAQC_SC = QAQC Sub-Committee
CA_SC = Collision Avoidance Sub-Committee
EMM_SC = Error Model Maintenance Sub-Committee
MWD = Measurement While Drilling
MASD = Minimum Allowable Separation Distance
ADP = Allowable Deviation from Plan

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