Collision Avoidance Calculations - Current Common Practice

Introduction
Many Operating companies and Directional Drilling contractors have policies that define how they manage the risk of well collision. Such policies invariably include one or more rules that define how close the reference well can be drilled to an offset well.

Collision avoidance policies normally specify the corrective actions triggered by comparison of the nominal well proximity with a minimum allowable separation distance. The prime purpose of this paper is to explain the ways in which minimum allowable separation is commonly defined and calculated.

The adoption of a particular minimum allowable separation rule, no matter how conservative, does not ensure acceptably low probability of collision. Many other factors contribute, including the level of compliance by office and rig personnel with collision avoidance procedures, and the completeness and correctness of the directional database.

Most of the terminology used in this document is explained in the Collision Avoidance Lexicon, which was also produced by the Collision Avoidance Work Group. Both documents are available on the ISCWSA web site.

Recommendations made in this document are based on consensus within the Work Group; no greater authority is claimed.

Collision Avoidance Work Group, 2011

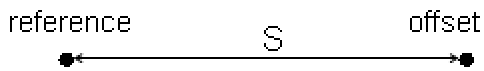
Contents

1.0 Classification

Collision avoidance rules can be generalised as falling into one of four categories based on the criterion used. The abbreviations S, E, R and P have been adopted here for convenience, but they are not an Industry standard nomenclature.

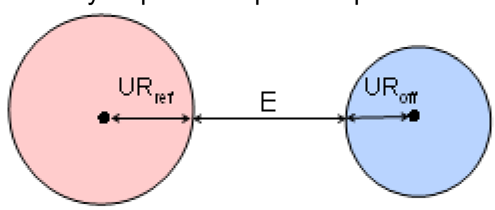
A collision avoidance policy may make use of more than one type of rule.

1.1 S type - Well separation distance



Since it does not account for position uncertainty, the S type rule is usually considered too simplistic to be used as the primary rule for a collision avoidance policy, but it may be the only meaningful rule at shallow depth and close proximity. Other rules may give a false sense of security when position uncertainty is very low and wells are very close, as might be the case at shallow depth. An S type rule is therefore sometimes used in conjunction with another rule as part of a collision avoidance policy.

1.2 E type - Position uncertainty ellipse or ellipsoid separation distance



UR_{ref} = radius of ellipse of uncertainty on reference well
UR_{off} = radius of ellipse of uncertainty on offset well

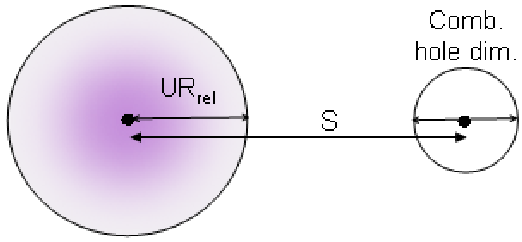
E may be calculated as minimum distance between ellipses or as $S-(UR_{ref}+UR_{off})$

1.3 R type - Ratio of well to well separation distance over combined position uncertainty

Frequently referred to as Separation Factor or Clearance Factor
Can be calculated as S/(S-E) or more commonly $S/(UR_{ref}+UR_{off})$

Separation Factor is often shortened to SF and therefore often misinterpreted as a safety factor. In fact, because the uncertainty dimensions relate to a probability distribution, a SF of 2 does not represent a situation that is 2 times safer than a SF of 1.

1.4 P type - Probability of intersection



UR_{rel} = combined relative uncertainty at 1 sigma.
Comb hole dim = Reference hole or csg diameter + Offset hole or csg diameter (see section 2.5).

Probability of intersection is calculated as a function of S, UR_{rel} and the combined hole dimensions (see section 2.11).

The P type rule is the only rule that provides quantification of probability of collision. However, current methods of calculation are based on assumptions that are not valid under all conditions.

2.0 Calculation Options

A rule consists of several components, and variations exist for each component, so it is necessary that each is specified clearly. Some variations may result in insignificant differences in results. However, such differences are noticeable in reports, so it is important to be consistent when implementing the same rule in different programs or on different computers. The following list describes variations affecting 13 commonly used components of collision avoidance rules:

When investigating discrepancies between two independent E, R or P collision scans, a sensible first step is to check that both systems return the same S scan result. If they do not, the difference is probably associated with items 2.1 or 2.2 below.

2.1 Well centre to centre distance calculation (Affects S, E, R, and P)

Typically, software supports 3 scanning methods:

- Minimum Distance (also referred to as 3D or closest approach)
    - the normal to the offset
    - where there is no normal to the offset for the current point of interest (such as when the reference well is deeper than the offset), minimum distance is calculated as the line joining the point of interest to the bottom hole location on the offset
    - typically used in numerical analysis
- Travelling Cylinder plane
    - the normal to the reference well
    - typically used only for plotting on a Travelling Cylinder diagram
- Horizontal plane
    - not typically used for collision avoidance calculations

Although the travelling cylinder is intended only as an alternative method of presenting proximity calculations, use of the TC plane in the calculation of the chosen rule does change the result, and can therefore affect real time directional drilling decisions. It is therefore a key calculation variable and not merely a reporting option.

The horizontal plane option is not supported by all software. Where it is present, there is a danger of it being selected in error.

All three scanning methods can fail to identify the depth of closest approach if the scanning interval is too great. It is therefore important that software and procedures are designed to ensure that all offset wells and closest approaches are identified in time to take corrective action (see item 2.2). Scanning in the horizontal and travelling cylinder planes can miss offset wells, or identify them late, if they lie close to the scanning plane. Also, wells approaching from ahead of the bit will not normally be identified by these scans. For TC clearance reports, these weaknesses are overcome by running Minimum Distance scans from the offsets back to the reference well. (Note that this method results in irregular report intervals.)

2.2 Scanning interval (Affects S, E, R, and P)

Scanning interval is not an explicit element of close drilling rules. It is normally assumed that the scanning method will identify all points of significantly close approach.

Software performs clearance scans at predefined intervals along the wellpath; for instance at each survey station for actual wellpaths, and at a regular MD increment (typically 30m or 100ft) for planned wells. The exact point of closest approach is then identified by interval bisection or a similar method. Some software will insert additional stations where it can determine that there are intermediate closest points between successive scanned stations (points of convergence).

As mentioned to in section 2.1, TC scans will normally be performed at regular intervals on the offset well, resulting in irregular reference well station intervals in the clearance report.

Collision scanning calculations can be time consuming on large congested fields, even at 30m intervals, so shorter intervals are unlikely to be set as the default. However, some wellpath geometries may require shorter increments to ensure identification of the intervals containing points of closest approach. Therefore users should understand the scanning logic of the software being used, and the software should allow the user to override the default interval.

2.3 Uncertainty models used to calculate position uncertainty (Affects E, R, and P)

Several different uncertainty models exist and may be in use. The ISCWSA general models are widely used, but cone models and Wolff and De Wardt models are still specified by some Operating companies. In any case, these are only general models that must be populated with tool specific term values, which may vary between users of the same general model.

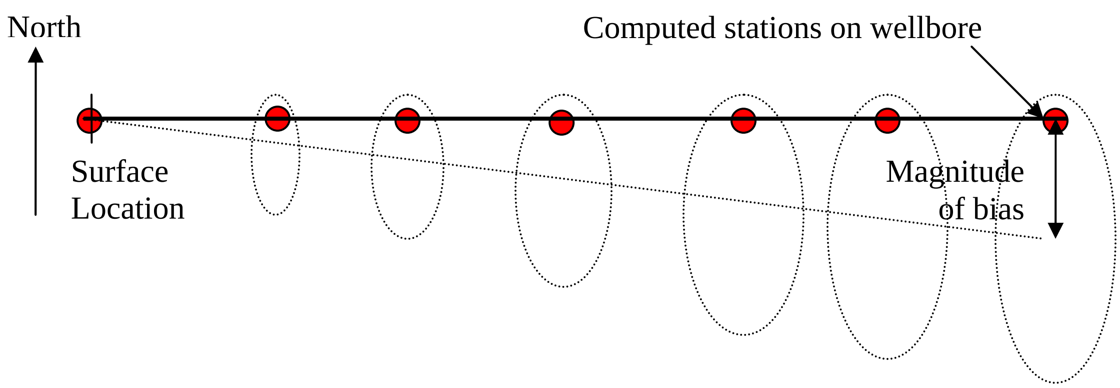
Management of biased error sources
Most errors are assumed to have distributions with a mean of zero, but some have non-zero means. The offset of the mean from zero is referred to as a bias error. It is treated as a known error, not a statistical uncertainty.

The ISCWSA model accommodates biased terms. Its generic MWD tool model identifies drill pipe stretch and axial magnetic interference as being terms that are likely to be biased, and provides bias and uncertainty values for both options. However, the inclusion of biased errors results in position and position uncertainty outputs that can be difficult to interpret and to apply in routine operations.

Several approaches to managing biased errors are in use:

- Remove bias
    - o Correct survey for bias error and set the term's bias value to zero
- Ignore bias
    - o Set the term's bias value to zero and increase the term's uncertainty to account for bias.
- Include bias in position uncertainty reports, separation distance calculations and collision avoidance rule calculations:
    - o Always include bias in separation calculations

    or
    - o Only include bias when it results in a larger minimum allowable separation distance (masd)



Example of effect of assumed biased azimuth error due to axial magnetic interference.

The above diagram shows the commonest method of representing bias. The ellipsoid centers are displaced, while the nominal wellpath remains unchanged. However, when incorporating bias into any of the 4 collision avoidance type rules, the bias is effectively applied to the well separation distance.

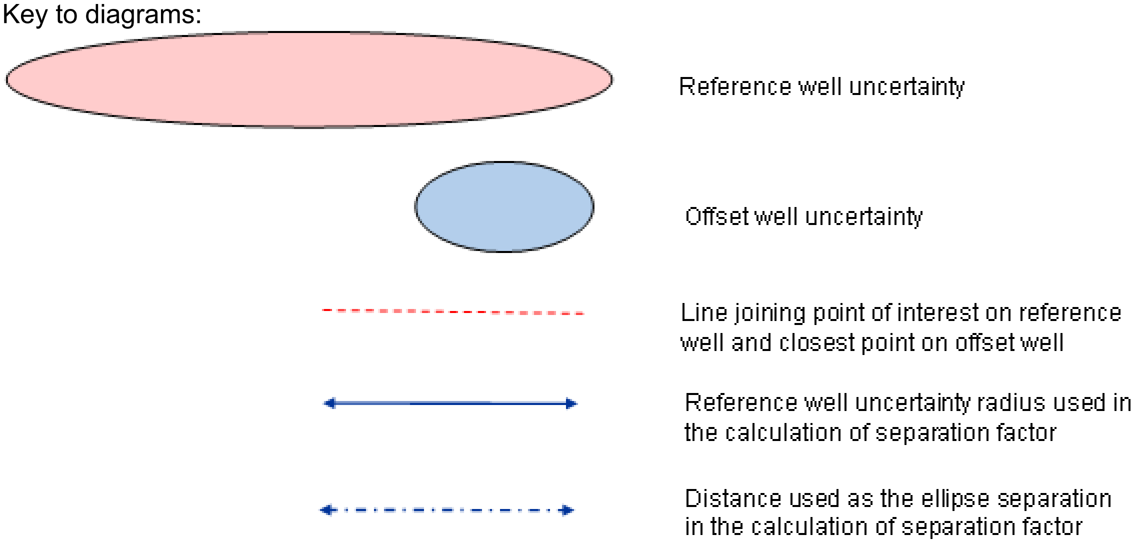
For drillstring magnetic interference, the sense of the bias error is dependent on the angle between the wellpath and the Earth's magnetic field vector. For instance, a wellpath drilled in the northern hemisphere will have an opposite bias to the same well path drilled in the equivalent location in the southern hemisphere. The bias term value provided in SPE 67616 for the ISCWSA generic MWD tool model is positive, and this might be misinterpreted as meaning that the term value is always positive. The implementation of this term may not be consistent across all software applications that allow the biased version of the term.

2.4 Ellipsoid radius (Affects E and R)

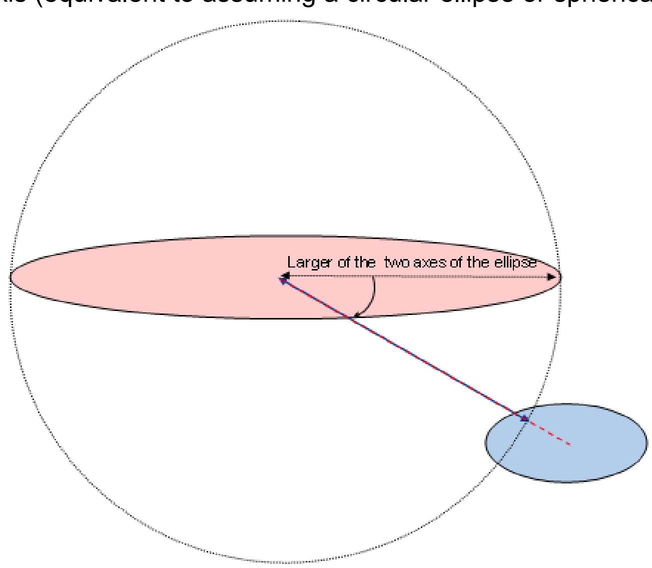
In some software, the actual 3D geometry is first projected onto a 2D plane, but the methods listed below may all be applied to ellipsoids or ellipses. The choice between 3D and 2D and, for 2D, the choice of the plane of projection, may have a minor effect on results.

In the following diagrams, only the construction of the radius on the reference well is shown, but the same method would be applied to determine the offset well's radius.

Key to diagrams:

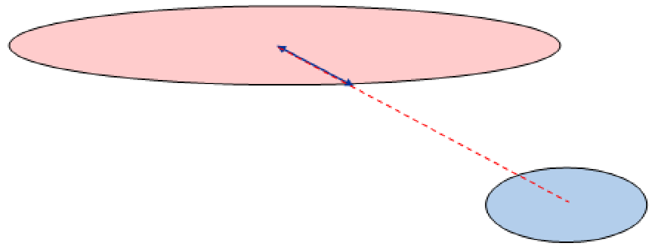


- Largest semi-axis (equivalent to assuming a circular ellipse or spherical ellipsoid)



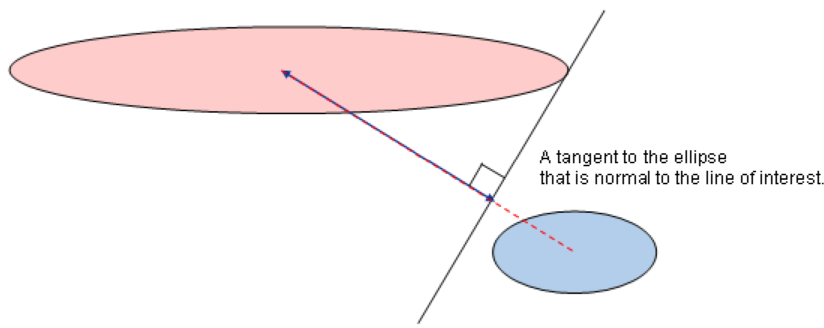
This method generally over estimates position uncertainty, but it does so in a poorly controlled way. It delivers no additional safety in certain circumstances, but can be over conservative in others. It may trigger unnecessary re-planning, steering or well intervention.

- Radius of the ellipse or ellipsoid along the line joining the points of interest on the reference and offset well (probably not implemented in any current software).



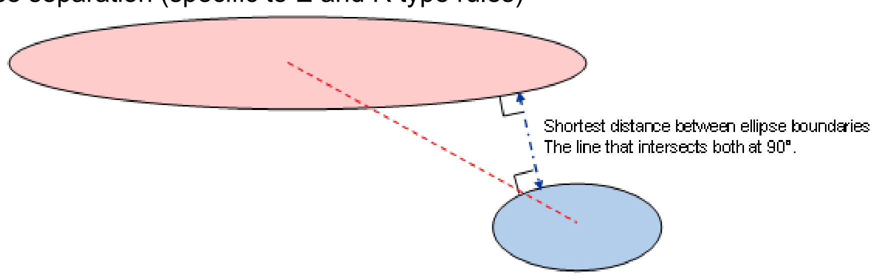
For some relative orientations of the ellipsoids, this method under estimates uncertainty.

- Radius of pedal curve or surface (projected dimension of the ellipse or ellipsoid on the line joining the points of interest on the reference and offset well).



The pedal curve ellipsoid radius is the default method for the majority of well planning software, but over estimates uncertainty for some relative orientations of the ellipsoids.

- Ellipsoid or ellipse separation (specific to E and R type rules)



The shortest distance between the ellipse or ellipsoid surfaces, independent of line of interest. When this method is used in an R type rule, the ratio is calculated as S/(S-E). (See 1.3.)

2.5 Inclusion of hole and/or casing diameters (Affects S, E, R, and P)

The inclusion of hole dimensions in the calculation is necessary for P type rules, and is recommended for all other rules. When wells are in close proximity, it is misleading and potentially dangerous not to include these dimensions in the calculations.

There are some minor variations in how the dimensions are accounted for:

What is included?

Reference	Offset
Hole	Csg
Csg	Csg
Hole	Hole
None (not an option for P type rule)	

How is it included?

- Subtracted from well separation distance
- Added to uncertainty dimension (Option for R type rules)

2.6 Scaling of ellipse or ellipsoid (Affects E and R)

Choice of confidence interval
This choice has a large effect on ellipsoid dimensions. The choice is often arbitrary, but 2, 2.58, 2.79 and 3 sigma are examples of values currently in use.

How it is specified

a. Number of standard deviations

- confidence level is implicit

Probability	standard deviations				
dimensions	±1	±2	±2.58	±2.79	±3
1	68.27%	95.45%	99.01%	99.47%	99.73%
2	39.35%	86.47%	96.41%	97.96%	98.89%
3	19.87%	73.85%	91.63%	94.93%	97.07%

b. Confidence level at specified number of dimensions

- number of standard deviations is implicit

Probability	Confidence level				
dimensions	68.3%	90.0%	95.0%	99.0%	99.7%
1	0.9999	1.6448	1.9599	2.5758	2.9677
2	1.5151	2.1459	2.4477	3.0348	3.4086
3	1.8779	2.5002	2.7954	3.3682	3.7325

2.7 Error distribution function (Affects P)

Universal current practice is to assume normal distribution. Analysis carried out by StatoilHydro showed evidence that some geomagnetic reference errors have a heavy tailed distribution. Work Group members report anecdotal evidence that several error terms may behave in a similar way. Such behaviour has significant implications for probability of collision calculations (P type rules).

A team from the Group looked at alternative distributions that would better model such behaviour. They found that very few suitable heavy tailed functions exist and all introduce computation complexity which may make their implementation impractical.

A 2009 re-evaluation of the uncertainties associated with the widely used BGS Global Geomagnetic Model (BGGM) resulted in error estimates significantly different to the normally distributed estimates currently in use. The resulting paper (Macmillan S., McKay A. and Grindrod S., "Confidence Limits Associated with Values of the Earth's Magnetic Field Used for Directional Drilling", SPE/IADC 119851) concluded that the error distributions are best modelled using look up tables categorized by desired confidence level, and recommended that the ISCWSA MWD model's geomagnetic term values be replaced with inputs from the look-up tables.

The likelihood of typical error distributions being thick tailed makes the estimation of probability of intersection based on the assumption of normal distributions optimistic. This may be one reason why some collision avoidance policies only apply P type rules in situations which do not represent a HSE risk.

The Work Group recommends that, when deriving error term values from data, 1 standard deviation is defined as the 95.4% confidence interval divided by 2. This method ensures a better fit between the normal and actual distribution within the critical range of confidence levels.

2.8 Inclusion of surface location uncertainty (Affects E, R, and P)

More correctly the well reference point position uncertainty, or the uncertainty associated with the tie-on depth for the first downhole survey station. This may be a sub-sea location on offshore developments.

Current practice varies:

- Included or not included
- If included:
    - Simply added to downhole survey uncertainty
    - Correlation with downhole survey uncertainty accounted for (invariably uncorrelated)
    - Correlation with offset well surface uncertainty accounted for (can be correlated or uncorrelated)

Surface location uncertainty can be significant with respect to well to well proximity, so it is good practice to always consider it. The correct way to include it is to properly account for its correlation with other survey uncertainties (bullets 2 and 3 under the "If included" option above).

2.9 Calculation of relative uncertainty (Affects R and P)

Accounting for correlation of errors well to well:

- Use separate ellipsoids for the two wells
    - Current common practice for R type
- Assume uncorrelated (coefficient 0)
    - Current common practice for P type
    - Achieved by adding the ref and offset wells' covariance matrices.
- Take proper account of actual correlation
    - Well to well correlation is handled correctly by the ISCWSA models through the rho 3 correlation coefficient, if implemented
    - The mathematics associated with the calculation of relative uncertainty is contained in SPE 67616

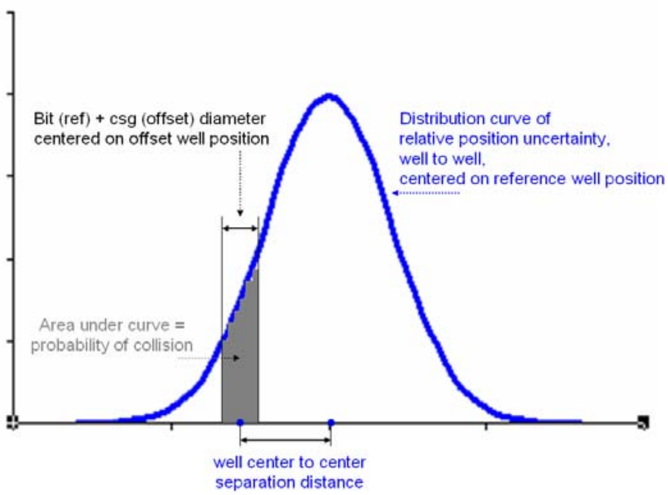
2.10 Inclusion of an arbitrarily quantified additional uncertainty (Affects S, E and R)

- Intended to account for gross errors and mistakes*
- May be added to the uncertainties or subtracted from the well separation distance
- May be a fixed value or a % of drilled depth
- % drilled depth may be capped or not

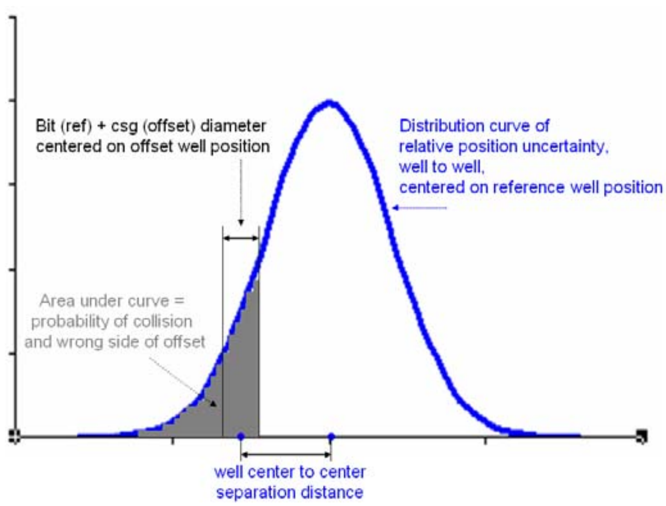
* Error models do not account for mistakes. Stringent QC procedures must be applied to survey data to ensure that they conform to model predictions.

2.11 Calculation of probability of collision (Affects P)

Only one method of calculating probability of collision is thought to be currently in use, although others have been proposed. The current method is based on integration of a one dimensional probability density function along the line normal to the two well paths, as shown in the following diagrams.



An alternative implementation of the method includes the probability of being on the wrong side of offset well.



Published methods have been assessed by the Work Group; SPE papers 20908, 23941/2, 36484, 92554, 101719, and 116155, US patent 5901795, and two methods previously presented to the Collision Avoidance Work Group by Angus Jamieson (minutes ISCWSA 28) and Jerry Codling (minutes ISCWSA 27).

It was agreed that the method described in SPE 36484 was valid in all cases except when the two wells are very near to parallel. The method would be improved by expressing it as a 2D integral over a finite interval along the reference well. In parallel well situations, the method used must consider a finite encounter length and either attitude uncertainty or variation in position uncertainty.

Methods that could be further evaluated for effectiveness in the parallel case include SPE 23941/2 and 116155, and the Jamieson and Codling methods. It was also noted that Monte Carlo modelling will be required to evaluate any candidate method, and does offer a solution in itself if computational difficulties and computer processing limitations can be overcome.

The phenomenon of probability dilution (in which a point is reached where probability of collision decreases as position uncertainty increases) had been considered, but the team had no recommendation on how to manage it with respect to collision avoidance.

2.12 Choice of how the parameter is quantified (Affects S, E, R, and P)

The base measures are:

- S distance
- E distance
- R ratio
- P fraction (reported as a decimal fraction, a % or as 1:x)

For all 4 rule types, the limit value can be expressed as a distance, specific to each station (the minimum allowable separation distance or masd). Actual well separation distance is then compared to the masd to determine if well proximity is acceptable.

2.13 The limit values that define the rule (Affects S, E, R and P)

A collision avoidance policy might make use of more than one limit value, defining escalating corrective actions as perceived probability of collision increases.

For E and R type rules, the choice of limit value is closely related to the choice of confidence interval (see 2.6). For example, an R rule with ellipses set at 3 sigma and a limit value of 1.0, results in the same masd values as a rule using 2 sigma ellipses and a limit value of 1.5.

3.0 Comparisons

The examples in the table below are typical of dimensions in feet, but the values of the results are independent of the units assigned. Units only have relevance for the outcomes of the S and E rules. 3 sigma ellipse dimensions have been used for the E and R type rules. This is common practice, but there is no *standard* practice in the Industry. To avoid issues of relative orientation, all examples assume spherical ellipsoids.

	Ref Well		**Offset Well**		**S**	**S**	**E**	**E**	**R**	**R**	**R**	**R**	**P**	**P**
	Bit	Uncert	Csg	Uncert		note		note	note	note	note	note		Note
	Diam.	3 σ	Diam.	3 σ		a.		a.	d.	b, d.	c, d.	c, e.		f.
1	2.00	5.0	2.00	3.0	16.0	14.0	8.0	6.0	2.0	1.6	1.8	2.4	1:3E12	1:3E12
2	0.80	30.0	1.00	50.0	80.0	79.1	0.0	-0.9	1.0	1.0	1.0	1.4	1:128,000	1:42,500
3	3.00	2.0	2.50	2.3	7.0	4.3	2.7	0.0	1.6	1.0	1.0	1.4	1:69,600	1:69,600
4	0.70	250.0	0.50	120.0	200.0	199.4	-170.0	-170.6	0.5	0.5	0.5	0.7	1:2,000	1:65
5	0.25	50.0	0.25	50.0	0.5	0.3	-99.5	-99.8	0.0	0.0	0.0	0.0	1:120	1:2
6	3.00	2.0	2.00	1.0	4.0	1.5	1.0	-1.5	1.3	0.7	0.5	0.7	1:45	1:45
7	3.00	6.0	3.00	6.0	7.0	4.0	-5.0	-8.0	0.6	0.5	0.3	0.5	1:13	1:13
8	0.25	1.0	0.25	1.0	0.5	0.3	-1.5	-1.8	0.3	0.2	0.1	0.2	1:4	1:3
9	2.00	0.5	2.00	0.5	2.0	0.0	1.0	-1.0	2.0	0.7	0.0	0.0	1:2	1:2

Notes:

a. Minus bit and csg radii
b. Bit and csg radii added to the uncertainty
c. Bit and csg radii subtracted from well separation
d. Well to well uncertainty calculated by simple summation of ellipse dimensions
e. Well to well correlation assumed to be 0
f. Include probability of being on the "wrong side" of the offset

Comparison of the various results is informative. It shows how planning or drilling decisions can be very different depending on which rule is in force. Although R type rules do not provide a standard measure of probability of collision, it appears that they may provide a warning of when the probability of collision increases to greater than one in tens of thousands

4.0 Recommendations

The R type is currently the most commonly used rule in collision avoidance policies. Of the thirteen calculation variables described in section 2, eleven apply to the R type rule. The Work Group has reviewed each option and recommends the following choices be made when defining an R type rule:

a. Do not use horizontal plane for scanning (2.1)
b. Use an error model that is capable of quantifying significant variables and which can be validated against QC parameters derived from the model (e.g. ISCWSA model). (2.3)
c. Do not use the bias option for the model's drillstring interference term. (2.3)
d. The ellipse radius should be based on the pedal curve or closest approach method. (2.4)
e. For the specified depth on the reference well, identify minimum R, not minimum S or minimum E (2.2, 2.4)
f. Include hole dimensions, preferably by subtracting the sum of the hole dimensions from S. (2.5)
g. Include the well reference/surface location uncertainty with appropriate correlation to downhole survey and other well surface location uncertainties. (2.8)
h. Compute relative uncertainty (a single ellipsoid associated with either the reference or offset well), but only if correlation is properly accounted for using the rho 3, well to well, correlation coefficient. (2.9)