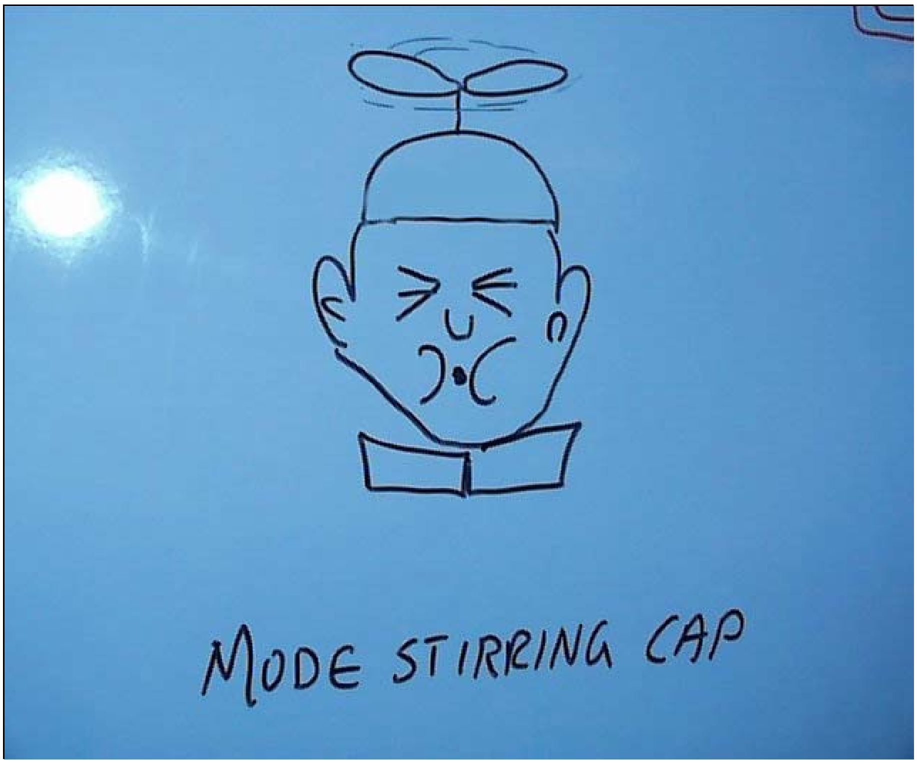
FOI-R--0468--SE
April 2002
ISSN 1650-1942

Technical report

Olof Lundén and Mats Bäckström

Design of Experiment. How to improve Reverberation Chamber Mode-Stirrer Efficiency



Sensor Technology
SE-581 11 Linköping

SWEDISH DEFENCE RESEARCH AGENCY

Sensor Technology
P.O. Box 1165
SE-581 11 Linköping

FOI-R--0468--SE

April 2002

ISSN 1650-1942

Technical report

Olof Lundén and Mats Bäckström

Design of Experiment. How to improve Reverberation Chamber Mode-Stirrer Efficiency.

<table>
<tr><td rowspan="6">Issuing organization
FOI – Swedish Defence Research Agency
Sensor Technology
P.O. Box 1165
SE-581 11 Linköping</td><td>Report number, ISRN
FOI-R--0468--SE</td><td>Report type
Technical report</td></tr>
<tr><td colspan="2">Research area code
6. Electronic Warfare</td></tr>
<tr><td>Month year
April 2002</td><td>Project no.
I3847</td></tr>
<tr><td colspan="2">Customers code
5. Commissioned Research</td></tr>
<tr><td colspan="2">Sub area code
61 Electronic Warfare including Electromagnetic Weapons and Protection</td></tr>
<tr></tr>
<tr><td rowspan="4">Author/s (editor/s)
Olof Lundén
Mats Bäckström</td><td colspan="2">Project manager
Mats Bäckström</td></tr>
<tr><td colspan="2">Approved by</td></tr>
<tr><td colspan="2">Sponsoring agency
FM, FMV</td></tr>
<tr><td colspan="2">Scientifically and technically responsible</td></tr>
<tr><td colspan="3">Report title
Design of Experiment. How to improve Reverberation Chamber Mode-Stirrer Efficiency.</td></tr>
</table>

Abstract (not more than 200 words)

What makes a Mode Stirrer efficient in a reverberation chamber, and how can one find the parameters of major importance? This is a problem that might be very complicated analyse theoretically or to model. An alternative interesting approach, that can be performed quite easily, is to carry out a Design of Experiment (DOE). The focus has been to investigate traditional rotational mode-stirrers. To perform a general factorial design, an investigator selects a fixed number of “levels” (or “versions”) for each of a number of variables (factors) and then runs the experiments with all possible combinations. The test criterion selected in this case study has been the specific lowest frequency for each stirrer chamber combination, which corresponds to at least 200 uncorrelated stirrer positions.
The outcome of the factorial design experiment shows that the effect of changing the diameter of the stirrer is much greater than changing the height. This seems to be more pronounced at 50 uncorrelated stirrer steps than at 200. The effect of changing the chamber volume is rather small. The latter is illustrated by the fact that the lowest frequency for 200 uncorrelated stirrer steps improves about 60 % if it is use in the small 1 m^3 chamber compared to the 210 m^3.

Keywords

Factorial Design, DOE, Reverberation chamber, Mode-Stirred chamber, EMC, HPM

Further bibliographic information	**Language** English
ISSN 1650-1942	**Pages** 37 p.
	Price acc. to pricelist

Utgivare	Rapportnummer, ISRN	Klassificering
Totalförsvarets Forskningsinstitut - FOI Sensorteknik Box 1165 581 11 Linköping	FOI-R--0468--SE	Teknisk rapport
	Forskningsområde 6. Telekrig	
	Månad, år April 2002	**Projektnummer** I3847
	Verksamhetsgren 5. Uppdragsfinansierad verksamhet	
	Delområde 61 Telekrigföring med EM-vapen och skydd	
Författare/redaktör Olof Lundén Mats Bäckström	**Projektledare** Mats Bäckström	
	Godkänd av	
	Uppdragsgivare/kundbeteckning FM, FMV	
	Tekniskt och/eller vetenskapligt ansvarig	

Rapportens titel (i översättning)

Faktorförsök för att förbättra effektiviteten hos omrörare i Modväxlande kammare.

Sammanfattning (högst 200 ord)

Vad gör att en omrörare är effektiv i en modväxlande kammare, och hur kan man finna de viktigaste konstruktionsparametrarna? Detta är ett problem som kan vara mycket komplicerat att modellera och analysera teoretiskt. Ett alternativt och intressant angreppsätt, som kan genomföras relativt lätt är att göra ett faktorförsök. Fokus har varit att undersöka traditionella roterande omrörare. För att genomföra ett faktorförsök, behöver man välja ett fast antal "nivåer" (eller "versioner") för varje variabel (faktor) och sedan utförs försöket vid alla tänkbara kombinationer. Testkriteriet som valts vid denna studie är den frekvens för varje omrörare, vilken korresponderar mot 200 okorrelerade omrörarpositioner.

Resultatet av faktorförsöket visar att effekten av att ändra diametern hos omröraren är mycket större än att ändra höjden. Detta verkar vara ännu tydligare vid 50 okorrelerade omrörarsteg än vid 200. Effekten av att ändra kammarens volym är ganska liten. Det senare illustreras av att frekvensen för 200 okorrelerade omrörarsteg förbättras bara omkring 60 % om kammaren är 1 m^3 jämfört med 210 m^3.

Nyckelord

Faktorförsök, Modväxlande kammare

Övriga bibliografiska uppgifter	Språk engelska
ISSN 1650-1942	**Antal sidor:** 37 s.
Distribution enligt missiv	**Pris: Enligt prislista**

INDEX

Rev: 15/04/2002 10:34

Cover picture: Suggestion for a more efficient Reverberation Chamber Operator.
Courtesy by Staffan Kindgren, Flextronics.

1. Introduction

The reverberation chamber (RC), also called mode-stirred chamber, is a highly conductive, electrically large, shielded cavity normally equipped with one or several stirrers (tuners) to provide a statistically uniform and statistically isotropic field. The reverberation chamber is used to conduct electromagnetic measurements on electronic equipment. The basic set-up consists of a transmitting antenna, used to excite the field, a receiving antenna, to calibrate the field, and the equipment under test (EUT). The measurements comprise radiated susceptibility (RS) testing, also denoted immunity testing, as well as emission measurements and determination of shielding effectiveness. The lowest usable frequency is mainly determined by the size of the chamber, the size and shape of the stirrer(s) and on the quality factor, Q, of the cavity. The RC has become a well-established tool for electromagnetic compatibility (EMC) testing and measurements. There are today several EMC standards that allow the use of reverberation chambers. Also, especially during the last years, a rapidly growing interest has been shown for using the RC to measure the radiation efficiency of electrically small antennas [1].

2. Background

What makes a Mode Stirrer efficient in a reverberation chamber, and how can one find the parameters of major importance? The work presented in this report was inspired after some discussion of the mode-stirrer performance in a new 133 m^3 chamber which was compared to the results that was given in our FOI report from May 1999 [2]. It turned out that the FOI stirrer gave twice as many, about 500, uncorrelated stirrer positions, using the 1/e criterion, at 1 GHz, in spite of the smaller size of both chamber and mode-stirrer. The FOI chamber is only 37 m^3. However, the stirrer used in the large 133 m^3 chamber was 3.5 m in height but had a diameter of only 1.2 m. The FOI stirrer is 0.85 m in height and has a diameter of 2.4 m. Obviously there is something here that need some investigations. This is a problem that might be very complicated analyse theoretically or to model. An alternative interesting approach, that can be performed quite easily, is to carry out a Design of Experiment (DOE).

3. Factorial Design.

The performed type of designed experiment was developed early in the 20th century. In the 1970s statisticians started to use the computer in experimental design by recasting the DOE in terms of optimisation [3]. Our test, however, has not been focused on optimisation but only to quantify the sensitivity of the design parameters for the mode-stirrer in a reverberation camber i.e. what makes the stirrer efficient. The focus has been to investigate traditional rotational mode-stirrers. To perform a general factorial design, an investigator selects a fixed number of "levels" (or "versions") for each of a number of variables (factors) and then runs the experiments with all possible combinations [4]. The test criterion selected in this case study has been the specific lowest frequency for each stirrer, which corresponds to at least 200 uncorrelated stirrer positions. In this type of full factorial experiment we have investigated three factors and their interactions using two levels. The factors are the diameter and the height of the stirrer and the chamber size. For each we need a large and a small value. This will give us 2^3 = eight test cases which can be illustrated using a cube, see figure 1. Four different mode-stirrers were used in the experiment. One with small height and small diameter. One with small height and large diameter. One large height small diameter, and finally one large height and large diameter. The two

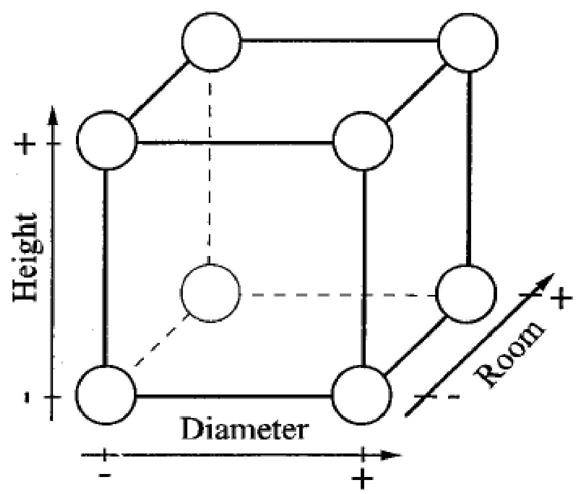


Figure 1.

chambers used in the first approach were FOI 37.6 m^3 and 27.1 m^3 reverberation chambers. Some additional measurements have also been performed in the 210 m^3 chamber at Saab Bofors Dynamics, Karlskoga, Sweden. Pictures of the stirrers etc. are found in appendix A.

The antenna configurations, using two EMCO 3106 horns for 200 MHz – 2 GHz and WJ4106 horns from 2 – 18 GHz, has not been changed during the experiment in each chamber. A full two port calibration was done for 201 frequencies, and corrections for antenna mismatch has been applied. This has however no influence on the outcome of test. 200 mode-stirrer steps was used for each run.

3.1 Efficiency Criterion

We have selected the lowest frequency at which we have at least 200 uncorrelated stirrer positions as the criterion for an efficient stirrer. Of course one can use a lower number of uncorrelated stirrer positions but that will give a higher uncertainty in the determination of the frequency. The correlation coefficients is calculated using an auto correlation function for each frequency and compared with the 5% and 1% probability levels that are based on the number of samples. It is also compared with the correlation level of $e^{-1} \approx 0.37$, see [5].

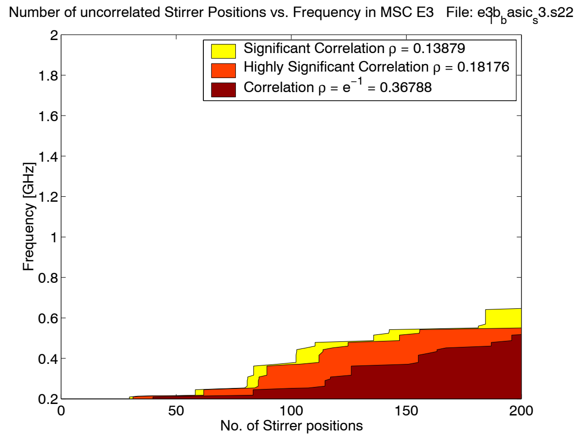


Figure 2. Performance of the Basic stirrer (d=2.4 m h= 0.28m) in the 37 m^3 chamber.

The results can be seen in appendix B. Data has been subjected to noise reduction. Figure 2 shows the number of uncorrelated stirrer positions vs. frequency for the basic stirrer in the 37 m^3 chamber. This corresponds to test condition no. 6 in table 1. The three colours is representing the different test-criterions. The yellow that corresponds to a Significant correlation and the orange that corresponds to a Highly significant correlation are based on the 5% and 1% probability levels for 200 samples and the red corresponds to the 1/e criterion.

Data for the reverberation chambers and the different mode-stirrers can be found in appendix A. In appendix B plots of the number of uncorrelated stirrer positions vs. frequency can be seen for the different stirrers and chambers.

Test condition no:	Chamber m^3	Height m	Diameter m	Frequency MHz	
1	27.1	0.28	0.71	3100	Figure B9,B10
2	27.1	0.28	2.4	761	Figure B13
3	27.1	2	0.71	1793	Figure B11
4	27.1	0.85	2.4	517	Figure B15
5	37.6	0.28	0.71	3500	Figure B1,B2
6	37.6	0.28	2.4	677	Figure B5
7	37.6	2	0.71	1821	Figure B3
8	37.6	0.85	2.4	470	Figure B7

Table 1. Geometrical data for the variables. Frequency given for 200 uncorrelated stirrer positions using the 5% probability criterion

Table 1 shows the data for the different chambers and stirrers and the corresponding frequency for 200 uncorrelated stirrer positions, using the 5% probability criterion.

Table 2 shows the basic design matrix for the 2^3 factorial experiment. Table 2 is illustrated in figure 3.

	Chamber	Height	Diameter	Frequency
1	-1	-1	-1	3100
2	-1	-1	1	761
3	-1	1	-1	1793
4	-1	1	1	517
5	1	-1	-1	3500
6	1	-1	1	677
7	1	1	-1	1821
8	1	1	1	470

Table 2. Design matrix. Frequency given for 200 uncorrelated stirrer positions using the 5% probability criterion.

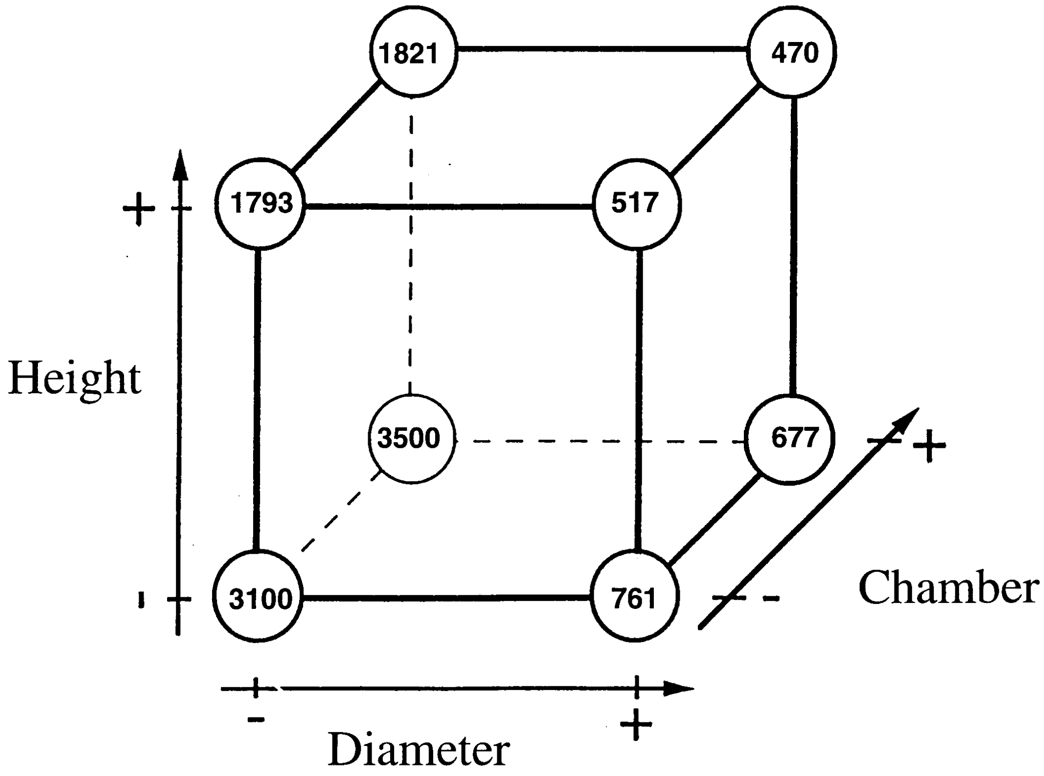


Figure 3. Illustration of Table 2 data using a cube. Frequency corresponds to 200 uncorrelated stirrer positions using the 5% probability criterion

3.2 Full 2^3 factor experiment

This full factor experiment apart from the main effects, chamber, height and volume, also addresses the different interaction or concurrent effects between the chamber and the height CxH, chamber and diameter CxD, height and diameter HxD and all parameters CxDxR. These interaction effects are not easily found in an 'one factor at the time' experiment.

Table 3 shows the design matrix including the interaction factors.

	Chamber	Height	Diameter	CxH	CxD	CxD	CxHxD	Frequency
1	-1	-1	-1	1	1	1	-1	3100
2	-1	-1	1	1	-1	-1	1	761
3	-1	1	-1	-1	1	-1	1	1793
4	-1	1	1	-1	-1	1	-1	517
5	1	-1	-1	-1	-1	1	1	3500
6	1	-1	1	-1	1	-1	-1	677
7	1	1	-1	1	-1	-1	-1	1821
8	1	1	1	1	1	1	1	470

Table 3. Design matrix for Full factor experiment. Frequency corresponds to 200 uncorrelated stirrer positions using the 5% probability criterion.

run	Chamber	Height	Diameter	CxH	CxD	HxD	CxHxD
1	-3100	-3100	-3100	3100	3100	3100	-3100
2	-761	-761	761	761	-761	-761	761
3	-1793	1793	-1793	-1793	1793	-1793	1793
4	-517	517	517	-517	-517	517	-517
5	3500	-3500	-3500	-3500	-3500	3500	3500
6	677	-677	677	-677	677	-677	-677
7	1821	1821	-1821	1821	-1821	-1821	-1821
8	470	470	470	470	470	470	470
effect	74.25	-859.25	-1947.25	-83.75	-139.75	633.75	102.25

Table 4. Estimated effects calculated for chambers E4 (27m^3) and E3 (37 m^3) using 200 samples and 5% probability

As an example the main effect of changing the chamber can be estimated like the following. For each combination of height and diameter we have two observations, see figure 3. This gives us four differences and each gives an estimation of the change of the chamber. The differences are 1821-1793 = 28; 470-517 = - 47; 3500-3100 = 400; 677-761 = -84. The arithmetic mean value of these gives an estimation of the average effect of changing the chamber from a low to a high level, i.e. from a small to a large chamber (28- 47+400-84)/4 = 74.25. In order to investigate the effect of the different factors we plug in our numbers and take the sum and divide by four for each column. This will indicate the influence each parameter has and the interaction effects, see [4]. A large number will indicate a big influence.

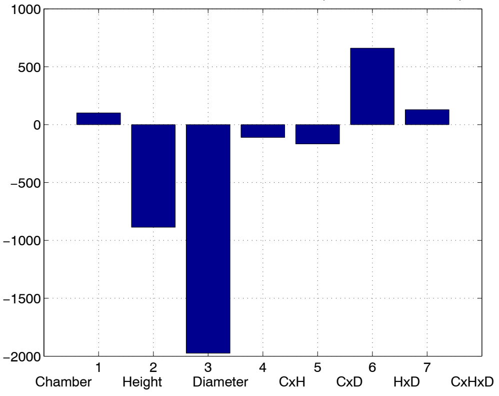


Figure 4. Estimated effects. Chambers E4 (27m^3) and E3 (37 m^3) 200 samples 5% probability

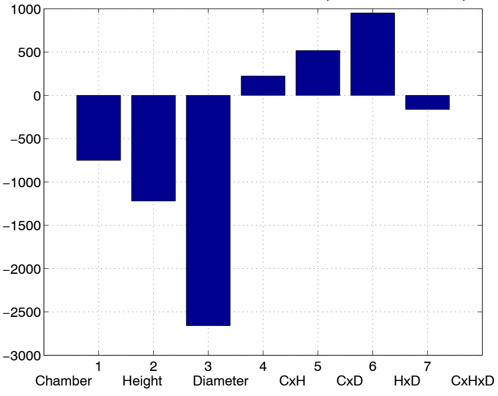


Figure 5. Chambers E4 (27m^3) and Bofors (210m^3). 200 samples 5% probability

The estimated effect in Table 4 is illustrated graphically in Figure 4. We note that the main effect of changing the diameter is more than twice as effective as changing the height or the stirrer volume. The chamber stirrer interactions was not as significant as expected. Maybe the volume change between the chambers was to small.

This concern caused us to perform some additional measurements at Saab Bofors Dynamics, Karlskoga, Sweden using our stirrers in their 210 m^3 chamber. Figure 5 illustrates the estimated effect from these measurements. Despite the large change in chamber volume, from 27 m^3 to 210 m^3 the effect of changing the volume is rather small. Thus, essentially the same conclusions can be made as above. A new improved long stirrer was developed to be able to interface to the Bofors stirrer configuration, see figure A1, A5, A7, A8 for comparison.

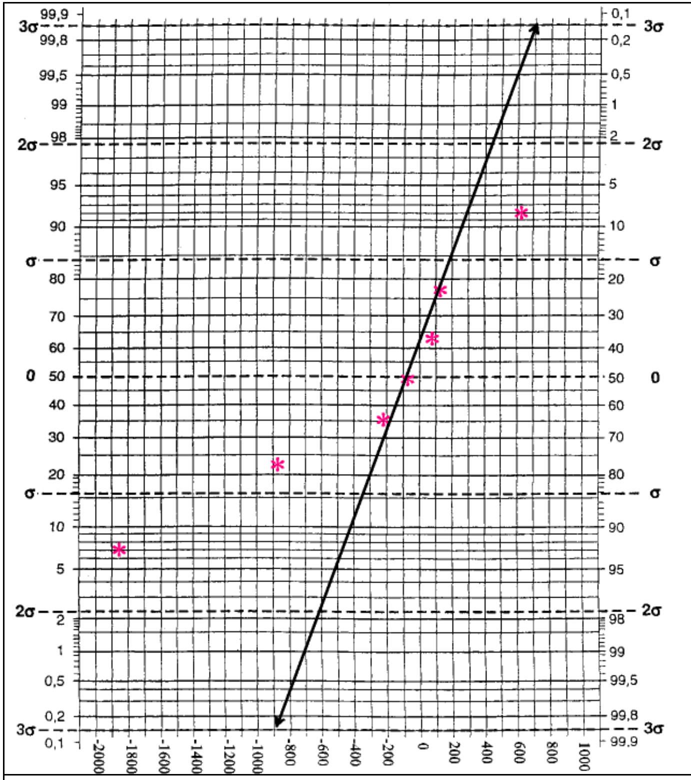


Figure 6a. Normal distribution plot. The reference line has been estimated.

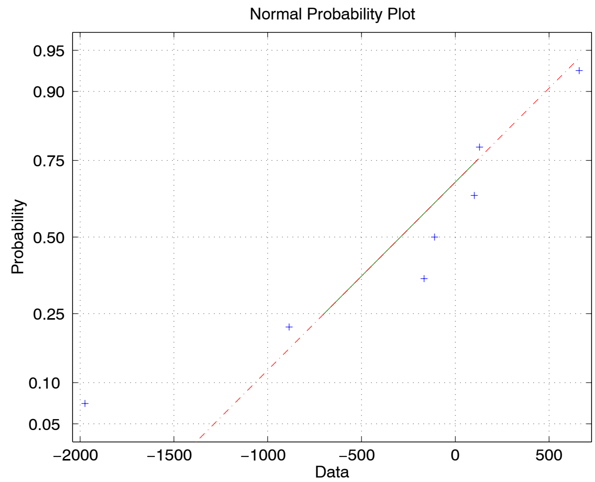


Figure 6b. Matlab Normal distribution plot based on the data in figure 4. The reference line based on normally distributed data.

3.3 Analysis of Factorial Designs using normal probability plots

If data have no active effects they will be normally distributed and fall on the reference line in a normal distribution plot. Matlab 'normplot' will take the data points and try to fit them to a normal distribution, if this is the case they will end up on a straight line, figure 6b. In the analysis of the effects it is necessary to allow for selection by the investigator. If you a priori know the spread in data, for instance in the case many measurements have been performed for the same configuration, you can estimate the appropriate normal distribution. In other case, the interaction effects that apparently have no significance might also be useful for estimating the spread of data in a normal distribution plot, figure 6a. Occasionally real and meaningful higher-interaction modes occur. On the Y-axis is the normalized CDF in percent and our seven results on the X-axis. The line that represents a normal distribution has been estimated from the four data around 50 % that appear to be insignificant (i.e. random).

The conclusion from figure 6a is that the values for the height -859.25 and for the stirrer volume 633.75 deviates a lot from the assumed normal distribution and that the value for the diameter -1947.25 deviates even more. Thus, it is very unlikely that these values are accidental. In other words, these are considered to have a significant influence on the stirrer performance.

3.4 Modelling of the parameters based on the DOE.

Another more modern approach to evaluate designed experiments is to use Multiple Regression Techniques. Apart from gaining understanding of which main factors that have the greatest effect and the direction of the effects as in the analysis above it will also be possible to get coefficients for a model to predict future values of the response when only the main factors are currently known. Response Surface Methodology (RSM) is a tool for understanding the quantitative relationship between multiple input variables and one output variable [3]. Consider one output, z, as a polynomial function of two inputs, x and y. The function $z = f(x,y)$ describes a two-dimensional surface in the space (x,y,z). Of course, you can have as many input variables as you want and the resulting surface becomes a hypersurface. For three inputs (x_1, x_2, x_3) the equation of a quadratic response surface is

$$
\begin{aligned}
y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots. \quad & \text{(linear terms)} \\
+ \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \ldots.. \quad & \text{(interaction terms)} \\
+ \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 \quad & \text{(quadratic terms)}
\end{aligned}
$$

It is difficult to visualise a k-dimensional surface in the k+1 dimensional space for k>2. The Matlab function *rstool* is a graphical user interface designed to make this visualisation more intuitive. This is used to produce a prediction plot for our designed experiment and provides a multiple input polynomial fit to data. It plots a 95% percent global confidence interval for predictions as two red curves. The default model is linear. Non linear models requires experiments at more levels than two.

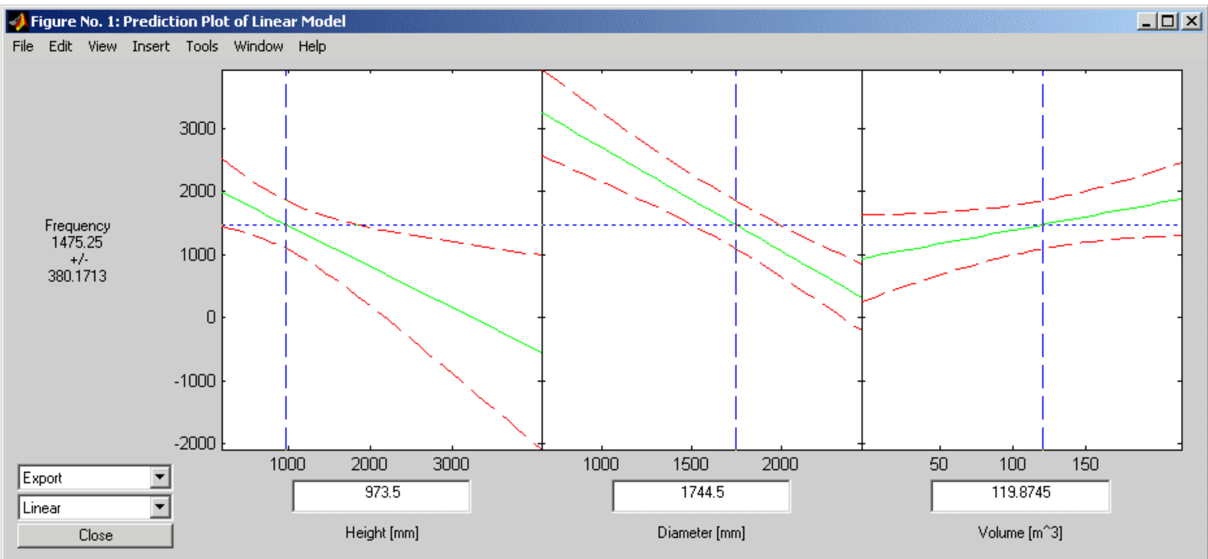


Figure 7. The Prediction of the Linear model based on 200 uncorrelated stirrer positions using the 5% probability criterion.

The Prediction of Linear model makes a prediction only on the main factors in the DOE according to:

$$F_{MHz} = \beta_0 + \beta_1 H + \beta_2 D + \beta_3 V \qquad (1)$$

where H and D is the height respectively the diameter given in mm and V is the volume given in m^3.

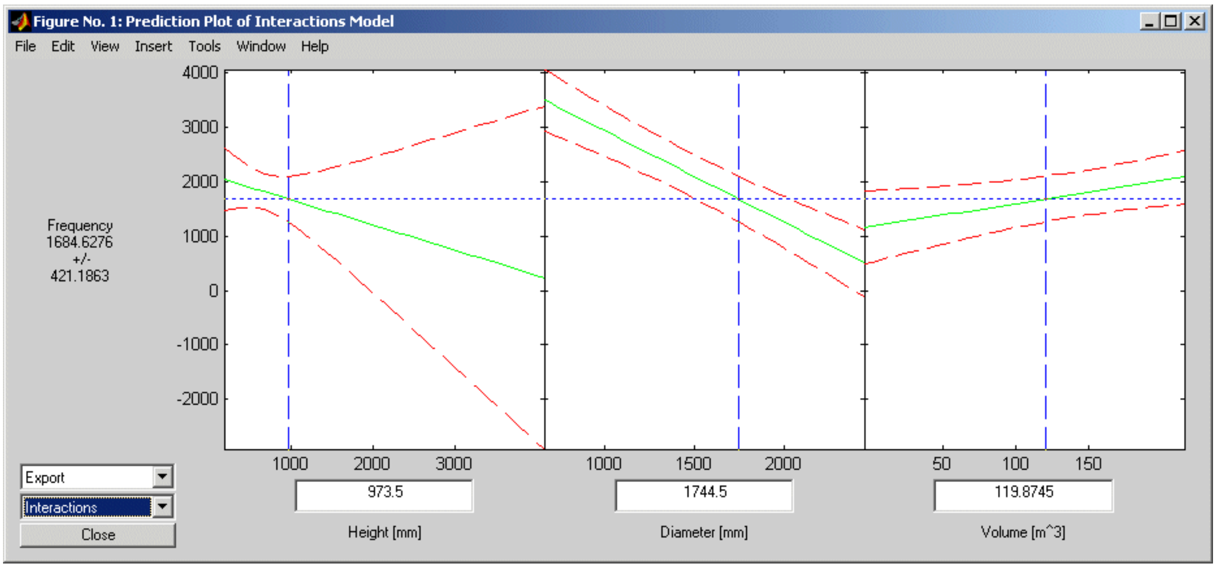


Figure 8. The Prediction of the Interaction model based on 200 uncorrelated stirrer positions using the 5% probability criterion.

The Prediction of the Interaction model also uses the interaction factors, according to:

$$F_{MHz} = \beta_0 + \beta_1 H + \beta_2 D + \beta_3 V + \beta_4 HD + \beta_5 HV + \beta_6 DV \qquad (2)$$

Where the coefficients are given as:

for 1% probability	*for 5% probability*	*for 1/e criterion*
β_0 = 3757.2	β_0 = 3244.9	β_0 = 2535.8
β_1 = -0.89194	β_1 = -0.71949	β_1 = -0.51704
β_2 = -1.3111	β_2 = -1.1528	β_2 = -0.8745
β_3 = 15.852	β_3 = 18.423	β_3 = 8.7274
β_4 = 0.00034022	β_4 = 0.00034118	β_4 = 0.00020493
β_5 = -0.0013714	β_5 = -0.0025089	β_5 = -0.00091374
β_6 = -0.0059055	β_6 = -0.0067135	β_6 = -0.0031859

Interaction models gives an better estimate, this is even further accentuated using quadratic models. However, as pointed out before, this DOE was not optimised for modelling.

It is of course necessary to be careful using eq. 2 when exceeding the values outside the tested range. However, if we for curiosity enters the 1/e criterion for the133 m^3 chamber data with the stirrer diameter 1.2 m and the height to 3.5 m we will find an estimate for 200 uncorrelated stirrer position to be about 764 MHz which corresponds rather well with what we might expect from the chamber performance described in chapter 2.

In this interactive fitting and visualisation of a response surface we have used the measured data from all chambers and stirrers. The Matlab program and a comparisons between measurements and modelled data is given in appendix E.

4. Miscellaneous

4.1 Peripheral movement

As the diameter showed to be the most important parameter there might be inferred that the peripheral movement for the mode-stirrer expressed in wavelength is approximately constant for the different stirrers for a certain number of uncorrelated stirrer positions. This has been investigated in the following plots. The plots are based on a linear interpolation from the curves in appendix B from the frequency point for 200 uncorrelated stirrer positions to the 200 MHz intercept point for each test criterion.

The peripheral movement related to λ has been calculated according to:

$$P_m = nus * \lambda / (\pi * d) \qquad (3)$$

where *nus* is the number of uncorrelated stirrer positions, λ is the wavelength and d is the diameter of the stirrer.

It seems that a movement of the periphery of about λ/10 to λ/15 is adequate for a reasonably sized tuner to yield uncorrelated data, see figure 9 to figure 11, see also appendix D. Note that this does not hold for low values of *nus*. The reason is that the size of the chamber puts an upper limit on λ. Above that limit the chamber is no longer overmoded and can not operate as a reverberation chamber. From the above and eq.3 you can estimate the frequency for a specific number of uncorrelated stirrer positions for a certain mode-stirrer diameter. For a stirrer with the diameter like the original Bofors stirrer ≈1.0 m this will give about 1.5 GHz for 200 uncorrelated stirrer positions, cf. also figure 17.

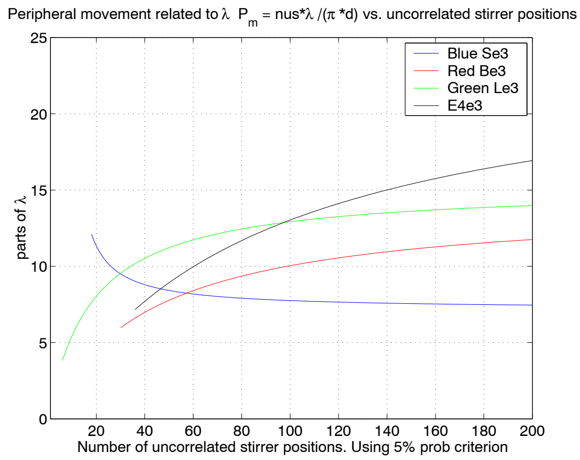


Figure 9. Peripheral movement in wavelength vs. the number of uncorrelated positions. Green: Long Stirrer, blue: Small stirrer, black: E4 stirrer, red: basic stirrer. E3 chamber 5% probability criterion

The peripheral movement related to λ , eq. 3 for *nus* uncorrelated stirrer positions for 4 different stirrers and 3 chambers can be found in appendix D. To conclude, it seems that the number of uncorrelated stirrer positions is strongly related to P_m.

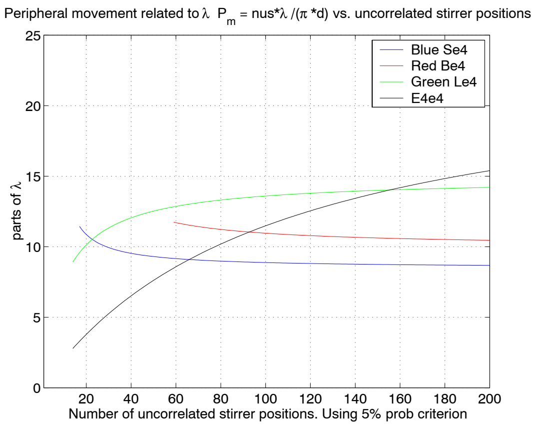


Figure 10. Peripheral movement in wavelength vs. the number of uncorrelated positions. Green: Long Stirrer, blue: Small stirrer, black: E4 stirrer, red: basic stirrer. E4 chamber 5% probability criterion

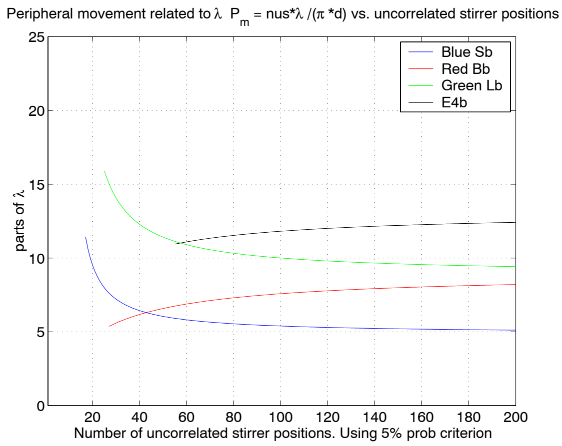


Figure 11. Peripheral movement in wavelength vs. the number of uncorrelated positions. Green: Long Stirrer, blue: Small stirrer, black: E4 stirrer, red: basic stirrer. Bofors chamber 5% probability criterion

4.2 Stirrer/Chamber interaction

It would be expected that a stirrer that occupies a large portion of the chamber interacts with the chamber and gives better performance. This is illustrated in figure 12 which shows the parts of lambda that the stirrer periphery has to move for achieve 200 uncorrelated stirrer positions for each of the 5 different stirrers in the 4 chambers. It can be noted that the mode-stirrers does not perform as good in the large as in a smaller chamber. See also the figures in appendix B. Note how the performance for all stirrers, especially the small stirrer Sb,Se3, Se4 and Sk0 (no: 1, 2 ,3 and 12), improves when the stirrer/chamber volume ratio increases.

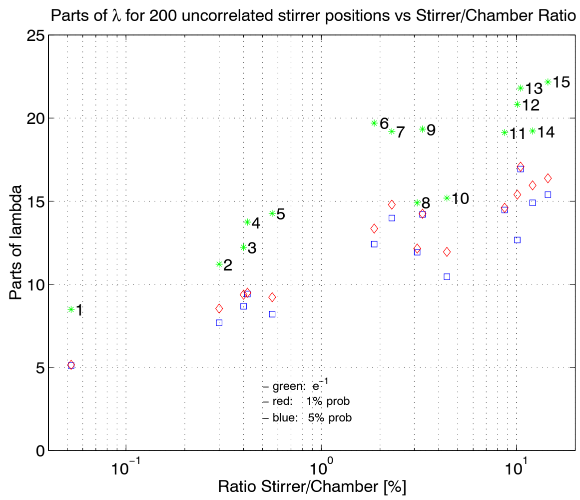


Figure 12. stirrer/chamber interaction.

The measurements using the small stirrer shows that the lowest frequency for 200 uncorrelated stirrer steps improves about 60 % if it is used in the small 1 m^3 chamber compared to the 210 m^3.

The numbers in figure 12 corresponds to: 1 = Sb, 2 = Se3, 3 = Se4, 4 = Lb, 5 = Bb, 6 = E4b, 7 = Le3, 8 = Be3, 9 = Le4, 10 = Be4, 11 = E3e3, 12 = Sk0, 13 = E4e3, 14 = E3e4, 15 = E4e4

<u>where the capital letters indicate the stirrer</u>:
S = small 0.11 m^3
L = long 0.88 m^3
B = basic 1.18 m^3
E3 = 3.27 m^3
E4 = 3.93 m^3

<u>and the small letters in the chambers</u>:
e3 = Large chamber 37 m^3
e4 = Small chamber 27 m^3
k0 = kiosk chamber 1m^3
b = Bofors chamber 210 m^3

4.3 2-blade stirrer and double 2-blade stirrer investigations

If only the peripheral change is the important parameter of the stirrer, then we would expect a 2 blade stirrer to perform as good as a 4 -blade. The stirrer used for this investigation was FOI largest with 3.93 m^3 rotational volume.

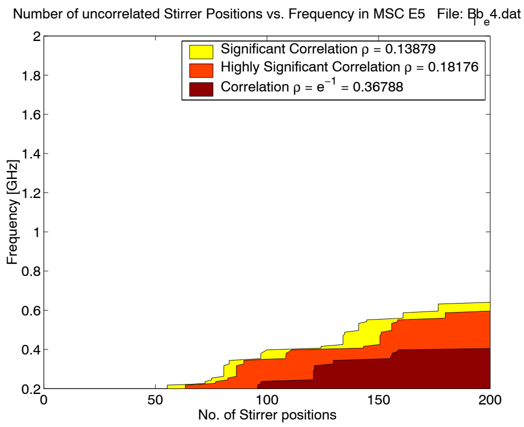


Figure 13. Chamber E3. 4-blades stirrer.

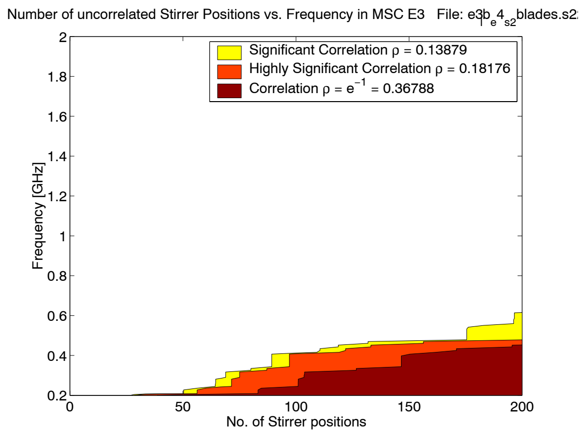


Figure 14. Chamber E3. 2-blades stirrer.

The frequency for 200 uncorrelated stirrer positions can be extracted from figure 13 and figure 14 and gives the following result:

	4-blades	2-single blades
5% =	492 MHz	615 MHz
1% =	459 MHz	478 MHz
1/e =	387 MHz	453 MHz

We see that a 4-blade stirrer only gives a slight improvement

As we now have two blades free we join them to the other ones to make the height twice as much. The stirrer rotational volume is now 7.86 m^3. See figure 16.

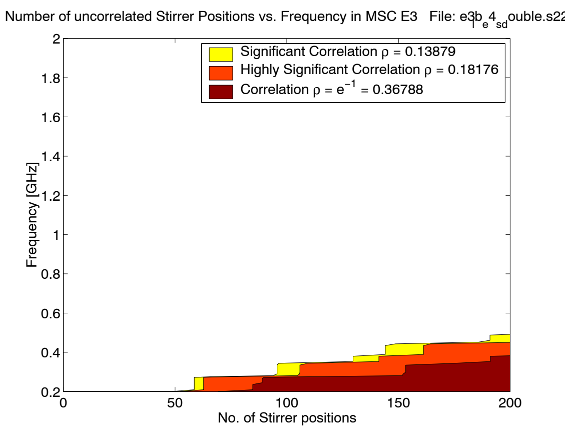


Figure 15. E3 2-double blades

Figure 16. E3 2-double blades

The frequency for 200 uncorrelated stirrer positions can be extracted from figure 13 and figure 15 and gives the following result:

These measurements turns out to have almost identical performance.

	4-blades	2-double blades
5% =	492 MHz	492 MHz
1% =	459 MHz	450 MHz
1/e =	387 MHz	382 MHz

Thus, wee see that the improvement of using 4 blades(cf. above) is compensated by the large height of the double stirrer. Results from 2-blades and 2-double blades for Bofors chamber can be seen in figure B33 and B34 in appendix B.

4.4 Bofors original Stirrer performance

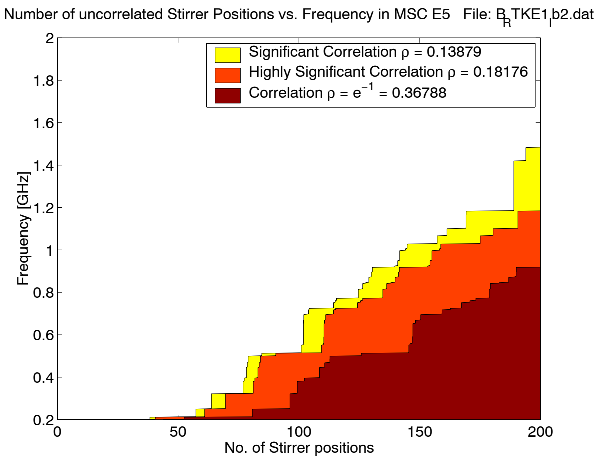


Figure 17. RTKE1_lb Bofors original stirrer

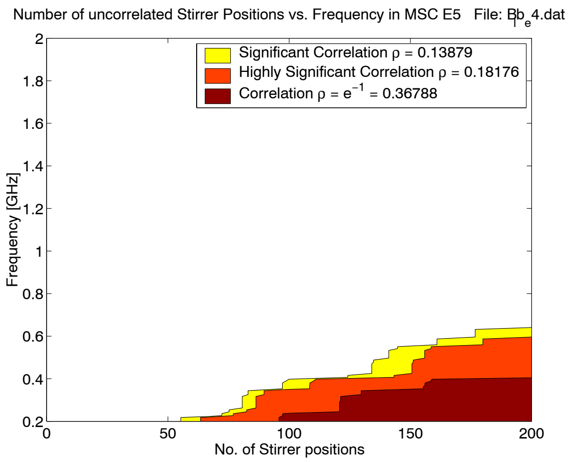


Figure 18. Bofors chamber E4 stirrer

Figure 17 and figure 18 shows a comparison of the number of uncorrelated stirrer positions vs. frequency between Bofors original tuner 1m diameter and FOI 2.4 m E4 tuner in Bofors 210 m^3 chamber. Again, we see the beneficial effect of a large diameter.

5. Conclusions

The outcome of the factorial design experiment shows that the effect of changing the diameter of the stirrer is much greater than changing the height. This seems to be more pronounced at 50 uncorrelated stirrer steps than at 200. The effect of changing the chamber volume is rather small. The latter is illustrated by the fact that the frequency for 200 uncorrelated stirrer steps improves about 60 % if it is use in the small 1 m^3 chamber compared to the 210 m^3.

Provided the chamber is overmoded a change of about $\lambda/10$ of periphery of the mode-stirrer will give uncorrelated data.

Accordingly, a 4-blade stirrer give a slight improvement compared to a 2-blade stirrer with the same diameter.

6. Acknowledgement

We like to recognise our appreciation to Peter Landgren and Patrick Svensén at Saab Bofors Dynamics, Karlskoga, Sweden for the valuable support and contributions to this study.

7. References

[1] M. Bäckström, O. Lundén and P-S Kildal, "Reverberation Chambers for EMC Susceptibility and Emission Analyses", Review of Radio Science 1999-2002, International Union of Radio Science (U.R.S.I.), c/o INTEC, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium.

[2] O Lundén, L Jansson, M Bäckström, "Measurements of Stirrer Efficiency in Mode-Stirred Reverberation Chambers", FOA-R--99-01139-612--SE, May 1999.

[3] Statistics Toolbox For Use with Matlab. Users Guide version 3.0. The MathWorks, Inc. Nov 2000.

[4] Box, G.E.P., Hunter, S., Hunter, W. "Statistics for Experimenters", Chapter 10-12, John Wiley & Son, 1978.

[5] O Lundén, M Bäckström, N Wellander, "Evaluation of Stirrer Efficiency in FOI Mode-Stirred Reverberation Chambers", FOI-R--99-0250--SE, Nov. 2001.

Appendix A

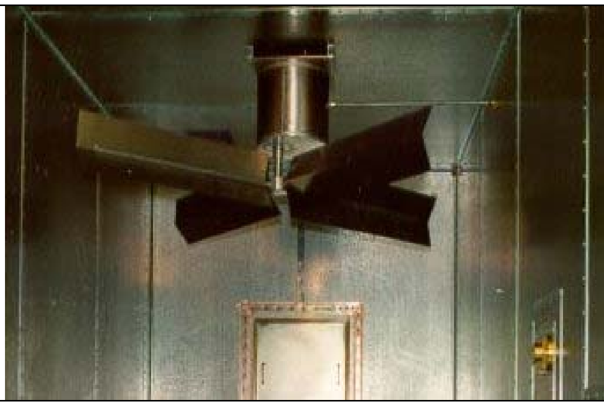
	
Figure A1. The long stirrer in the 37 m^3 chamber E3. Rotational volume 0.88 m^3	*Figure A2. The small stirrer in the 37 m^3 chamber E3. Rotational volume 0.11 m^3*
	
Figure A3. The large stirrer in the 37 m^3 chamber E3. Rotational volume 3.93 m^3	*Figure A4. The basic stirrer in the 37 m^3 chamber E3. Stirrer rotational volume 1.18 m^3*

Figure A5. The improved long stirrer in the 37 m^3 chamber E3. Rotational volume 0.88 m^3

Figure A6. Double stirrer blades made from the E4 stirrer. Rotational volume 7.86 m^3

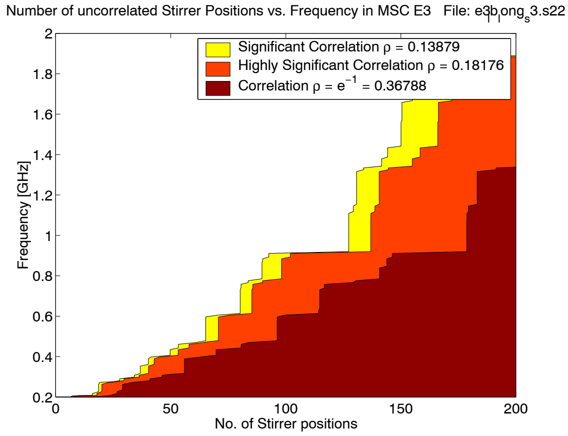


Figure A7. Chamber E3. The long stirrer figure A1.

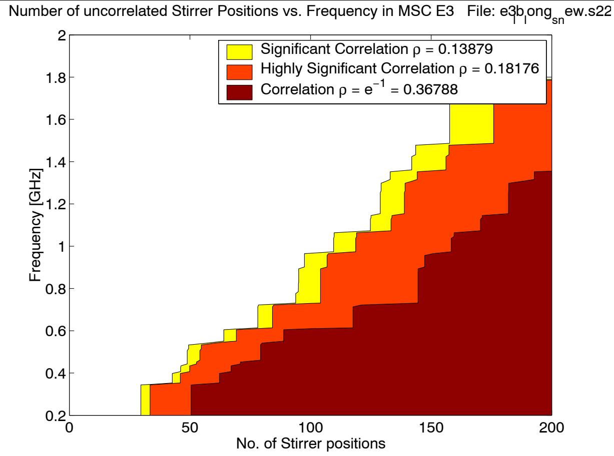


Figure A8. Chamber E3. The improved long stirrer figure A5.

Figure A9. Bofors 210 m^3 Chamber. The improved long stirrer. Rotational volume 0.88 m^3.

Figure A10. The large stirrer in the 210 m^3 chamber at Bofors. Rotational volume 3.93 m^3

Figure A11. The small stirrer in the 210 m^3 chamber at Bofors. Stirrer Rotational volume 0.11 m^3

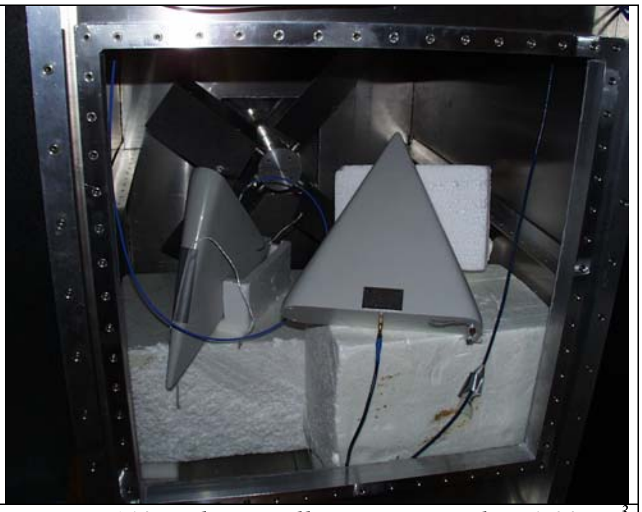


Figure A12. The small stirrer in the 1.09 m^3 chamber. Stirrer Rotational volume 0.11 m^3. 0.5-18 GHz Condor Systems logperiodic antennas

Figure A13. The original stirrer in the 210 m^3 chamber at Bofors. Rotational volume 4 m^3.

Figure A14. The original stirrer in the 210 m^3 chamber at Bofors. Rotational volume 4 m^3. Tuner in other position.

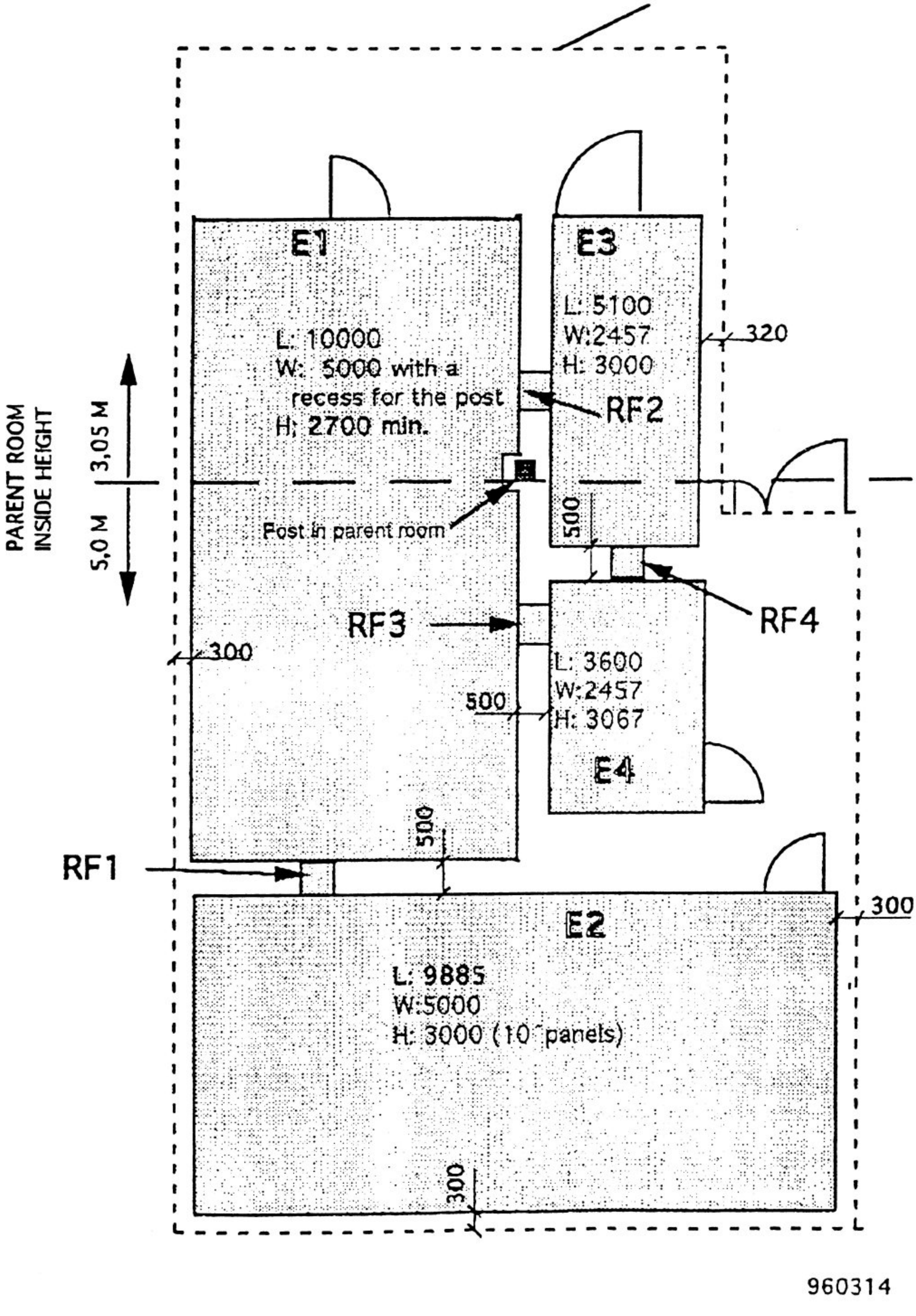


Figure A15. FOI EMC-test facilities. E3 and E4 are the Reverb chambers

Appendix B.

This appendix includes in the tables below some data for the mode-stirrers and the chambers. These are calculations for the frequency where we will correspond to 200 uncorrelated samples. Measurements include 6 different paddles and 4 chambers.

E3 chamber L: 5.1 m W: 2.457 m H: 3.0 m. Vol. 37.6 m^3. Frequency for 200 uncorrelated stirrer steps.

Volume m^3	Height mm	Diameter mm	Circumfer. mm		X	Y	Z	5%	1%	1/e	R%	Figure
0.11	280	710	2230	Small	-	-	-	3500	3150	2400	0.3	B1,B2
0.88	2000	750	2356	Long	-	-	+	1821	1722	1327	2.3	B3,A8
1.18	280	2400	7540	Basic	+	+	-	667	655	534	3.1	B5
3.27	710	2400	7540	E3	+	+	+	550	545	416	8.7	B29
3.93	850	2400	7540	E4	+	+	+	470	466	365	10.5	B7

E4 chamber L: 3.6 m W: 2.457 m H: 3.067 m. Vol. 27.1 m^3. Frequency for 200 uncorrelated stirrer steps.

Volume m^3	Height mm	Diameter mm	Circumfer. mm		X	Y	Z	5%	1%	1/e	R%	Figure
0.11	280	710	2230	Small	-	-	-	3100	2870	2200	0.4	B9,B10
0.88	2000	750	2356	Long	-	-	+	1793	1788	1317	3.3	B11
1.18	280	2400	7540	Basic	+	+	-	761	666	524	4.4	B13
3.27	710	2400	7540	E3	+	+	+	534	499	414	12.1	B30
3.93	850	2400	7540	E4	+	+	+	517	486	359	14.5	B15

Kiosk chamber L: 1.19 m W: 0.87 m H: 1.05 m. Vol. 1.09 m^3. Frequency for 200 uncorrelated stirrer steps.

Volume m^3	Height mm	Diameter mm	Circumfer. mm		X	Y	Z	5%	1%	1/e	R%	Figure
0.11	280	710	2230	Small	-	-	-	2124	1748	1292	10.1	B31

Bofors chamber L: 8.5 m W: 5.5 m H: 4.5 m. Vol. 210 m^3. Frequency for 200 uncorrelated stirrer steps.

Volume m^3	Height mm	Diameter mm	Circumfer. mm		X	Y	Z	5%	1%	1/e	R%	Figure
0.11	280	710	2230	Small	-	-	-	5260	5220	3170	0.05	B17-18
0.88	2000	750	2356	Long	-	-	+	2704	2683	1853	0.42	B21-22
1.18	280	2400	7540	Basic	+	+	-	970	863	558	0.56	B19
3.93	850	2400	7540	E4	+	+	+	641	596	404	1.87	B23
~ 4	4000	1000	3500	Bofors	-	-	+	1485	1184	919	1.80	B27

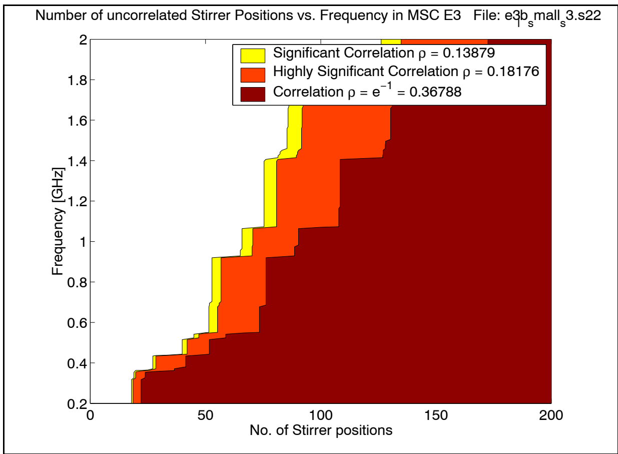


Figure B1. Se3_lb

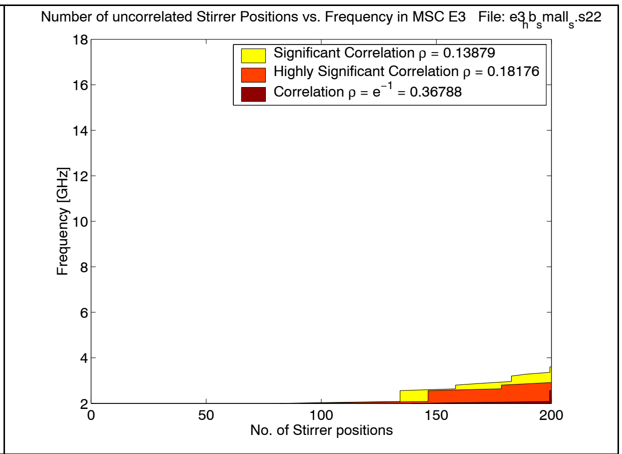


Figure B2. Se3_hb

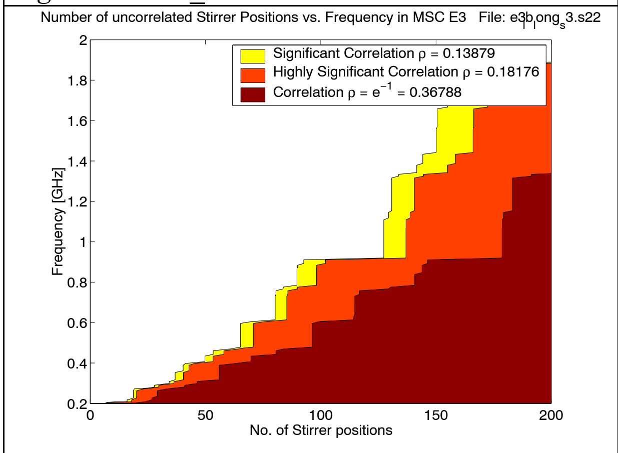


Figure B3. Le3_lb

N/A

Figure B4. Le3_hb

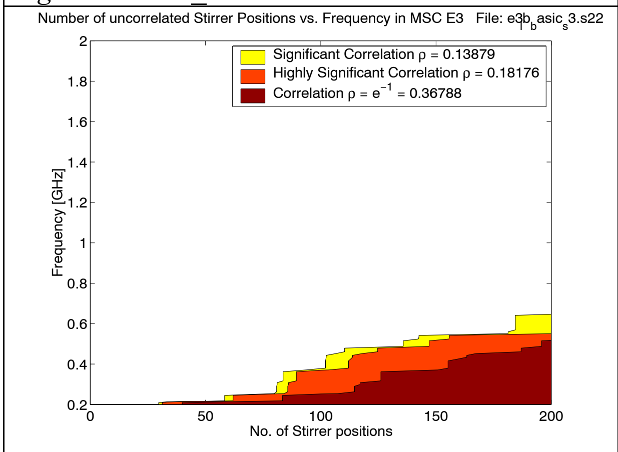


Figure B5. Be3_lb

N/A

Figure B6. Be3_hb

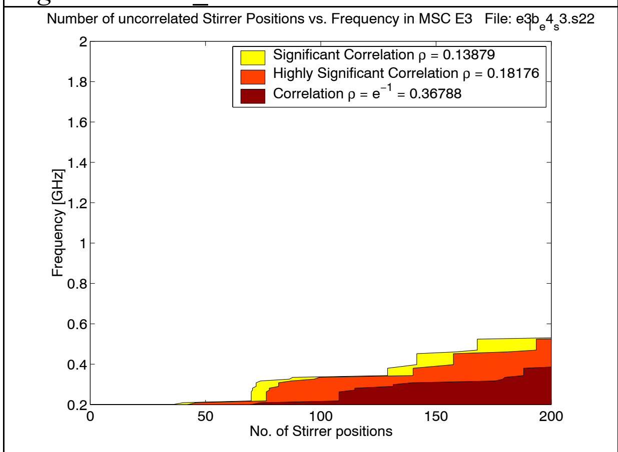


Figure B7. E3e4_lb

N/A

Figure B8. E3e4_hb

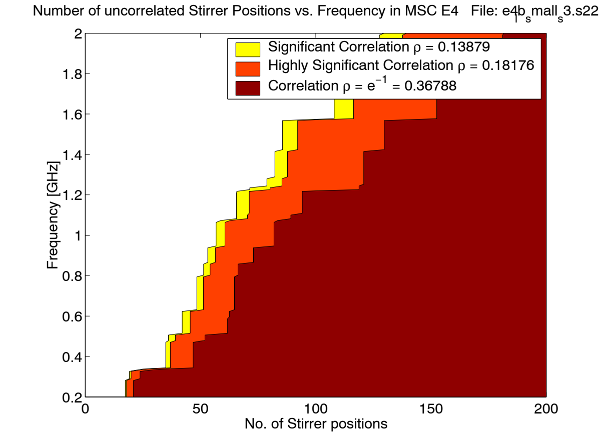


Figure B9. Se4_lb

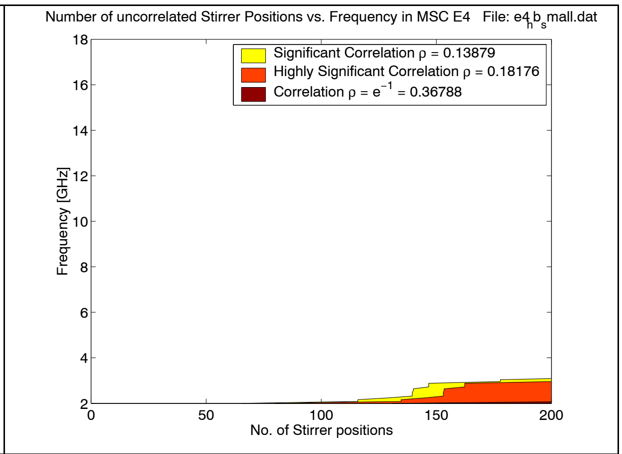


Figure B10. Se4_hb

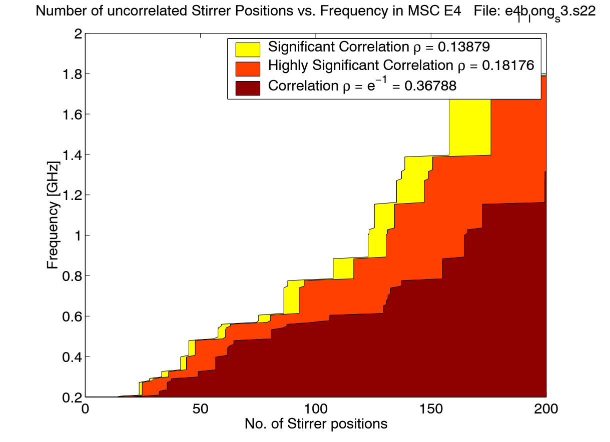


Figure B11. Le4_lb

N/A

Figure B12. Le4_hb

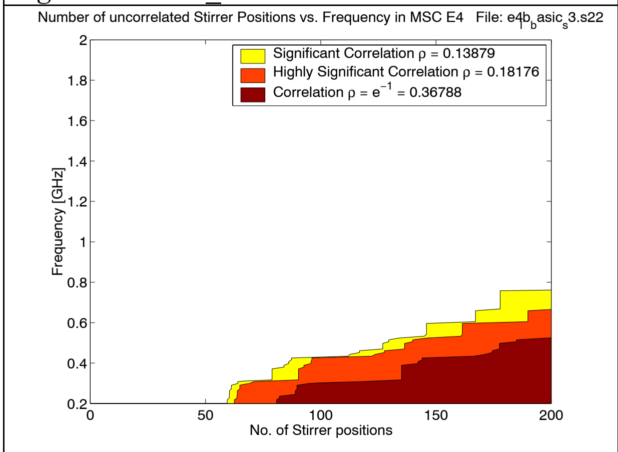


Figure B13. Be4_lb

N/A

Figure B14. Be4_hb

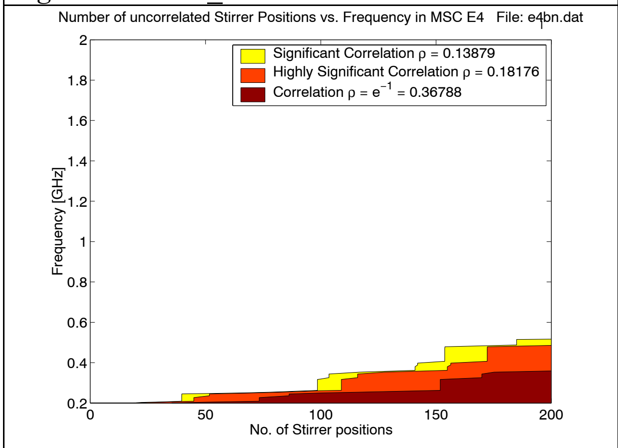


Figure B15. E4e4_lb

N/A

Figure B16. E4e4_hb

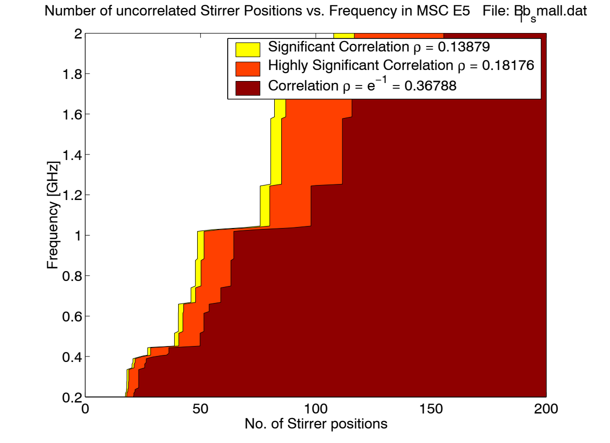


Figure B17. Sb_lb

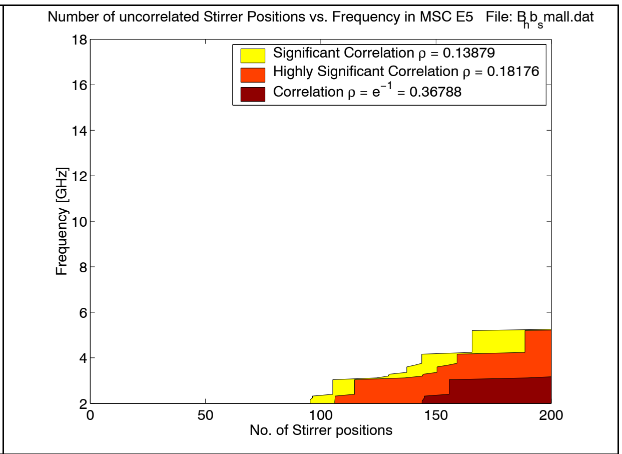


Figure B18. Sb_hb

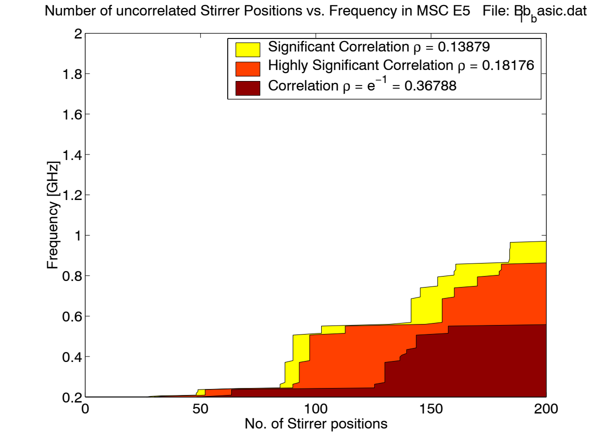


Figure B19. Bb_lb

N/A

Figure B20. Bb_hb

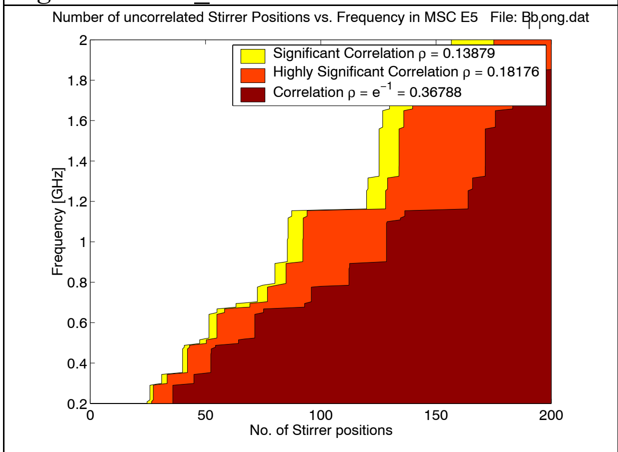


Figure B21. Lb_lb

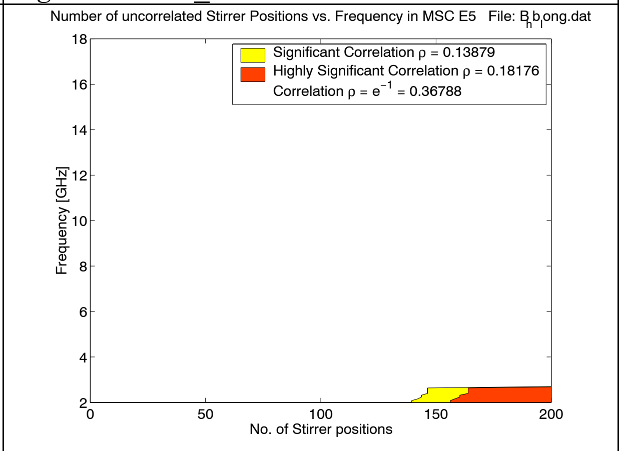


Figure B22. Lb_hb

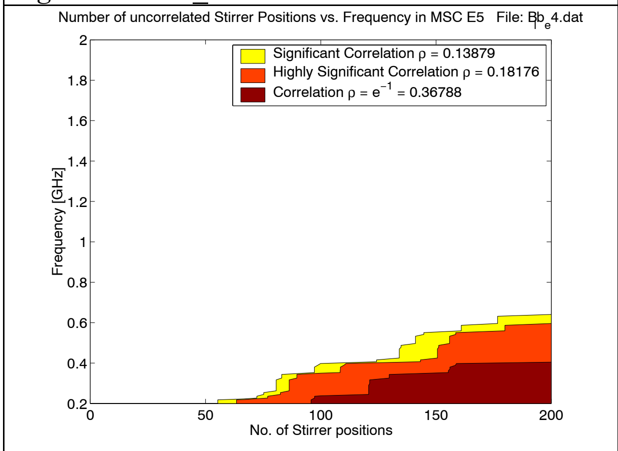


Figure B23. E4b_lb

N/A

Figure B24. E4b_hb

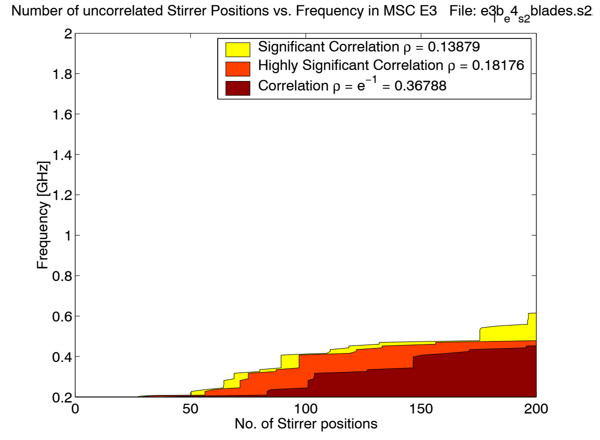


Figure B25. E4 2blades chamber E3

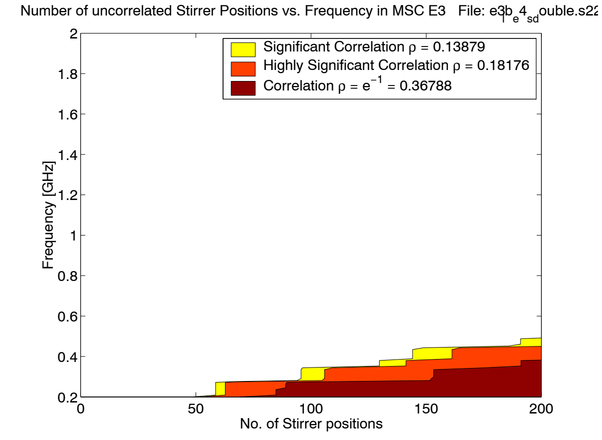


Figure B26. E4 double e3

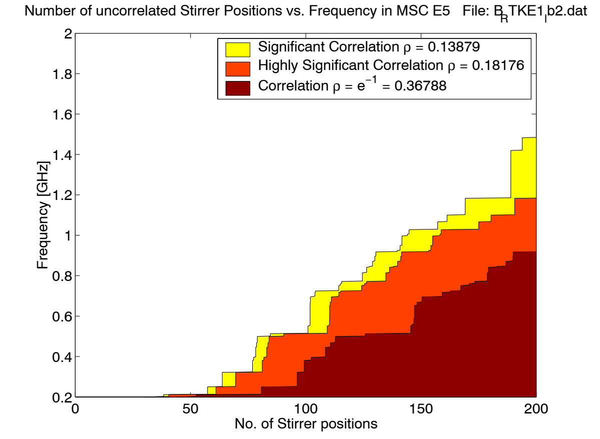


Figure B27. RTKE1_lb Bofors original stirrer

N/A

Figure B28.

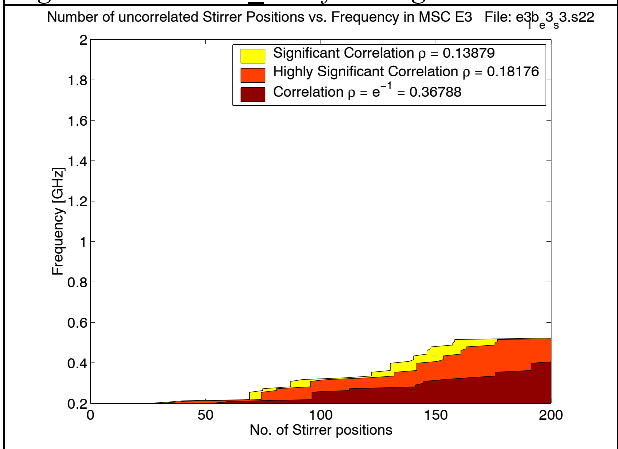


Figure B29. E3e3

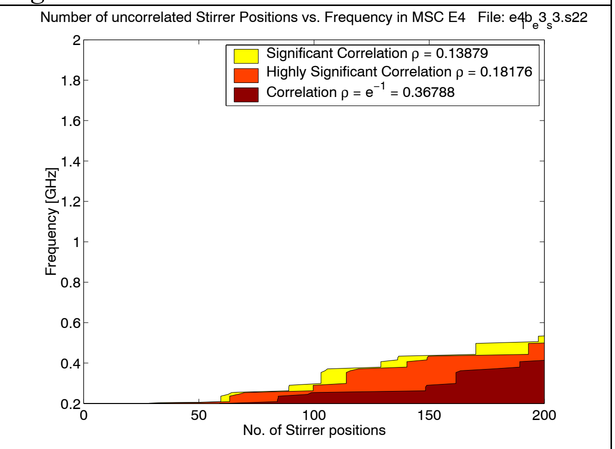


Figure B30. E4e3

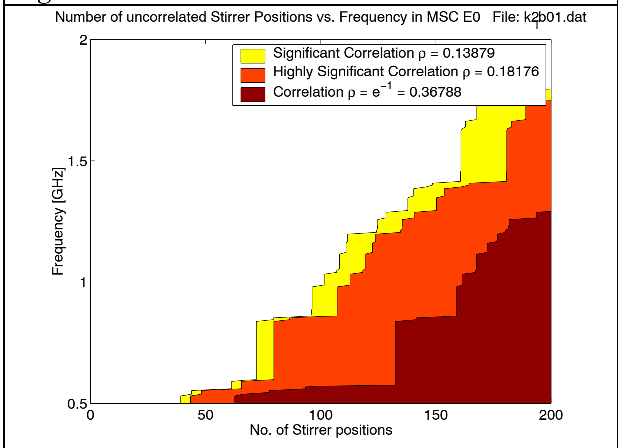


Figure B31. Sk0

N/A

Figure B32.

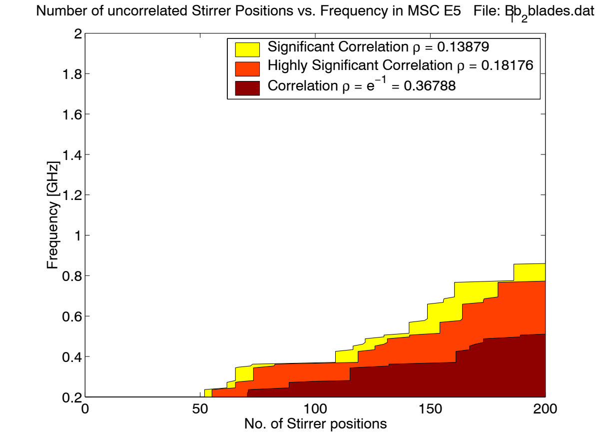


Figure B33. E4 2-blades Bofors cham

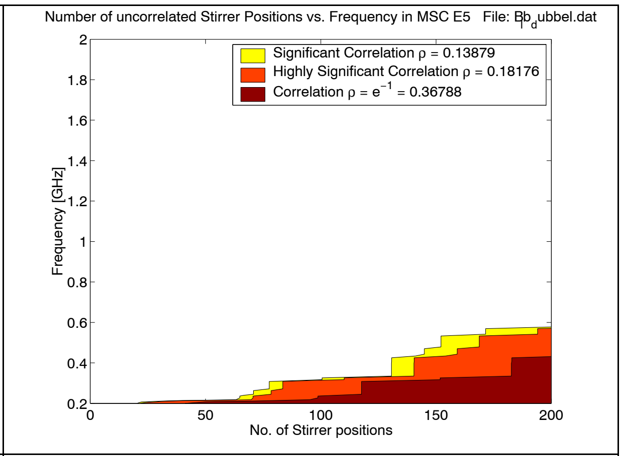


Figure B34. E4 2-double blades Bofors cham

Appendix C

This appendix includes the estimated effects summarised in the table below

Chambers	Number of uncorrelated samples	Criterion	Figure	normplot
E4&E3	200	5% probability	C1a	C1b
E4&E3	200	1% probability	C2a	C2b
E4&E3	200	1/e	C3a	C3b
E4&E3	50	5% probability	C4a	C4b
E4&E3	50	1% probability	C5a	C5b
E4&E3	50	1/e	C6a	C6b
E4&Bofors	200	5% probability	C7a	C7b
E4&Bofors	200	1% probability	C8a	C8b
E4&Bofors	200	1/e	C9a	C9b
E4&Bofors	50	5% probability	C10a	C10b
E4&Bofors	50	1% probability	C11a	C11b
E4&Bofors	50	1/e	C12a	C12b

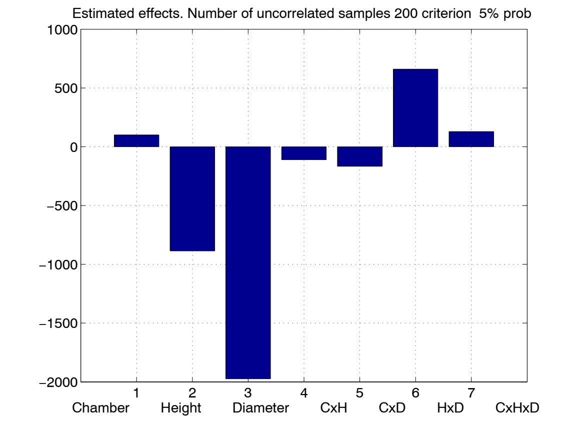


Figure C1a. e4e3_200_5

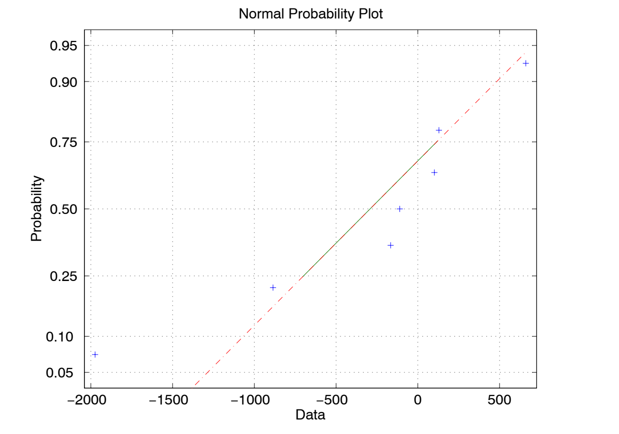


Figure C1b. e4e3_200_5

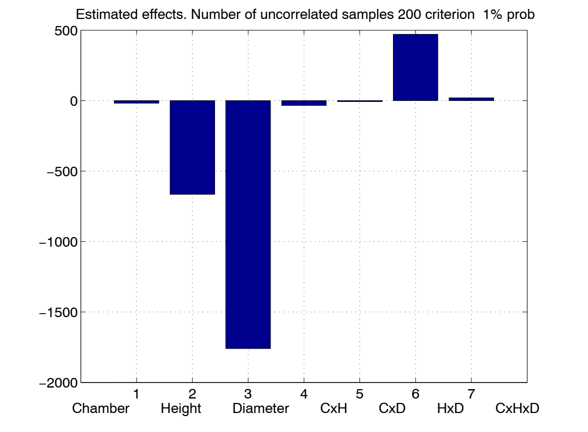


Figure C2a. e4e3_200_1

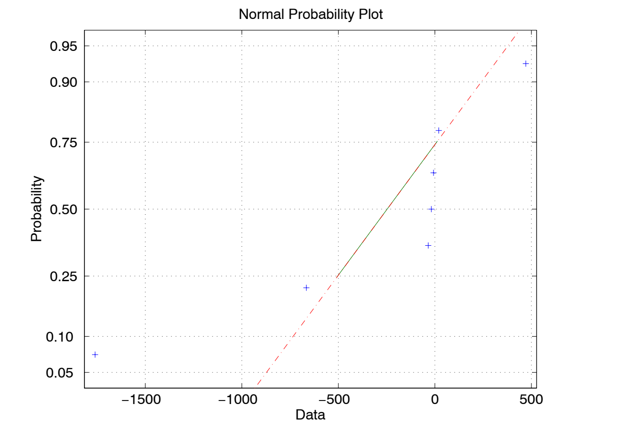


Figure C2b. e4e3_200_1

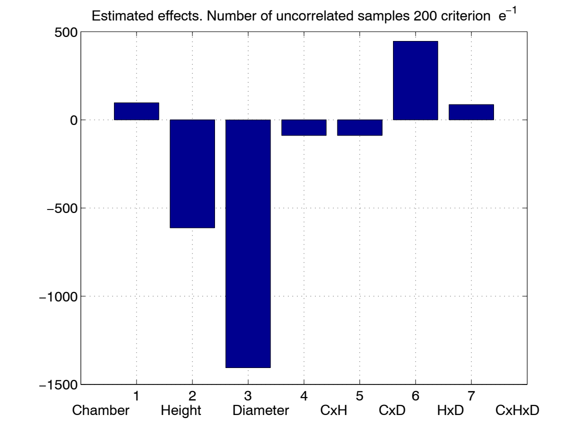


Figure C3a. e4e3_200_e

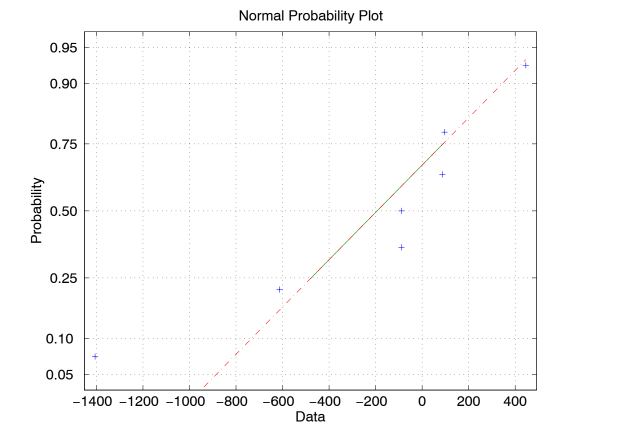


Figure C3b. e4e3_200_e

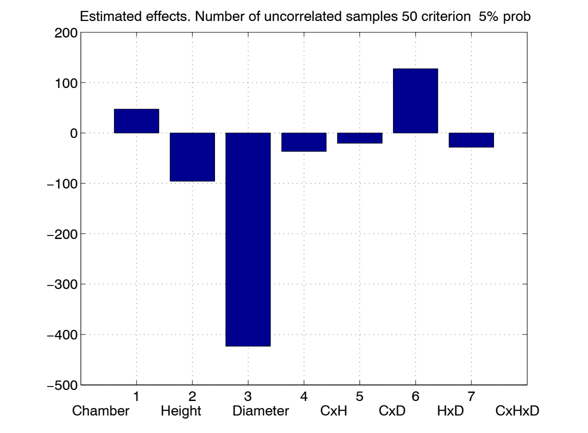


Figure C4a. e4e3_50_5

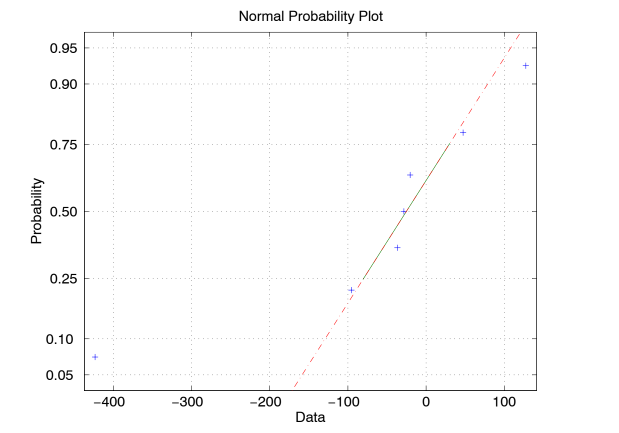


Figure C4b. e4e3_50_5

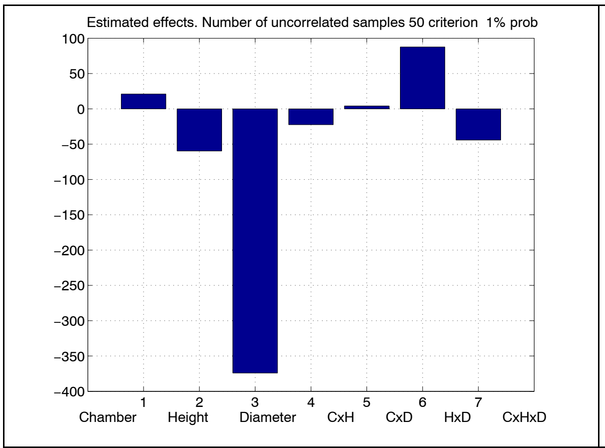


Figure C5a. e4e3_50_1

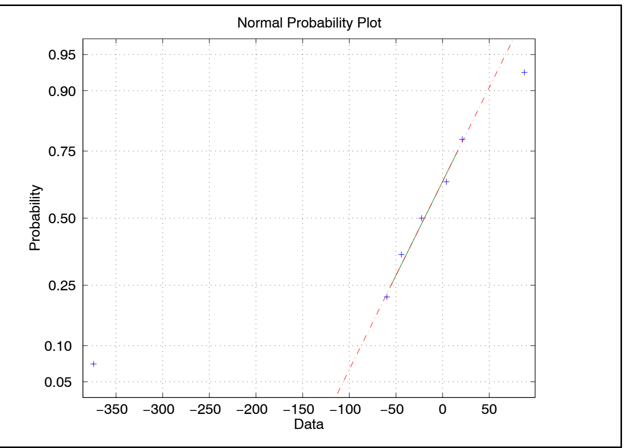


Figure C5b. e4e3_50_1

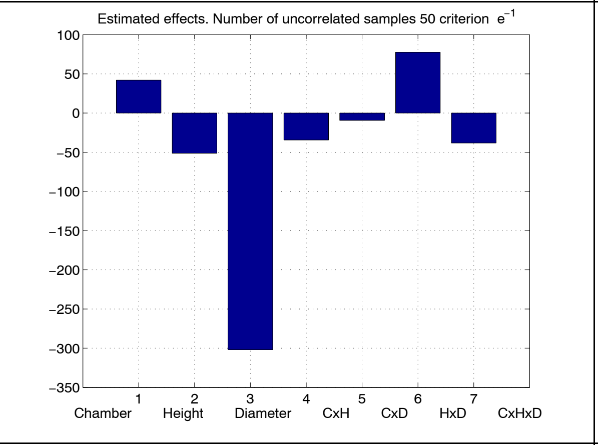


Figure C6a. e4e3_50_e

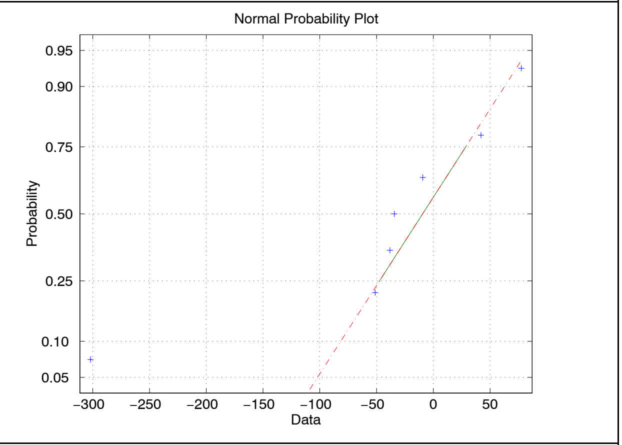


Figure C6b. e4e3_50_e

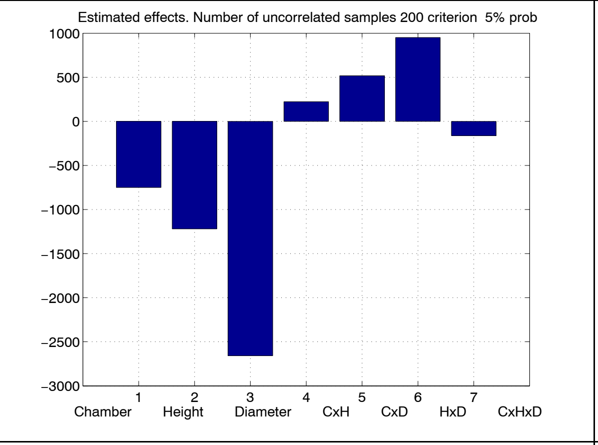


Figure C7a. e4b_200_5

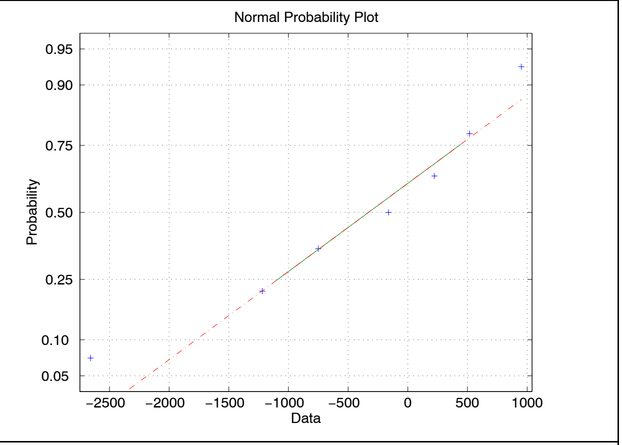


Figure C7b. e4b_200_5

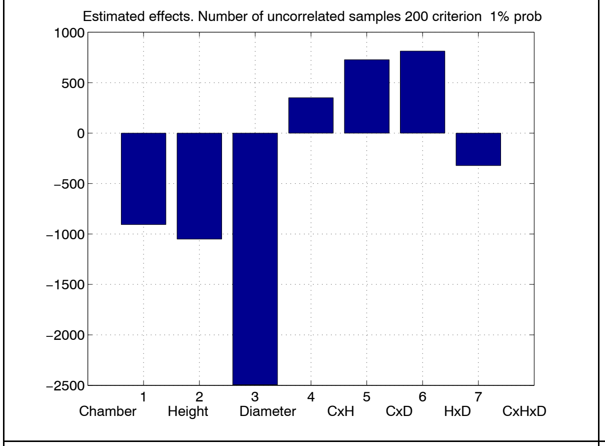


Figure C8a. e4b_200_1

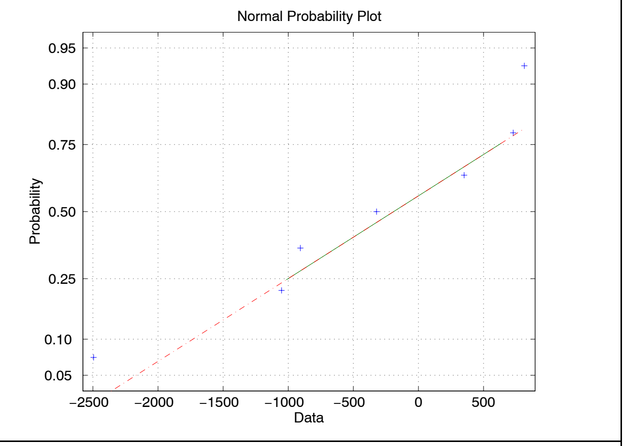


Figure C8b. e4b_200_1

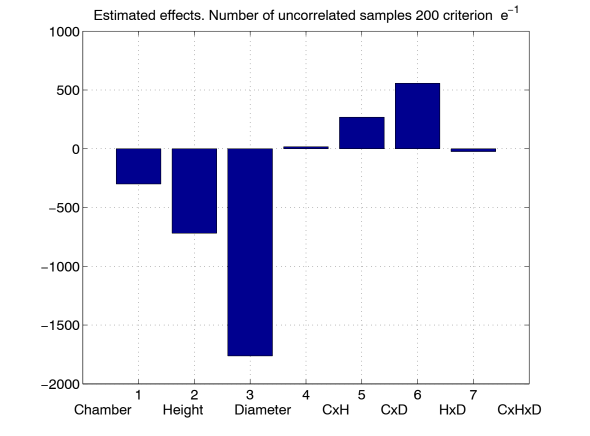


Figure C9a. e4b_200_e

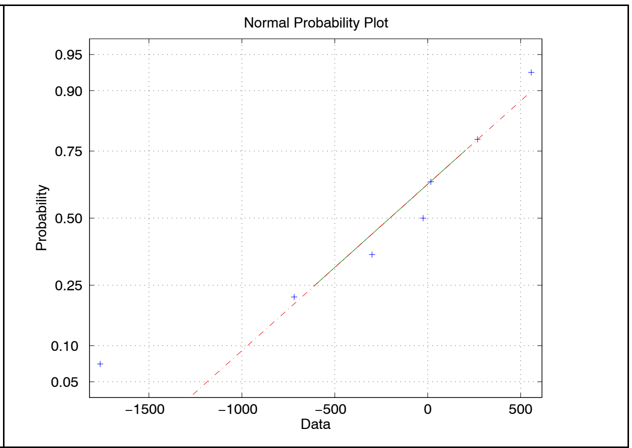


Figure C9b. e4b_200_e

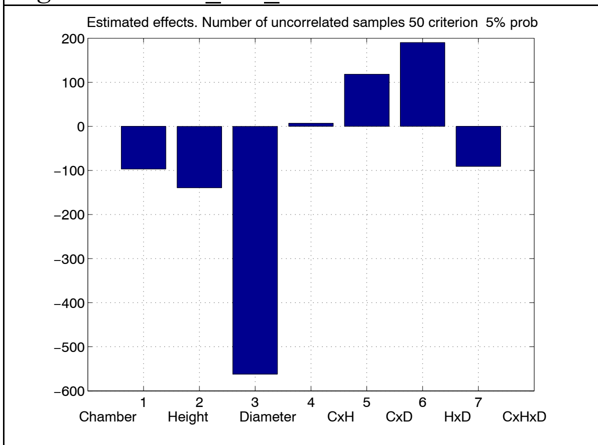


Figure C10a. e4b_50_5

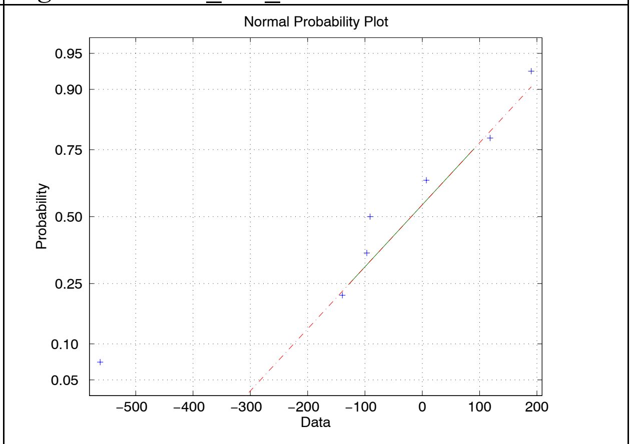


Figure C10b. e4b_50_5

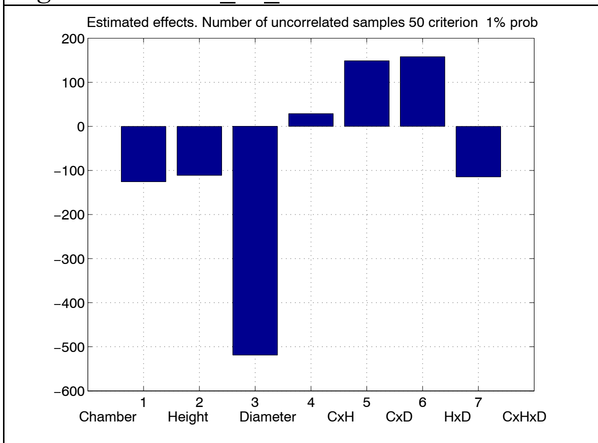


Figure C11a. e4b_50_1

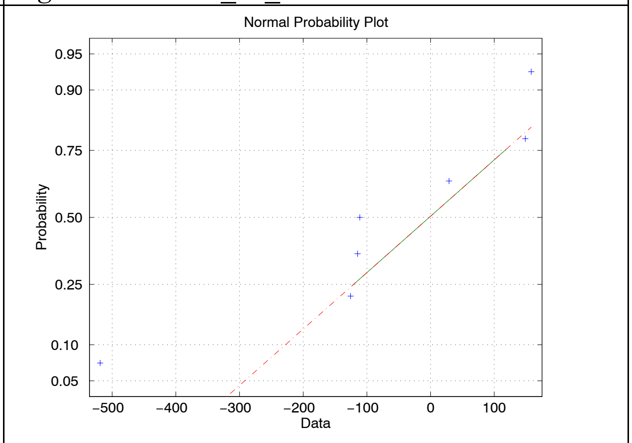


Figure C11b. e4b_50_1

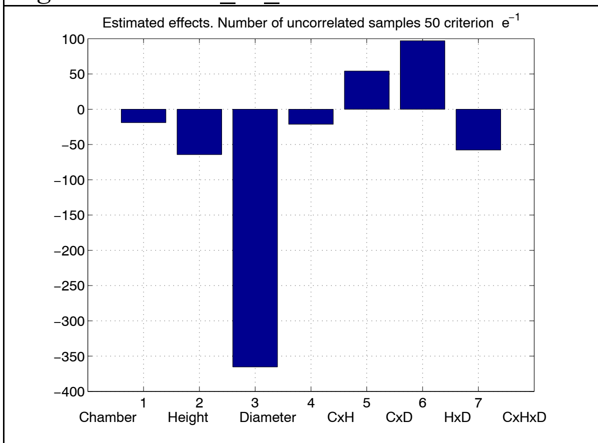


Figure C12a. e4b_50_e

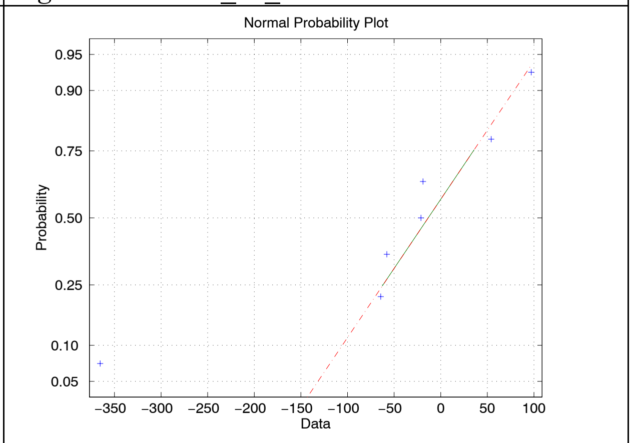


Figure C12b. e4b_50_e

Appendix D

This appendix includes the peripheral movement for the different stirrers vs. numbers of uncorrelated stirrer positions summarised in the table below

Chamber	Criterion	Figure
E3	5% probability	D1
E3	1% probability	D2
E3	1/e	D3
E4	5% probability	D4
E4	1% probability	D5
E4	1/e	D6
Bofors	5% probability	D7
Bofors	1% probability	D8
Bofors	1/e	D9

Table D1

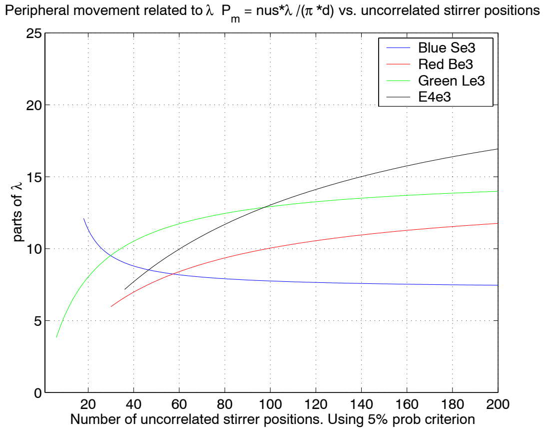


Figure D1. E3 chamber 5% prob. criterion

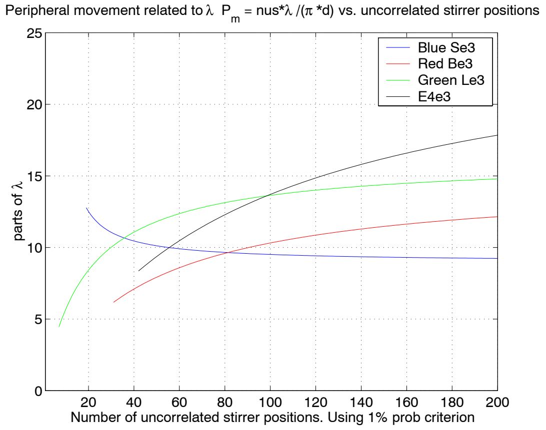


Figure D2. E3 chamber1% probability criterion

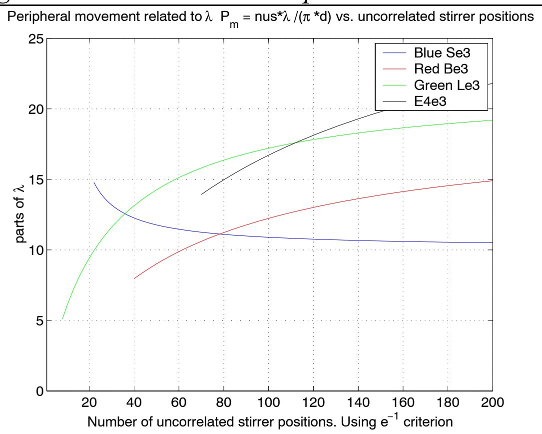


Figure D3. E3 chamber 1/e criterion

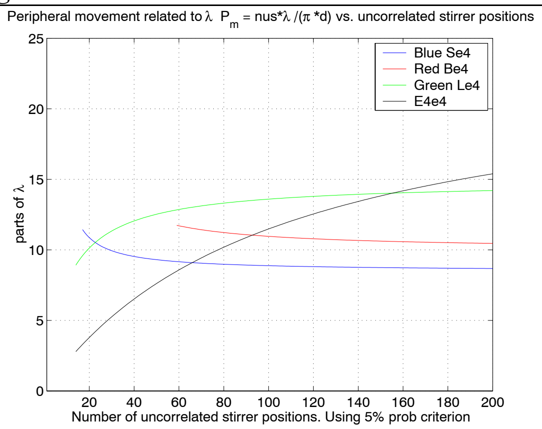


Figure D4. E4 chamber 5% prob. criterion

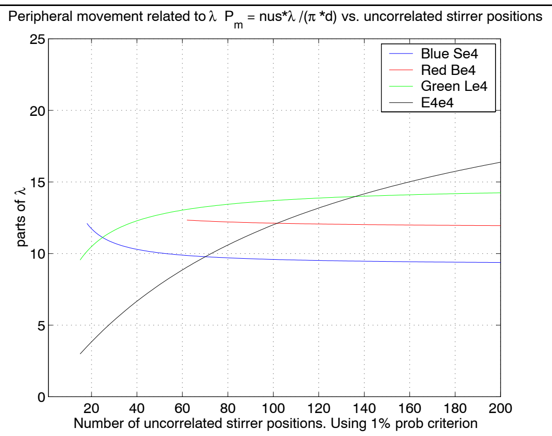


Figure D5. E4 chamber 1% prob. criterion

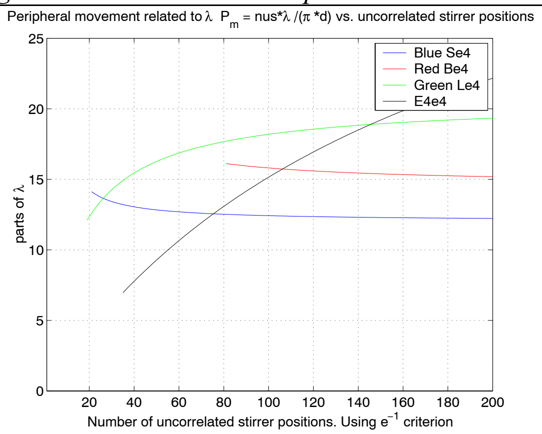


Figure D6. E4 chamber 1/e criterion

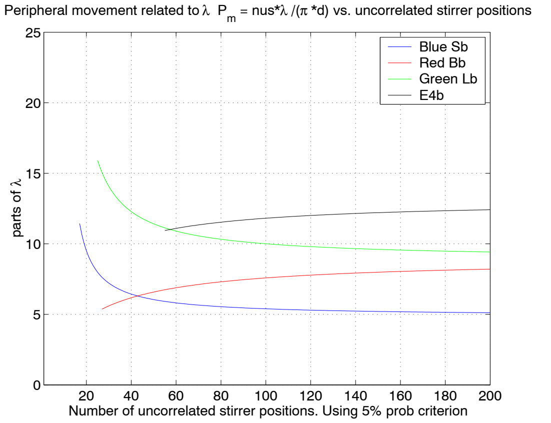
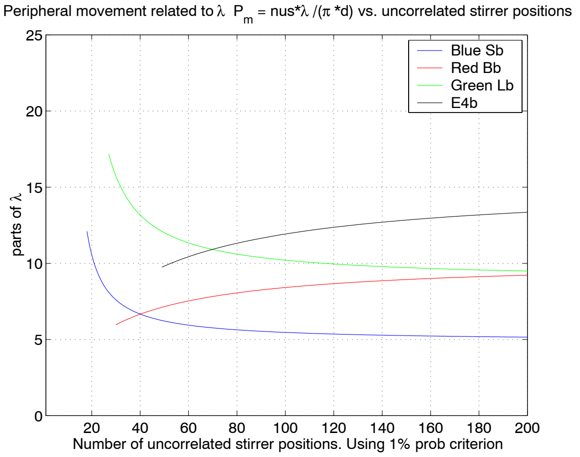
	

Figure D7. Bofors chamber 5% probability criterion	*Figure D8. Bofors chamber 1% probability criterion*

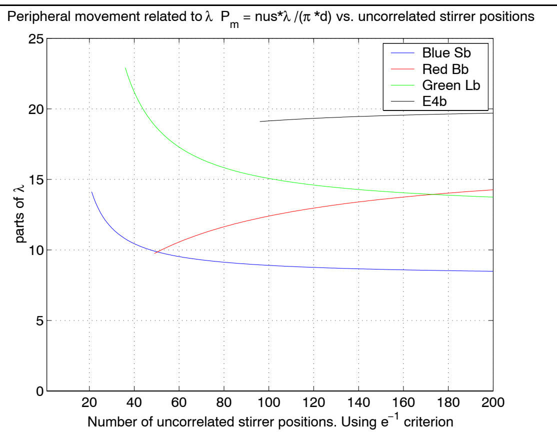



Figure D9. Bofors chamber 1/e criterion	

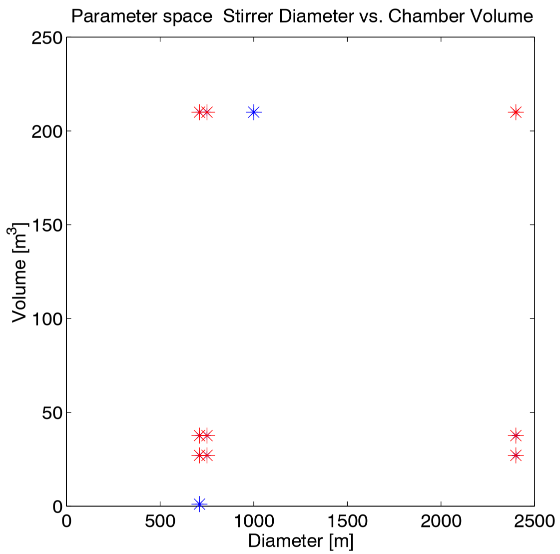
Appendix E

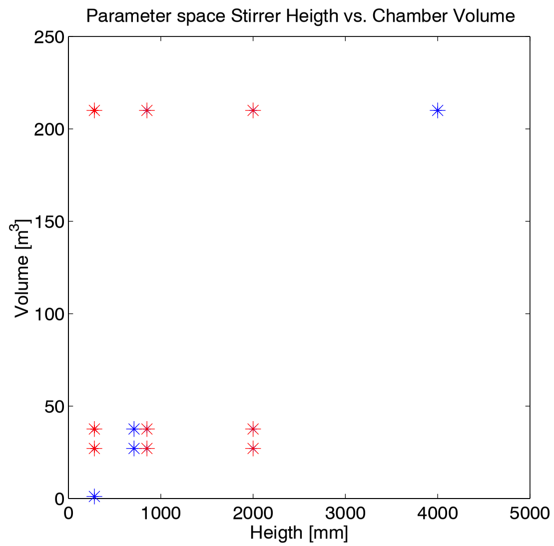
This appendix includes the Matlab program for interactive fitting and visualisation of a response surface. It also includes comparisons between measured and modelled data as well as an illustration of the parameter space.

```
% rsm_test data from E3, E4, kiosk and Bofors chambers
% 200 uncorrelated stirrer steps
%
clear

reactants(1,:)=[280 710 27.1];%___Se4
reactants(2,:)=[280 2400 27.1];%__Be4
reactants(3,:)=[2000 750 27.1];%__Le4
reactants(4,:)=[850 2400 27.1];%__E4e4
reactants(5,:)=[280 710 210];%____Sb
reactants(6,:)=[280 2400 210];%___Bb
reactants(7,:)=[2000 750 210];%___Lb
reactants(8,:)=[850 2400 210];%___E4b
reactants(9,:)=[280 710 37.6];%___Se3
reactants(10,:)=[280 2400 37.6];%_Be3
reactants(11,:)=[2000 750 37.6];% Le3
reactants(12,:)=[850 2400 37.6];%_E4e3
reactants(13,:)=[710 2400 37.6];%_E3e3
reactants(14,:)=[280 710 1.09];%__Sk0
reactants(15,:)=[850 2400 210];%__E4b42
reactants(16,:)=[850 2400 210];%__E4b43
reactants(17,:)=[850 2400 210];%__E4b44
reactants(18,:)=[850 2400 210];%__E4b45
reactants(19,:)=[850 2400 210];%__E4b46
reactants(20,:)=[4000 1000 210];%_Original Bofors

pro=input ('Test criterion 5%=1 1%=2 1/e=3 [5%=1]');
if isempty(pro);
  pro=1;
end

switch pro
case 1
%  5% probability
rate(1)=3100;%__Se4
rate(2)=761;%___Be4
rate(3)=1793;%__Le4
rate(4)=517;%___E4e4
rate(5)=5260;%__Sb
rate(6)=970;%___Bb
rate(7)=2704;%__Lb
rate(8)=641;%___E4b
rate(9)=3500;%__Se3
rate(10)=667;%__Be3
rate(11)=1821;%_Le3
rate(12)=470;%__E4e3
rate(13)=550;%__E3e3
rate(14)=2124;%_Sk0
rate(15)=596;%__E4b42
rate(16)=595;%__E4b43
rate(17)=678;%__E4b44
rate(18)=637;%__E4b45
rate(19)=636;%__E4b46
rate(20)=1485;%_Original Bofors
```

```
case 2
%  1% probability
rate(1)=2870;%__Se4
rate(2)=666;%___Be4
rate(3)=1788;%__Le4
rate(4)=486;%___E4e4
rate(5)=5220;%__Sb
rate(6)=863;%___Bb
rate(7)=2683;%__Lb
rate(8)=596;%___E4b
rate(9)=3150;%__Se3
rate(10)=655;%__Be3
rate(11)=1722;%_Le3
rate(12)=466;%__E4e3
rate(13)=545;%__E3e3
rate(14)=1748;%_Sk0
rate(15)=591;%__E4b42
rate(16)=590;%__E4b43
rate(17)=591;%__E4b44
rate(18)=592;%__E4b45
rate(19)=592;%__E4b46
rate(20)=1184;%_Original Bofors

case 3
%  1/e criterion
rate(1)=2200;%__Se4
rate(2)=524;%___Be4
rate(3)=1317;%__Le4
rate(4)=359;%___E4e4
rate(5)=3170;%__Sb
rate(6)=558;%___Bb
rate(7)=1853;%__Lb
rate(8)=404;%___E4b
rate(9)=2400;%__Se3
rate(10)=534;%__Be3
rate(11)=1327;%_Le3
rate(12)=365;%__E4e3
rate(13)=416;%__E3e3
rate(14)=1292;%_Sk0
rate(15)=506;%__E4b42
rate(16)=500;%__E4b43
rate(17)=501;%__E4b44
rate(18)=500;%__E4b45
rate(19)=499;%__E4b46
rate(20)=919;%_Original Bofors

end

xn=['Height [mm]  ' ; 'Diameter [mm]' ; 'Volume [m^3] '];
yn='Frequency';
model='linear';
rstool(reactants,rate,model,0.05,xn,yn)
```

Stirrer Height mm	Stirrer Diam. mm	Cham. Vol. m^3		MEASURED Frequency in MHz			MODELLED Frequency in MHz			% DIFFERENCE		
				5%	1%	1/e	5%	1%	1/e			
280	710	37,6	Small	3100	2870	2200	3068	2779	2044	3,171	3,171	7,091
2000	750	37,6	Long	1793	1788	1317	1827	1768	1318	-1,896	1,119	-0,076
280	2400	37,6	Basic	761	666	524	638	566	461	16,16	15,02	12,02
710	2400	37,6	E3	534	499	414	583	569	435	-9,176	-14,03	-5,072
850	2400	37,6	E4	517	486	359	565	569	427	-9,284	-17,08	-18,94
280	710	27,1	Small	3100	2870	2200	2949	2643	1797	4,871	7,909	18,32
2000	750	27,1	Long	1793	1788	1317	1735	1680	1275	3,235	6,04	3,189
280	2400	27,1	Basic	761	666	524	624	550	452	18	17,42	13,74
710	2400	27,1	E3	534	499	414	576	563	430	-7,865	-12,83	-3,865
850	2400	27,1	E4	517	486	359	560	567	424	-8,317	-16,67	-18,11
280	710	1,09	Small	2124	1748	1292	2656	2306	1817	-25,05	-31,92	-40,63
280	710	210	Small	5260	5220	3170	5011	5013	3115	4,734	3,966	1,735
2000	750	210	Long	2704	2683	1853	3323	3210	2100	-22,89	-19,64	-13,33
280	2400	210	Basic	970	863	558	861	843	603	11,24	2,317	-8,065
850	2400	210	E4	641	596	404	654	600	479	-2,028	-0,671	-18,56





Cut to centre and fold this piece behind the picture above!

* Indicates points that are included in the designed experiments.

* Indicates points that are also included in the Response Surface Modelling.