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A Computer Model For Estimation Of Horizontal Stress And Stress Directions From Inversion Of Extended Leakoff Test(Xlot) Data

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Abstract: *In-situ strains play the most vital role in borehole steadiness during drilling operation. Problems pose by uncertainties in the measurement of strain during drilling are enormous in the petroleum industry. In this paper a handy computer tool for estimating the magnitude and direction of horizontal matrix strains was developed. A solution set is gotten using data from a LOT together with overburden strain, pore pressure and well orientation data. The inversion methodology is established by means of a case history from* ***Snorre field in the North Sea.***

Keywords: *Azimuth, Fracturing, Gradient, In-situ, Inversion, LOT-Leakoff Test, Overburden Stress and Pore Pressure*

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I. Introduction

Accurate prediction of the in-situ strains (S_h, S_H) is vital in the petroleum industry. Knowledge of the in-situ strain has implications for not only drilling safety and well design but also the costs of extraction of hydrocarbons. It is generally accepted that hydraulic fracturing is the most accurate method to measure strain at deep hole. As shown by Aadnoy (1989), the magnitude and direction of the horizontal in-situ strains can be approximated from leak-off data using inversion method.

Hubbert and willis (1957) afforded the most vital effort in the interpretation of hydraulic fracturing mechanism, by means of the theory of elasticity to reach the conclusion that the direction of the induced hydraulic fracture and the pressures recorded during borehole pressurization are unswervingly related to the principal in situ strains, this ensued the thriving use of hydraulic fracture as stimulation strategy in the 1940s. Hydraulic fracturing has now become one of the key tactics for rock strain estimation as suggested by the International Society for Rock Mechanics (ISRM). Fairhurst was amongst the first to advocate the use of hydraulic fracturing for in situ strain determination.

Kirsch (1989) accessible solutions from which the basic equations describing the strain distribution around a horizontal, vertical and inclined wellbore may be derived. It is generally alleged that a fracture initiates when the maximum tensile strain induced at any point around the wellbore exceeds the tensile strength of the formation at that point. When this transpires, the resulting fracture on the wellbore wall will have a course that is perpendicular to the direction of the most tensile principal strain. According to Kirsch (1989) the pressure of wellbore malfunction is given by eqn 1.3.

Aadnoy Bs. (1990) accessible a strategy for inverting results from a minimum of two leakoff tests at diverse well inclinations and azimuths. This method gives an estimate of the both horizontal strain (maximum and minimum) magnitudes and directions. Nevertheless, the published strategy suffers from the assumption that shear strains are neglected. As exposed by Aadnoy (1990), the magnitude and direction of the horizontal in-situ strains can be approximated from leak-off data using inversion method. The method makes use of the fracture equation which is derived from the Kirsch equations and strain transformation equation. Gjones et al.(1998) suggested the original method was inaccurate, because it ignores shear strain, and proposed an improved method. Nevertheless, Gjonnes et al. (1998) found that the enhanced inversion also contained large uncertainties, in part due to the inaccuracy of the LOTs and suggested the use of multiple strategies to decide the insitu strain.

Djurhuus and Aadnoy (2003) accessible a theory for determining the in situ strain state from multiple fracturing data and induced fractures from image logs. A solution can be gotten with a minimum of two data sets. Nevertheless, using an inversion strategy, a solution can be gotten with any number of Datasets, as the solution is over decided.

1.1 Theoretical Tactics for Determination of horizontal strain

Leak-off test (LOT), extended leak-off tests (XLOT) and minifracture tests can be used to constrain horizontal strain magnitudes (Haimson and Frairhurst, 1967; Breckels and van Eeklen, 1982; Kunze and Steiger, 1991). All the test involve escalating fluid pressure in the wellbore until a fracture is created at the wellbore wall. The LOT is the most frequently undertaken and the simplest of these tests. LOTs are conducted not for the intention of making strain estimates, but in order to decide the maximum mud weight that can be used when drilling ahead. An XLOT is conducted when information on the strain tensor is of interest (Kunze and Steiger, 1991). As the name suggests an XLOT is an extended version of LOT, using the same basic tools, but a diverse test procedure. The third type of test discussed in this sector is the minifracture or hydraulic fracture test, which is specifically designed to decide the horizontal strain magnitudes. LOTs can be used to estimate σ_h. XLOTs and minifracture test afford a more reliable estimate of σ_h and under definite circumstances, an estimate of σ_H.
To calculate the fracture pressure using data from wellbore fracture, Aadnoy and Chenevert (1987) gave the subsequent equation:

$$P_{wf} = 3\sigma_y - \sigma_x - P_0 + \sigma_{tensile} \qquad 1.3$$

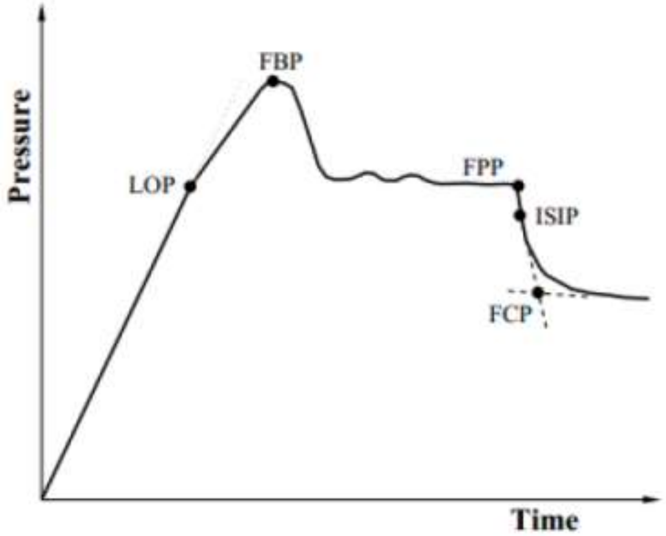

Fig 1.0: XLOT pressure versus time showing; LOP , FBP, FPP

Extended leak-off tests and minifracture tests are conducted specifically for the intention of strain determination (Haimson and Fairhurst, 1967; Kunze and Steiger, 1991; Enever et al., 1996). These tests involves multiple cycles of pressurisation and de-pressurisation (Enever et al., 1996), but use diverse tool. An XLOT can be conducted in place of a LOT during drilling when better quality strain information is requisite (Kunze and Steiger, 1991; Enever etal., 1996).

Extended leak-off test apart from the fact that it a method for measuring σ_h they can also be used to estimate σ_H. σ_H can be decided from these tests by means of fracture initiation and/or reopening pressure (Hubbert and willis, 1957; Haimson and Fairhurst, 1967). The fracture initiation and/or reopening pressure depend on the strain concentration around an open hole. The minimum strain concentration around the wellbore is given by:

$$\sigma_{\theta\theta\,min} = 3\sigma_h - \sigma_H - P_w - P_p \qquad 1.4$$

Tensile malfunction transpires when the concentration exceeds the tensile potency of the rock (in an absolute sense, tensile strains have been definite as negative). Hence for tensile malfunction of the wellbore wall:

$$\sigma_{\theta\theta\,min} = 3\sigma_h - \sigma_H - P_w - P_p \leq T \qquad 1.5$$

The fracture initiation pressure (P_i, LOP) is P_w at fracture initiation, hence:

$$3\sigma_h - \sigma_H - P_w - P_p = T \qquad 1.6$$

The fracture initiation pressure can be read unswervingly from the pressure record, as can σ_h which is the fracture closure pressure (fig 1.0). Hence eqn 1.6 can be rewritten as:

$$\sigma_H = 3P_c - P_i - P_p - T \qquad 1.7$$

Since the initial fracturing cycle overcomes tensile rock strength, for subsequent cycles equation 1.7 can be rewritten as

$$\sigma_H = 3P_c - P_r - P_p \quad 1.8$$

1.1.1 Method of Breckels and Van Eekelen (1982)

Breckels and van Eekelen (1982) afforded a good summary of the work of previous authors such as Matthews and Kelly (1967), Pennebaker (1968), Eaton (1969) and Pilkington (1978) on fracture gradients and lower bounds to LOPs for the US Gulf Coast. Each of these authors use the k value (ratio of horizontal to vertical effective strain) to define their affiliations of how strain changes with depth. Differences only actually transpire in the way they decide the minimum effective strain. For additional information see Breckels and van Eekelen (1982). Following this historical review, Breckels and van Eekelen (1982) derived an affiliation amid the minimum strain (Sh) and depth for the US Gulf Coast using fracture or "instantaneous shut-in" pressure data. Using a data set of over 300 points from the US Gulf Coast, they mathematically fitted a curve that described the lower bound to 93% of the data. The curve, a combination of a linear and power-law affiliation, meant the magnitude of Sh might be decided solely from the depth (D):

S h = 0.0197 Du45 for D<7500 feet. 1.9

Sh = 1.167 D- 4596 for D>7500feet. 1.10

More complex affiliations were derived for Sh in abnormally pressured formations in the US Gulf Coast region by means of the depth and the magnitude of under/over-pressure (actual minus normal pore pressure). Data from Venezuela and Brunei were also used to attain power-law affiliations for minimum strain determination with a combination of depth and under/over-pressure magnitude.

1.1.2 Method of Djurhuus and Aadnoy

Djurhuus and Aadnoy (2003) accessible a theory for determining the in situ strain state from multiple fracturing data and induced fractures from image logs. The position of the fracture on the borehole wall was decided by minimization of the tangential strain σ_θ resulting in the equation

$$\tan(2\theta) = \frac{2\tau_{xy}}{\sigma_x - \sigma_y} \quad 1.11$$

thus the fracturing position on the borehole wall calculated from Eq. (1.11) will be either $\theta = 0$ or θ =90.

At tensile malfunction (assuming rock tensile strength is zero)

when $\theta = 0$, and $\sigma_x > \sigma_y$

$$P_{wf} = 3\sigma_y - \sigma_x - P_0 + T \quad 1.12$$

and when $\theta = 0$, and $\sigma_x < \sigma_y$

$$P_{wf} = 3\sigma_x - \sigma_y - P_0 + T \quad 1.13$$

After substitution of the strain transformation equations, the above equations take the form;

$$\frac{P_{wf} + P_0 - \sigma_{tensile}}{\sigma_v} + \sin^2\gamma = \{3\sin^2\varphi - \cos^2\varphi\cos^2\gamma\}\frac{\sigma_H}{\sigma_v} + \{3\cos^2\varphi - \sin^2\varphi\cos^2\gamma\}\frac{\sigma_h}{\sigma_v} \quad 1.14$$

$$\frac{P_{wf} + P_0 - \sigma_{tensile}}{\sigma_v} - 3\sin^2\gamma = \{3\cos^2\varphi\cos^2\gamma - \sin^2\varphi\}\frac{\sigma_H}{\sigma_v} + \{3\sin^2\varphi\cos^2\gamma - \cos^2\varphi\}\frac{\sigma_h}{\sigma_v} \quad 1.15$$

Aadnoy (1989) redefined Eqs. (1.14) and (1.15) in the form

$$P' = a\frac{\sigma_H}{\sigma_v} + b\frac{\sigma_h}{\sigma_v} \quad 1.16$$

and in combination with a number of data sets, the two-unknown horizontal in situ strains sH and sh were decided from Eq. (1.16) using the least square method. Gjones et al. (1998) used an alike approach, but shear strain was included. Affordd sH and sh have been gotten, Djurhuus and Aadnoy (2003) further decided γ and φ from Eqs. (1.11) but the back-figured values of γ and φ were not the same as the originally assumed values.

1.1.3 Proposed Method

In this section the method of inversion as proposed by Aadnoy is used for estimating the magnitude of the minimum and utmost horizontal strains and their directions. The input data for this method includes: pore pressure, overburden pressure, azimuth and inclination and data accrued from Leak-off, tests from diverse wells. The data are gotten from the already drilled wells and back calculation is done to settle on the horizontal strain magnitudes of the field formation. As mentioned in the previous section this method is primarily based on the Kirsch's wellbore malfunction equation given. The fracture equation is in reference to an arbitrarily chosen borehole coordinate system x, y and z and consequently, it is pertinent to any wellbore orientation.

A critical look at eqn. 1.16 reveals that the only unknown terms are σ_H and σ_h. Inserting the well geometry constants azimuth, and inclination, the square terms are resolved and the equations become linear. The linearized equations can be placed in a matrix form and be solved. When many datasets are accessible from diverse leak-off tests, the equations can be accessible in the following simple form:

$$[P'] = [A][\sigma] \qquad 1.17$$

Though, equation 1.17 can be solved with as many datasets as available, a minimum of two datasets are required. The more the datasets used, the better the results gotten. When many datasets are used to solve for only the two unknowns, the equation would result in an over-decided system of linear equations. An exact solution cannot be gotten from the resolution of the over-decided system. The error which is the disparity between the measured data and the solutions gotten from the computer model built in this paper is given by:

$$[e] = [A][\sigma] - [P'] \qquad 1.18$$

The error gotten from the above equation is squared using the least square method. The squared error is minimized by diverseiating it with respect to $[\sigma]$ and equating the resultant equation to zero. The maximum and minimum in-situ strains can be calculated with the subsequent equations:

$$[\sigma] = \{[A]^T[A]\}^{-1}[A]^T[P'] \qquad 1.19$$

In order to solve the right hand side (RHS) of the above equation it is vital to note that not all matrices are invertible but if a matrix is invertible then for a matrix A.

$$A^{-1}A = AA^{-1} = I \qquad 1.20$$

It turns out that a naive approach to finding the inverse of a matrix for solving systems of linear equation is recurrently inefficient. In practice other strategies such as LUP decomposition will be more numerically stable. For the model accessible in this paper the LU Decomposition method is used to obtain matrix inverse for solutions to the RHS of eqn. 1.19. the algorithm for the LU Decomposition is given below.

```
Initialize U = A, L = I
        for k = 1 : m − 1
                for j = k + 1 : m
L(j, k) = U(j, k)/U(k, k)
U(j, k : m) = U(j, k : m) − L(j, k)U(k, k : m)
                end
end.
```

II. Results And Discussion

Snorre field in the North Sea

Three wells, P-7, P-8 and P-9 are considered for this test. The depths of the wells range from about 0.7 to 2.4 km and are accessible in Table 1.0 Data sets from the table are inputted into the model to decide the in-situ strains and their directions. strain values Gotten from the model are used to compute the fracture pressures used for the validating the model. The process comprises comparing the distinction amid results gotten from the model and the values from the measured data and selecting the set of results with the smallest error.

Table 1.0: Fractured data for Field case1

Data Set	Well	Depth (m)	P_{wf} (s.g.)	P_0 (s.g.)	σ_v (s.g.)	γ (°)	φ (°)
1	P-7	1160	1.44	0.9767	1.8481	19.37	196.92
2	P-7	1774	1.71	1.3993	1.9649	70.63	195.90
3	P-7	2369	1.87	1.3814	2.0511	60.56	220.76
4	P-8	756	1.39	0.9483	1.7325	8.61	167.78
5	P-8	1474	1.65	1.2213	1.9151	60.26	187.65
6	P-8	2321	1.83	1.3789	2.0475	43.82	129.16
7	P-9	1005	1.59	0.9685	1.8087	16.88	92.77
8	P-9	1503	1.62	1.2568	1.9199	36.30	85.69
9	P-9	2418	1.75	1.3840	2.0548	55.09	89.13

Fig 1.1 below shows the input interface for the computer replica comprising inputs for 2, 5 and 8 data sets. A simulation of all datasets (1,2,3,4,5,6,7,8,9) is run for all probable combinations around the wellbore (360 degrees) to decide state of strain, based on the minimum squared error. In validating results gotten using the above datasets by computing fracture pressure from the approximated strain value, the results from the model do not match the test data as indicated by large error values, this signify that the simulated datasets do not accurately represent the state of strain of the complete field depth. To get an enhanced representation of the strain state of the field, simulations are done in smaller areas**.** For the sake of this study only three datasets (2,5,8) are used since for the three wells, these datasets transpire in the same hole section and as such affords a better depiction for the state of strain in the formation.

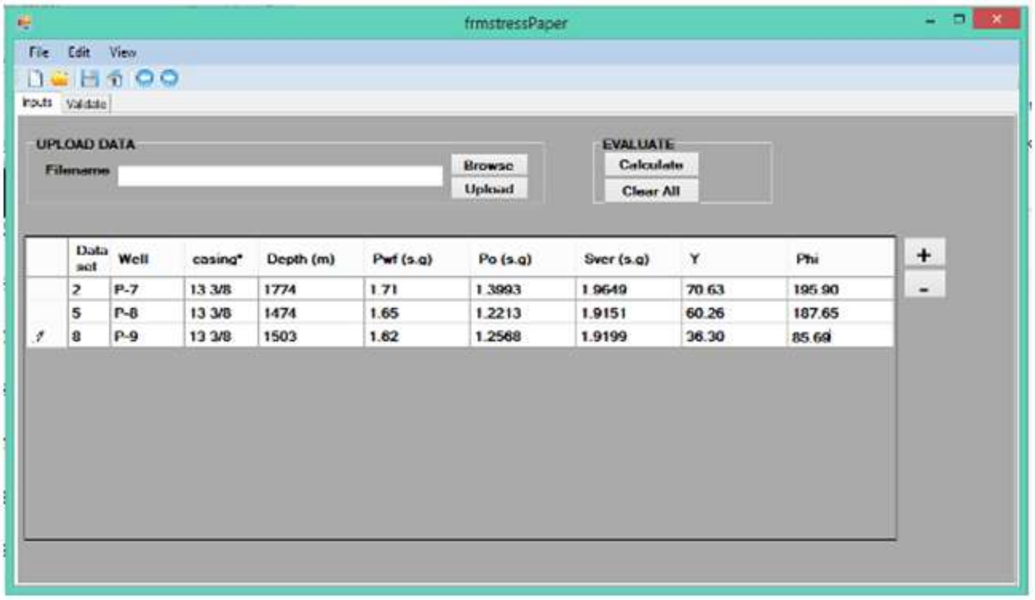

Fig 1.1: Input interface for the computer model.

Running the model by means of the selected datasets for all probable combinations around the wellbore (360 degrees) to decide state of strain, based on the minimum squared error, the most apposite result (i.e the solution with the smallest error using the least square method) is selected and given as:

$$\frac{\sigma_H}{\sigma_v} = 0.9213078$$

$$\frac{\sigma_h}{\sigma_v} = 0.59729985$$

$$\beta = 134^0$$

Squared error= 0.00005

The results given for the horizontal strains ratio illustrate that the maximum horizontal principal in-situ strain is 0.9213078 times the overburden, the minimum horizontal strain is 0.59729985 times the overburden and the angle beta gives the direction of the maximum in-situ strain with reference to the North. Fig 1.2 below shows the result interface for the computer model.

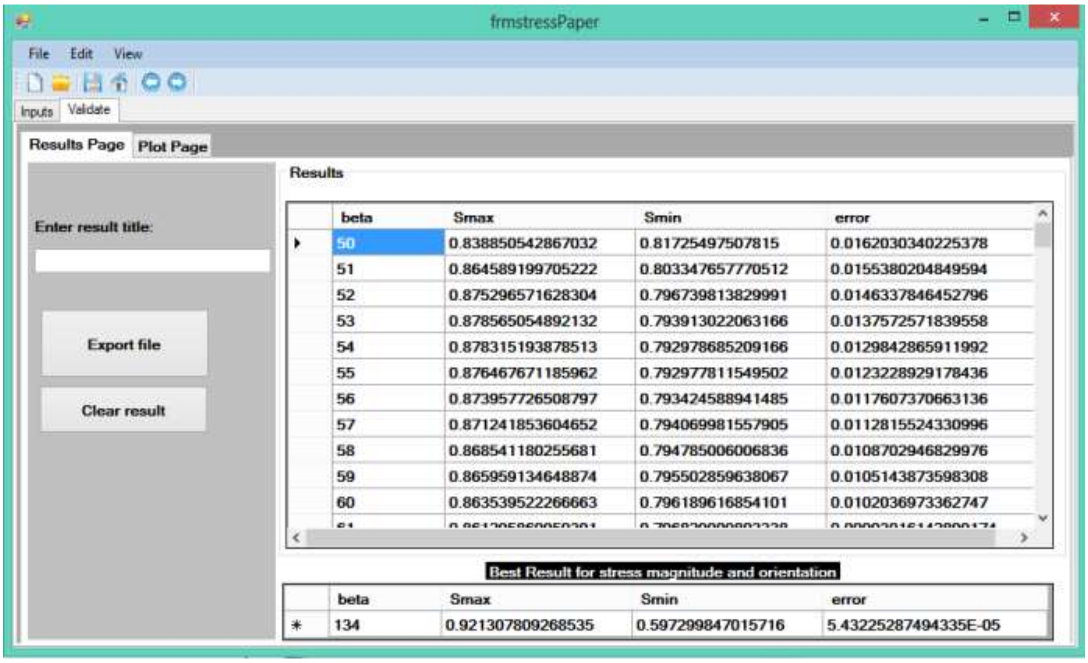

Fig 1.2: Result interface for the computer model

The interface above shows two separate tables. The first table displays the strain results and their corresponding directions for all possible combination around the wellbore (through 360 degrees). The second table shows the best match for the strain value and strain direction based on smallest squared error. Fig 1.3 below demonstrate the validation of this matched value relative to the other values gotten from the computer model.

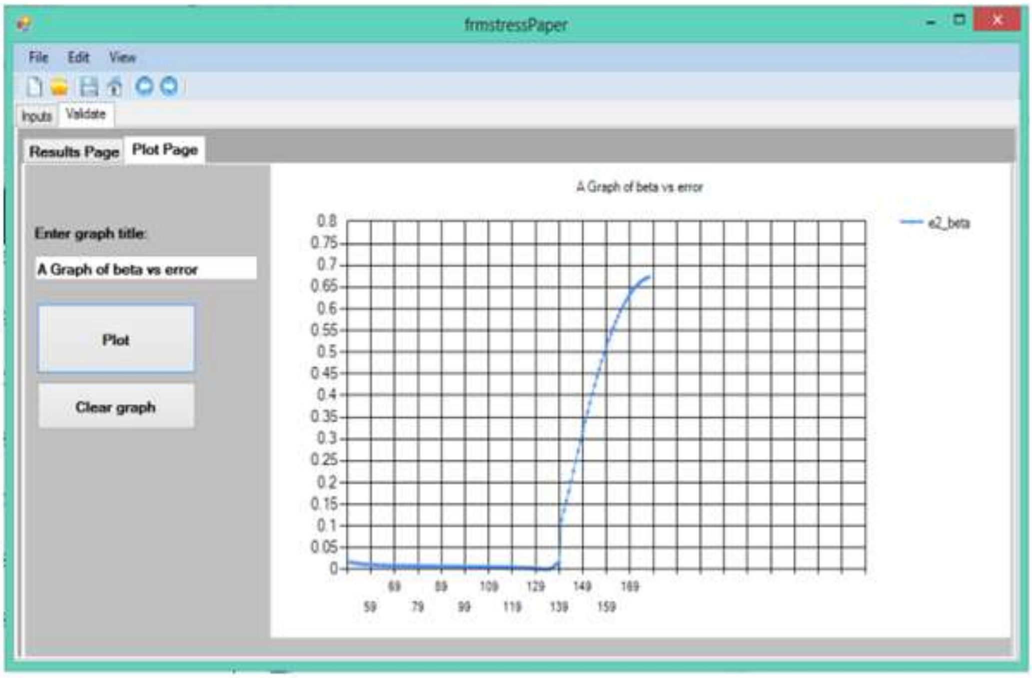

Fig 1.3: A plot of β vs squared error showing direction of σ_H

The results for selected Dataset run are displayed in the appendix

III. Conclusion

Wellbore in steadiness problems which result to additional drilling cost are majorly owing to matrix strain. Consequently, accurately predicting the in-situ strains in a rock formation can go a long way to solve a lot of the dares facing the petroleum and mining industries and a whole lot of money could be saved and accidents averted. In this project, a handy tool that is unproblematic to use to predict the horizontal principal in-situ strains was developed. The results from simulations gotten from this work demonstrated the reliability of this program to:

1. Estimate the magnitude of the horizontal principal matrix strains of a rock field based on data gotten from LOT, pore pressures, overburden strains and well directions. The model can accommodate any number of input data but a minimum of three input data is requisite to get a meaningful result.
2. The approximated magnitude of the matrix strains can be used to calculate fracture pressures.

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Appendix

β	$\frac{\sigma_H}{\sigma_v}$	$\frac{\sigma_H}{\sigma_v}$	**Squared error**
50	0.838850542867032	0.81725497507815	0.0162030340225378
51	0.864589199705222	0.803347657770512	0.0155380204849594
52	0.875296571628304	0.796739813829991	0.0146337846452796
53	0.878565054892132	0.793913022063166	0.0137572571839558
54	0.878315193878513	0.792978685209166	0.0129842865911992
55	0.876467671185962	0.792977811549502	0.0123228929178436
56	0.873957726508797	0.793424588941485	0.0117607370663136
57	0.871241853604652	0.794069981557905	0.0112815524330996
58	0.868541180255681	0.794785006006836	0.0108702946829976
59	0.865959134648874	0.795502859638067	0.0105143873598308
60	0.863539522266663	0.796189616854101	0.0102036973362747
61	0.861295860959391	0.796829009803338	0.00993016142899174
62	0.859226503125309	0.797414328099249	0.00968737387762403
63	0.857322547062641	0.79794401505087	0.00947022720962884
64	0.855572003660176	0.798419233330325	0.00927462388895462
65	0.85396198033385	0.79884250447445	0.00909725229009785
66	0.852479799906464	0.799216945599564	0.00893541486832753
67	0.85111354270907	0.799545843607931	0.00878689677851594
68	0.849852276332249	0.799832422353013	0.00864986522865026
69	0.848686118176835	0.800079720860271	0.00852279201934713
70	0.847606211172081	0.800290535484637	0.00840439356238269
71	0.84660465728091	0.800467398573808	0.00829358411372414
72	0.845674433435153	0.800612577535167	0.00818943904559873
73	0.844809303283168	0.800728084814862	0.00809116579067924
74	0.844003731758339	0.800815693199392	0.00799808068773419
75	0.843252805874515	0.800876953172715	0.00790959039734615
76	0.842552163138437	0.800913210452232	0.00782517688053778
77	0.841897927864727	0.800925622660069	0.0077443851734731
78	0.841286655099705	0.800915174583674	0.00766681337042099
79	0.840715281581425	0**.800882691773**294	0.0075921043613033
80	0.840181083054676	0.800828852393633	0.00751993897125487
81	0.83968163724467	0.800754197340437	0.00745003022630603
82	0.839214791827676	0.800659138680038	0.00738211852780377
83	0.838778636795113	0.800543966488756	0.00731596756308459
84	0.838371480675102	0.800408854171129	0.00725136081456442
85	0.837991830144222	0.80025386232714	0.00718809855627019
86	0.83763837262804	0.80007894122405	0.00712599524776064
87	0.837309961550021	0.799883931909538	0.00706487725172119
88	0.837005603944095	0.799668565981487	0.00700458081431108
89	0.836724450196705	0.79943246400617	0.00694495025733587
90	0.83646578572999	0.799175132550901	0.00688583633912274
91	0.836229024479843	0.798895959769205	0.00682709474700112
92	0.836013704061767	0.798594209445437	0.00676858468887777
93	0.835819482554684	0.798269013371024	0.00671016755477996
94	0.835646136869239	0.797919361884581	0.00665170562159648
95	0.835493562703809	0.797544092362003	0.00659306077569828
96	0.835361776129654	0.797141875388294	0.00653409322873155
97	0.835250916887687	0.796711198277944	0.00647466020169253
98	0.835161253525106	0.796250345532636	0.00641461455139619
99	0.835093190552348	0.795757375729737	0.00635380331160033
100	0.835047277862053	0.795230094218146	0.00629206611825546
101	0.83502422272504	0.794666020853213	0.0062292334844844
102	0.835024904767503	0.794062351821639	0.00616512488576094
103	0.835050394443976	0.793415914380424	0.0060995466091054
104	0.835101975658534	0.792723113046474	0.0060322893115852
105	0.835181173361326	0.79197986540773	0.00596312522257964
106	0.835289787170359	0.791181525257383	0.00589180491050807

107	0.835429932355899	0.790322790146714	0.00581805351731003
108	0.835604089898374	0.789397589663598	0.00574156634185279
109	0.835815167820635	0.788398949710367	0.00566200362535858
110	0.836066576643381	0.787318826689764	0.00557898435618433
111	0.836362322677195	0.786147903690059	0.0054920788656535
112	0.83670712402852	0.784875338319548	0.0054007999283452
113	0.837106555778596	0.783488448533605	0.00530459200570599
114	0.837567232964318	0.781972318275688	0.00520281817666725
115	0.838097042997369	0.780309298511002	0.00509474417787819
116	0.838705443369512	0.778478370527241	0.00497951882344552
117	0.839403846454329	0.77645432611432	0.00485614988452616
118	0.840206121751503	0.774206701778474	0.00472347428085376
119	0.841129258280011	0.771698379031067	0.00458012117706646
120	0.842194247930774	0.768883726284504	0.00442446631836897
121	0.843427277403088	0.765706104304198	0.00425457577020172
122	0.844861356469777	0.762094477876667	0.0040681373589532
123	0.846538570842917	0.75795875841556	0.00386237904185886
124	0.848513239614404	0.753183326876016	0.00363397629762787
125	0.850856395693436	0.747617928633016	0.00337895801213026
126	0.853662212622996	0.741064766380329	0.00309263820241295
127	0.857057287812815	0.733260145655415	0.00276964328723255
128	0.861214031548835	0.723848585101269	0.00240420512141005
129	0.866369581544968	0.712347519698784	0.00199113148418028
130	0.8728507256524	0.698103939995059	0.00152845640144262
131	0.881099795176144	0.680258629529337	0.00102424023496015
132	0.891674180985399	0.657786267799832	0.000513625674200632
133	0.905112436616509	0.629857155605929	0.00010070937934591
134	0.921307809268535	0.597299847015716	0.0000543225287494335
135	0.93746237490722	0.567043341766276	0.000975141183573695
136	0.944005264611821	0.560232341455631	0.00380338075971586
137	0.925957509124309	0.607022115678056	0.00873056225409314
138	0.884557231475457	0.699874833335905	0.0135425697539379
139	0.843660303528262	0.786166581745686	0.0159311613582524
140	1.99515295954198	0.472106099551516	0.113949347874849
141	2.03542020245174	0.557852274364309	0.135142733589768
142	2.06990628066773	0.639079713153741	0.157152073123614
143	2.09870559804928	0.715499104787395	0.179759057591886
144	2.12196368028863	0.78691301180499	0.20276318652632
145	2.13986597183613	0.853205358940119	0.225982879872826
146	2.15262754249968	0.914330533443066	0.249255828836673
147	2.16048390646119	0.97030260390239	0.272438734761705
148	2.16368305168408	1.0211850350029	0.295406579241589
149	2.16247869537355	1.06708115829556	0.318051555468791
150	2.15712472069145	1.1081255587418	0.340281773562967
151	2.147870709004	1.14447645551882	0.36201983375293
152	2.13495845736402	1.17630909306914	0.383201342604351
153	2.11861935925405	1.2038101129536	0.403773430166149
154	2.09907252455175	1.22717284627242	0.423693310627424
155	2.07652351933639	1.24659344753956	0.442926916127907
156	2.05116361514017	1.26226778128486	0.461447622774248
157	2.02316944869367	1.27438896993121	0.479235079536253
158	1.99270300572272	1.2831455136254	0.496274144287662
159	1.95991185494563	1.2887198980463	0.512553926529244
160	1.92492957044403	1.29128761349431	0.528066932995722
161	1.88787629164608	1.29101651682684	0.542808310127768
162	1.84885938006959	1.28806647635923	0.556775176041547
163	1.80797414065837	1.28258924823229	0.569966033942025
164	1.76530458303403	1.27472854065883	0.582380258729955
165	1.72092420436057	1.26462022972822	0.594017648707283
166	1.67489678089468	1.25239269698996	0.604878034683575

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