Coning

is a grid-size sensitivity study for radial coning

using

Eclipse *

Reservoir Simulation Software **

vended by

Schlumberger (GeoQuest)

* Eclipse is Schlumberger (GeoQuest) software.

** This tutorial is based on Grid version 1999a_1.

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Preface and Introduction

Thank you for visiting www.EricLaine.com.

The primary purpose of this document is to serve as a memory aid for the author. Thus, the author is also the target audience. (In other words, the quality of the composition is 100% sufficient for me to understand what I wrote.)

The secondary purpose is to share this tutorial with the public. I appreciate the possibility that the general public may have some difficulty understanding the my personal abbreviations and my intuitive logic.

This presents the results of a series of single-well, radial, 3-phase, coning runs.
- The primary parameter is grid size.
- Timestep size is also a consideration.

This is for a 720-day, black-oil simulation.
- Thickness, permeability, and porosity are homogeneous by layer.
- Capillary pressures are modest.
- The well is controlled on oil rates of 100 and 1,000 stbd.
- Flowing bottom-hole pressure is limited to 3,000 psi.
- The model is based on previous work by Weinstein, Chappalear and Nolan.

This study ran a 12,150-cell model in about 2 hours. The oil and the water predictions are converged. However, the gas predictions are only partially converged. Truly converged studies are not yet cost effective.

Today's computers can cost-effectively run 10,000-cell models. In contrast, studies done in the middle 1980s were run on 100-cell models. It appears that a truly converged solution requires a prohibitive number of cells, possibly 100,000.

Attempts to run a 270 x 1 x 405-cell model proved difficult. Small cells combined with the 1,000-to-100-stbd rate change at day 10 iterated excessively, even with timesteps of only 0.0001 days (8.64 seconds.)

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This presents the results of a series of single-well, radial, 3-phase, coning runs.

The primary parameter is grid size.

The five models include	10x1x15	30x1x45	40x1x61	60x1x90	90x1x135
The number of cells is	150	1,350	2,440	5,400	12,150
The number of timesteps is	30	50	100	170	460
The nominal cpu seconds are	2	20	100	700	6000

Several factors impact run time.

Writing files to another computer and saving data for pseudo curves adds runtime.

Timestep size is also a consideration.

It is important (albeit very subjective) to converge in both space and time.

This requires advance knowledge about the converged solution.

The nominal relationship is (dt)/(dx)**2.

Reducing the time dimension by 4 matches a space dimension reduction of 2.

Timesteps typically need to be smaller whenever there is a rate change.

There is a balance between how small, convergence tolerance, & cell size.

This study also considers the effect of the maximum timestep size.

This study used a SUN ULTRASPARCIIi workstation running at 440 Mhz with 256Mb of RAM and 2 Mb of L2 cache. SUN currently offers cpu speeds up to 600 Mhz.

This report discusses saturation maps and production plots from the simulations. There is some discussion about calculating well indices (for the perforated cells.)

The oil-saturation maps are for vertical cross sections. The cross sections show the water and gas coning through time. The wellbore is on the left.

The production plots are grouped for easy comparison:

- Production ratios and flowing-bottom-hole pressures,
- Production rates and a close-up view of flowing-bottom-hole pressures, and
- Production cumulatives and average reservoir pressure.

A spreadsheet highlights the input variables for calculating the completion factors.

A summary of the simulated results for the 30 x 1 x 45 case is in the appendix.

Overview - RZ Cross Sections

Each of the RZ cross sections is an oil-saturation map. There are two versions of the 10 x 1 x 15 cross section (an overview and a close up,) and there are close-up cross sections of the 30 x 1 x 45 model.

The overview 150 cells from 0.25 to 2050 ft. This pictures the important features of the reservoir:

- Perforation locations,
- Transition zones:
  - Gas-oil capillary pressure, and
  - Oil-water capillary pressure.

However, there is too little detail to show the coning.

The close ups (of the 10 x 1 x 15 model) enlarge the cells closest to the perforations.

- The perforated cells and the transition zones provide reference points.
- The water cone and the gas cone are easy to see.

The close ups (of the 30 x 1 x 45 model) also zoom into the near-wellbore cells.

- This is the same area covered by the second cross section.
- The additional detail gives better views of the water and the gas cones.

The plots consistently support the conclusions drawn from the cross sections.

There has been considerable discussion about which fluid phase wets reservoir rock. The reality is that any phase might be the dominate wetting phase. It is also possible for two phases to share wetness.

The capillary pressures used for this study are for:
- A water-wet aquifer,
- A water-wet oil zone, and
- An oil-wet gas cap.

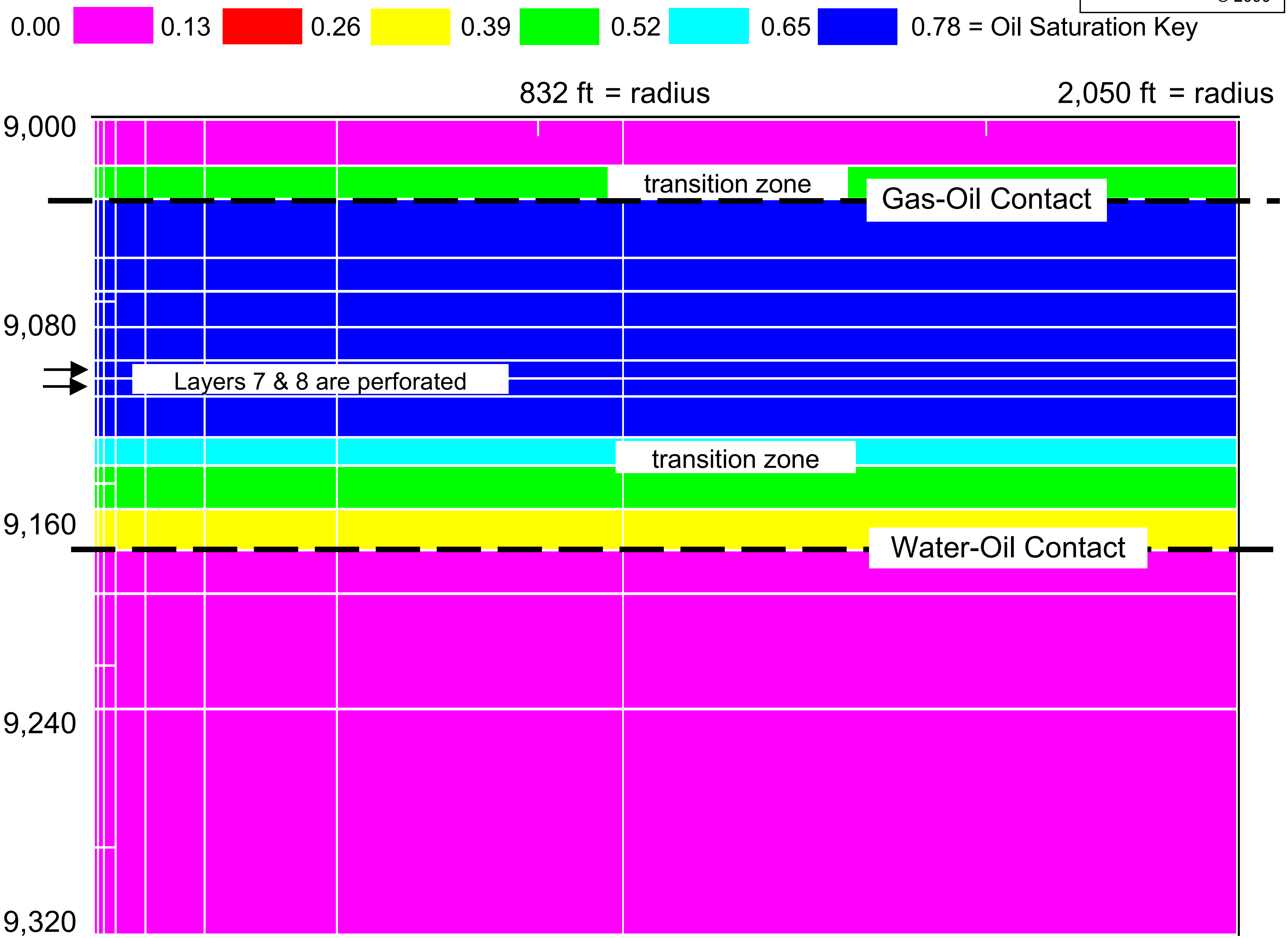
A phase (water, oil, or gas) can only flow at saturations above the critical saturation.
This also means the phase relative permeability is above zero.

The gas-oil and the water-oil contact depths are defined as follows.
- Gas saturation is at (or below) the critical gas saturation below the goc.
- Oil saturation is at (or below) the critical oil saturation below the woc.

Interfacial-surface tension forces wetting phases beyond the contact. In this study:
- Mobile oil rises above the goc, and
- Mobile water rises above the woc.

Note: negative capillary pressures indicate an oil-wet aquifer and a gas-wet oil zone.
- Mobile gas would exist below the goc, and
  - Oil saturation is at (or below) the critical oil saturation above the goc.
- Mobile oil would exist below the woc.
  - Water saturation is at (or below) the critical water saturation above the woc.

R-Z Cross Section, 10 x 1 x 15 (SPE Comparative Study) model



Oil Rates

1,000 stbd	from day	0	to day	10
100 stbd	from day	10	to day	100
1,000 stbd	from day	100	to day	720
100 stbd	from day	720	to day	900

Water Cone

The first close up shows that water cones (up to the lower perforation) within 10 days.

The second and third close ups show that the cones are stable (no change) at 100 stbd. Controlling (healing) the cone at this rate is probably uneconomic.

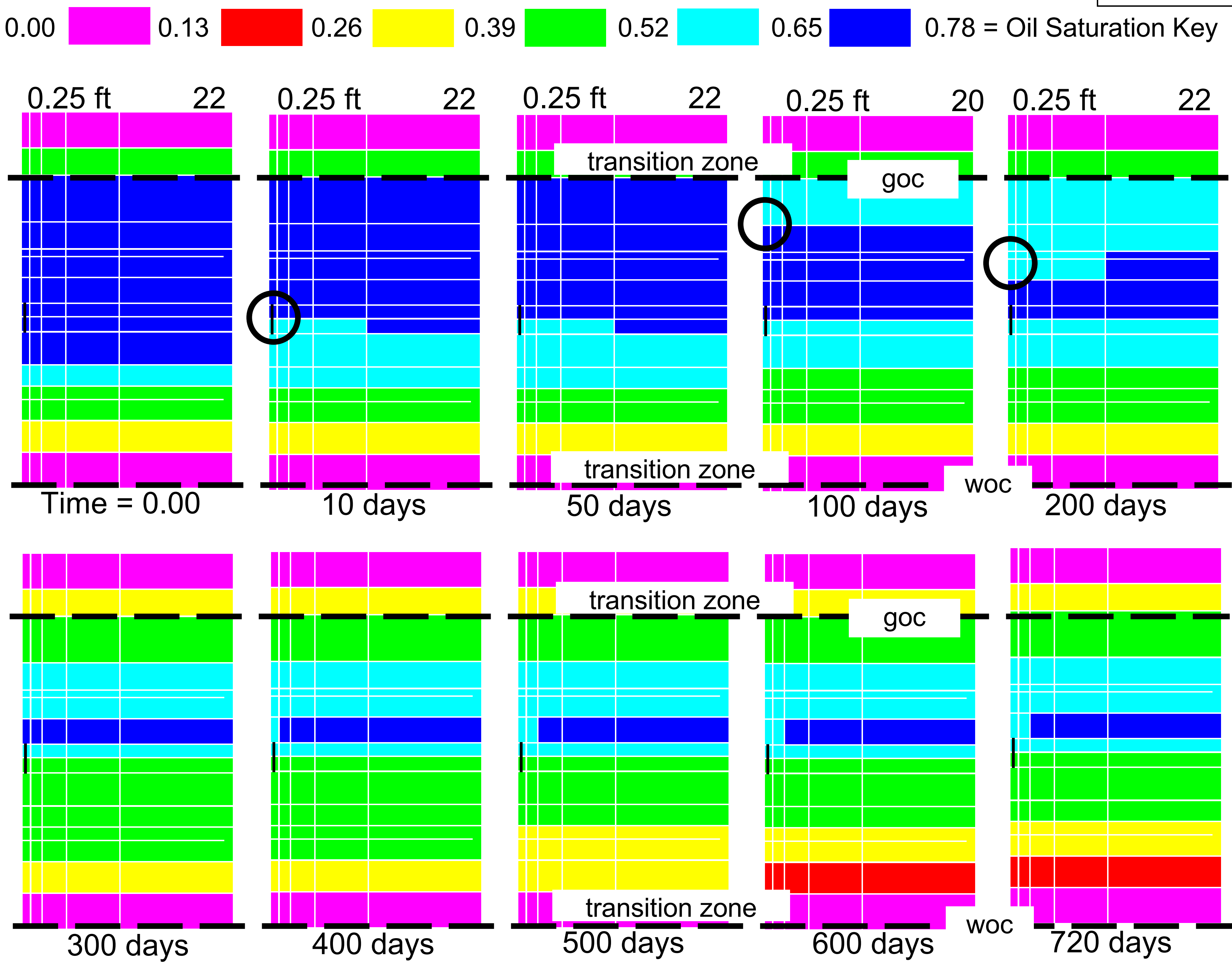
The rest of the close ups show the water cone growing.

Gas Cone

The gas may have reached the upper perforation as early as day 100. The probability of gas breakthrough is even higher by day 200.

The rest of the close ups show the water cone growing.

RZ Cross Section, 10 x 1 x 15 Model, Layers 1 to 13, Wellbore to 4th radius



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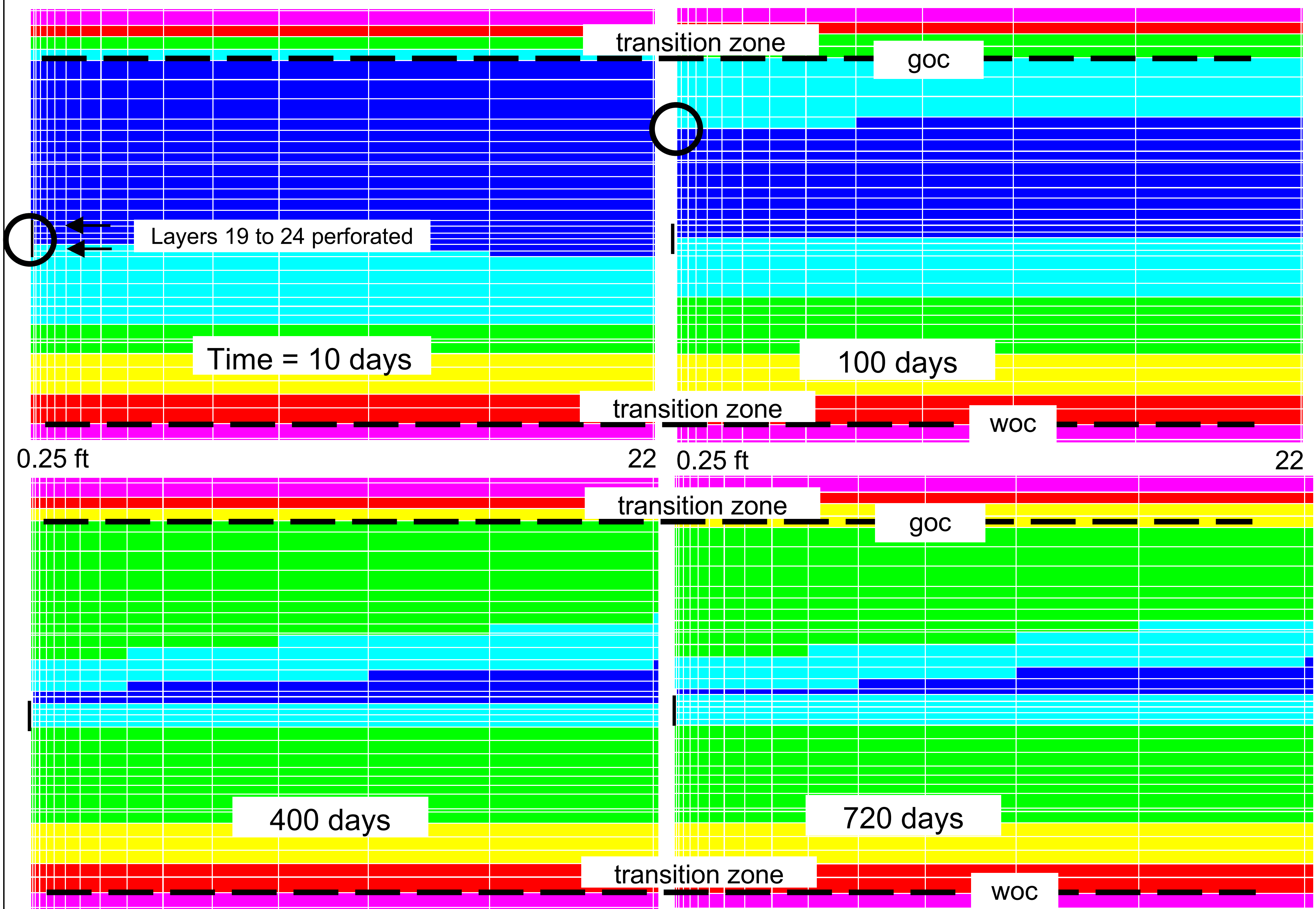
Both grid sizes show the same gas-coning trends.

However, the gas cone is closer to the upper perforation by 100.
- Perhaps the finer grid is predicting more coning:
  - Gas breakthrough might be sooner, or
  - More gas may be breaking through.
- This appears to be a convergence issue.

In summary, grid size affects the gas coning predictions.
- The sizes of the water cone and the gas cone increase with time.
- It appears uneconomical to control coning with a lower oil rate.
- Finer grids should be investigated (for convergence.)

RZ Cross Section, 30 x 1 x 45 Model, Layers 3 to 38, Wellbore to 15th radius

0.00 | 0.13 | 0.26 | 0.39 | 0.52 | 0.65 | 0.78 = Oil Saturation Key



Each group of plots provides an easy comparison of related data.
- Production ratios and flowing-bottom-hole pressures,
- Production rates and a close-up view of flowing-bottom-hole pressures, and
- Production cumulatives and average reservoir pressure.

All three groups look at solution convergence as a function of grid resolution.
- The first set of plots tends to be the most useful, especially for history matching.

Oil rate is a common input, either for history matching or as a production target.
- Naturally, gas rate would be input for a gas field.

It is easier to compare ratios (water cut and produced gas-oil ratio) than rates. This is equally true for history matching and for comparing field-development scenarios.

It is also easier to compare ratios than cumulative production.
- The summations give larger values that automatically mask rate variations.
  - Integration smoothes data whereas.
  - Differentiation introduces noise.

This study focuses on the effect of grid size on coning performance.

All the grids switch to bottom-hole pressure control near 300 days.

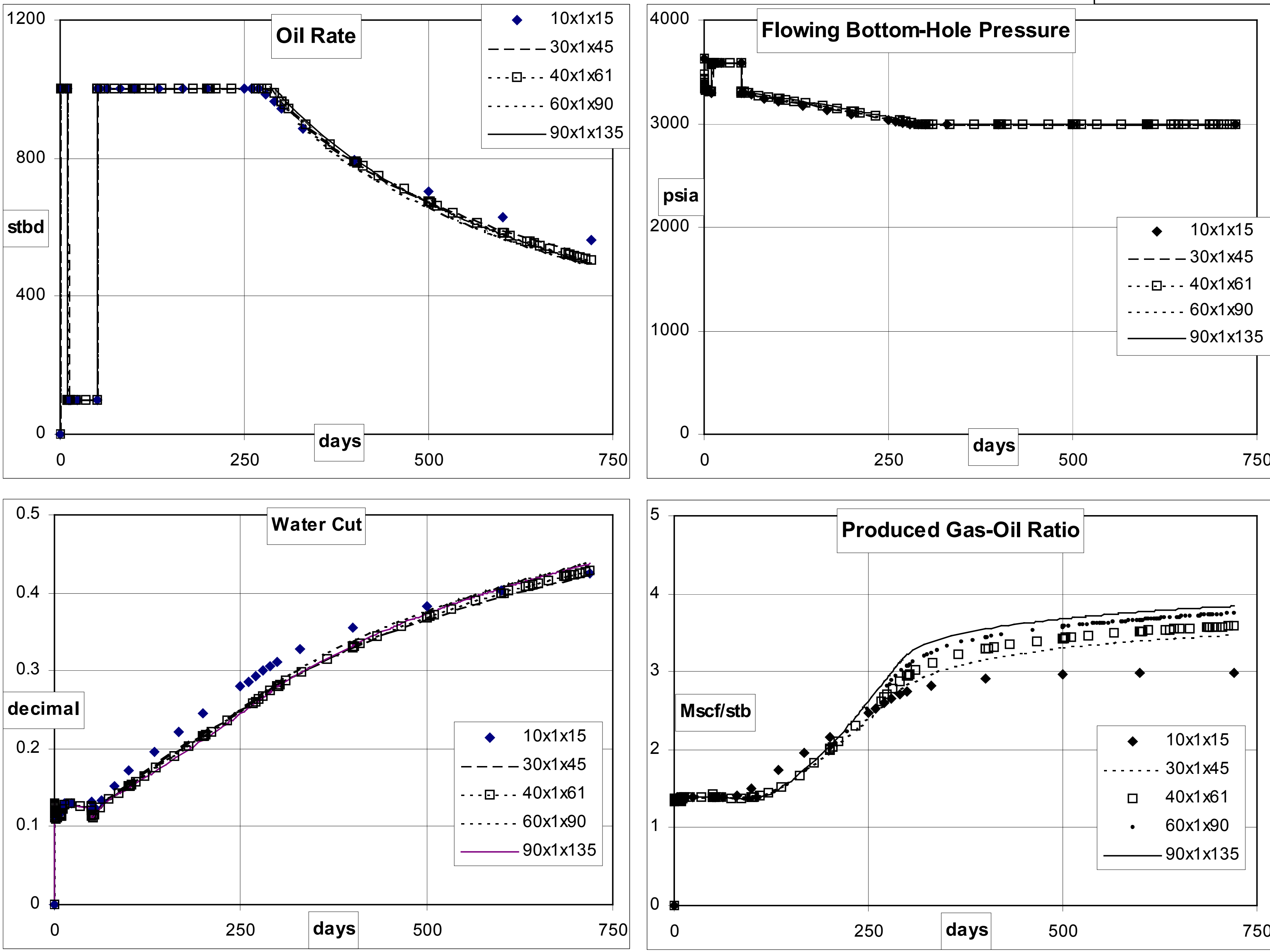
The ratio plots clearly indicate the 10 x 1 x 15 grid is unconverged.
This grid is too coarse.

The finer grids give converged values.
The exception is the produced gas-oil ratio.

Increasing grid resolution shows a trend towards convergence.
The produced gas-oil ratio diverges:
at about 60 days for the 10 x 1 x 15 grid,
at about 120 days for the 30 x 1 x 45 grid,
at about 180 days for the 40 x 1 x 61 grid, and
at about 200 days for the 60 x 1 x 90 grid.
This suggests that a much finer grid will be needed to get a converged gas-oil ratio.
Perhaps a 120 x 1 x 180 or a 180 x 1 x 270 grid will converge.
These will be much longer runs.
A 21,600 cell run might be six to ten hours.
An 86,400 cell run might be 18 to 40 hours.
Neither run was considered cost-effective for this study.

Engineering judgement suggests treating gas-oil ratio convergence as a sensitivity item.
The divergence time is approaching the asymptotic portion of the curve.
Perhaps the limiting gas-oil ratio is near 4.2 Mscf/stb.

Results Plots, Ratios



Production Plots - Rates and Flowing-Bottom-Hole Pressure

The next set of plots includes a close up of the flowing-bottom-hole pressure.
Pressure control replaces oil-rate control at about the same time for all grids.
The switch seems to happen between 275 and 290 days.
This is a narrow range.
The exaggerated scale of the close-up plot is visually misleading.

The rate plots, like the (previous) ratio plots indicates:
The 150-cell grid is too coarse to converge,
The finer grids all converge for flowing-bottom-hole pressure,
The finer grids all converge for water production, however,
Gas production is (probably) not yet converged.

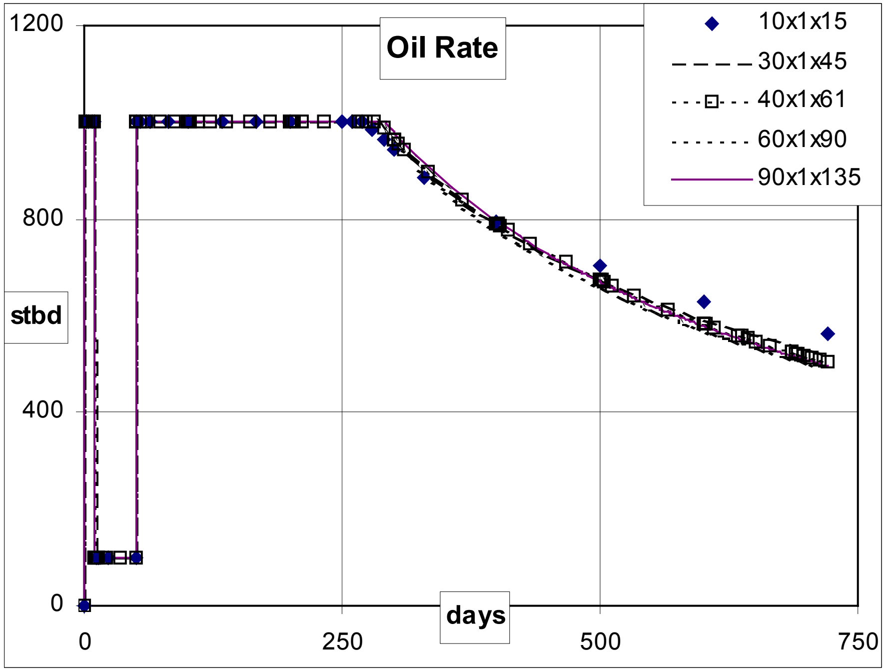
The gas-rate divergence times are about the same as for the gas-oil ratio.

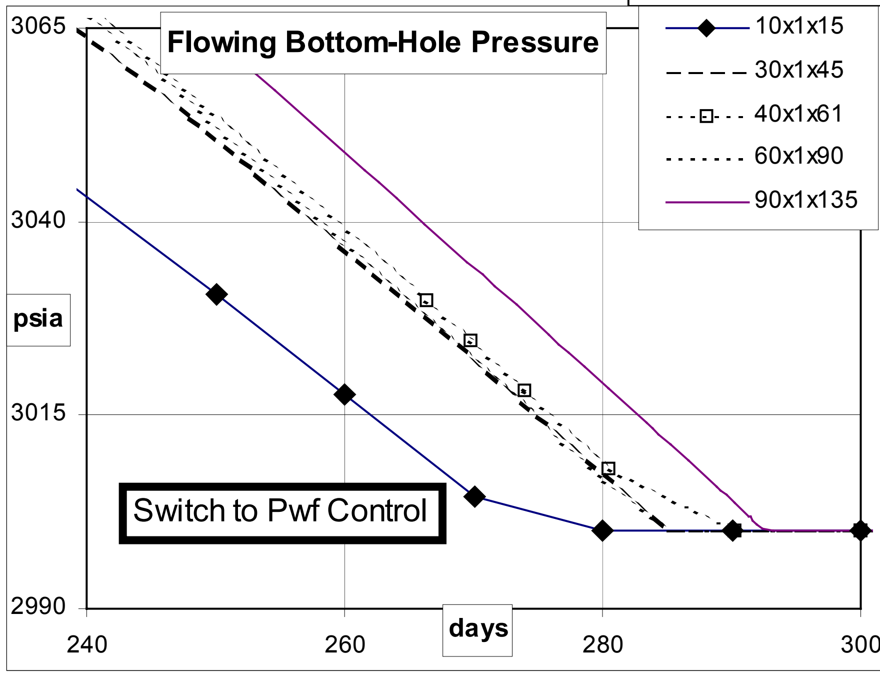
The predicted gas rate seems to:
Be a little later as grid resolution (fineness) increases,
Peak a little higher as fineness goes up.

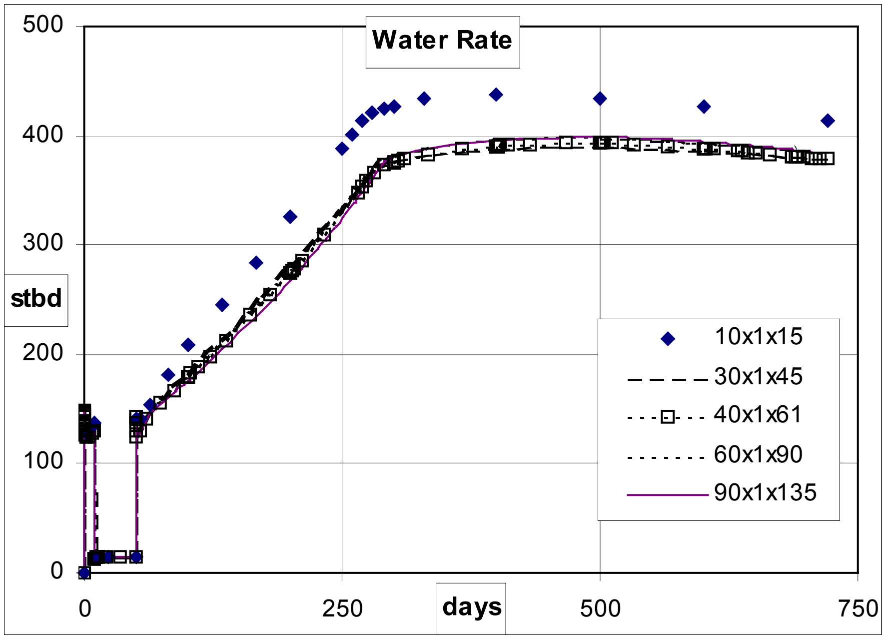
In addition, the decline ratio looks like it is about the same for all grid resolutions.

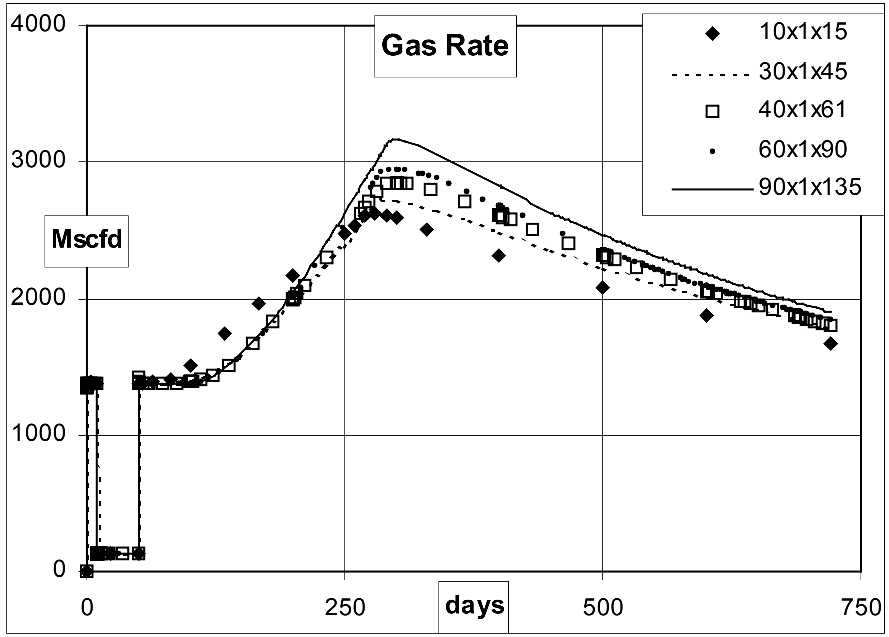
Engineering judgement suggests treating gas-rate convergence as a sensitivity item.
The divergence time is approaching the switch to pressure control.
Perhaps the limiting gas rate is just below 4,000 Mscfd.

Results Plots, Rates









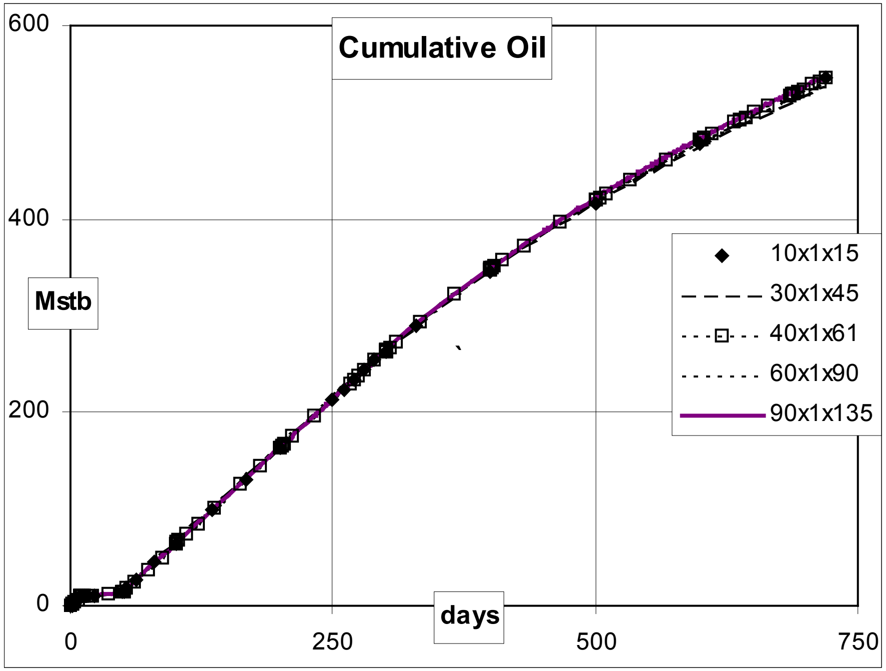
The cumulative plots tend to support previous (ratio and rate) conclusions.

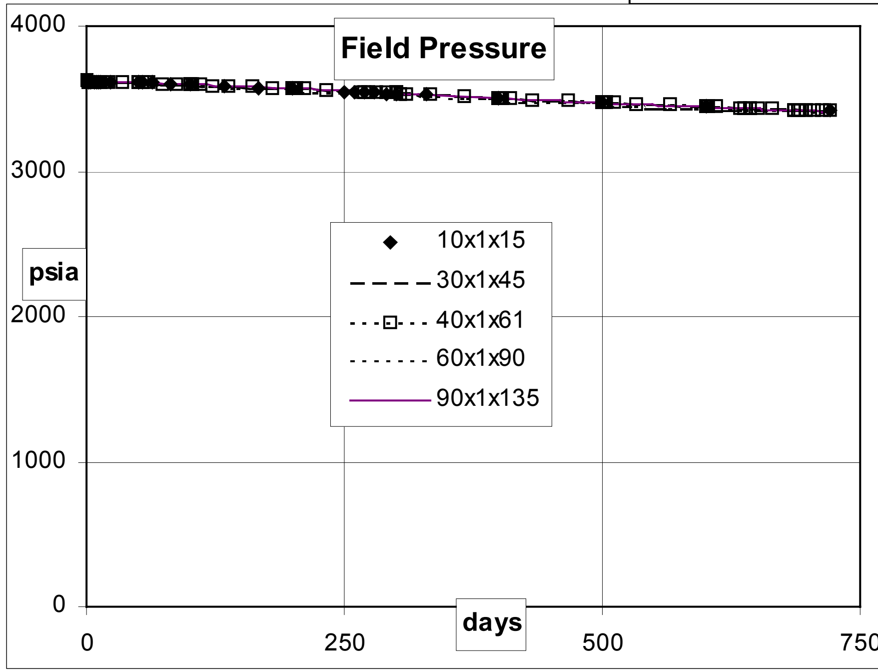
The cumulative-produced-gas plot disguises the divergence times because it takes awhile for the (relatively) small rate differences to add up to noticeable cumulative differences.

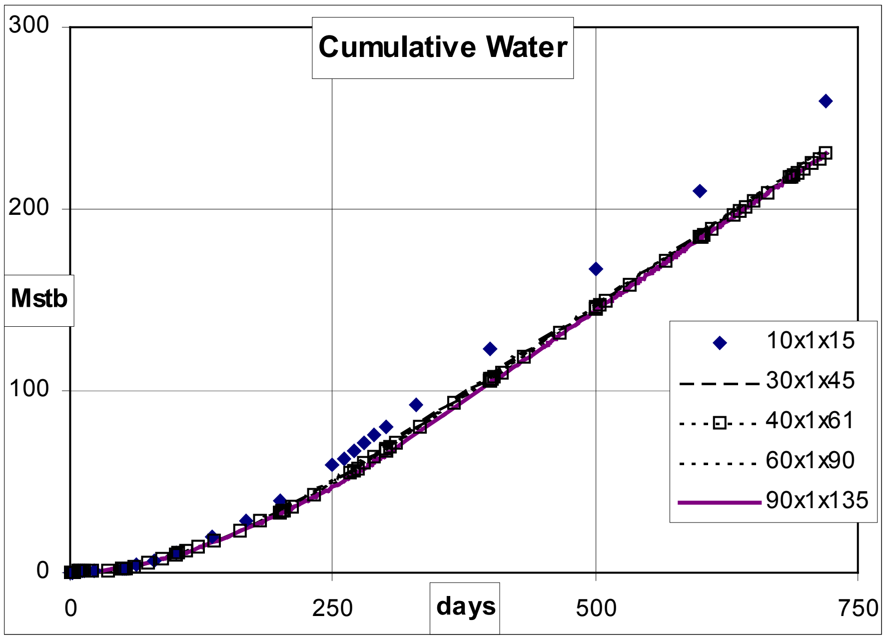
Most of the cumulative difference happens at the end of the second year.

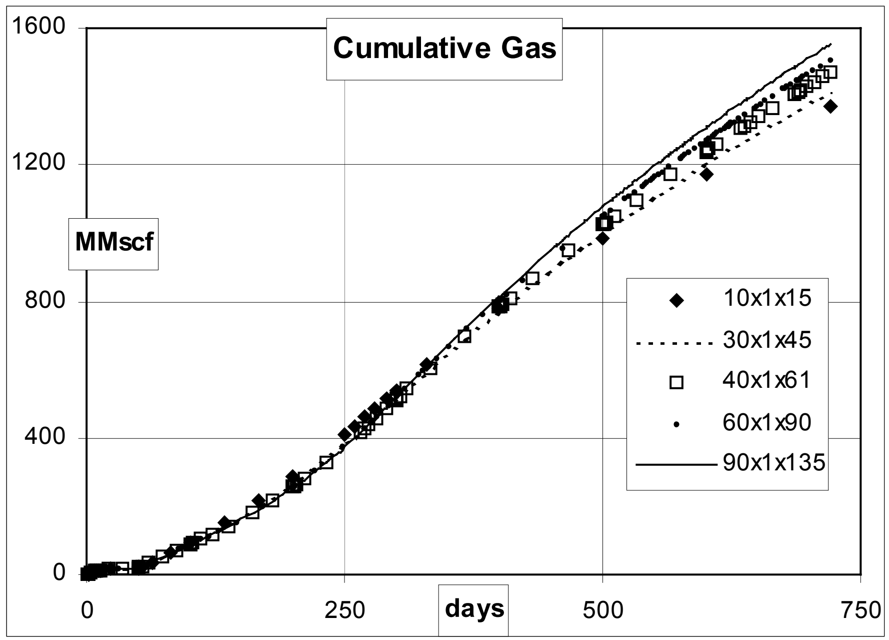
Engineering judgement suggests treating cumulative-gas as a sensitivity item.
Perhaps the limiting gas quantity is about 100 MMscf higher at 720 days.

Results Plots, Cumulatives (Totals)









Convergence is clearly a function of grid resolution.
None of the grids fully converged for gas production.

This casts doubt on using a 10 x 1 x 15 grid for the Second SPE Comparative Study Project. A review of JPT, March 1986, pp345-53 is in order.

Grid resolution is a relative term. Contemporary computers now run two orders of magnitude faster. This indicates that a 10 x 1 x 15 was a fine-grid model in 1986.

In summary, the 60 x 1 x 90 grid resolution (with its 15-minute run time) is great predictor for water coning (with today's computers.) The same grid is an adequate predictor for gas coning, provided the economic analyses reflect the sensitivity to gas coning.

Faster computers will continue to redefine the fine and coarse adjectives used to characterize relative cell sizes.

Convergence is clearly a function of grid resolution.
- The finer grids converge nicely for water production.
- They also converge well for flowing-bottom-hole pressure.
- None of the grids fully converged for gas production.
  - This study concluded converged runs would NOT be cost effective.
  - Engineering judgement extrapolated the gas values.

The increasing gas coning does seem reasonable.
- Gas preferentially cones into the cell closest to the top perforation.
- This becomes more noticeable as the cell sizes get smaller.
  - The gas saturation is higher with finer grids.
  - Gas relative permeability is also higher with finer grids.

This means gas cones faster with finer grids (which is what the models tell us.)

Alas, there is no convergence. The obvious mathematical recommendation is to further reduce the cell size and the timestep size. The equally obvious engineering solution is to recognize the trade-off between study cost and field profitability.

An extra 100 MMscf production (7%) in the second year has a small impact.
- Sales increase about $200,000 (at $2 / Mscf.)

This adds to the oil and the other gas sales.
- Other gas sales are $3,000,000 (for 1,500,000 Mscf.)
- Oil sales are about $11,000,000 (for 550,000 stb at $20 /stb.)

The net effect is a 2% increase in gross revenue.

Intuitively, marginal projects become unattractive with a 2% revenue reduction.

The next group of plots focuses on the gas plots (ratio, rate, and cumulative.)
- The solid line is from the previous plots for:
  - The 90 x 1 x 135 grid, and
  - A maximum timestep of 44 days.
- The symbols are from a special model with:
  - A 90 x 1 x 135 grid, and
  - A maximum timestep of 0.5 days.

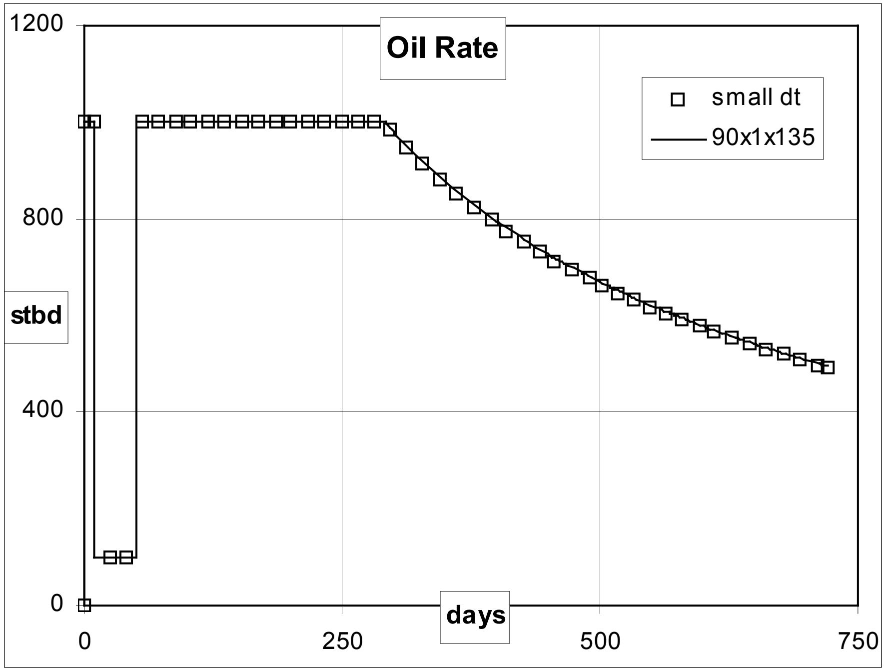
The results appear to be identical.
- The largest difference for the production and pressure variables is 1.6%.
- Only four differences are greater than 1%.

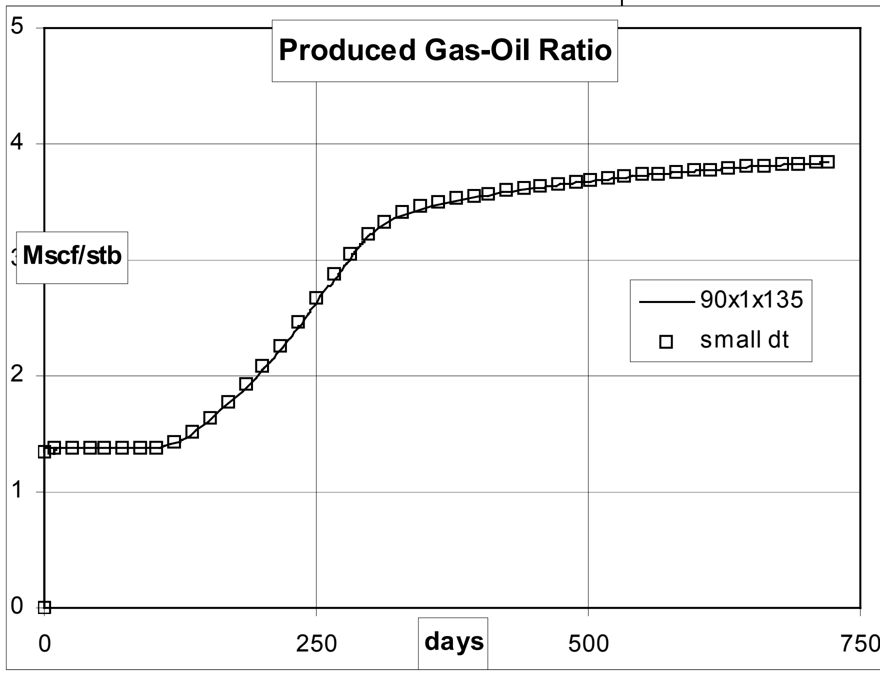
The results are identical (within engineering accuracy.)

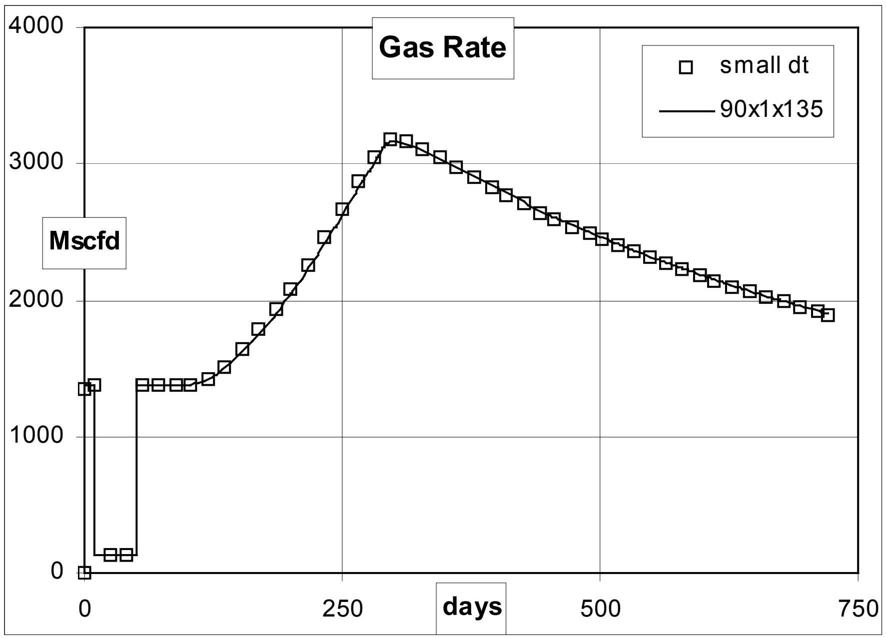
In addition:
- The runtimes were within 5%.
- The runtimes were within six cpu minutes (out of two hours.)

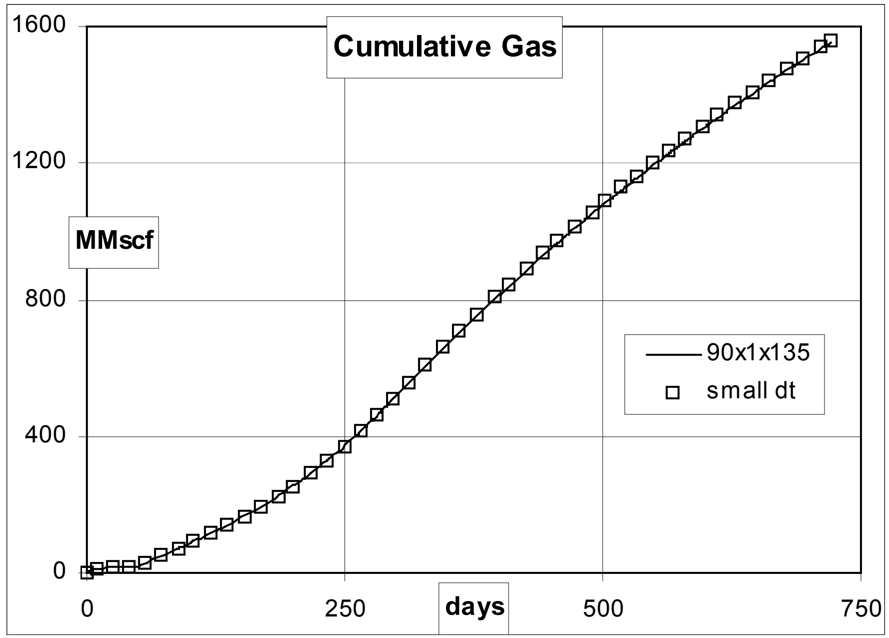
Curiously, the faster run was for the 0.5-day maximum timestep.
- This may not be a general result.
- In general, there is some timestep size that optimizes the iterations.

Gas Plots and Timestep size









Calculating completion factors (well indices) is straight forward.
- The calculation must be completed for each completed cell (grid block.)
- It is easy to overlook a variable.

The simulated results are rather insensitive to completion factors.
- This does NOT justify introducing careless errors.

Completion factors are the time-invariant portion of productivity indices.

Peaceman developed a robust procedure for calculating completion factors.
- Peaceman's procedure works for vertical and horizontal wells.
- Eclipse uses Peaceman's procedure.

There is a difference between grid-block and field productivity.
- Simulators must use grid-block productivity.
- Grid-block productivity accounts for the well-to-cell connection.

Please note that many authors have derived productivity-index equations.
- Some of these equations give productivities that differ by an order of magnitude.
- One cause seems to be grid-block versus field productivities.

Completion Factor Spreadsheet

RADIAL-WELL Connection Transmissibility Factor (proportional to productivity index)

See J_ecl.ppt for background information.

ECLIPSE's connection factor = (J)*(Bo)*(Muo)/(Kro)

Field	(rb*cp)/(day*psi)	
Metric	(m3*cp)/(day*bar)	
Lab	(cm3*cp)/(hr*atm)	

input = solid, bold, red box & numbers
intermediate = black letters only
output = bold, dashed, blue box & numbers
instructions = bold, purple letters

0.001127	= conversion constant (0.001127 for field units, .008527 for metric, 1.0000 **????????** for lab)
6.283185	= sector angle, radians
60	= first perpendicular-to-wellbore permeability, md (md or md)
60	= second perpendicular-to-wellbore permeability, md (md or md)
60	= permeability perpendicular to wellbore, md (md or md)
1.3333	= net thickness, ft (m or cm)
60	= # radial cells
0.25	= rw, ft (m or cm) (cement o.d.)
2050	= re, ft (m or cm) (field outer radius)
0	= Skin
0	= optional manual-override for 1st cell outer radius, ft (m or cm) — **Enter zero to accept calculated outer radius of the 1st cell.**
1.16206449	= radius ratio, (re/rw)/(1/# cells)
0.29051612	= 1st cell outer radius, ft
7.183941	= **RADIAL-WELL** perforation connection factor (item #8 of COMPDAT keyword)

CHAP_E

	10x1x15	30x1x45	40x1x61	60x1x90	90x1x135
net thickness	8	2.6667	2	1.3333	0.8889
# radial cells	10	30	40	60	90
1st radius	0.615632	0.337598	0.313174	0.290516	0.276329
775 md factor	75.807	88.613	90.649	92.793	94.289
60 md factor	5.869	6.86	7.018	7.184	7.3

The 60 x 1 x 90 grid resolution is appropriate for this coning study.
Adding cells improves convergence and increases runtime.

The common adjectives for describing grid resolution (fine and coarse) are relative terms that reflect cost-effective engineering (with "today's" computers.)

The 10 x 1 x 15 grid resolution was a fine grid in the mid 1980s.
The mid 1980s grid may not have been a converged solution, yet
It was a cost-effective solution.

Today a 60 x 1 x 90 grid is considered "fine" resolution.
It is only converged for pressure and water, although
It is NOT converged for gas, yet
It is cost effective.

Tomorrow's computers will use a 270 x 1 x 405 grid for fine-scale studies.
It seems likely that this will be a fully converged solution, including gas.

Several factors impact run time.
Runtimes increase about 33% when files are written to another computer.
Runtimes increase about 33% when pseudo-curve files are saved.

Timestep size is also a consideration.
Maximum timesteps of 0.5 and 44 days are compared.
The results are identical (for practical use.)

Use a spreadsheet to calculate the completion factors (It helps avoid errors.)

Appendix - 30 x 1 x 45 Simulation Results Table

30 x 1 x 45											
SUMMARY OF RUN CHAP3045_E											
TIME	YEARS	FOPR	FWPR	FGPR	FOPT	FWPT	FGPT	FWCT	WGOR	WBHP	FPR
DAYS	YEARS	stbd	stbd	Mscfd	Mstb	Mstb	MMscf		mscf/stb	psia	psia
					1000	1000	1000		producer	producer	
0	0	0	0	0	0	0	0			3628.22	3621.18
0.0010	2.74E-06	1000	128.755	1339.61	0.001	0.000129	0.001	0.11407	1.33961	3424.43	3621.18
0.0040	1.10E-05	1000	136.569	1341.69	0.004	0.000538	0.005	0.12016	1.34169	3390.28	3621.18
0.0087	2.39E-05	1000	136.637	1349.41	0.009	0.001185	0.012	0.12021	1.34941	3372.81	3621.17
0.0147	4.02E-05	1000	136.666	1352.94	0.015	0.001999	0.020	0.12023	1.35294	3362.61	3621.16
0.0262	7.17E-05	1000	136.396	1355.84	0.026	0.003567	0.035	0.12003	1.35584	3353.40	3621.14
0.0485	0.00013	1000	135.424	1359.29	0.049	0.006593	0.066	0.11927	1.35929	3345.80	3621.11
0.0906	0.00025	1000	133.750	1363.02	0.091	0.012224	0.123	0.11797	1.36302	3339.91	3621.06
0.1708	0.00047	1000	131.474	1366.84	0.171	0.022769	0.233	0.11620	1.36684	3335.73	3621.00
0.3222	0.00088	1000	128.947	1370.58	0.322	0.042287	0.440	0.11422	1.37058	3332.78	3620.91
0.6004	0.00164	1000	126.636	1373.97	0.600	0.077519	0.822	0.11240	1.37397	3330.44	3620.76
1.1034	0.00302	1000	124.927	1376.76	1.103	0.140361	1.515	0.11105	1.37676	3328.04	3620.51
2.1854	0.00598	1000	124.238	1379.21	2.185	0.274785	3.007	0.11051	1.37921	3324.46	3619.99
4.2394	0.01161	1000	125.463	1381.08	4.239	0.532486	5.844	0.11148	1.38108	3318.88	3619.02
7.1197	0.01949	1000	128.087	1382.97	7.120	0.901413	9.827	0.11354	1.38297	3313.04	3617.74
10	0.02738	1000	131.467	1382.96	10.000	1.280076	13.811	0.11619	1.38296	3307.46	3616.47
11	0.03012	100	13.875	137.69	10.100	1.293951	13.948	0.12185	1.37688	3591.44	3616.55
14	0.03833	100	14.853	138.29	10.400	1.338511	14.363	0.12932	1.38288	3591.15	3616.44
23	0.06297	100	14.877	138.44	11.300	1.472400	15.609	0.12950	1.38442	3590.75	3616.03
36.500	0.09993	100	14.569	138.49	12.650	1.669087	17.479	0.12717	1.38493	3590.43	3615.46
50	0.13689	100	14.403	138.51	14.000	1.863529	19.349	0.12590	1.38505	3590.00	3614.90
53.933	0.14766	1000	131.481	1384.31	17.933	2.377845	24.795	0.11620	1.38431	3303.04	3613.19
60.574	0.16584	1000	142.411	1383.50	24.574	3.323596	33.983	0.12466	1.38350	3290.10	3610.63
75.287	0.20612	1000	158.057	1383.01	39.287	5.648997	54.331	0.13649	1.38301	3269.99	3605.45
87.643	0.23995	1000	169.676	1381.72	51.643	7.745623	71.404	0.14506	1.38172	3254.60	3601.56
100	0.27379	1000	181.548	1387.73	64.000	9.988950	88.552	0.15365	1.38773	3238.89	3597.90
118.57	0.32463	1000	198.784	1434.11	82.571	13.680610	115.185	0.16582	1.43411	3215.95	3592.74
146.58	0.40130	1000	225.737	1572.19	110.576	20.002320	159.214	0.18416	1.57219	3181.38	3585.16
173.29	0.47444	1000	251.913	1757.34	137.288	26.731420	206.156	0.20122	1.75734	3149.16	3577.94
200	0.54757	1000	279.495	1968.22	164.000	34.197280	258.731	0.21844	1.96822	3115.45	3570.54
253.23	0.69330	1000	335.520	2423.06	217.229	51.771790	385.271	0.25123	2.42306	3046.00	3554.20
269.87	0.73888	1000	355.011	2585.50	233.875	57.603370	427.666	0.26200	2.58550	3022.21	3548.87
284.94	0.78012	999.35	373.261	2731.27	248.928	63.225660	468.807	0.27194	2.73305	3000	3543.75
300	0.82136	962.44	376.582	2729.19	263.424	68.897960	509.915	0.28124	2.83570	3000	3538.65
338.72	0.92736	885.46	382.702	2656.11	297.709	83.715880	612.757	0.30178	2.99969	3000	3525.87
369.36	1.01125	833.65	386.126	2580.85	323.252	95.546950	691.836	0.31655	3.09584	3000	3516.03
400	1.09514	788.34	388.490	2495.91	347.407	107.450400	768.311	0.33012	3.16601	3000	3506.49
450	1.23203	725.85	390.085	2354.88	383.700	126.954700	886.056	0.34956	3.24429	3000	3491.71
500	1.36893	673.69	390.456	2229.02	417.385	146.477500	997.506	0.36692	3.30866	3000	3477.64
600	1.64271	591.65	386.957	2013.43	476.549	185.173200	1198.849	0.39542	3.40310	3000	3451.91
720	1.97125	515.63	378.434	1790.79	538.424	230.585400	1413.744	0.42328	3.47304	3000	3424.12
721	1.97399	100	75.208	233.47	538.524	230.660600	1413.978	0.42925	2.33471	3341.78	3424.20
726.83	1.98995	100	77.044	144.91	539.107	231.107500	1414.881	0.43517	1.44913	3345.25	3424.09
754.43	2.06552	100	79.951	133.29	541.867	233.305400	1418.573	0.44429	1.33287	3343.48	3423.31
778.18	2.13053	100	78.939	133.20	544.242	235.186500	1421.737	0.44115	1.33198	3343.90	3422.67
800	2.19028	100	77.877	133.14	546.424	236.891900	1424.642	0.43781	1.33137	3344.27	3422.10
857.09	2.34659	100	75.215	133.14	552.134	241.236400	1432.244	0.42927	1.33140	3344.98	3420.64
900	2.46407	100	73.514	133.15	556.424	244.407600	1437.956	0.42368	1.33146	3345.23	3419.57