- Home
- Contact
- Software
  - FEAT2D/FEAT3D
  - FEAST
  - FEATFLOW
  - FEATFLOW2
  - FEAT3
  - parPP3D
  - Documentation
- Team
- Links
  - Websites
  - Software
- Benchmarks
  - FeatFlow Benchmark Suite
  - CFD Benchmarking Project
    - Flow around a Cylinder
    - Rising Bubble
      - Geometry and flow configurations
      - Verification
      - Participate
      - Reference data
    - FSI Benchmark
    - MIT Benchmark
- Publications
- Services
  - Sitemap
  - Impressum
  - Datenschutzerklärung
- News
- Examples

Bubble Benchmark

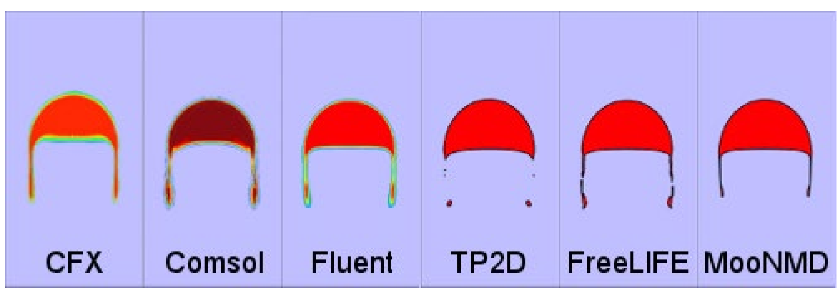
- Rising Bubble
- Geometry and flow configurations
- Verification
- Participate
- Reference data

Two-dimensional rising bubbles

General information and references:

In the absence of analytical solutions, which are very hard to come by for the considered two-phase flow problem class, validation of the mathematical modeling is best accomplished with numerical benchmarking. Pure numerical benchmarks on the other hand are of limited use if they cannot be employed to make quantitative comparisons, mere visual inspection is rarely, if ever, enough to draw hard conclusions. To illustrate this, consider the bubble shapes shown in the figures below

Numerical simulations of a two-dimensional rising bubble for six different codes with identical problem formulations



These shapes were calculated by six different codes with identical problem formulations and should thus ideally give six identical solutions. Unfortunately this is not the case. The shapes are quite similar but it is not possible to tell which solutions, if any, are really correct. In order to be able to do this one must leave the "picture norm" behind and instead use some more rigid metrics with which convergence can be measured directly.

With this in mind two benchmark configurations have been proposed and rigorous benchmark quantities have been defined to measure direct topological parameters, such as interface deformation, and also indirect ones, such as velocity. The task of the proposed benchmarks is to track the evolution of a single two-dimensional bubble rising in a liquid column. This configuration is simple enough to compute accurately yet allows for very complex topology change, giving the interface capturing techniques of today an adequate challenge.

References:

[1]	Hysing, S.; Turek, S.; Kuzmin, D.; Parolini, N.; Burman, E.; Ganesan, S.; Tobiska, L.: Quantitative benchmark computations of two-dimensional bubble dynamics, International Journal for Numerical Methods in Fluids, Volume 60 Issue 11, Pages 1259-1288, DOI: 10.1002/fld.1934, 2009, [Webpage]
[2]	Hysing, S.; Turek, S.; Kuzmin, D.; Parolini, N.; Burman, E.; Ganesan, S.; Tobiska, L.: Proposal for quantitative benchmark computations of bubble dynamics, Ergebnisberichte des Instituts für Angewandte Mathematik, Nummer 351, Fakultät für Mathematik, TU Dortmund, 2007 [PDF]
[3]	Hysing, S.; Turek, S.: Benchmark proposals for incompressible two-phase flows, 80, ICMF 2007 Programme and Abstracts of the 6th International Conference on Multiphase Flow, Wiley-VCH, 2007

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- Home
- Contact
- Software
  - FEAT2D/FEAT3D
  - FEAST
  - FEATFLOW
  - FEATFLOW2
  - FEAT3
  - parPP3D
  - Documentation
- Team
- Links
  - Websites
  - Software
- Benchmarks
  - FeatFlow Benchmark Suite
  - CFD Benchmarking Project
    - Flow around a Cylinder
    - Rising Bubble
      - Geometry and flow configurations
      - Verification
      - Participate
      - Reference data
    - FSI Benchmark
    - MIT Benchmark
- Publications
- Services
  - Sitemap
  - Impressum
  - Datenschutzerklärung
- News
- Examples

Home » Benchmarks » CFD Benchmarking Project » Rising Bubble » Geometry and flow configurations

Bubble Benchmark

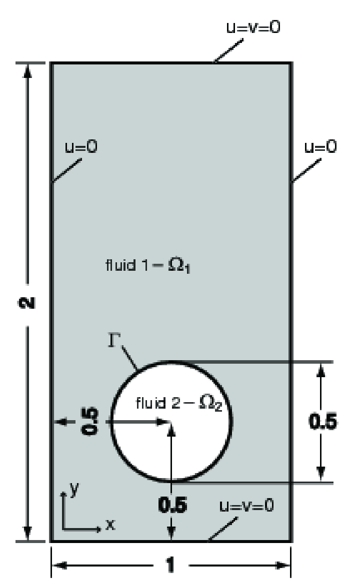
- Rising Bubble
- Geometry and flow configurations
- Verification
- Participate
- Reference data

Geometry and flow configurations:

The initial configuration, see the figure below, is identical for both test cases and consists of a circular bubble of radius r_0 = *0.25* centered at *(x,y)* = *(0.5, 0.5)* in a 1 by 2 rectangular domain. The density of the bubble is smaller than that of the surrounding fluid ($\rho_2 < \rho_1$). The no-slip boundary condition (***u*** = *0*) is used at the top and bottom boundaries, whereas the free slip condition ($\mathbf{u}\cdot\hat{\mathbf{n}}=0$, $\hat{\boldsymbol{\tau}}\cdot(\nabla\mathbf{u}+(\nabla\mathbf{u})^T)\cdot\hat{\mathbf{n}}=0$, $\hat{\boldsymbol{\tau}}$ - the tangent vector) is imposed on the vertical walls.

Initial configuration and boundary conditions for the test cases

Initial configuration and boundary conditions for the test cases



Initial configuration and boundary conditions for the test cases

The table below lists the fluid and physical parameters which specify the test cases. The evolution of the bubbles should be tracked for 3 time units during which the defined benchmark quantities should be measured.

The first test case models a rising bubble with Reynolds number *Re=35*, Eötvös number *Eo=10*, and both density and viscosity ratios equal to 10. The second and more challenging test case models a rising bubble with *Re=35*, *Eo=125*, and with large density and viscosity ratios (1000 and 100).

Physical parameters and dimensionless numbers defining the test cases.

Test Case	ρ_1	ρ_2	μ_1	μ_2	g	σ	Re	Eo	ρ_1/ρ_2	μ_1/μ_2
1	1000	100	10	1	0.98	24.5	35	10	10	10
2	1000	1	10	0.1	0.98	1.96	35	125	1000	100

Continue reading:

- Verification

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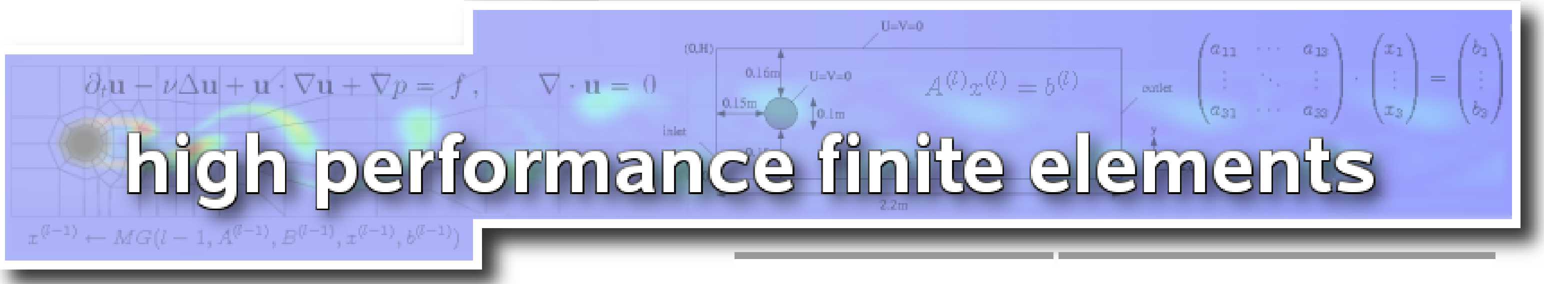


- Home
- Contact
- Software
  - FEAT2D/FEAT3D
  - FEAST
  - FEATFLOW
  - FEATFLOW2
  - FEAT3
  - parPP3D
  - Documentation
- Team
- Links
  - Websites
  - Software
- Benchmarks
  - FeatFlow Benchmark Suite
  - CFD Benchmarking Project
    - Flow around a Cylinder
    - Rising Bubble
      - Geometry and flow configurations
      - Verification
      - Participate
      - Reference data
    - FSI Benchmark
    - MIT Benchmark
- Publications
- Services
  - Sitemap
  - Impressum
  - Datenschutzerklärung
- News
- Examples

Home » Benchmarks » CFD Benchmarking Project » Rising Bubble » Verification

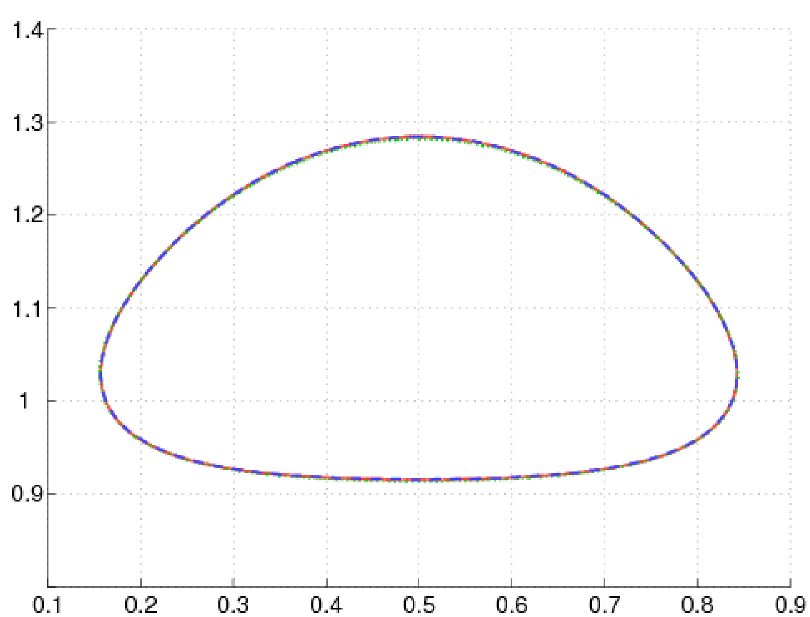
Bubble Benchmark

- Rising Bubble
- Geometry and flow configurations
- Verification
- Participate
- Reference data

Verification of the results by the picture norm:

To visually verify the results the following approximate bubble shapes can be used. (The raw data for the bubble shapes can be obtained from the Reference data page.)

Bubble shapes at the final time (*t*=3) Test case 1 Test case 2



Bubble shapes at the final time (*t*=3) for test case 1
(TP2D (solid red), FreeLIFE (dotted green), and MooNMD (dashed blue))

Verification of the results by quantitative data:

Since mere visual inspection is not really enough to say anything about the accuracy of the simulations the following benchmark quantities have been defined and computed.

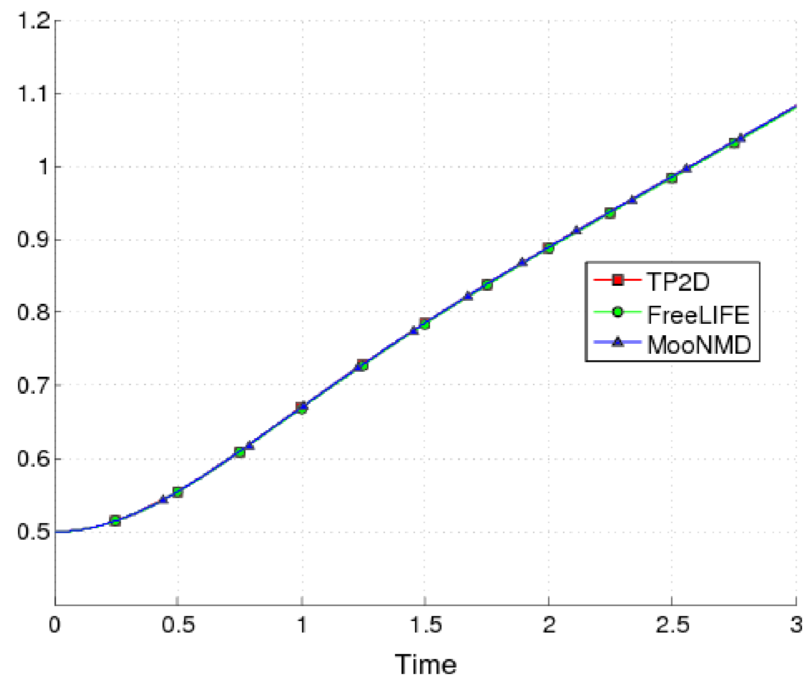
Center of Mass

The centroid or center of mass of the bubble is defined by

$$\mathbf{X}_c = (x_c, y_c) = \frac{\int_{\Omega_2} \mathbf{x}\ dx}{\int_{\Omega_2} 1\ dx}$$

where Ω_2 denotes the region that the bubble occupies.

Center of Mass for all groups Test Case 1 Test Case 2



Center of Mass for all groups (test case 1)

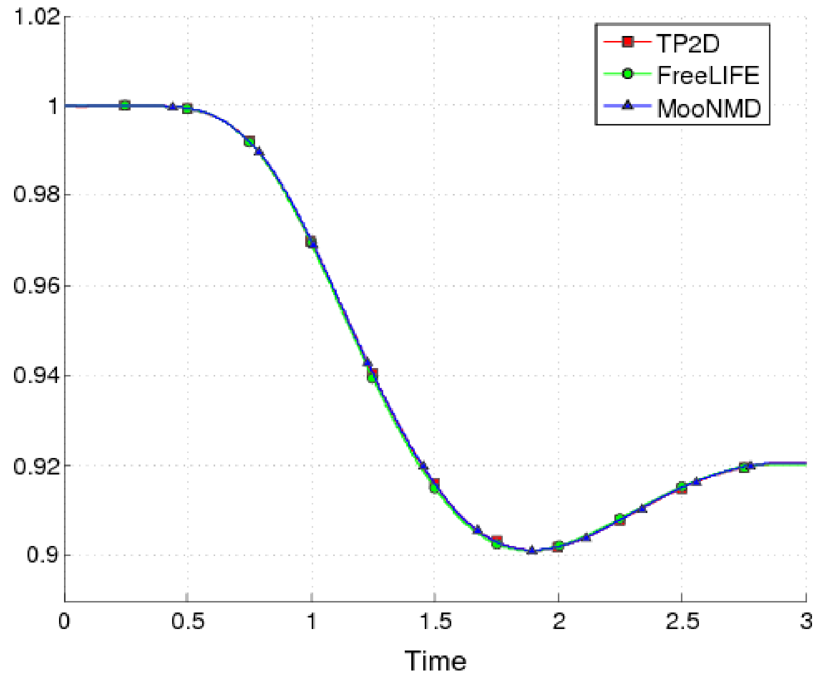
Circularity

The "degree of circularity" in $\mathbb{R}^2$ can be defined as

$$\not{c} = \frac{P_a}{P_b} = \frac{\text{perimeter of area-equivalent circle}}{\text{perimeter of bubble}} = \frac{\pi d_a}{P_b}\,.$$

Here, P_a denotes the perimeter or circumference of a circle with diameter d_a which has an area equal to that of a bubble with perimeter P_b. For a perfectly circular bubble or drop the circularity will be equal to unity and decrease as the bubble is deformed.

Circularity for all groups Test Case 1 Test Case 2



Circularity for all groups (test case 1)

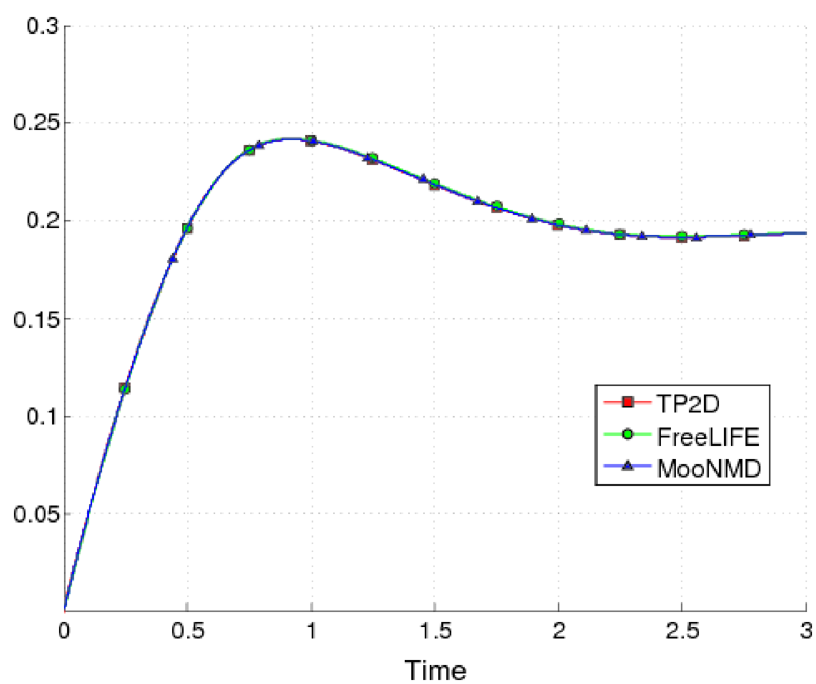
Rise Velocity

The mean velocity with which a bubble is rising or moving is a particularly interesting quantity since it does not only measure how the interface tracking algorithm behaves but also the quality of the overall solution. The mean bubble velocity is defined as

$$\mathbf{U}_c = \frac{\int_{\Omega_2} \mathbf{u}\ dx}{\int_{\Omega_2} 1\ dx}$$

where Ω_2 again denotes the region that the bubble occupies.

Rise velocity for all groups   Test case 1   Test case 2



Rise velocity for all groups (test case 1)

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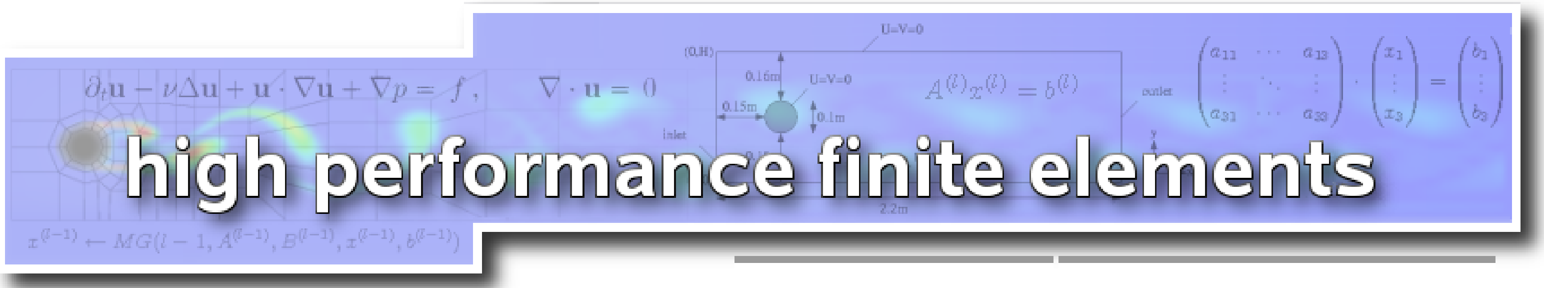

Bubble Benchmark

- Rising Bubble
- Geometry and flow configurations
- Verification
- Participate
- Reference data

Participate in this benchmark:

Register to download the reference data. Alternatively if you or your group have data to submit for these benchmark test cases please contact

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- Reference data

- Home
- Contact
- Software
  - FEAT2D/FEAT3D
  - FEAST
  - FEATFLOW
  - FEATFLOW2
  - FEAT3
  - parPP3D
  - Documentation
- Team
- Links
  - Websites
  - Software
- Benchmarks
  - FeatFlow Benchmark Suite
  - CFD Benchmarking Project
    - Flow around a Cylinder
    - Rising Bubble
      - Geometry and flow configurations
      - Verification
      - Participate
      - Reference data
    - FSI Benchmark
    - MIT Benchmark
- Publications
- Services
  - Sitemap
  - Impressum
  - Datenschutzerklärung
- News
- Examples

Home » Benchmarks » CFD Benchmarking Project » Rising Bubble » Reference data

Bubble Benchmark

- Rising Bubble
- Geometry and flow configurations
- Verification
- Participate
- Reference data

Reference data

The benchmark data is provided in the following ascii text files. File names use the notation `c#g#l#` with `c#` indicating the test case, `g#` the group and `l#` the refinement level:

c1	Test Case 1
c2	Test Case 2
g1	TU Dortmund (TP2D)
g2	EPFL Lausanne (FreeLIFE)
g3	Uni Magdebug (MooNMD)
l#	Grid Refinement Level (higher number means denser grid)

File	Action
All in one zip file	Download
c1g1l4.txt	Download
c1g1l5.txt	Download
c1g1l6.txt	Download
c1g1l7.txt	Download
c1g2l1.txt	Download
c1g2l2.txt	Download
c1g2l3.txt	Download
c1g3l1.txt	Download
c1g3l2.txt	Download
c1g3l3.txt	Download
c1g3l4.txt	Download
c2g1l4.txt	Download
c2g1l5.txt	Download

c2g1l6.txt	Download
c2g1l7.txt	Download
c2g1l8.txt	Download
c2g2l1.txt	Download
c2g2l2.txt	Download
c2g2l3.txt	Download
c2g3l2.txt	Download
c2g3l3.txt	Download
c2g3l4.txt	Download

The data is given in ascii format with columns corresponding to the following quantities.

Benchmark file format

Column	Quantity
1	Time
2	Bubble mass or area
3	Circularity
4	Center of mass (y-coordinate)
5	Rise velocity

The benchmark curves can the be plotted with standard postprocessing tools like Matlab or Gnuplot:

Gnuplot code

```
plot "c1g1l4.txt" using 1:2 with \
lines linestyle 1 title 'Bubble mass/area'; set xlabel 'Time'
plot "c1g1l4.txt" using 1:3 with \
lines linestyle 1 title 'Circularity'; set xlabel 'Time'
plot "c1g1l4.txt" using 1:4 with \
lines linestyle 1 title 'Center of mass'; set xlabel 'Time'
plot "c1g1l4.txt" using 1:5 with \
lines linestyle 1 title 'Rise velocity'; set xlabel 'Time'
```

Matlab code

```
load c1g1l4.txt, plot(c1g1l4(:,1),c1g1l4(:,2)), ...
title('Bubble mass/area'), xlabel('Time')
load c1g1l4.txt, plot(c1g1l4(:,1),c1g1l4(:,3)), ...
title('Circularity'), xlabel('Time')
load c1g1l4.txt, plot(c1g1l4(:,1),c1g1l4(:,4)), ...
title('Center of mass'), xlabel('Time')
load c1g1l4.txt, plot(c1g1l4(:,1),c1g1l4(:,5)), ...
title('Rise velocity'), xlabel('Time')
```

The data for the bubble shapes can be found in the files that end with a `s` character, for example `c1g1l4s.txt`. The shapes are stored as line segments with x-coordinates in the first column and y-coordinates in the second in consecutive line pairs (that is the first line end point is stored at odd numbered lines and the other end points on the following lines). The shapes can for example be plotted in Gnuplot or Matlab with the following code:

Gnuplot code

```
plot "c1g1l4s.txt" with lines linestyle 1; \
```

```
unset key; set size ratio -1
```

Matlab code

```
load c1g1l4s.txt
data = c1g1l4s;
hold on
nSegments = size(data,1)/2;
for i=1:nSegments
  plot(data(2*(i-1)+1:2*i,1),data(2*(i-1)+1:2*i,2))
end
axis equal
```

Downloads

File	Action
All in one zip file	Download
c1g1l4s.txt	Download
c1g1l5s.txt	Download
c1g1l6s.txt	Download
c1g1l7s.txt	Download
c1g2l1s.txt	Download
c1g2l2s.txt	Download
c1g2l3s.txt	Download
c1g3l4s.txt	Download
c2g1l4s.txt	Download
c2g1l5s.txt	Download
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c2g2l3s.txt	Download
c2g3l4s.txt	Download

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Back to top

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