Interpolation of Relative Permeability in STARS

STARS has a very useful feature, enabling use of interpolated relative permeability values

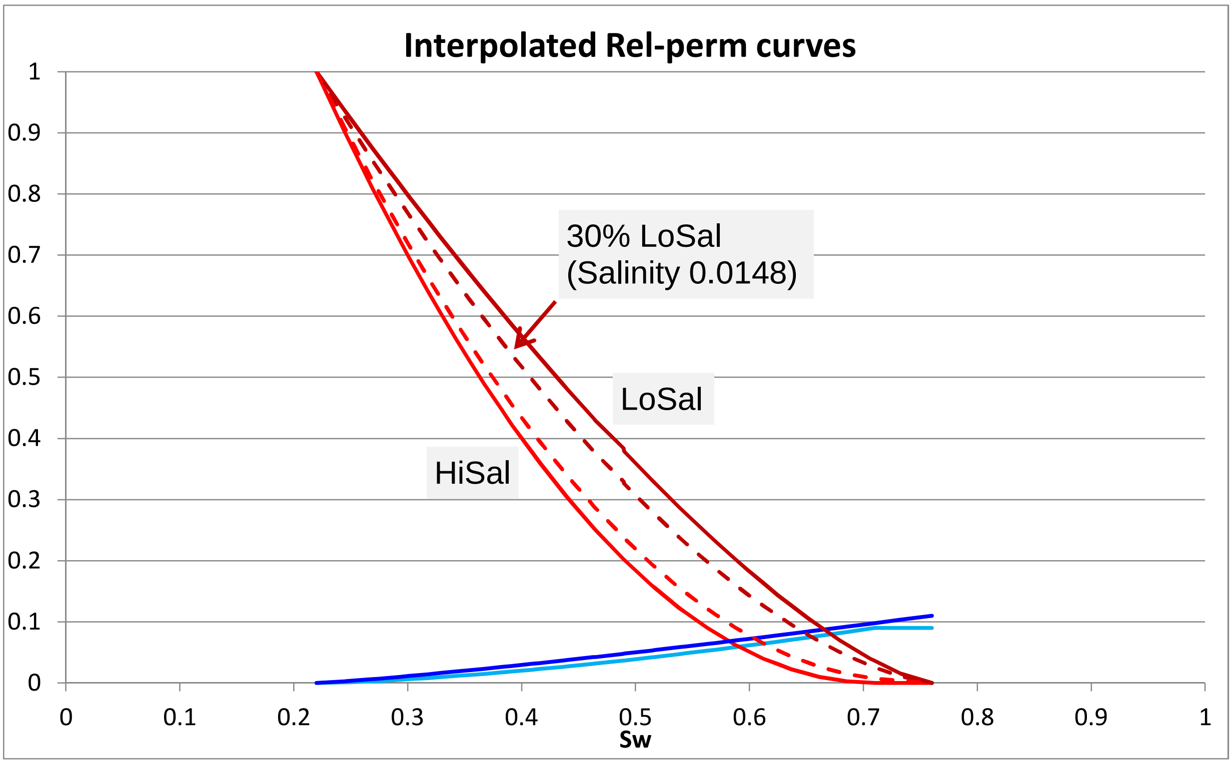


Figure 1. Example Relative Permeability Curves

Figure 1 shows a relative permeability *set*. Focusing on the oil rel-perm K_{ro}, the leftmost curve is valid for high salinity, in this example a brine with 4% salt; while the rightmost curve is valid for low salinity, in the example brine with 0.4% salt.

The interpolation mechanism now works as follows,

- For salinity larger than 4% the HiSal curve is used
- For salinity lower than 0.4% the LoSal curve is used
- When salinity is between 0.4 and 4 %, an interpolated rel-perm is used.
  E.g., a salinity of 1.48% corresponds to 30% Hisal, 70% LoSal, hence an intermediate rel-perm interpolated by 0.3HiSal + 0.7LoSal is computed and used (Rightmost dashed curve in Figure 1). Another example interpolation curve, for 80% HiSal, 20% LoSal is also shown.
- Note that in this example the interpolation is performed directly on the salt *concentration*.

In STARS the lower and upper interpolation bounds (0.04 and 0.004 in the example) are designated DTRAPW for the wetting phase, DTRAPN for nonwetting. (Usually DTRAPW = DTRAPN, in which case only one needs to be defined).

The interpolation option is activated by keyword INTCOMP in the ROCKFLUID section.

Example of relative permeability definition for example curve above:

```
** ROCK FLUID TYPE 1: Salinity
RPT 1 STONE1 WATWET

INTCOMP 'Salt' WATER

KRINTRP 1
DTRAPW 0.004   ** conc corresponding to LoSal

SWT
 SMOOTHEND QUAD
** Table Corey, co = 1.4, cw = 1.2
**     Sw           Krw          Kro          Pc
       0.22         0.00000      1.00000      0
       0.247        0.00302      0.93071      0
       0.274        0.00694      0.86286      0
       0.301        0.01129      0.79650      0
       0.328        0.01595      0.73169      0
       0.355        0.02084      0.66848      0
       0.382        0.02594      0.60693      0
       0.409        0.03121      0.54712      0
       0.436        0.03663      0.48912      0
       0.463        0.04219      0.43302      0
       0.49         0.04788      0.37893      0
       0.517        0.05368      0.32696      0
       0.544        0.05959      0.27726      0
       0.571        0.06560      0.22998      0
       0.598        0.07170      0.18534      0
       0.625        0.07789      0.14359      0
       0.652        0.08416      0.10506      0
       0.679        0.09051      0.07023      0
       0.706        0.09694      0.03981      0
       0.733        0.10343      0.01509      0
       0.76         0.11000      0.00000      0


KRINTRP 2 COPY 1 1
DTRAPW 0.04    ** conc corresponding to HiSal

** Sw               Krw          Kro          Pc
SWT
 SMOOTHEND QUAD
** Table Corey, co = 2, cw = 1.5
**     Sw           Krw          Kro          Pc
       0.22         0.00000      1.00000      0
       0.2445       0.00101      0.90250      0
       0.269        0.00285      0.81000      0
       0.2935       0.00523      0.72250      0
       0.318        0.00805      0.64000      0
       0.3425       0.01125      0.56250      0
       0.367        0.01479      0.49000      0
       0.3915       0.01864      0.42250      0
       0.416        0.02277      0.36000      0
       0.4405       0.02717      0.30250      0
       0.465        0.03182      0.25000      0
       0.4895       0.03671      0.20250      0
       0.514        0.04183      0.16000      0
       0.5385       0.04716      0.12250      0
       0.563        0.05271      0.09000      0
       0.5875       0.05846      0.06250      0
       0.612        0.06440      0.04000      0
       0.6365       0.07053      0.02250      0
       0.661        0.07684      0.01000      0
       0.6855       0.08334      0.00250      0
       0.71         0.09000      0.00000      0
```

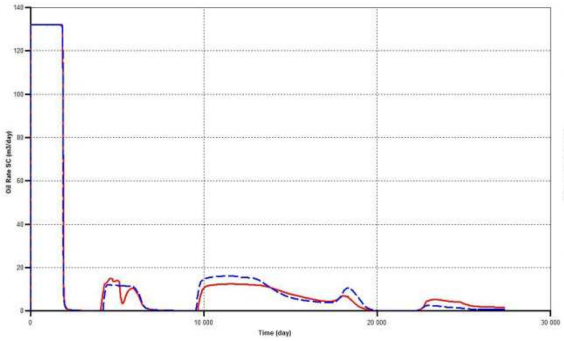
Interpolation on Concentration or Capillary Number

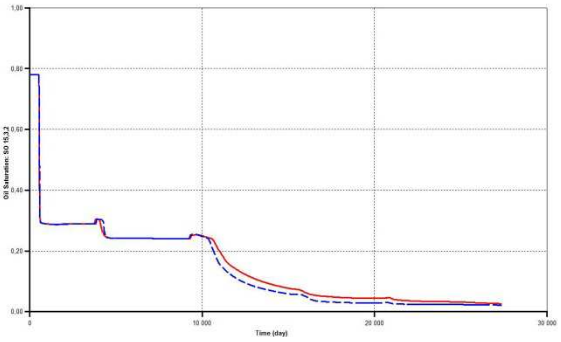
The interpolation parameter can be either the concentration as above, or log(N_c), where N_c is the capillary number

$$N_c = \frac{\mu^f v}{\sigma}$$

(μ^f: phase viscosity, v: velocity, σ: interfacial tension).

STARS' rule here: If an IFT-TABLE has been defined, interpolation will be based on (log) capillary number, else concentration is used. As the IFT-table defines interfacial tension as a function of concentration, there's a one-to-one correspondence between these two, and hence interpolation should be equivalent in the two cases. However, the concentration-based interpolation will be linear, while the capillary number based one will be exponential, so the end result is different. Physics should determine which option to use. (Example; for salinity concentration appears appropriate, while capillary number is best for surfactant concentration.)





The figures above show an example of the difference for interpolation on surfactant concentration. (Left hand curve: Oil rate, Right hand curve: Oil Saturation in a grid cell near the injection well):

The red curves were obtained using concentration as interpolation parameter, while (log) capillary number was used for the blue curves.

(The interpolation scheme also allows for non-linear interpolation by defining interpolation exponents. Hence some of the effect of the exponential interpolation using capillary numbers can alternatively be defined by the interpolation exponents.)

Note on computing capillary numbers: STARS doesn't use the formula above, but calculates these numbers in an alternative way, which apparently is independent of velocity. The consequence is that it isn't easy to hand calculate these numbers as input to STARS. As an example, for the example above, I computed the limit numbers to be: DTRAPW = log(N_c) = 7.28E-8 and 2.33E-4. However this didn't work out as expected, and when I checked the capillary numbers from the actual run I found that STARS had computed these numbers to DTRAPW = log(N_c) = 6.25E-13 and 1.54E-9. Puzzling, but the obvious solution was to use STARS' numbers in the further simulations; which worked out fine.

Double Interpolation – Interpolation between Rock Regions.

Complicating the example above, the next example needs STARS to perform “double interpolation”.

The process is as follows: In a reservoir initially filled with oil and high salinity brine, we first inject low salinity brine for a period, and then continue with injection of low salinity water containing surfactant (for the example 0.5% surfactant). During the LoSal injection, the relevant rel-perm will be computed as shown above; then during surfactant injection, we will need;

1. An interpolated rel-perm-value based on the salinity
2. Another interpolated rel-perm value based on the surfactant content
3. The final rel-perm must be found by interpolating (1) and (2), based on both salinity and surfactant content – denoted double interpolation.

To define this process to STARS, the two different rel-perm interpolation sets must be defined as two different rock type regions, and then the keyword RPT_INTERP instructs STARS to interpolate between the rock types. The input is a straightforward extension of the example above, and is given below (note that interpolation on salinity is based on concentration, while surfactant is based on the capillary number and IFT table).

```
*ROCKFLUID

** RPT 1: Surfactant

RPT 1 STONE1 WATWET

INTCOMP 'Surf' WATER
** Set #1: No surf

KRINTRP 1
** Nc = 6.25e-13 taken from STARS report

DTRAPW -12.20412

SWT
 SMOOTHEND QUAD
**     Sw           Krw          Kro          Pc
       0.22         0.00000      1.00000      0
       0.2445       0.00101      0.90250      0
       0.269        0.00285      0.81000      0
       0.2935       0.00523      0.72250      0
       0.318        0.00805      0.64000      0
       0.3425       0.01125      0.56250      0
       0.367        0.01479      0.49000      0
       0.3915       0.01864      0.42250      0
       0.416        0.02277      0.36000      0
       0.4405       0.02717      0.30250      0
       0.465        0.03182      0.25000      0
       0.4895       0.03671      0.20250      0
       0.514        0.04183      0.16000      0
       0.5385       0.04716      0.12250      0
       0.563        0.05271      0.09000      0
       0.5875       0.05846      0.06250      0
       0.612        0.06440      0.04000      0
       0.6365       0.07053      0.02250      0
       0.661        0.07684      0.01000      0
       0.6855       0.08334      0.00250      0
       0.71         0.09000      0.00000      0
```

```
** Set #2: Max surf conc. curves

KRINTRP 2 COPY 1 1

** log(Nc) corresponding to concentration 0.005:
** Nc = 2.0e-9 taken from STARS report

DTRAPW -8.69897

SWT
 SMOOTHEND QUAD
**      Sw            Krw           Kro           Pc
        0.22          0.00000       1.00000       0
        0.2515        0.00961       0.93071       0
        0.283         0.02208       0.86286       0
        0.3145        0.03592       0.79650       0
        0.346         0.05073       0.73169       0
        0.3775        0.06631       0.66848       0
        0.409         0.08253       0.60693       0
        0.4405        0.09930       0.54712       0
        0.472         0.11656       0.48912       0
        0.5035        0.13425       0.43302       0
        0.535         0.15235       0.37893       0
        0.5665        0.17081       0.32696       0
        0.598         0.18960       0.27726       0
        0.6295        0.20872       0.22998       0
        0.661         0.22813       0.18534       0
        0.6925        0.24782       0.14359       0
        0.724         0.26778       0.10506       0
        0.7555        0.28799       0.07023       0
        0.787         0.30843       0.03981       0
        0.8185        0.32911       0.01750       0
        0.85          0.35000       0.00800       0
        0.875         0.36000       0.00350       0
        0.9           0.368         0.00200       0
        0.925         0.37          0.00050       0
        0.95          0.37200       0.00000       0


IFTTABLE
** cift     sigift
   0.0        16
   0.001      0.01
   0.005      0.005

** End RPT 1

** ROCK FLUID TYPE 2: Salt

RPT 2 STONE1 WATWET

** Interpolation between salinity and surfactant curves

RPT_INTRP
 COMP 'Salt' WATER
 LOWER_BOUND 0.0
 UPPER_BOUND 0.04
 UPPERB_RPT 1

INTCOMP 'Salt' WATER

** Set #1: High Sal no surfactant curves

KRINTRP 1

DTRAPW 0.004   ** comp corresponding to Lo sal
```

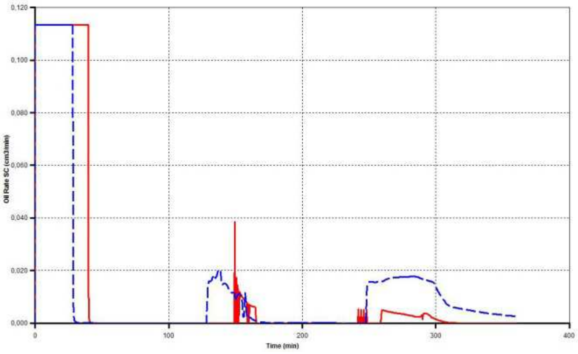
```
SWT
 SMOOTHEND QUAD
**     Sw           Krw          Kro          Pc
       0.22         0.00000      1.00000      0
       0.247        0.00302      0.93071      0
       0.274        0.00694      0.86286      0
       0.301        0.01129      0.79650      0
       0.328        0.01595      0.73169      0
       0.355        0.02084      0.66848      0
       0.382        0.02594      0.60693      0
       0.409        0.03121      0.54712      0
       0.436        0.03663      0.48912      0
       0.463        0.04219      0.43302      0
       0.49         0.04788      0.37893      0
       0.517        0.05368      0.32696      0
       0.544        0.05959      0.27726      0
       0.571        0.06560      0.22998      0
       0.598        0.07170      0.18534      0
       0.625        0.07789      0.14359      0
       0.652        0.08416      0.10506      0
       0.679        0.09051      0.07023      0
       0.706        0.09694      0.03981      0
       0.733        0.10343      0.01509      0
       0.76         0.11000      0.00000      0


KRINTRP 2 COPY 2 1

DTRAPW 0.04    ** comp corresponding to High sal

SWT
 SMOOTHEND QUAD
**     Sw           Krw          Kro          Pc
       0.22         0.00000      1.00000      0
       0.2445       0.00101      0.90250      0
       0.269        0.00285      0.81000      0
       0.2935       0.00523      0.72250      0
       0.318        0.00805      0.64000      0
       0.3425       0.01125      0.56250      0
       0.367        0.01479      0.49000      0
       0.3915       0.01864      0.42250      0
       0.416        0.02277      0.36000      0
       0.4405       0.02717      0.30250      0
       0.465        0.03182      0.25000      0
       0.4895       0.03671      0.20250      0
       0.514        0.04183      0.16000      0
       0.5385       0.04716      0.12250      0
       0.563        0.05271      0.09000      0
       0.5875       0.05846      0.06250      0
       0.612        0.06440      0.04000      0
       0.6365       0.07053      0.02250      0
       0.661        0.07684      0.01000      0
       0.6855       0.08334      0.00250      0
       0.71         0.09000      0.00000      0

** End RPT 2

** Define all grid cells as KRTYPE 2
** (Then UPPERB_RPT 1 above takes care of the interaction between these)

KRTYPE CON 2
```

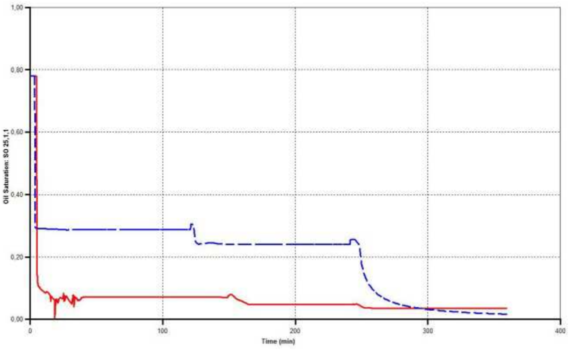
Note that in this example the surfactant curves have been defined first (RPT 1), and then the salinity curves (RPT 2). One would think that the order was of no significance, as the computation of the final rel-perm value does not depend on the which number comes first or second in the calculation.

However, **the order in which these curves are defined makes a big difference (!!).** The way it’s done in the example is the only one that works:

RPT 1: Surfactant	**RPT 2: Salinity**	**Works fine**
RPT 1: Salinity	**RPT 2: Surfactant**	**Doesn’t work at all.**

(No good explanation for this, just has to be accepted…)





In the figures above (oil rate and oil saturation), the blue curves are the “working” ones (Surfactant as RPT 1), while the red curves are for the other way around (Salinity as RPT 1).

Note that the “no-surfactant” curves are identical to the high salinity curves for the salinity set, although the reservoir state is far from HiSal at the time surfactant is injected. This is however logical: Initially, STARS checks the surfactant concentration, and on finding it is zero, will use the no-surfactant curves for interpolation – the same procedure is used whether surfactant injection has commenced or not.

Lastly:

STARS only handles two interpolation regions as in this example.

If a third set is needed, e.g. by introducing polymer injection after the LoSal – Surfactant sequence, then it’s not possible to define polymer rel-perm curves as a third set. One way of handling this could be by doing a restart and define appropriate curves. But this is very dependant on the actual process. (E.g. if all or most of the reservoir was flooded to low salinity before the polymer injection, the high salinity curves are no longer needed, and more appropriate curves could be defined for a restart run. But as said – no general advice can be given; however many situations can be handled by such kind of approach.)