TNO innovation for life

RECENT OPM DEVELOPMENTS BY TNO

› CÍNTIA G. MACHADO, PAUL EGBERTS, EDUARDO BARROS

OPM SUMMIT – 30-31 AUGUST 2022 – TRONDHEIM, NORWAY

OUTLINE

- Recently completed activities (2021/2022):
  - Salt precipitation and water evaporation [separate presentation]
  - Gas-water
  - Temperature output for wells
  - Joule-Thompson
  - Radial/Spider grid
  - Keyword Validation
  - Others
- On-going activities:
  - LGR
  - Grid independent specification of the well
- What is next?

TNO-OPM Team

Reservoir Engineer

Goncalves Machado, C. (Cintia)

Project Manager

Barros, E. (Eduardo)

Mathematician

Egberts, P.J.P. (Paul)

Software Engineer

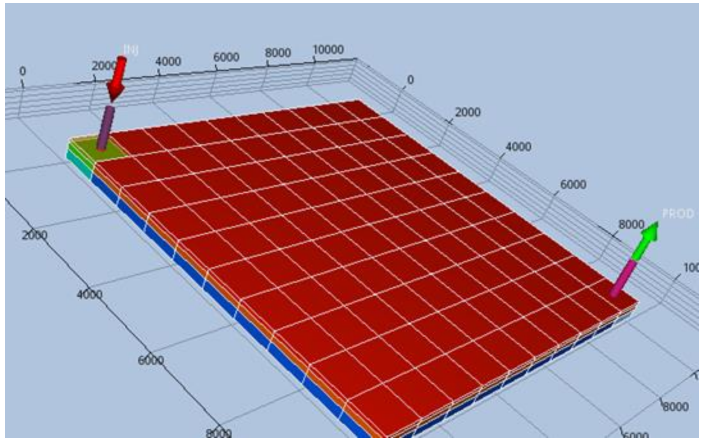
Verveer, P.J. (Pieter)

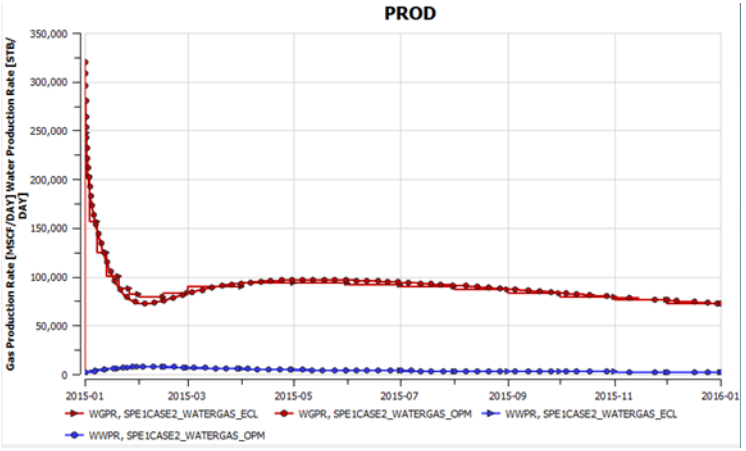
TWO-PHASE GAS-WATER

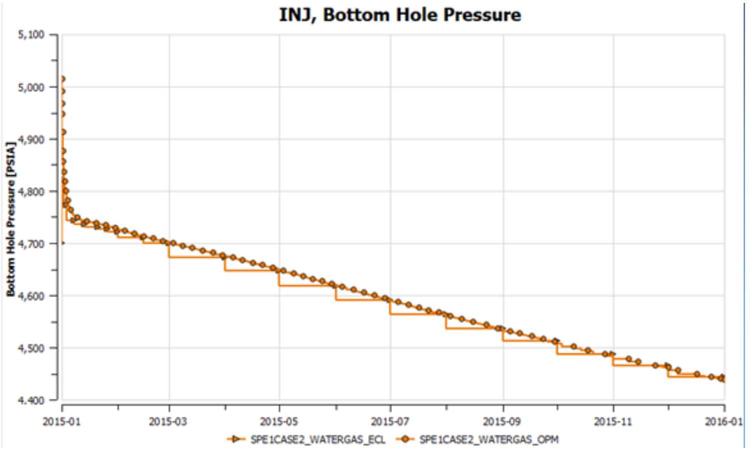
- Motivation: modelling of CO_2 storage in aquifers, gas reservoirs, salt precipitation near wells, …
- Material laws specified by SWFN and SGFN tables:

```
SWFN                                 SGFN
--Sw      Krw     Pcwg              --Sg      Krg     Zero in water-gas system
  .25      .0     7.0                 .25      .0     0.0
  .7      1.0     2.0/                .7      1.0     0.0/
```

- Excellent comparison with Eclipse:







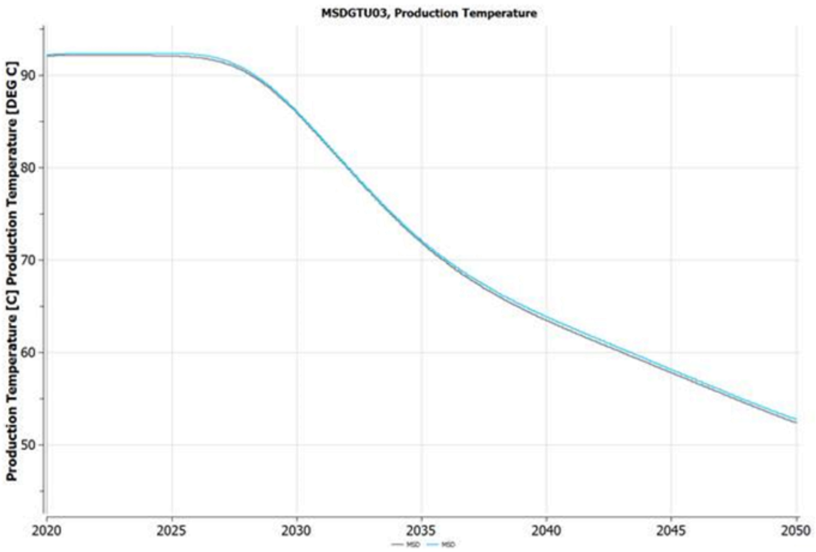
WELL PRODUCTION TEMPERATURE OUTPUT

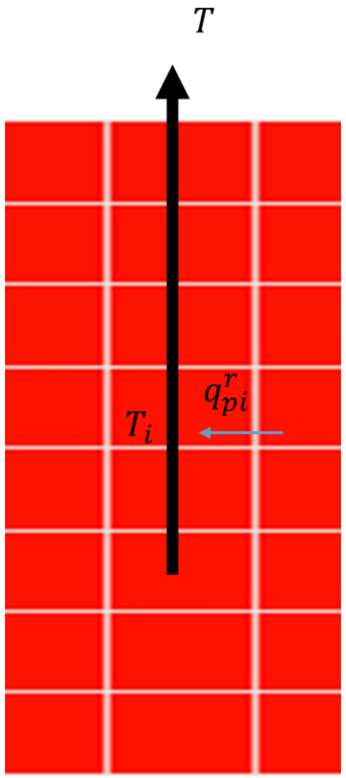
- Crucial for geothermal applications

- Reported production temperature T of the flow of a producer is computed as the weighted sum of the cell temperatures T_i
  - $T = \frac{\sum_{i=1}^{M} W_i T_i}{\sum_{i}^{M} W_i}$ with
  - $W_i = \sum_\alpha \rho_{\alpha i}^r q_{\alpha i}^r C_{p\alpha},$

  $q_{\alpha i}^r$: perforation phase rate (at reservoir conditions)
  $C_{p\alpha}$: specific heat capacity of phase α

- Excellent match with Eclipse:
  - Even tough it is unknown how Eclipse computes it
  - Derived own equation





JOULE-THOMSON (JT) EFFECT

- JT effect: temperature change of a fluid due to expansion/compression
  - Assuming no heat exchange (constant enthalpy)
- Joule-Thomson Coefficient: $\varepsilon_{JT} = \left(\frac{\partial T}{\partial p}\right)_H$
  - Ratio of change of temperature for a given pressure change
  - $\varepsilon_{JT} = -\frac{1}{C_{pg}}\left\{\frac{1}{\rho_g} - T\left[\frac{\partial}{\partial T}\left(\frac{1}{\rho_g}\right)\right]_p\right\}^{(*)}$
- $\rho_g = \rho_g(p, T)$ internally computed from via $B_g(p, T_{ref})$ and GASDENT (OPM-Flow) keyword
- JT effect implemented for all phases
  - New keywords: JT_GAS, JT_WATER, JT_OIL
  - Either internally calculated using theoretical formula (default) or via provided input of single JT coefficient

- No JT physics in E100
- In E300
  - Limited way of specifying heat capacities
  - JT effect only computed for gas phase
  - Constant input value for JT coefficient

(*) https://en.wikipedia.org/wiki/Joule-Thomson_effect

JOULE-THOMSON SIMULATION EXPERIMENT

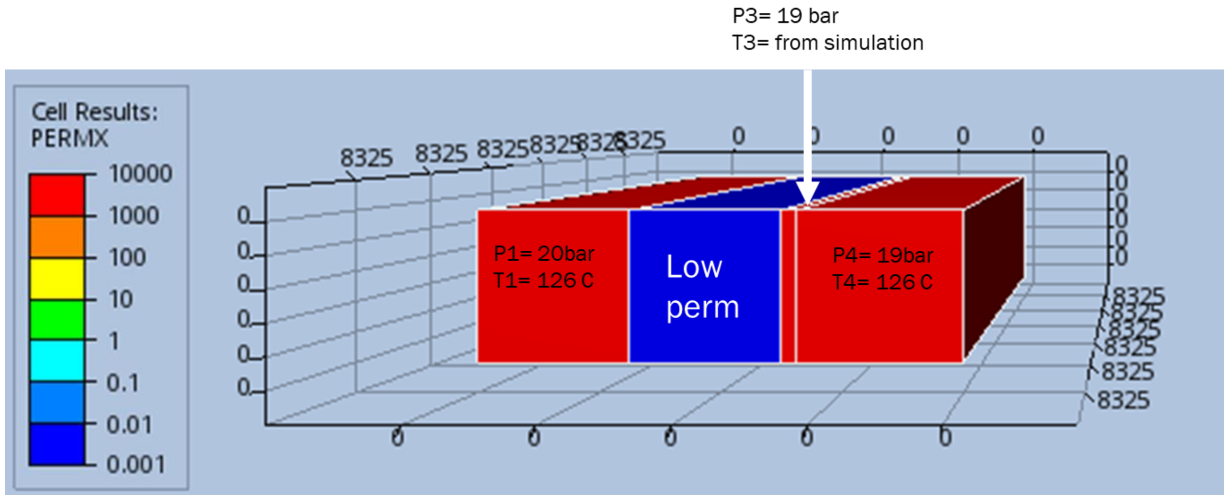
- Example taken from:

C.M Oldenburg (2007). Joule-Thomson cooling due to CO_2 injection into natural gas reservoirs. Energy Conversion and Management 48,1808–1815

```
--
--      GAS JOULE-THOMSON COEFFICIENT (OPM FLOW EXTENSION KEYWORD)
--
--      REF          GAS
--      PRESS        JTC
--      --------     -------
GASJT
        20.0         1*                      / TABLE NO. 01
```

- Initial temperature T_0 = 126 °C

- $\varepsilon_{JTg} \approx \frac{\Delta T}{\Delta P} = \frac{T3-T0}{P3-P1}$

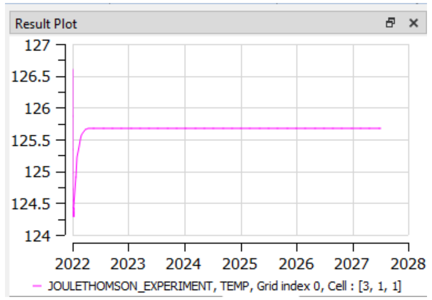


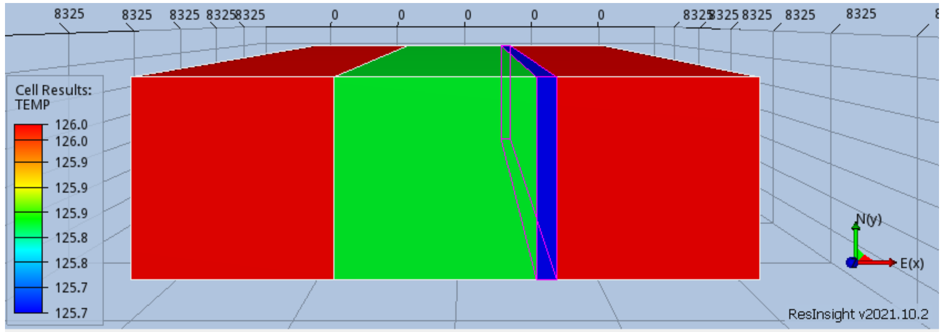
- OPM results:
  - Theoretical formula:

JTC = 0.318 K/bar at T = 126 °C and p = 20 bar

  - Value obtained from simulation:

$$\text{JTC} = \frac{\Delta T}{\Delta p} = \frac{126.0-125.681}{20.0-19.0} = 0.318\ \text{K/bar}$$





RADIAL & SPIDER GRID
DESCRIPTION INCLUDED IN THE RELEASE 04.2021 MANUAL

DATA REQUIREMENTS

6.2.2 Spider GRID

This type of grid defines a radial grid based on cartesian coordinates (corner-point grid) defining the r, theta and z dimensions of all the cells. Figure 6.2 shows an example of a Spider Grid.

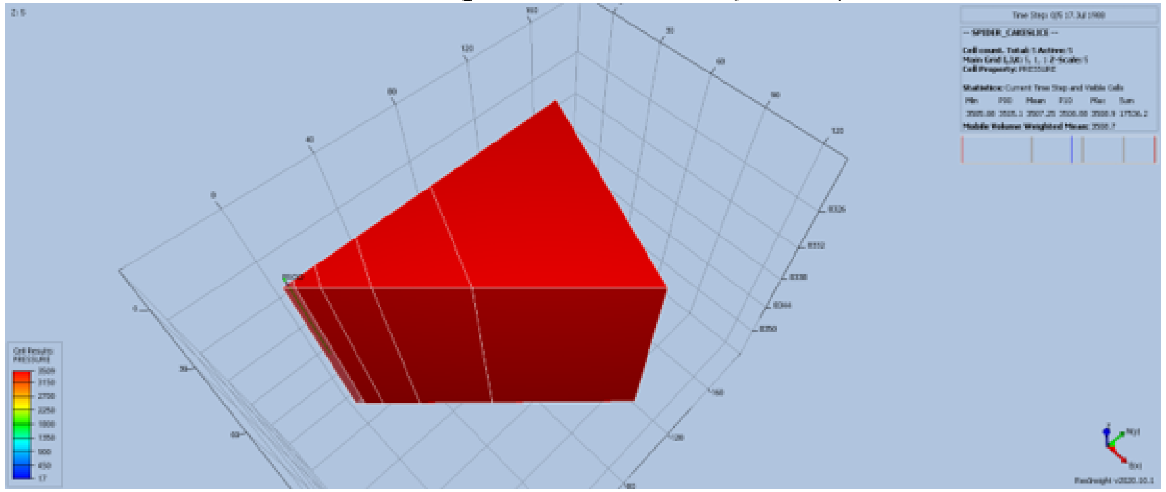


Figure 6.X: SPE Simulation Case #01 Spider Grid.

The model consists of a simple 5 x 5 x 1 (NR, NTHETA, NZ) grid and is defined using the following GRID section keywords to define the grid geometry:

```
--
-- DEFINE GRID BLOCK R DIRECTION CELL SIZE (BASED ON NR x NTHETA x NZ = 5)
-- The Innermost-Cell Innermost-Face Radius Is 0.25 FT
-- INRAD
0.25 /
-- (There Are In Total 5 Cells With Varying Length In R-Direction)
DRV
```

Keyword: SPIDER

SPIDER activates the radial grid geometry option for the model using cartesian coordinates, if this keyword is omitted then Cartesian geometry is assumed by OPM Flow. This keyword will create a spiderweb-shaped grid based on a corner-point grid.

See also keywords INRAD, DRV, DTHETAV, DZ/DZV in GRID the section to fully define a spiderweb grid.

keyword: RADIAL

RADIAL activates the radial grid geometry option for the model using cylindrical coordinates, if this keyword is omitted then Cartesian geometry is assumed by OPM Flow.

Although this keyword is read by OPM Flow, radial grids have not been fully implemented and therefore the SPIDER web grid should be used instead to model radial flow.

Note: Keywords INRAD, DRV, DTHETAV, DZ/DZV should be correct to mention it can be used with both RADIAL and SPIDER grid models.

TNO innovation for life

KEYWORD VALIDATION
OUTLINE OF THE VALIDATION PROCEDURE

- Added a new keyword validation class:
  1. Checks for unsupported keywords
  2. Checks for partially supported keywords (items with values that are not supported)
  3. The validation class compiles a list of unsupported keywords and/or item values
  4. After validation, problems that are not critical are reported as warnings, and critical problems as errors
  5. If there are any critical problems, execution of the program is halted

EXAMPLE OUTPUT

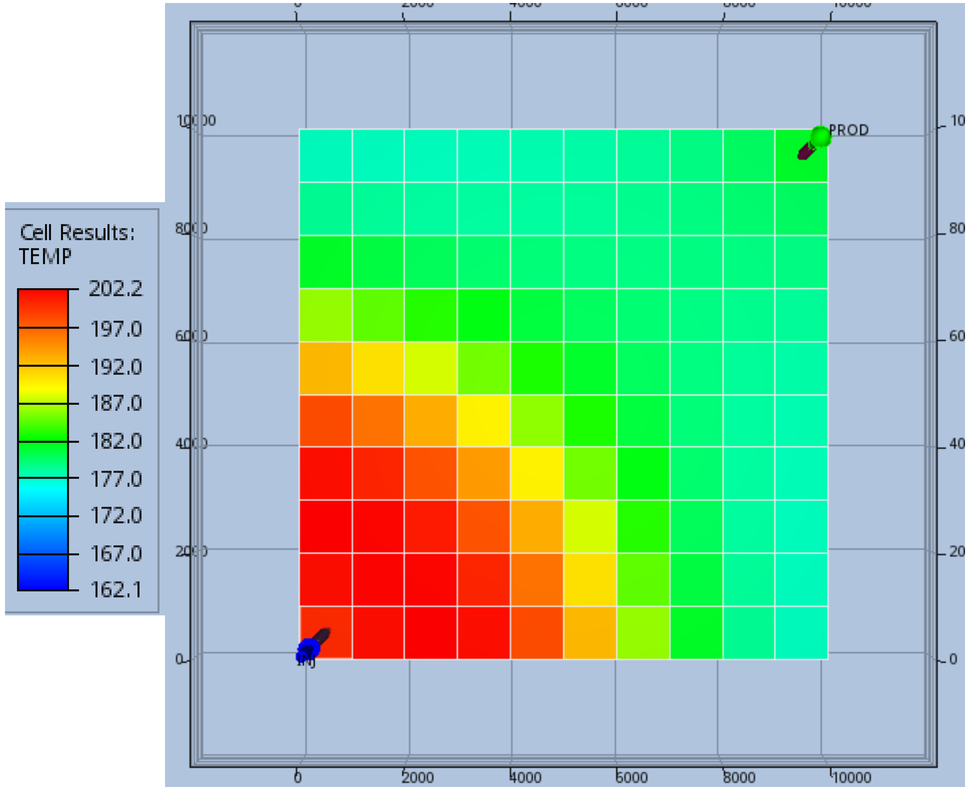
```
Warning: Unsupported keywords or keyword items:
PINCH: invalid value 'FOO' in record 1 for item 2
  In file: /home/user/EXAMPLE.DATA, line 20

Error: Unsupported keywords or keyword items:
NOECHO: keyword not supported
  In file: /home/user/EXAMPLE.DATA, line 108, line 68
```

- What is next?
  - Add critical and non-critical keywords to the list
  - Add useful messages
  - Improve checking capability (non-fixed list of values

BUGS AND OUTPUTS
USERS REPORTS AND REQUESTS

- Thermal output
- Grid and summary outputs
- Finalized single-phase models
  - Widely used in geothermal and heat storage studies
- Bugs fixes, etc.

- TNO complex geothermal case run 5× faster with flow single-phase than 3-phase thermal module ☺

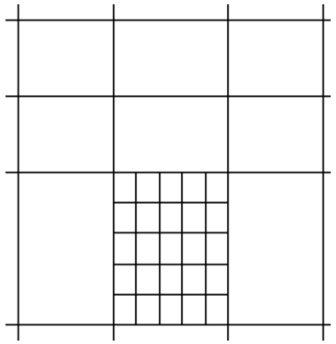


TNO innovation for life

LOCAL GRID REFINEMENT (LGR)

- Support LGR functionalities currently available in Eclipse:
  - Automatic Cartesian refinement
- Prepared complex test cases that can be run in Eclipse:
  - Including faults
  - Corner point grids:
    - Cartesian shape
    - With skewed pillars
  - Including multi-segment wells
- LGR cannot be created dynamically in Eclipse (i.e. at a time-step)
  - But can activate and deactivate
- Development work in collaboration with SINTEF and OPM-OP AS

```
CARFIN

-- NAME    I1-I2 J1-J2 K1-K2 NX NY NZ NWMAX--

 'LGR1'   2   2   3   3   3   4   5   5   8   5        /
PORO

200*0.2 /
EQUALS

'PERMX'  500  /
'PERMY'  500  /
'PERMZ'  50  /

/
ENDFIN
```

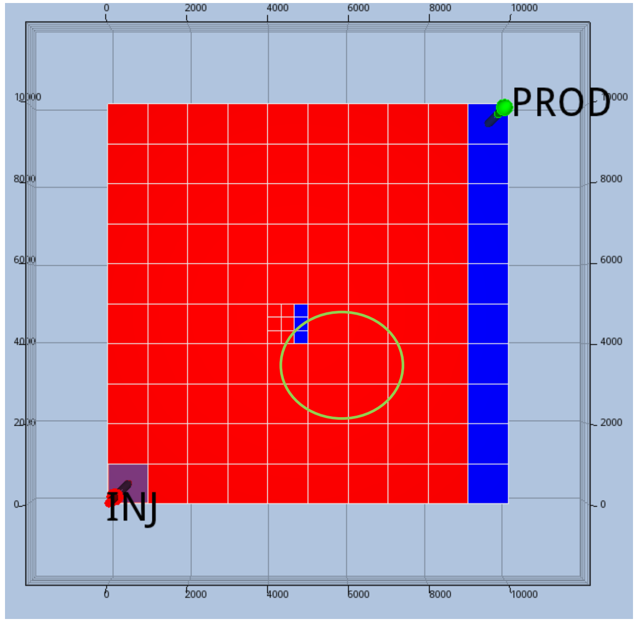


SPE1CASE1 WITH LGR

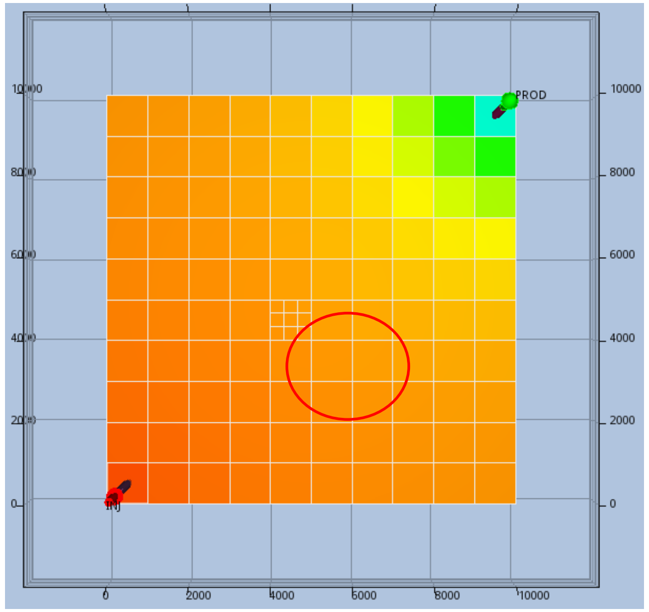
CARFIN KEYWORD

```
GRID

CARFIN
'LGR1' 5 5 5 5 1 3 3 3 3 /
ENDFIN
```

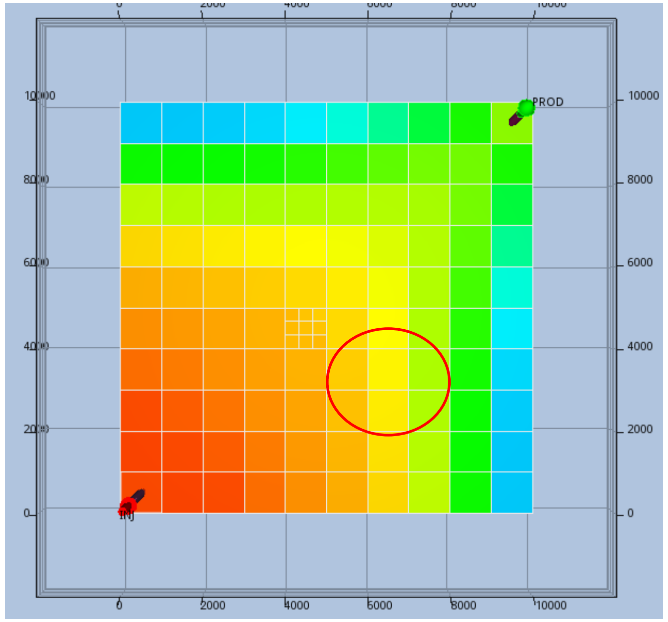
TRANX



PRESSURE



SGAS

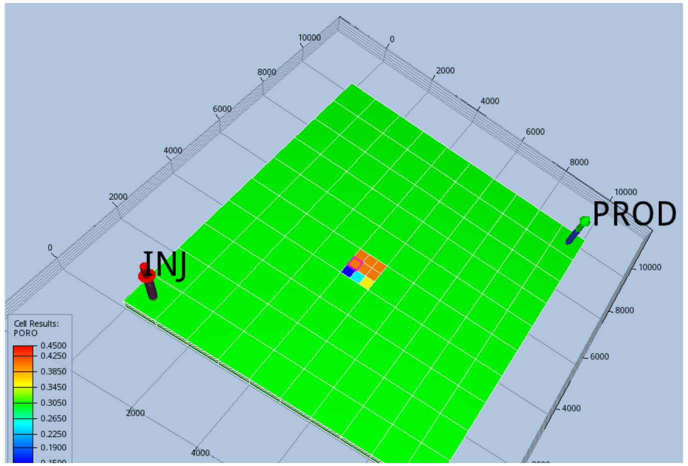


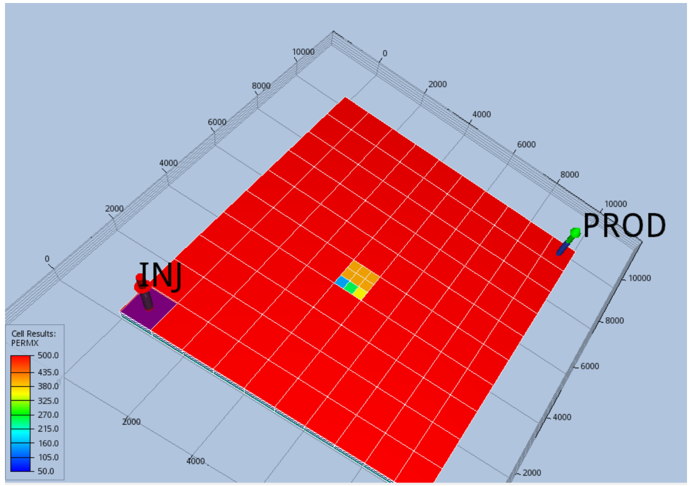
- Each grid is a separate entity, with global grid corresponding to index 0 (zero)
- Grids interact through non-neighboring connections

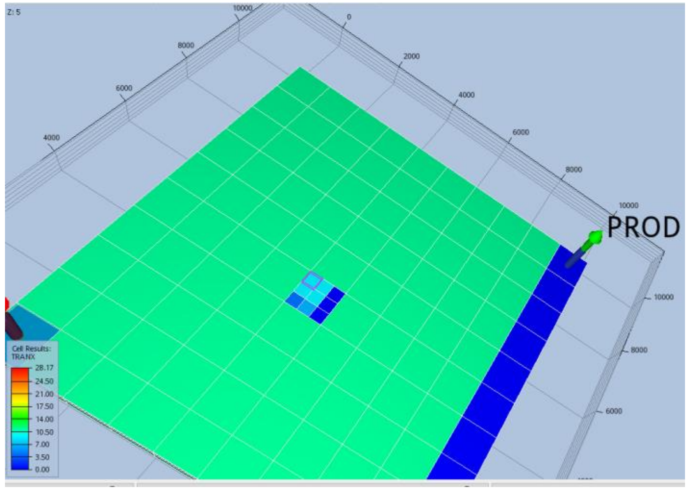
SPE1CASE1 WITH LGR AND HETEROGENEITY

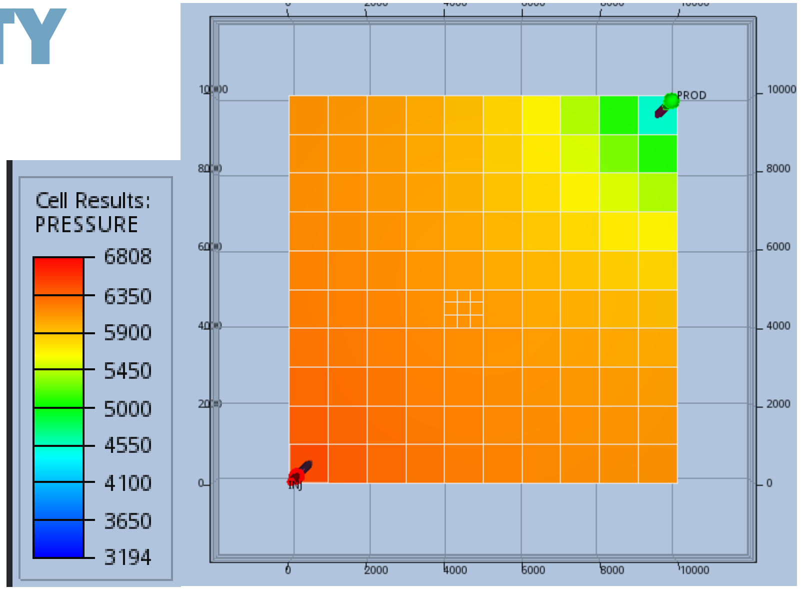
- Field properties can be specified for each refined cell

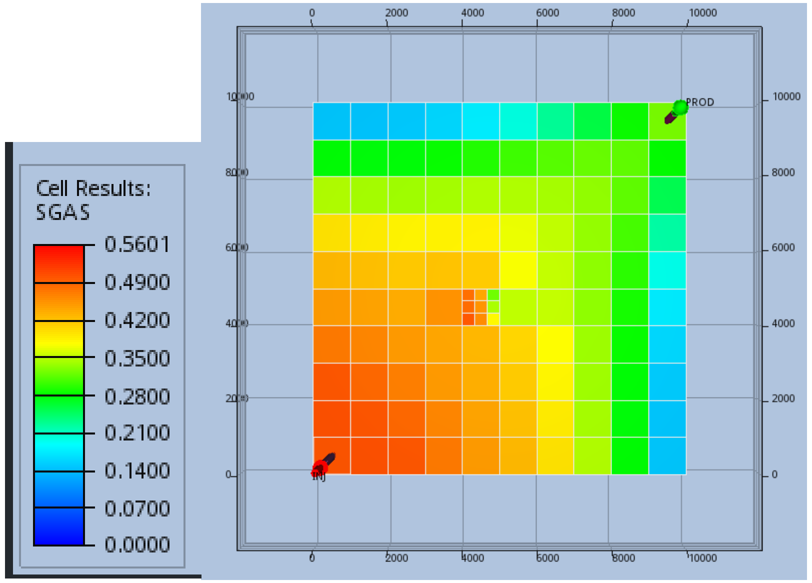
```
CARFIN
'LGR1' 5 5 5 5 1 3 3 3 3 /
PORO
0.15 0.25 0.35 6*0.4 9*0.3 9*0.45 /
PERMX
150 250 350 6*400 9*500 9*500 /

ENDFIN
```









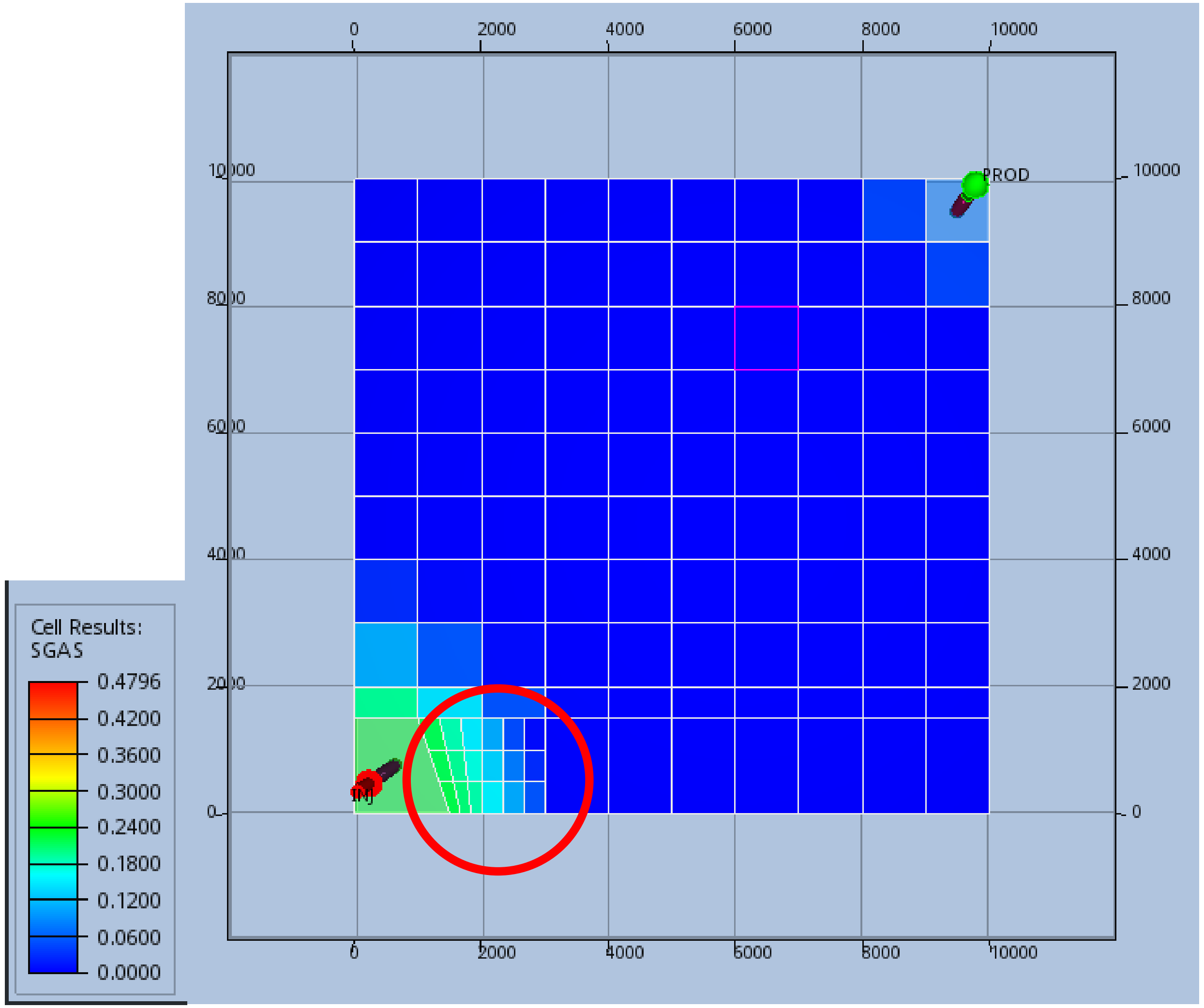


TNO innovation for life

SPECASE1 WITH LGR AND CPGRID
SKEWED PILLARS

- Refined grids are created by dividing global cell faces in equal parts
- Odd divisions not allowed

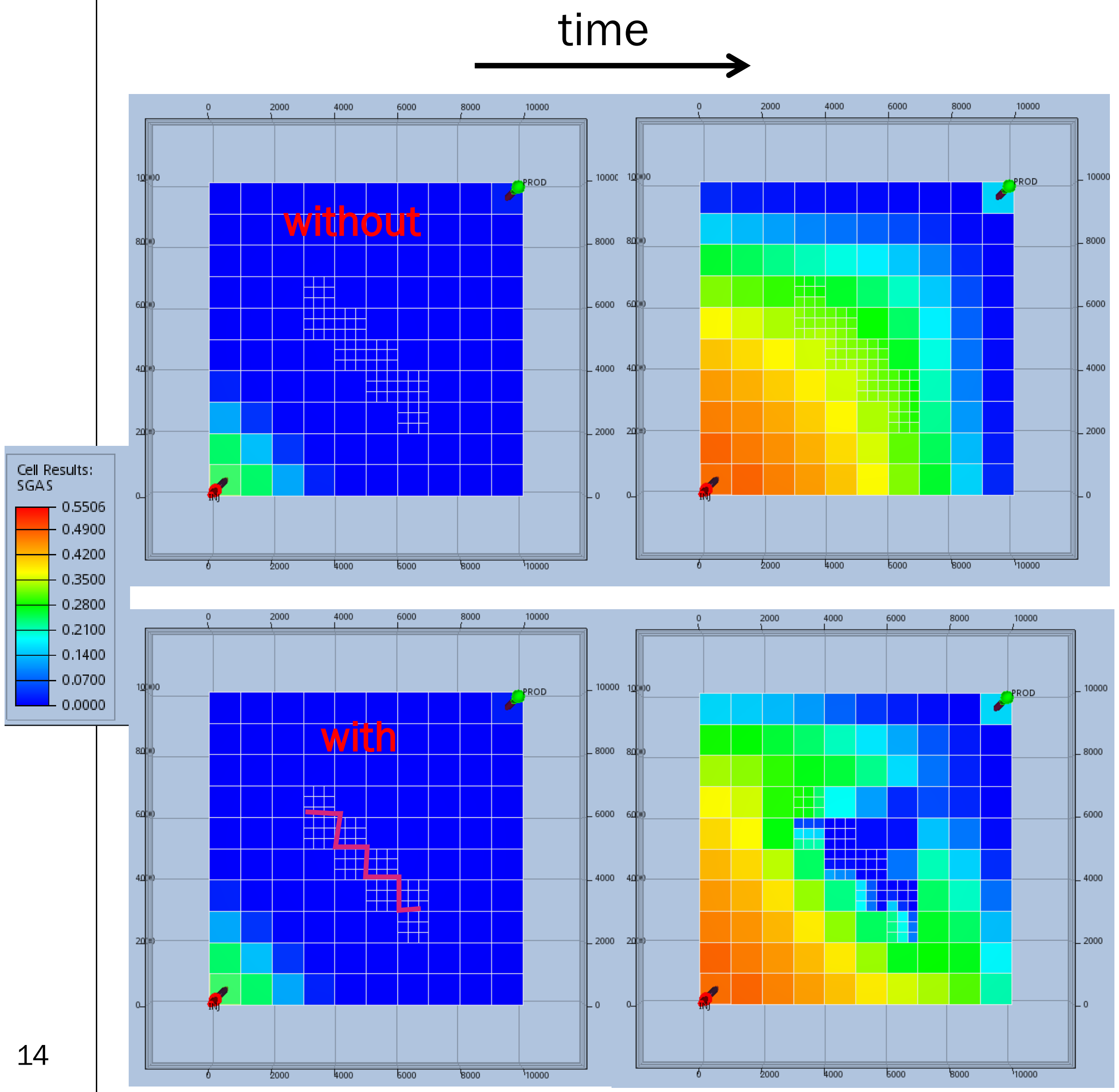
```
CARFIN
'LGR1' 2 3 1 1 1 1 6 3 1 /
ENDFIN
```

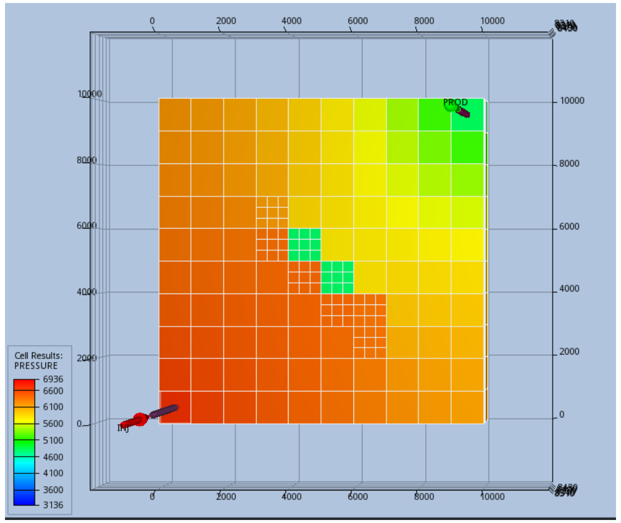


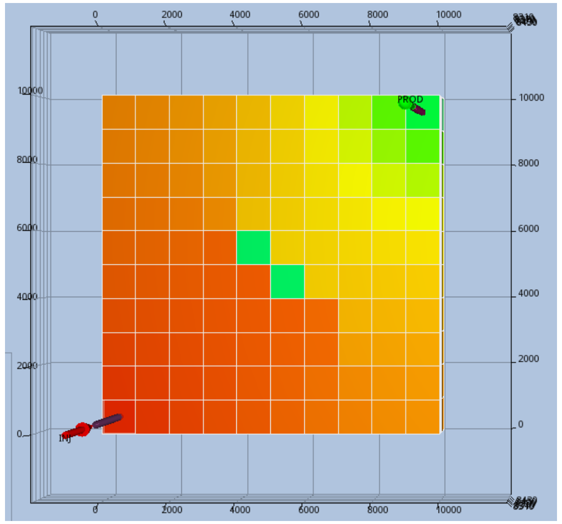
error	1/1/2015	0.0000000000000	FAULTS IS NOT VALID WITHIN A LOCAL GRID BETWEEN THE CARFIN/REFINE AND ENDFIN KEYWORDS. KEYWORD FAULTS CAN ONLY BE USED TO REFER TO THE GLOBAL GRID IN THIS VERSION OF ECLIPSE

SPECASE1 WITH LGR AND FAULTS

- What do we want for OPM-Flow?
  - Should faults be allowed to be in the refined grid?








```
CARFIN
'LGR0' 4 4 6 7 1 3 3 6 3 /
ENDFIN
CARFIN
'LGR1' 5 5 5 6 1 3 3 6 3 /
ENDFIN
CARFIN
'LGR2' 6 6 4 5 1 3 3 6 3 /
ENDFIN
CARFIN
'LGR3' 7 7 3 4 1 3 3 6 3 /
ENDFIN

AMALGAM
'LGR0' 'LGR1' 'LGR2' 'LGR3'/
/

FAULTS
-- IX1 IX2 IY1 IY2 IZ1 IZ2 FACE
'LGR'  4 4 6 7 1 3 x/
'LGR'  4 5 6 6 1 3 y/
'LGR'  5 5 5 6 1 3 x/
'LGR'  5 6 5 5 1 3 y/
'LGR'  6 6 4 5 1 3 x/
'LGR'  6 7 4 4 1 3 y/
'LGR'  7 7 3 4 1 3 x/
/

MULTFLT
-- Multiplier (no diffusion)
LGR 0/
/
```

WELL PLACEMENT

- In Eclipse, wells can only be located in a single grid:
  i.e., a well should be either in the global grid or in one LGR

```
WELSPECL

--   WELL   --  GROUP -- LOCAL GRID -- LOCATION --  BHP  -- PREF

--   NAME   --  NAME  --    NAME    --   I  J   -- DEPTH -- PHASE

    'HORIZ'     'G'        'LGR1'        1  3       8060    'OIL'  /

/
COMPDATL

-- WELL -- LOCAL --  LOCATION  --- OPEN - SAT - CONN - WELL - KH - S - D - PEN

-- NAME -- GRID  --  IX JY K1 K2 -- SHUT - TAB - FACT - DIAM -    -   -   - DRN

'HORIZ'  'LGR1'   1  3  3  3  'OPEN'  0    -1    0.4  3*             'X' /
'HORIZ'  'LGR1'   2  3  3  3  'OPEN'  0    -1    0.4  3*             'X' /

'HORIZ'  'LGR1'   3  3  3  3  'OPEN'  0    -1    0.4  3*             'X' /

'HORIZ'  'LGR1'   4  3  3  3  'OPEN'  0    -1    0.4  3*             'X' /

'HORIZ'  'LGR1'   5  3  3  3  'OPEN'  0    -1    0.4  3*             'X' /

/
```

<u>Multisegment wells</u>

Example

The following example defines the completions for two oil producing segment oil wells (OP01 and OP02) using the COMPSEGS keywords.

```
--       COMPLETION SEGMENT SPECIFICATION DATA
--
-- WELL
-- NAME
COMPSEGS
OP01                                                              /
--       LGR   --LOCATION--  BRAN  TUBING  NODAL   DIR  LOC    MID   COMP    ISEG
--       NAME  II   JJ  K1   NO    LENGTH  DEPTH   PEN  I,J,K  PERFS LENGTH
         LGR01 10   10   1    1    2512.5  2525.0                             /
         LGR01 10   10   2    1    2525.0  2550.0                             /
         LGR01 10   10   3    1    2550.0  2575.0                             /
         LGR01 10   10   4    1    2575.0  2600.0                             /
         LGR01 10   10   5    1    2600.0  2625.0                             /
         LGR01 10   10   6    1    2625.0  2650.0                             /

         LGR01  9   10   2    2    2637.5  2837.5                             /
         LGR01  8   10   2    2    2837.5  3037.5                             /
         LGR01  7   10   2    2    3037.5  3237.5                             /
         LGR01  6   10   2    2    3237.5  3437.5                             /
         LGR01  5   10   2    2    3437.5  3637.5                             /
/
```

Note that the COMPDATL keyword in the SCHEDULE section must also be defines for this well.

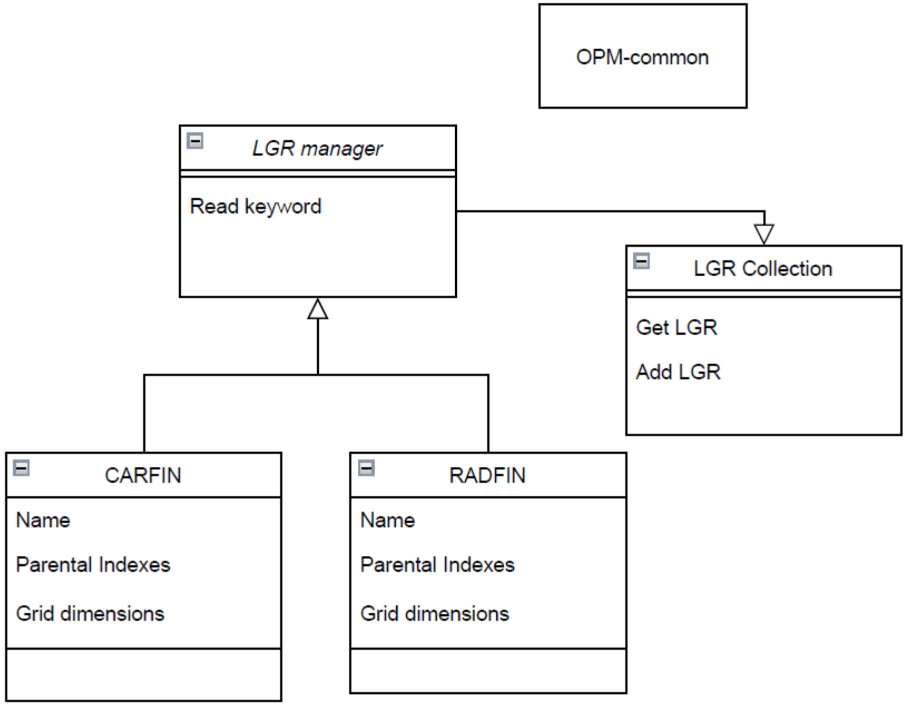
- What do we want for OPM-Flow?
  - Should wells be allowed to cross between grids?

LGR ACTIVITIES
CURRENT STATUS

- Literature and simulators reviewed: Eclipse, CMG, MRST, papers...
- Tests cases created and pushed to opm-tests
- Designing plan for code implementation to support the following aspects of LGR functionality (in cooperation with SINTEF and OPM-OP AS)
- Requires code changes in several repositories: opm-common, opm-grid and opm-simulators
- Challenges:
  - Allow wells to cross over grids (means solving the all the grid as one system?, different from Eclipse)
  - Output and restart of models with LGR
  - Extensive code refactoring in opm-grid needed

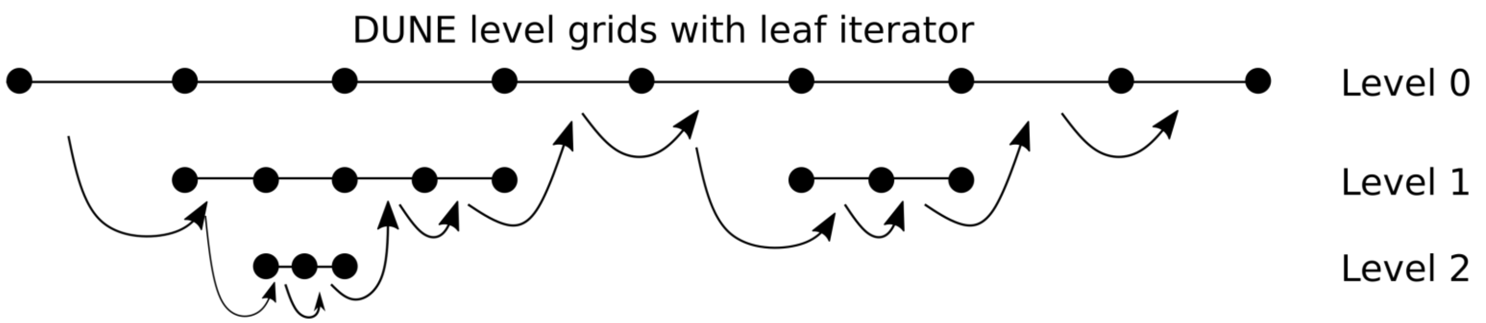
LGR EFFORT – ON-GOING ACTIVITIES

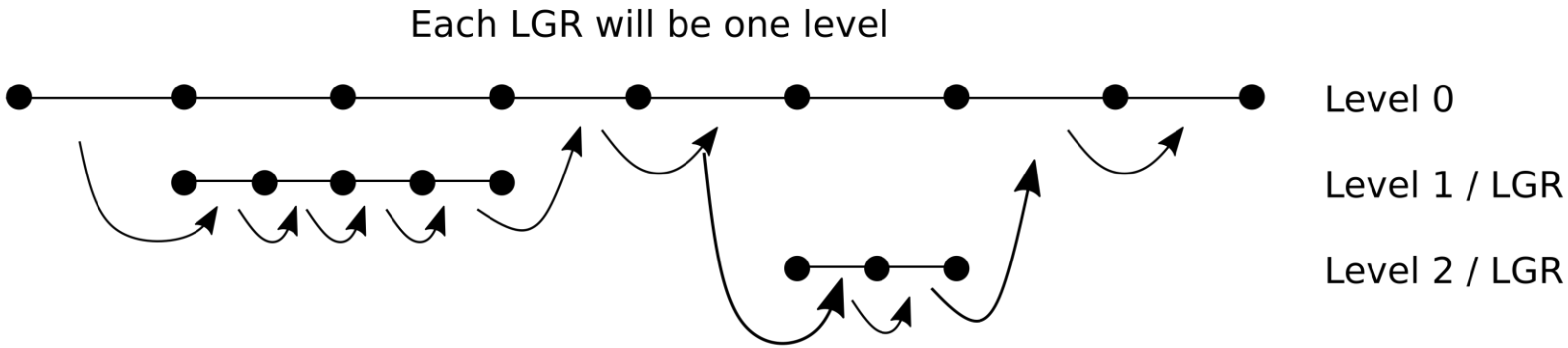
- Parsing under development in opm-common:
  - WIP PR submitted to read multiple CARFIN/ENDFIN blocks and store information in a collection of LGR's
  - Create field properties container for each LGR to be able to compute/store grid properties for each LGR
- PR merged in opm-grid to refine a geometry object in regular grid, returning a vector of the new geometry objects



LGR EFFORT – ON-GOING ACTIVITIES

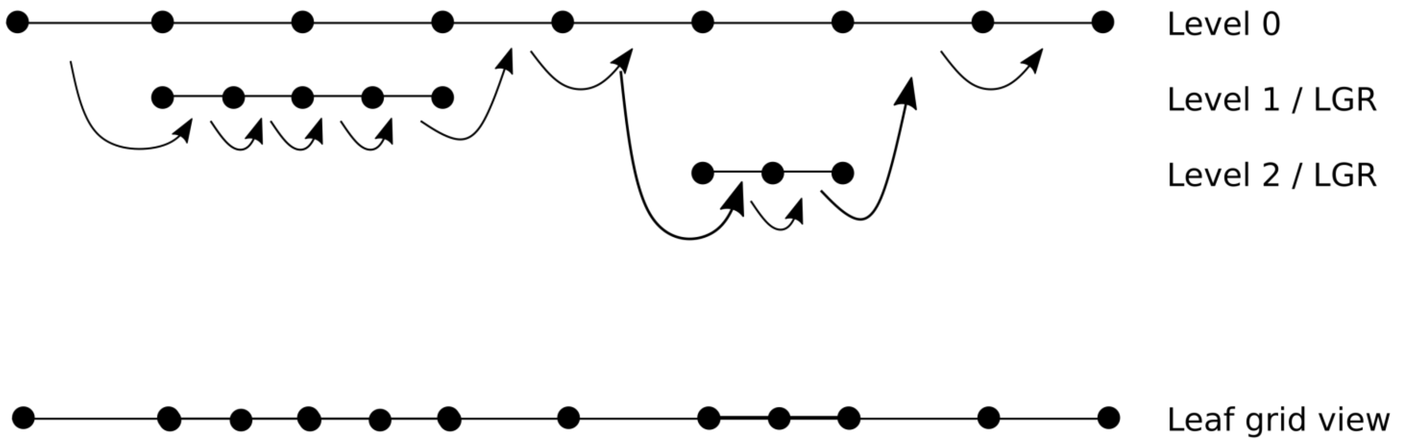
- Using DUNE's adaptive grid interface to store LGR
- No nested refined grids foreseen





LGR EFFORT – ON-GOING ACTIVITIES

- Changes to opm-grid:
  - Store multiple level grids in CpGrid
  - Identify Mother-Child relationships
  - Store/Compute/Iterate over leaf grid view



GRID-INDEPENDENT SPECIFICATION OF WELLS

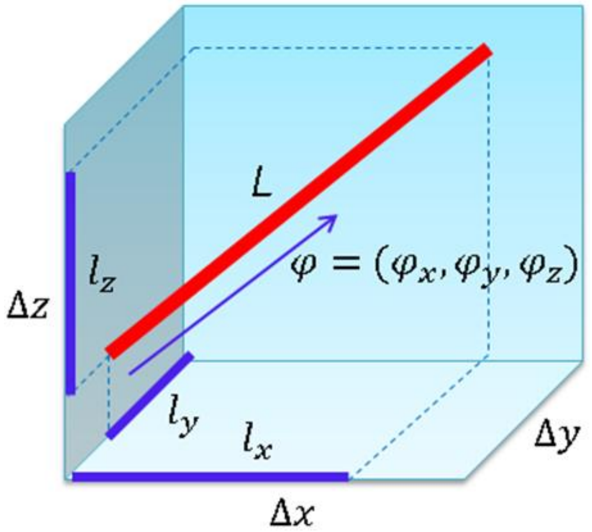
- Goal: Specification of **well geometry** and **perforations** independent of grid
- Geometrical description is relevant for:
  - Field cases with complex grids and deviated wells (grid-wise specification becomes cumbersome)
  - Optimization of well location and trajectories
  - Sensitivity Analysis studies with respect to grid
- Several simulators can handle geometric description of wells:
  - INTERSECT
  - tNavigator
  - MoReS

GRID INDEPENDENT SPECIFICATION OF WELLS

- Implemented input tables:
  - New OPM keywords

```
WELTRAJ
-- WELL X          Y            TVDEPTH     AHDEPTH
'PROD'  500000.0   6000000.0    -20.0       0.0 /
'PROD'  500000.0   6000000.0    2980.0      3000.0 /
'INJ'   400000.0   8000000.0    -20.0       0.0 /
'INJ'   400000.0   8000000.0    2980.0      2000.0 /
/

WELCOMPL
-- WELL      COMPLETION  AHDEPTH_UPPER   AHDEPTH_LOWER   DIAMETER    SKIN
  'PROD'     'P1'        2000.0          2500.0          0.2         1* /
  'INJ'      'I1'        2000.0          2500.0          0.2         1* /
/
```

- To do:
  - Trajectory transformation from map coordinates to grid coordinates
    - Derive the well-block indices
    - Derive well-length and projections
  - Projection method $CF = \sqrt{CF_x^2 + CF_y^2 + CF_z^2}$ (used by petrel)
  - Investigate (re-)use of code from ResInsight



SUMMARY

RECENT OPM DEVELOPMENTS BY TNO

- TNO has being working on several OPM developments
- Next months:
  - Work on LGR (in collaboration with SINTEF and OPM-OP AS) and grid-independent wells will continue
- What is next:
  - Extension to salt modelling
  - Collaboration for modelling of CO_2 storage in depleted gas fields

Contact at TNO: eduardo.barros@tno.nl / cintia.machado@tno.nl

THANK YOU!

TNO innovation for life