OPM Flow

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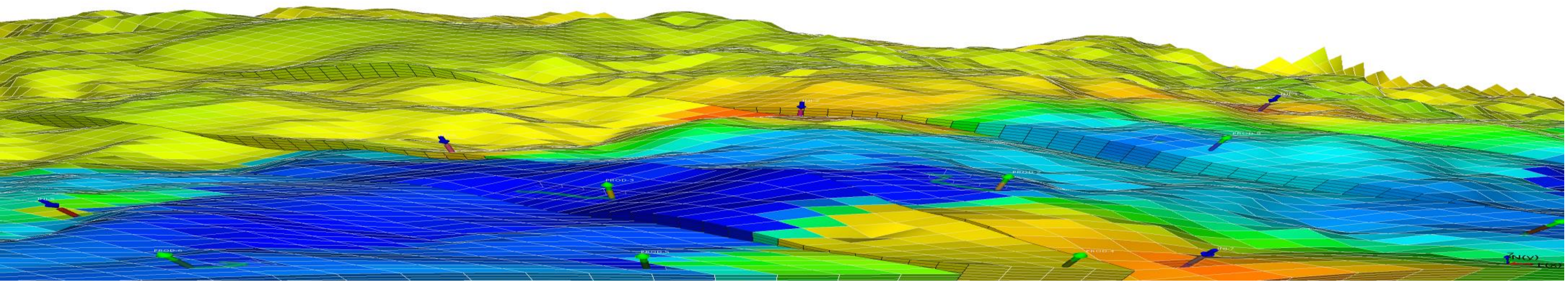
and Alf Birger Rustad

What is OPM Flow

OPM Flow is an **open source reservoir simulator** that is:

- developed collaboratively,
- in commercial use,
    - extensively tested on actual industrial reservoir problems,
    - compatible with de-facto industry standards,
    - well documented,
- extensible and supports multiple applications,
    - including CO_2 storage, geothermal, oil/gas
- implemented in modern C++,
- parallel and high-performance.

OPM-OP



Above:
main contributors to OPM

Left:
simulation of OLYMPUS field

User focused

- **Extensive user manual**
  - 2496 pages!
  - Documents input deck format, command line options, methods etc.
  - Continuously updated and expanded
- **Binary packages**
- **Ongoing effort to run more models out of the box**
  - Continuously adding new features
- **Ongoing effort to make error messages user friendlier**
- **Commercial support available**
  - Provided by SINTEF, NORCE, OPM-OP

O P M OPEN POROUS MEDIA

OPM Flow Reference Manual (2022-10) Revision: Rev-0

12.3.254 WCONPROD – Define Well Production Targets and Constraints

RUNSPEC	GRID	EDIT	PROPS	REGIONS	SOLUTION	SUMMARY	SCHEDULE

Description

The WCONPROD keyword defines production targets and constraints for wells that have previously been defined by the WELSPECS keyword in the SCHEDULE section. Note that wells can be allocated to a group when they are specified by the WELSPECS keyword. Wells defined to be under group control will have their production rates controlled by the group to which they belong, in addition to any well constraints defined for the wells using this keyword.

No.	Name	Description			Default
		Field	Metric	Laboratory	
1	WELNAME	A character string of up to eight characters in length that defines the well name for which the well production targets and constraints data are being defined. Note that the well name (WELNAME) must have been declared previously using the WELSPECS keyword in the SCHEDULE section, otherwise an error may occur.			None
2	STATUS	A defined character string that declares the status of the well. STATUS should be set to one of the following character strings: 1) OPEN: the well is open to flow and will attempt to produce the required production volumes. 2) STOP: the well is "stopped" at the surface and will not produce any fluids to surface; however, if there any open connections then flow may occur within the wellbore and between the open connections depending on a connection's potential with respect to all the other connections. Inter-connection flow (cross flow) can be prevented by setting the XFLOW variable on the WELSPECS keyword to NO. In this case the well's behavior will be similar to the SHUT option described below. 3) SHUT: the well is shut at the surface and downhole, this results in no flow at the surface and no cross flow downhole. 4) AUTO: the well is initially SHUT, but may be opened automatically if an economic limit is violated. This option is currently not supported by OPM Flow. Note a well's STATUS should always be set either STOP or SHUT if the well's production is to be set to zero. Just setting a well's production rate to zero means that the well is open to flow with a zero rate, this will cause numerical issues especially for wells under THP control.			OPEN

A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

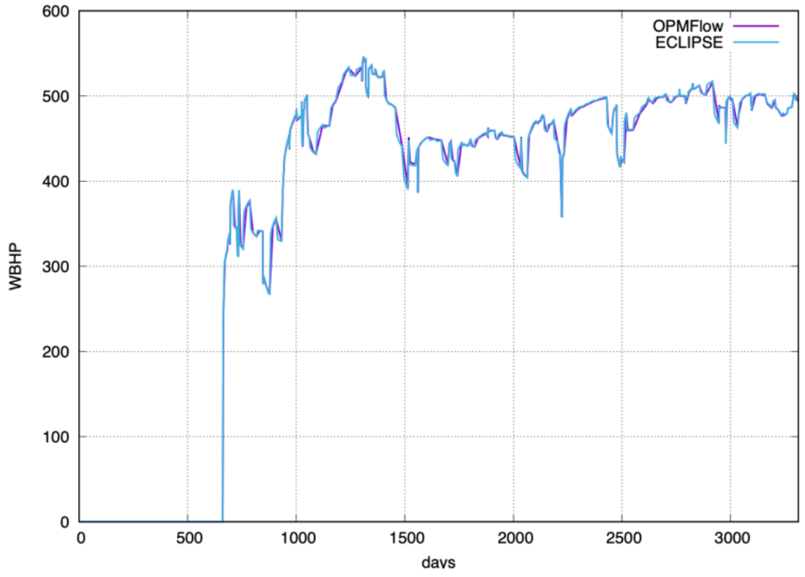
Right: a page from the OPM Flow manual

Below: a typical error message

```
Error: Problem with keyword WELTARG
In PUNQS3_MODIFIED.DATA line 863
No wells/groups match the pattern: 'DONTEXIST'
```

Compatibility

- Workflow compatibility with de facto industry standards
  - Supports Eclipse input deck format
  - Hundreds of keywords/features
  - Supports Eclipse Output formats, restart compatible
- Results closely match commercial simulators



Left: Well BHP curves showing close match between ECLIPSE and OPM Flow

Rigth: Example ECLIPSE-compatible deck input

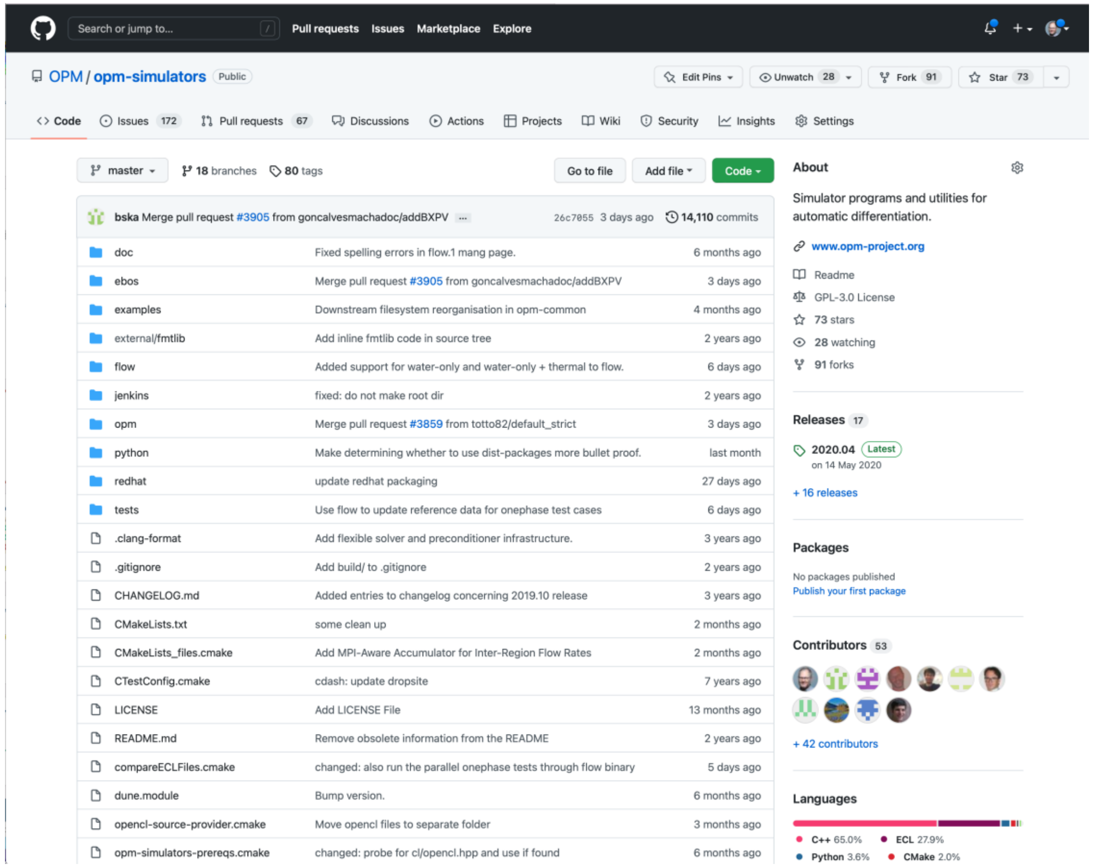
```
INCLUDE
'./INCLUDE/PVT/PVT-WET-GAS.INC' /

TRACER
SEA  WAT  /
HTO  WAT  /
S36  WAT  /
2FB  WAT  /
4FB  WAT  /
DFB  WAT  /
TFB  WAT  /
/

-- initial water saturation
INCLUDE
'./INCLUDE/PETRO/SWINITIAL.INC' /

-- relative perm.
INCLUDE
'./INCLUDE/RELPERM/SCAL_NORNE.INC' /

SCALECRS
YES /

-- endpoints may be used as tuning papameters
EQUALS
SWL 0.04 1 46 1 112 1  1   /
SWL 0.05 1 46 1 112 2  2   /
SWL 0.15 1 46 1 112 3  3   /
SWL 0.15 1 46 1 112 4  4   /
SWL 0.05 1 46 1 112 5  10  / Ile 2.2.2 and Ile 2.
SWL 0.16 1 46 1 112 11 12  / ile 1.1 and tofte 2.
SWL 0.07 1 46 1 112 13 15  / tofte 2.1
SWL 0.06 1 46 1 112 16 16  / tofte 1.2.2
SWL 0.12 1 46 1 112 17 22  / Tofte 1.2.1, Tofte 1.
/

COPY
  SWL SWCR /
  SWL SGU  /
/


ADD
SWCR   0.08  1 46 1 112 1 22  /
/

-- SGU = 1 - SWL
MULTIPLY
SGU  -1  1 46 1 112 1 22  /
/

ADD
SGU   1  1 46 1 112 1 22  /
/

EQUALS
SGL   0.0  1 46 1 112 1 22  /
SGCR  0.03 1 46 1 112 1 22  /
```

Open development

- Open source: all software available on GitHub
- Open development model:
  - Contributions welcome
  - No private, secret or proprietary parts
  - Distributed ownership
  - Multiple maintainers with right to merge
- Open test case suite
- License: GNU General Public License version 3

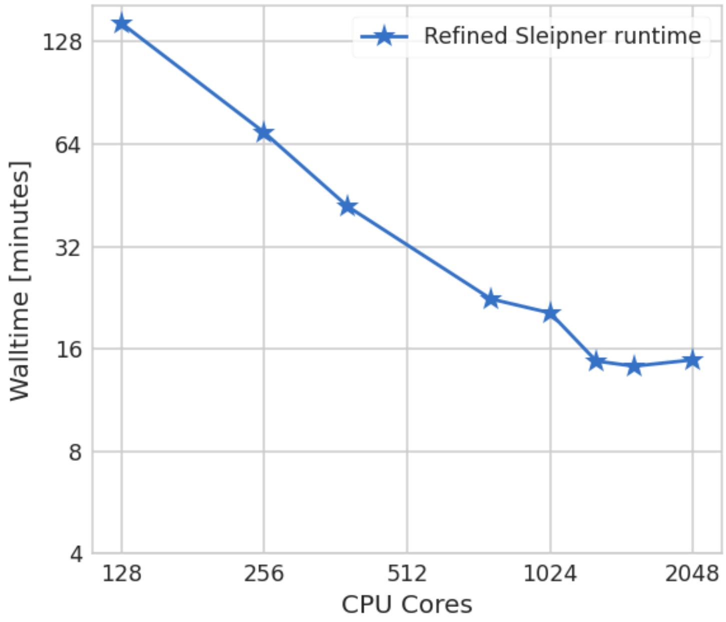
Collaboration

Innovation



Performant and extensible

- Based on Automatic Differentiation (AD)
- High-performance implementation in C++
- Parallel (MPI and openMP)
- Flexible and extensible to new flow physics
- Examples: CO_2 storage, solvent model, foam model, polymer injection, geothermal.



Above: Scalability test on 18M cell CO2 storage case (Karolina cluster)

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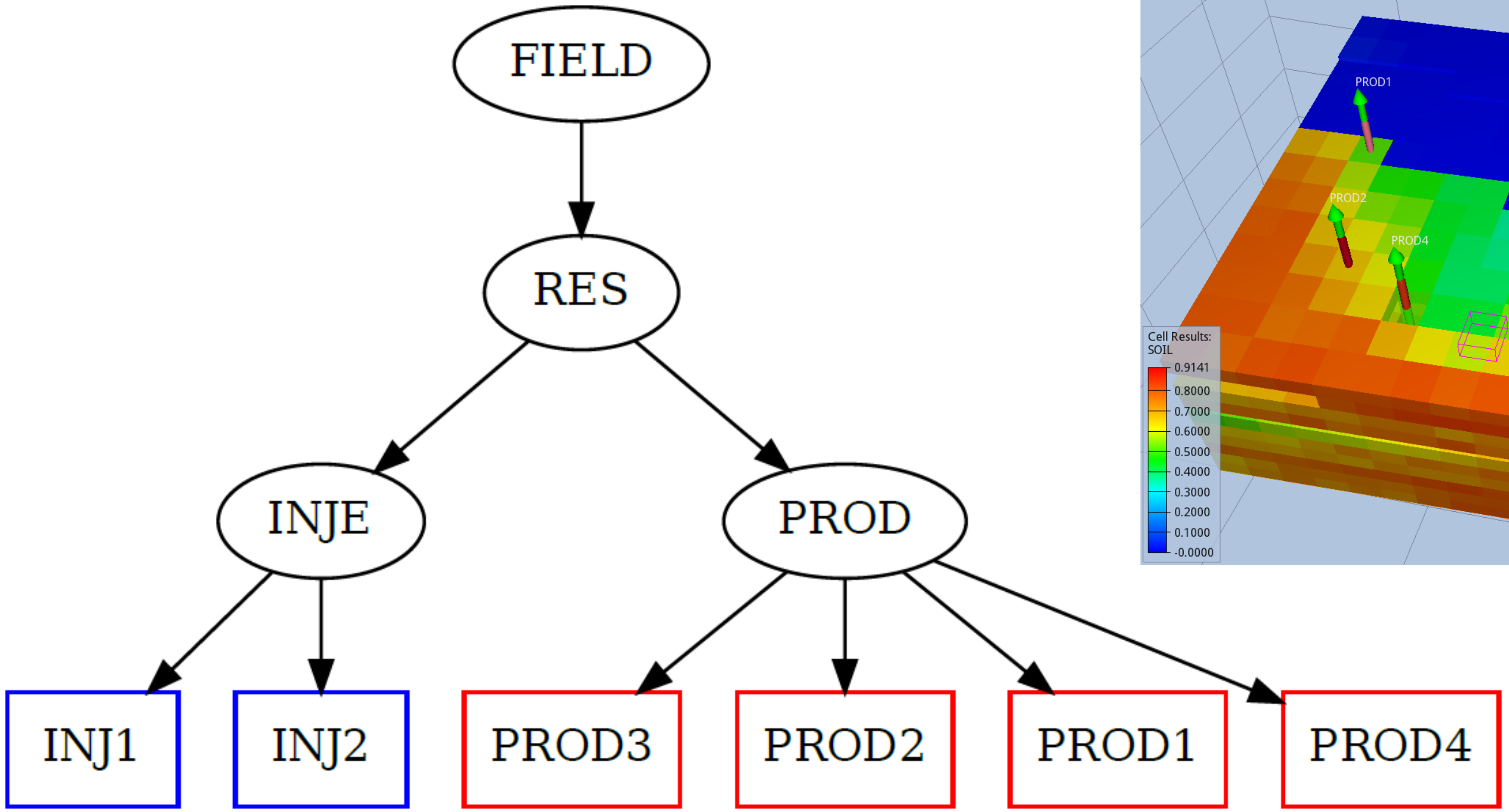
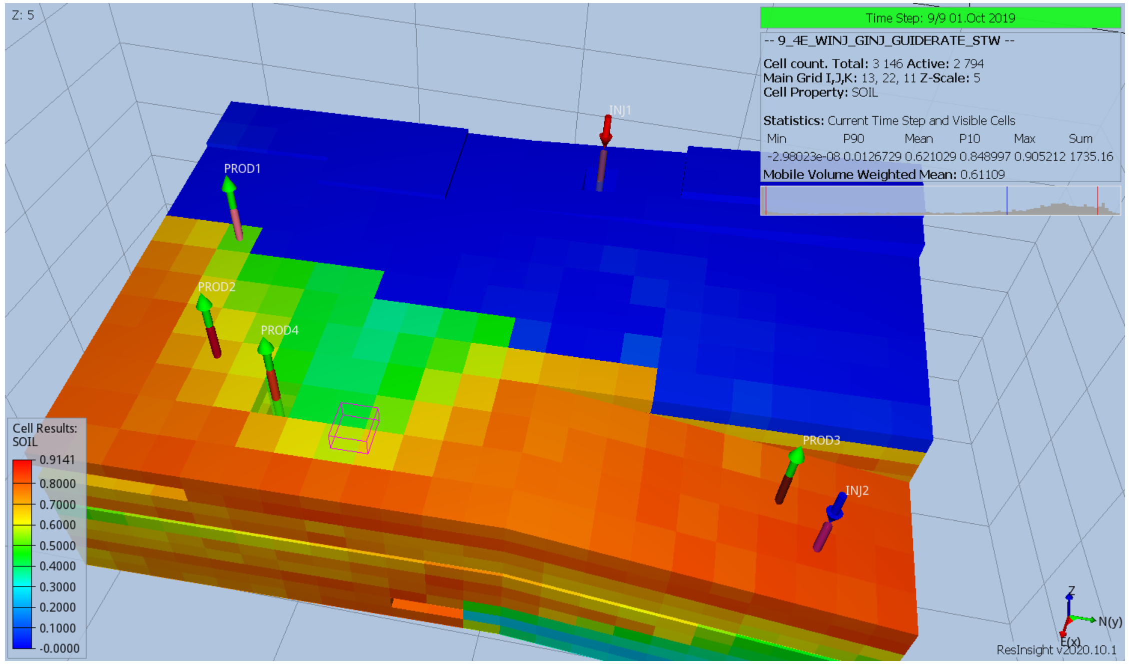
ACROSS
HPC Big DAta ArtifiCial intelligence cross Stack PlatfoRm TOwardS ExaScale

Examples

- Blackoil case with group-controlled wells
- CO_2 injection in aquifers

Black-oil case with group-controlled wells





9_4E_WINJ_GINJ_GUIDERATE.DATA

12.3.88 GCONPROD – Group Production Targets and Constraints

RUNSPEC	GRID	EDIT	PROPS	REGIONS	SOLUTION	SUMMARY	SCHEDULE

Description

The GCONPROD keyword defines production targets and constraints for groups, including the top most group in the group hierarchy known as the FIELD group. Wells are allocated to groups when the wells are specified by the WELSPECS keyword in the SCHEDULE section. Wells defined to be under group control will have their production rates controlled by the group to which they belong, in addition to any well constraints defined for the wells.

No.	Name	Description			Default
		Field	Metric	Laboratory	
1	GRPNAME	A character string of up to eight characters in length that defines the group name for which the group target and constraints are being defined. The group named FIELD is the top most group and should be used to set targets and constraints for the field. Note that the group hierarchy should be defined by the GRUPTREE keyword in the SCHEDULE section, when there is more than one level of groups, otherwise all the groups will sit directly under the FIELD group in the group tree hierarchy.			None
2	TARGET	A defined character string that sets the target production phase for the group, all the other phases will therefore act as constraints. The simulator will attempt to meet the TARGET based on the phase rate stated in items (3) to (6) on this keyword. TARGET should be set to one of the following character strings: 1) NONE: the group has no target phase, but if entered, constraints are still defined and active. 2) FLD: this group is controlled from a higher level group, including the FIELD group. 3) ORAT: the target is set to the surface oil production rate as defined by item (3). 4) WRAT: the target is set to the surface water production rate as defined by item (4). 5) GRAT: the target is set to the surface gas production rate as defined by item (5). 6) LRAT: the target is set to the surface liquid (oil plus water) production rate as defined by item (6). 7) RESV: the target is set to the in situ reservoir volume rate as defined by item (14). All other options are not supported by OPM Flow.			None
3	ORAT	A real positive value that defines the maximum surface oil production rate target or constraint.			
		stb/d	sm^3/day	scc/hour	None
4	WRAT	A real positive value that defines the maximum surface water production rate target or constraint.			
		stb/d	sm^3/day	scc/hour	None
5	GRAT	A real positive value that defines the maximum surface gas production rate target or constraint.			
		Mscf/d	sm^3/day	scc/hour	None
6	LRAT	A real positive value that defines the maximum surface liquid (oil plus water) production rate target or constraint.			
		stb/d	sm^3/day	scc/hour	None
7	ACTION	A defined character string that defines the action to be taken if the constraints in (3) to (6) are violated. ACTION should be set to one of the following character strings: 1) NONE: no action is taken. 2) CON: close the worst offending connection in the worst offending well. If connections have been grouped as completions then the worst offending completion in the worst offending well will be closed. 3) +CON: close the worst offending connection and all below it in the worst offending well. If connections have been grouped as completions then the worst offending completion and all below it in the worst offending well will be closed. 4) WELL: close the worst offending well. 5) PLUG: plug back the worst offending well. This option is not implemented in OPM Flow. 6) RATE: control the group production rate to equal the upper limit. This effectively changes the TARGET to be the violated phase constraint. The corrective action takes places at the end of the time step in which the constraint is violated.			None
8	GRPCNTL	A defined character string that determines if this group is subject to higher level group control. 1) YES: then this group is subject to a higher level group's control and the flow rates for this group will be adjusted accordingly. 2) NO: then this group is NOT subject to a higher level group's control and the flow rates for this group will only be control by the parameters for this group. GRPCNTL will be ignored for the FIELD group.			None
9	GRPGUIDE	A real positive value that defines a group's production guide rate expressed as a dimensionless number. A group requires a value for GRPGUIDE only if it is required to produce a specified proportion of a higher level group's rate			
		dimensionless	dimensionless	dimensionless	None

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OPM Flow Reference Manual (2022-10) Revision: Rev-0

12.3.86 GCONINJE – Group Injection Targets and Constraints

RUNSPEC	GRID	EDIT	PROPS	REGIONS	SOLUTION	SUMMARY	SCHEDULE

Description

The GCONINJE keyword defines injection targets and constraints for groups, including the top most group in the group hierarchy known as the FIELD group. Wells are allocated to groups when the wells are specified by the WELSPECS keyword in the SCHEDULE section. Wells defined to be under group control will have their injection rates controlled by the group to which they belong, in addition to any well constraints defined for the wells.

No.	Name	Description			Default
		Field	Metric	Laboratory	
1	GRPNAME	A character string of up to eight characters in length that defines the group name for which the group target and constraints are being defined. The group named FIELD is the top most group and should be used to set targets and constraints for the whole field. Note that the group hierarchy should be defined by the GRUPTREE keyword in the SCHEDULE, when there is more than one level of groups, otherwise all the groups will sit directly under the FIELD group in the group tree hierarchy.			None
2	TYPE	A defined character string that defines the type of injection fluid. TYPE should be set to one of the following character strings: 1) GAS: for a gas injection well. 2) OIL: for a water injection well. 3) WAT: for a water injection well.			None
3	TARGET	A defined character string that sets the target injection control for the group, all the other phases will therefore act as constraints. The simulator will attempt to meet the TARGET based on the phase rate stated in items (4) to (7) on this keyword. TARGET should be set to one of the following character strings: 1) NONE: the group has no target phase, but if entered, constraints are still defined and active. 2) FLD: this group is controlled from a higher level group, including the FIELD group. 3) RATE: the injection phase will be control by the surface fluid rate for the phase defined by the TYPE variable. For example, if TYPE has been set to WAT then this would mean the water injection rate as defined by item (4). 4) RESV: the target is set to the in situ reservoir volume rate as defined by item (5). 5) REIN: the target is set to groups production of the phase defined by TYPE multiplied by the value on item (6). For example, if TYPE has been set to WAT then this would mean the groups water production multiplied by item (6). 6) VREP: the target is set to the groups voidage replacement ratio as defined by item (7).			None

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No.	Name	Description			Default
		Field	Metric	Laboratory	
4	RATE	A real positive value that defines the maximum surface injection rate target or constraint for the phase declared by the TYPE variable.			
		Liquid stb/d Gas Mscf/d	Liquid sm^3/day Gas sm^3/day	Liquid scc/hour Gas scc/hour	None
5	RESV	A real positive value that defines the maximum reservoir volume injection rate target or constraint. Note setting a value here other than the default means that TYPE, item (2) will be the supplement or "make up" phase.			
		rtb/d	rm^3/day	rcc/hour	None
6	REIN	A real positive value that defines the target or constraint re-injection fraction for the produced phase defined by the TYPE variable. For example, if TYPE is equal to GAS and REINJ is equal to 0.85, then 85% of the produced gas will be re-injected.			
		dimensionless	dimensionless	dimensionless	None
7	VREP	A real positive value that defines the target or constraint of the voidage replacement ratio based on all the produced fluids. For example, if TYPE is equal to WAT and VREP is equal to 1.00, then 100% of the produced reservoir volume will be re-inject as an equivalent water volume. Note setting a value here other than the default means that TYPE, item (2) will be the supplement phase.			
		dimensionless	dimensionless	dimensionless	None
8	GRPCNTL	A defined character string that determines if this group is subject to higher level group control. 1) YES: then this group is subject to a higher level group's control and the flow rates for this group will be adjusted accordingly. 2) NO: then this group is NOT subject to a higher level group's control and the flow rates for this group will only be control by the parameters for this group. This variable is ignored if GRPNAME is equal to FIELD.			YES
9	GRPGUIDE	A real positive value that defines a group's injection guide rate expressed as a dimensionless number. A group requires a value for GRPGUIDE only if it is required to produce a specified proportion of a higher level group's rate. Defaulting GRPGUIDE results in the subordinate groups and wells under guide control having their rates dictating by any higher level groups under guide rate control. In other words the GRPNAME is masked out. Setting GRPGUIDE to a real positive value and GUIPHASE to either RATE or RESV will result in a constant injection guide rate.			
		dimensionless	dimensionless	dimensionless	None

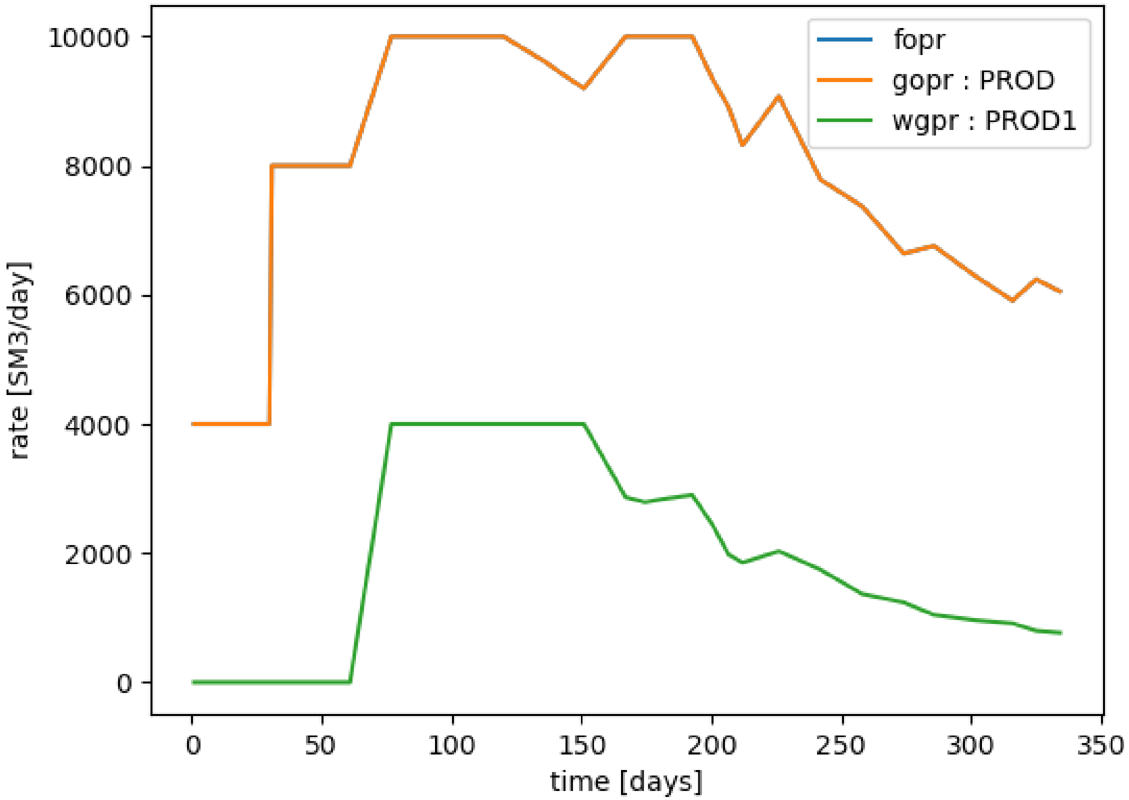
Python.

OPEN POROUS MEDIA

```python
from opm.io.ecl import ESmry
from matplotlib import pyplot as plt

casename = "9_4E_WINJ_GINJ_GUIDERATE_STW"
smry = ESmry(casename + ".SMSPEC")

fopr = smry["FOPR"]
gopr = smry["GOPR:PROD"]
wopr = smry["WOPR:PROD1"]
days = smry["TIME"]
plt.plot(days, fopr, label="fopr")
plt.plot(days, gopr, label="gopr : PROD")
plt.plot(days, wopr, label="wgpr : PROD1")
plt.ylabel('rate [SM3/day]')
plt.xlabel('time [days]')
plt.legend()
plt.savefig('rates.png')
```



CO2STORE

Brine-CO2 fluid system

- PVT and solubility computed internally as function of temperature, pressure, composition and salinity using standard models found in the literature.
- Pre-computed tables for CO2 density and enthalpy based on Span-Wagner.
- Converted to a black-oil formulation internally
- *DISGAS: Dissolved CO2 in Brine*
- *THERMAL: Dynamic temperature*
- *DIFFUSE: Diffusion*
- *DRSDTCON*: Upscaled convective dissolution rate control*

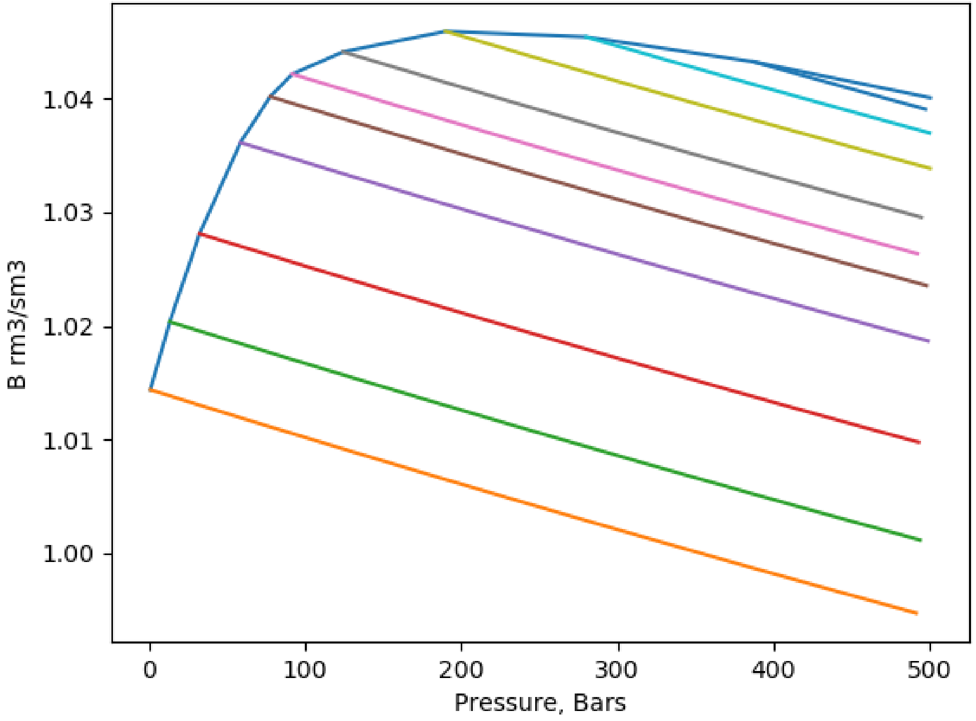
CO2STORE: CO2-Brine properties

Density	Brine	Water	Hu, J., Duan, Z., Zhu, C., & Chou, I. M. (2007), Wagner, W., & Pruß, A. (2002).
		Salinity	Batzle, M., & Wang, Z. (1992).
		Dissolved CO2	Garcia, J. E. (2001).
	CO2		Span, R., & Wagner, W. (1996)
Viscosity	Brine		Batzle, M., & Wang, Z. (1992).
	CO2		Fenghour, A., Wakeham, W. A., & Vesovic, V. (1998).
Solubility			Spycher, N., Pruess, K., & Ennis-King, J. (2003). Duan, Z., & Sun, R. (2003)
Enthalpy	Brine	Water	Wagner, W., & Kruse, A. (2013).
		Salinity	Daubert, T. E., Daubert, T. E., & Danner, R. P. (1989)
		Dissolved CO2	Duan, Z., & Sun, R. (2003)
	CO2		Span, R., & Wagner, W. (1996).

Diffusivity	Water	McLachlan, C. N. S., & Danckwerts, P. V. (1972).
	Salinity	Ratcliff, G. A., & Holdcroft, J. G. (1963)
	Tortuosity	Millington, R. J., & Quirk, J. P. (1961).

* Sandve, T. H., Gasda, S. E., Rasmussen, A., & Rustad, A. B. (2021). Convective Dissolution in Field Scale Co2 Storage Simulations Using the OPM Flow Simulator. In *TCCS–11. CO2 Capture, Transport and Storage. Trondheim 22nd–23rd June 2021 Short Papers from the 11th International Trondheim CCS Conference*. SINTEF Academic Press.

CO2STORE



opm-common/example

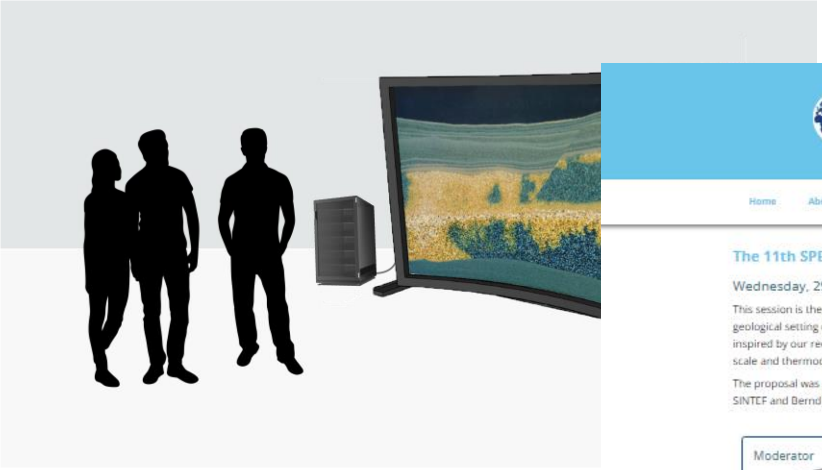
Usage: co2brinepvt <prop> <phase> <p> <T> <salinity> <rs>

Example: co2brinepvt B brine 200 329.15 0.4 0.0

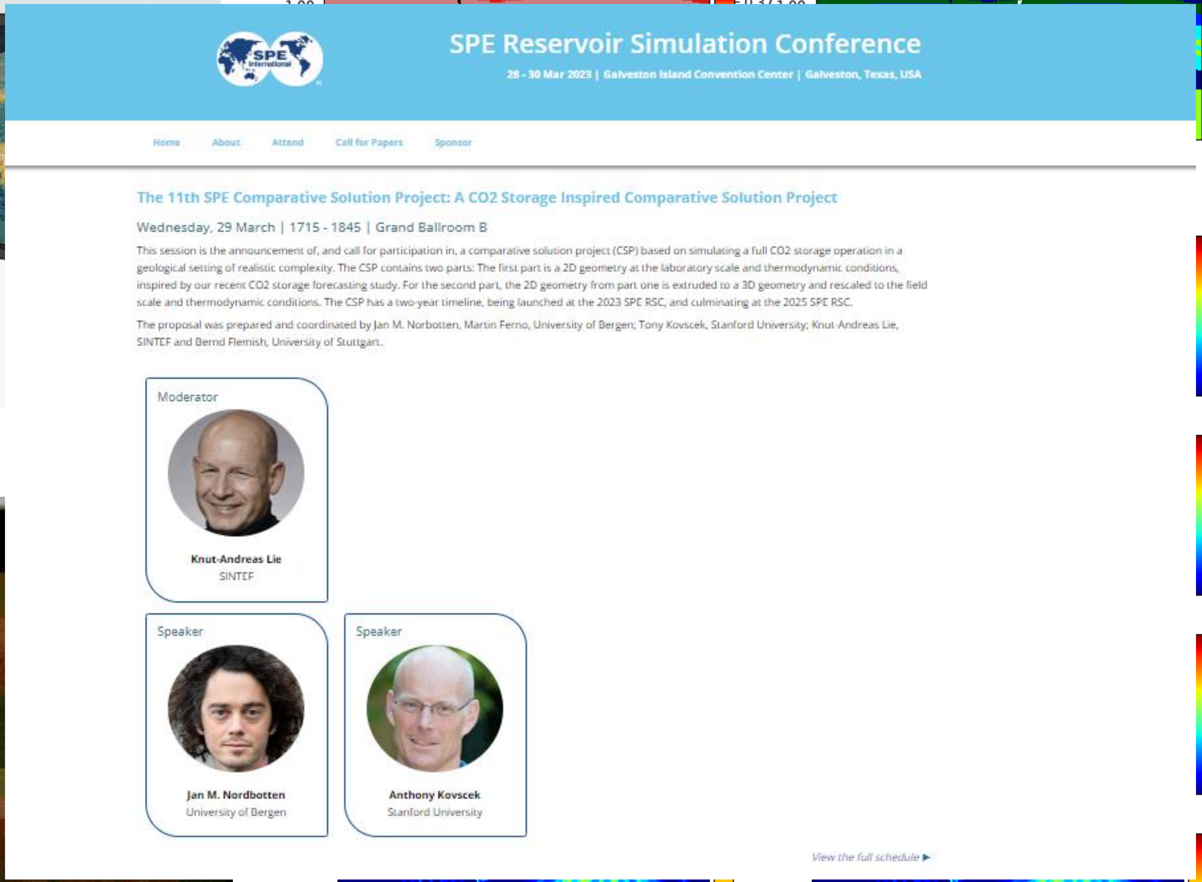
CO2STORE

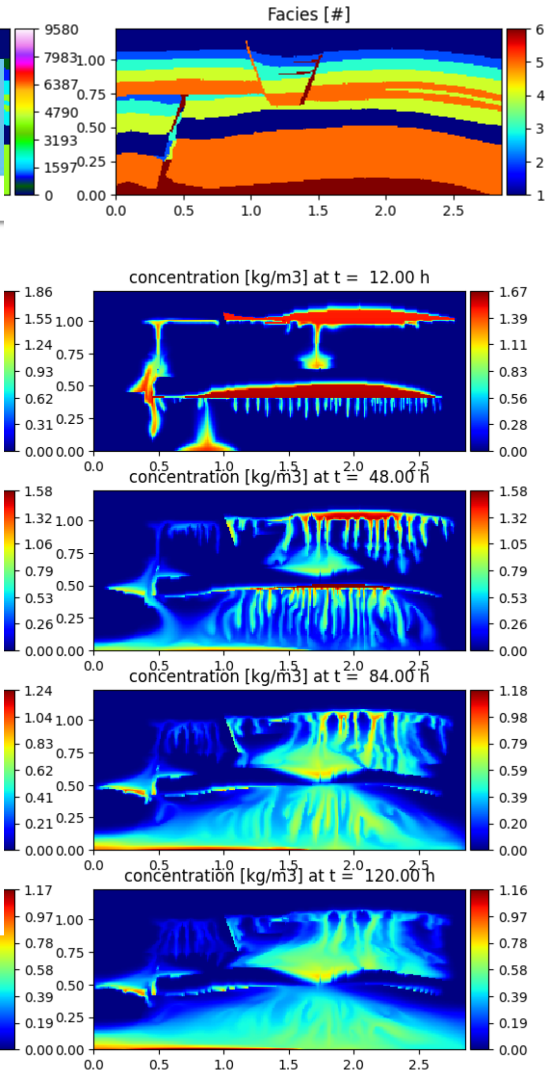
https://github.com/OPM/opm-tests/blob/master/co2store/

CO2STORE

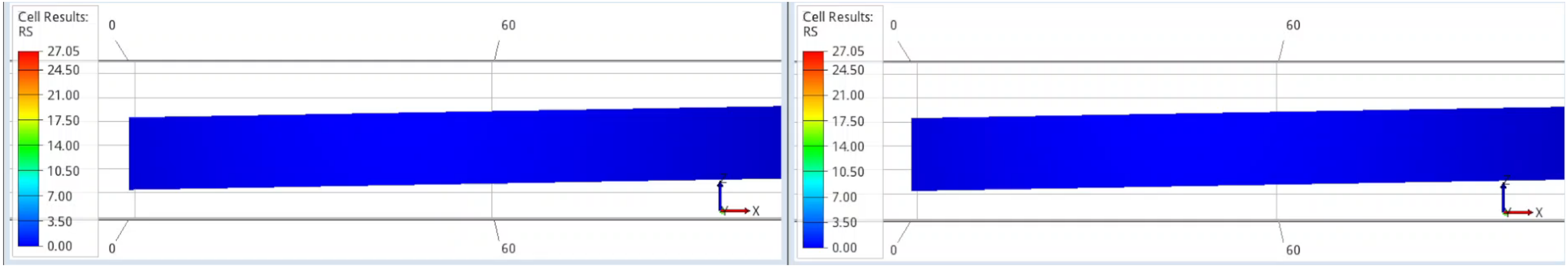


https://fluidflower.w.uib.no/

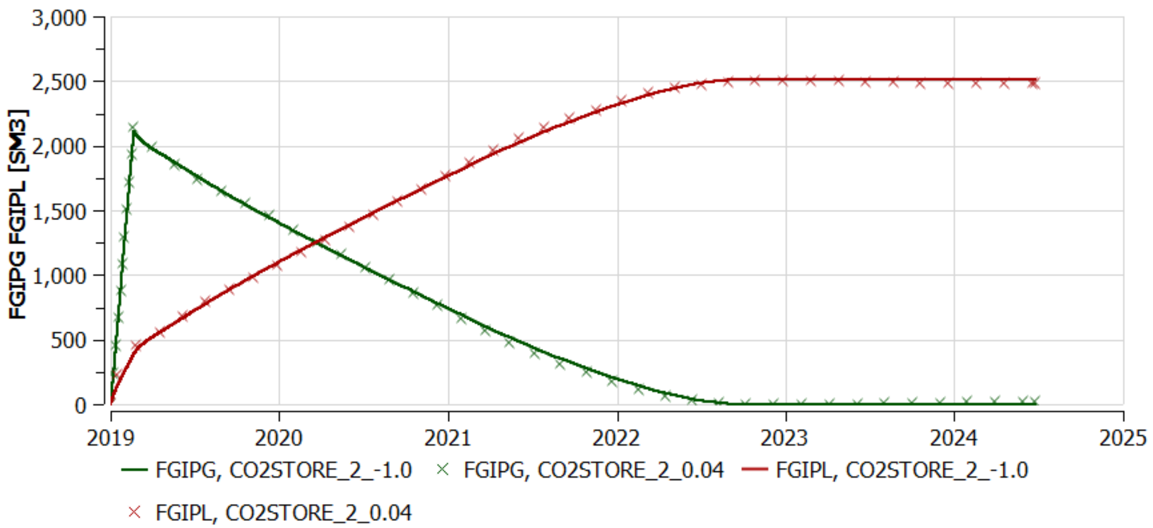




CO2STORE



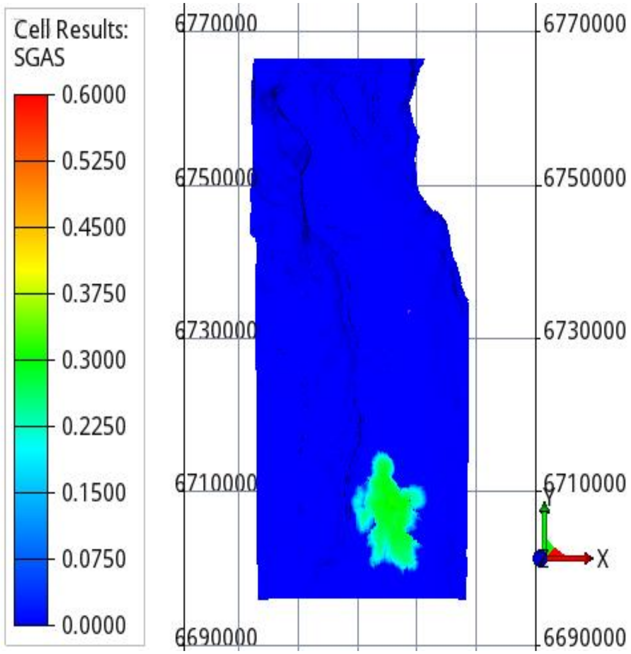
Upscaled convective mixing



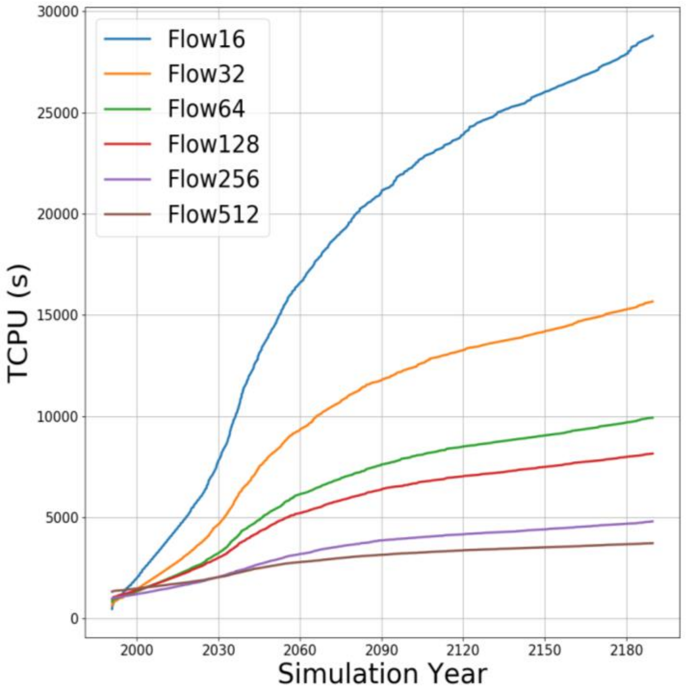
* Trine Mykkeltvedt, Tor Harald Sandve, Sarah Gasda (2023)
UPSCALING CONVECTIVE MIXING IN RESERVOIR SIMULATION
Submitted to *TCCS–12.*

CO2STORE

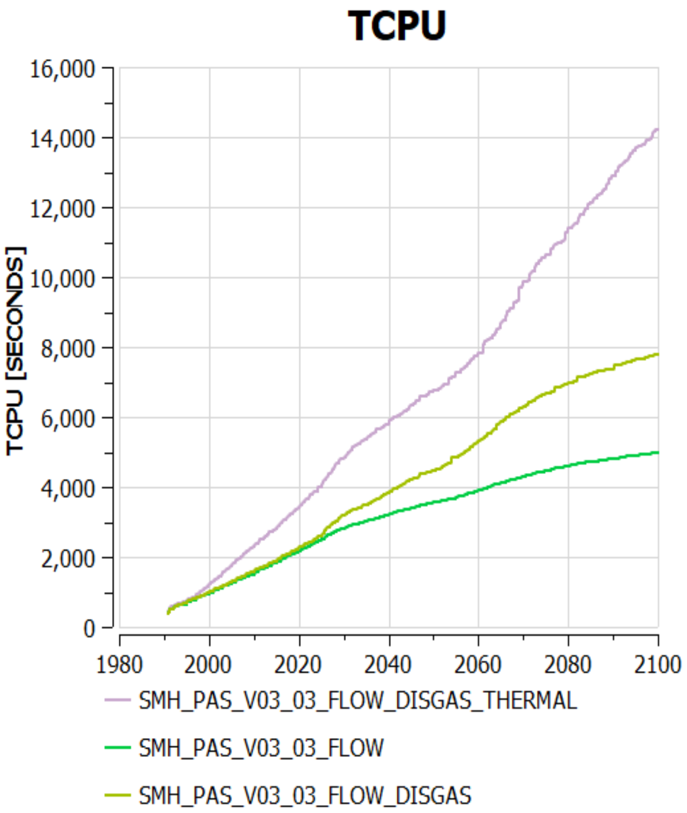
- Model created by CO2 storage team in Equinor for testing.
- 9 million active cells



Simulation results in 2100



Simula eX^3 HPC infrastructure



Runtime with 64 processes

Sandve, T. H., Rustad, A. B., Thune, A., Nazarian, B., Gasda, S., & Rasmussen, A. F. (2022, April). Simulators for the Gigaton Storage Challenge. A Benchmark Study on the Regional Smeaheia Model. In *EAGE GeoTech 2022 Sixth EAGE Workshop on CO2 Geological Storage* (Vol. 2022, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.

OPM is more than Flow

- https://github.com/OPM
- https://opm-project.org/

Summary/Questions

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What is the main purpose of your framework and what makes it unique?

- Bridge the gap between research and industry.
- Drop-in replacement in industrial workflows.
- Close collaboration with industry.

What is your targeted users?

- Reservoir engineers in small and large companies,
- Researchers and students.
  - "blackbox" users
  - researchers that want to test new methods and models.

Summary/Questions

Why have you decided to make it open source?

- Faster transition from research to industrial usage.
- Easier to collaborate.
- Visibility.
- Enables funding.
- Personal motivation.
- Transparency.
- Reproducibility.
- Increase life-span of the code.

Summary/Questions

OPM OPEN POROUS MEDIA

What was your original ambitions and how (if) they changed with time?

- Create open-source code that can both be used by industry and researchers.
- Framework to test methods on industry relevant problems.
- Avoid licensing issues for ensemble simulations.

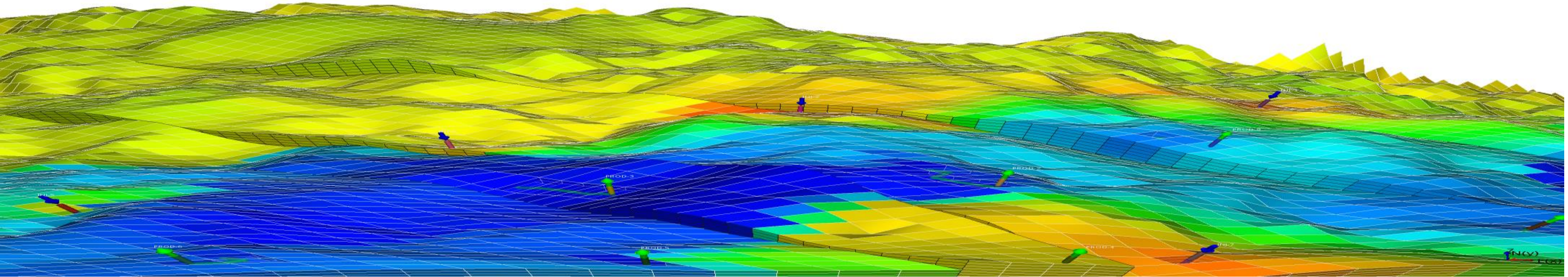
How do you see your framework in 5 and 10 years?

- In wide industrial use for hydrocarbon extraction and CO2 storage.
- State-of-the-art methods and models beyond what commercial simulators offer.
- Well established community code. (10 years)

OPM Flow

OPM Flow is an **open source reservoir simulator** that is:

- developed collaboratively,
- in commercial use,
- extensible and supports multiple applications,
- implemented in modern C++,
- parallel and high-performance.



Above:
main contributors to OPM

Left:
simulation of OLYMPUS field