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1. Table of Contents for J_ecl.ppt (Eclipse' Well-Connection Factor)
2. Preface and Introduction
3. J_ecl_R.xls
4. Well Inflow Performance & Connection Factor
5. Cartesian Connection Transmissibility Factor
6. Radial Connection Transmissibility Factor
7. COMPDAT Keyword (items 1 to 6)
8. COMPDAT Keyword, (items 7 to 8)
9. COMPDAT Keyword, (item 8 continued to item 10)
10. COMPDAT Keyword, (items 11 to 13)
11. COMPDAT Keyword, (item 13 continued to 14)
12. Summary and Conclusions

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Preface

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.

Introduction

The following material summarizes background information on the Eclipse (GeoQuest) approach to productivity indices for horizontal and vertical wells in cartesian and radial grids. Much of the material has been copied from a variety of sources including the E100 & E300 Reference & Technical Manuals.

There is at least one companion spreadsheet for calculating (what Schlumberger & GeoQuest call) the TRANSMISSIBILITY CONNECTION FACTOR.

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	A	B	C	D	E	F	G	H	I	J	K	L	M
1		**RADIAL-WELL** Connection Transmissibility Factor (proportional to productivity index)											
2		**See J_ecl.ppt for background information.**											
3		ECLIPSE's connection factor = (J)*(Bo)*(Muo)/(Kro)						**input = solid, bold, red box & numbers**					
4			Field	(rb*cp)/(day*psi)				intermediate = black letters only					
5			Metric	(m3*cp)/(day*bar)				**output = bold, dashed, blue box & numbers**					
6			Lab	(cm3*cp)/(hr*atm)				**instructions = bold, purple letters**					
7													
8	**0.001127**	= conversion constant (0.001127 for field units, .008527 for metric, 1.0000 **????????** for lab)											
9	**6.28318531**	= sector angle, radians											
10	**622**	= first perpendicular-to-wellbore permeability, md (md or md)											
11	**622**	= second perpendicular-to-wellbore permeability, md (md or md)											
12	622	= permeability perpendicular to wellbore, md (md or md)											
13	**34**	= net thickness, ft (m or cm)											
14	**3**	= # radial cells											
15	**0.25**	= rw, ft (m or cm) (cement o.d.)											
16	**2050**	= re, ft (m or cm) (field outer radius)											
17	**0**	= Skin											
18	**0**	= optional manual-override for 1st cell outer radius, ft (m or cm)						**Enter zero to accept calculated outer radius of the 1st cell.**					
19													
20	20.1652968	= radius ratio, (re/rw)/(1/# cells)											
21	5.04132419	= 1st cell outer radius, ft											
22	**59.6296991**	= **RADIAL-WELL** perforation connection factor (item #8 of COMPDAT keyword)											
23													
24													
25		CHAP_E											
26			10x1x15	30x1x45	40x1x61	60x1x90	90x1x135						
27	net thickness	34	8	2.6667	2	1.3333	0.8889						
28	# radial cells	3	10	30	40	60	90						
29	1st radius	5.04132	0.615632	0.337598	0.313174	0.290516	0.276329						
30	775 md factor		75.807	88.613	90.649	92.793	94.289						
31	60 md factor		5.869	6.86	7.018	7.184	7.3						
32	62 md factor	59.630											

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This chapter outlines the relationships that **ECLIPSE** uses to calculate well inflow performance.

We define the flow path between the well bore and a single reservoir grid block as a "connection". The flow rate of a phase p (oil, water or gas) across a connection j is given by the Inflow Performance Relationship

$$q_{p,j} = T_{wj} M_{p,j} (P_j - P_w - H_{wj}) \qquad \text{[EQ 30.1]}$$

where

$q_{p,j}$ is the volumetric flow rate of phase p in connection j at stock tank conditions. The flow is taken as positive from the formation into the well, and negative from the well into the formation.

T_{wj} is the connection transmissibility factor, defined below.

$M_{p,j}$ is the phase mobility at the connection.

P_j is the nodal pressure in the grid block containing the connection.

P_w is the bottom hole pressure of the well.

H_{wj} is the well bore pressure head between the connection and the well's bottom hole datum depth.

The calculation of the terms in this relationship is described in the following sections of this chapter.

Darcy's Law for Radial Flow (field units)

$$qo = \frac{0.001127*2*pi*K*Kro*Hnet*(Pe-Pwf)}{Bo*Muo*[\ln(re/rw) +S]}$$

Rearrange to solve for constants (I.e., Connection Factor.)
Substitute for field productivity index (J.)

$$\frac{qo*Bo*MUo}{(Pe-Pwf)*Kro} = J \frac{Bo*MUo}{kro} = \frac{0.001127*2*pi*K*Hnet}{\ln(re/rw) +S}$$

Convert to wellbore-cell Connection Factor.
Substitute for Tw, and Mp.

$$\frac{qoj}{(Pj-Pwf-Hwj)*Mpj} = Twj = \frac{0.001127*2*pi*K*Hnet}{\ln(rj/rw) +S}$$

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Cartesian

In a Cartesian grid, **ECLIPSE** uses the relationship

$$T_{wj} = \frac{c\theta Kh}{\ln(r_o/r_w) + S} \qquad \text{[EQ 30.2]}$$

where

c	is a unit conversion factor (0.001127 in field units, 0.008527 in metric units, 3.6 in lab units).
θ	is the angle of the segment connecting with the well, in radians. In a cartesian grid its value is 6.2832 ($= 2\pi$), as the connection is assumed to be in the centre of the grid block. For wells located on an edge (or a corner) of a cartesian grid block, use keyword WPIMULT after COMPDAT to scale the resulting connection factors by 0.5 (or 0.25).
Kh	is the effective permeability times net thickness of the connection. The permeability used here is the geometric mean of the x- and y-direction permeabilities, $K = (K_x K_y)^{1/2}$.
r_o	is the "pressure equivalent radius" of the grid block, defined below.
r_w	is the well bore radius.
S	is the skin factor.

The pressure equivalent radius of the grid block is defined as the distance from the well at which the local pressure is equal to the nodal average pressure of the block. In a cartesian grid **ECLIPSE** uses Peaceman's formula, which is applicable to rectangular grid blocks in which the permeability may be anisotropic. The well is assumed to penetrate the full thickness of the block, through its centre, perpendicularly to two of its faces.

$$r_o = 0.28 \frac{\left[D_x^2 \left(\frac{K_y}{K_x}\right)^{1/2} + D_y^2 \left(\frac{K_x}{K_y}\right)^{1/2} \right]^{1/2}}{\left(\frac{K_y}{K_x}\right)^{1/4} + \left(\frac{K_x}{K_y}\right)^{1/4}} \qquad \text{[EQ 30.3]}$$

where D_x and D_y are the x- and y- dimensions of the grid block, and K_x and K_y are the x- and y- direction permeabilities.

Horizontal Wells

[EQ 30.2] & [EQ 30.3] are intended for vertical wells. Horizontal wells may penetrate the block in either the x- or y- direction, and the appropriate components of permeability and block dimensions are substituted in these equations. For a well penetrating in the x-direction, for example, the quantities K_y, K_z, D_y, D_z will be used in [EQ 30.3], and in [EQ 30.2] $Kh = D_x(K_y K_z)^{1/2}$.

A net-to-gross ratio applied to a grid block containing a horizontal well will not affect Kh, but will still affect r_o through the reduction in the value of D_z.

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Cartesian

In radial geometry, the formula used to calculate T_{wj} depends on the location of the connecting grid block.

When the connection is situated in one of the inner-most grid blocks (i = 1), it is assumed to lie on the inner boundary of the block. The connection factor is

$$T_{wj} = \frac{c\theta Kh}{\frac{r_2^2}{r_2^2 - r_w^2}\ln(r_2/r_w) - 0.5 + S} \qquad \text{[EQ. 30.4]}$$

where

θ	is the segment angle of the grid block in radians,
r_2	is the block's outer radius.

A warning will be printed if the well bore radius differs from the inner radius of the grid block.

If a connection is situated in one of the outer-most blocks (i = NDIVIX), it is assumed to occupy the outer boundary of the block for the purpose of applying boundary conditions. The corresponding connection factor is

$$T_{wj} = \frac{c\theta Kh}{\frac{r_1^2}{r_2^2 - r_1^2}\ln(r_1/r_2) + 0.5 + S} \qquad \text{[EQ. 30.5]}$$

where r_1 and r_2 are the inner and outer radii of the block.

This enables you to use a BHP-controlled well to apply constant pressure outer boundary conditions. If on the other hand you wish to model a real well in an outer block, the calculated connection factor will be much too large. In this case, you should either supply an appropriate connection factor value in item 8 of the COMPDAT keyword, or add an extra ring of inactive cells so that the well is no longer in an outer block.

If a well is completed in any other block (1 < i < NDIVIX), its connection factor is calculated as if it were in a cartesian grid block with $D_x = r_2 - r_1$ and $D_y = \theta(r_1 + r_2)/2$

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The COMPDAT keyword locates perforations and provides data for calculation the well's productivity index.

Some simulation engineers prefer to calculate and input each perforation's "connection transmissibility factor."

Eclipse can do this calculation, given data.

COMPDAT is followed by any number of records, described below, each record terminated by a slash (/). A record may be terminated at any item after item 9; the remaining items will assume their default values. If the well bore diameter is not required (See item 9), the record can be terminated after item 8.

A single record can be used to assign the properties of several connections of a well, as long as they are situated in the same vertical column of grid blocks. A deviated well can be completed in more than one column, but each column will require a separate record.

The set of records must end with a blank record, containing only a slash (/).

1 Well name or well name root
A well name root, ending with an asterisk (*), can be used to refer to several wells in one record.

2 I - location of connecting grid block(s)
If a default, zero or negative value is entered, the I - location of the well head (entered in keyword WELSPECS) will be used.

3 J - location of connecting grid block(s)
If a default, zero or negative value is entered, the J - location of the well head (entered in keyword WELSPECS) will be used.

4 K - location of upper connecting block in this set of data

5 K - location of lower connecting block in this set of data

The following data then applies to each layer (or connection) with K - locations between the upper and lower values given above.

6 Open/shut flag of connection

'OPEN'	Connection open to flow
'SHUT'	Connection closed off
'AUTO'	Connection initially closed, but will be opened automatically when another connection in the well is closed during an automatic workover. A connection on AUTO is opened each time the well is worked over, in the order in which the connections are first defined in COMPDAT. Connections on AUTO will also be opened when necessary to maintain group production rate targets if the 'REPERF' action is selected in keyword PRORDER.

(The word may be abbreviated, only the first character is significant)

- DEFAULT: 'OPEN'

COMPDAT Keyword (items 1 to 6)

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7 Saturation table number for connection relative permeabilities

If a default, zero or negative value is entered, the relative permeabilities will be calculated using the same saturation table as the grid block containing the connection.

In runs using the Vertical Equilibrium option (keyword VE in RUNSPEC) the end-points of the saturation table are used to calculate the contact depths and relative permeabilities at the well connection.

In runs using the Hysteresis option (keyword SATOPTS in RUNSPEC), the saturation table number entered here will apply to both imbibition and drainage processes. If a different table number is required for imbibition, it should be set using COMPIMB after the COMPDAT keyword. If a default, zero or negative value is entered, the respective tables for the grid block containing the connection (defined using SATNUM for the drainage table and IMBNUM for the imbibition table) will be used.

8 Transmissibility factor for the connection

If a default, zero or negative value is entered, the connection transmissibility factor will be calculated using the remaining items of data in this record. See "Well Inflow Performance" on page 30-1 of the "ECLIPSE 100 Technical Description" for an account of the methods used in Cartesian and radial geometries. The well bore diameter must be set in item 9.

- UNITS: cP-m^3/day-bars (METRIC), cP-rb/day-psi (FIELD), cP-cm^3/hr-atm (LAB)

Note the following two points:

- If the well is situated on an edge (or a corner) of a Cartesian grid block, use keyword WPIMULT after COMPDAT to multiply the calculated value by 0.5 (or 0.25).
- A well connection in an outer-most block of a radial grid (I = NDIVIX) is assumed to occupy the entire outer boundary of the block for the purpose of applying boundary conditions. If you wish to model a real well in an outer block of a radial grid, the calculated connection factor will be much too large. In this case, you should either supply an appropriate connection factor value yourself, or add an extra ring of inactive cells so that the well is no longer in an outer block.

If a value > 0.0 is entered, the connection transmissibility factor will be set to this value. The value will also be used to calculate either the connection's effective Kh or the denominator term $\ln(r_o/r_w) + S$ according to the following rules:

- If the Kh value in item 10 is defaulted or set negative, and the well bore diameter set in item 9, the Kh value will be calculated from the connection transmissibility factor and the denominator term. In this case, however, the Kh will only be used for output (if Schedule data output is requested in RPTSCHED). The denominator term will be calculated from the grid block dimensions, as described in the "Well Inflow Performance" on page 30-1 of the "ECLIPSE 100 Technical Description".

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- If the Kh value is set > 0.0, the denominator term will be calculated from the connection transmissibility factor and the given Kh value, instead of the well bore radius and the grid block dimensions.
- If the Kh value is set = 0.0, it will be replaced by the effective Kh of the grid block, then used to calculate the denominator term in the same way as if it had been set > 0.0.
- The recalculation of Kh or the denominator term may be turned off by setting the OPTIONS keyword switch 45 > 0. The denominator term will then always be calculated from the grid block dimensions and the well bore radius. This option can be used to achieve back-compatibility with pre-95A datasets, if required.

The denominator term will be used when calculating the well's Productivity/Injectivity index and when calculating the effects of a D-factor (see "Well Inflow Performance" on page 30-1 of the "ECLIPSE 100 Technical Description"). Thus, when the connection factor is set to a positive value, the results of these calculations will depend on the setting of the Kh value in item 10.

NB If a positive value is entered for the connection transmissibility factor, this should include the effect of any skin entered in item 11, but exclude the effect of any D-factor. The effect of a D-factor will be modelled separately by adjusting the mobility (see "Well Inflow Performance" on page 30-1 of the "ECLIPSE 100 Technical Description").

---

9 Well bore internal diameter at the connection
This quantity is required for:

- Calculating the Connection Transmissibility Factor
  (If a zero or negative value was supplied for Item 8)
- Calculating the Well's Productivity/ Injectivity Index
  (If a positive value was supplied for the drainage radius in Item 7 of keyword WELSPECS)
- Calculating the Effects of a D-Factor

The quantity will be ignored if not required.

- UNITS: m (METRIC), ft (FIELD), cm (LAB)

10 Effective Kh value of the connection

If a default, zero or negative value is entered, the Kh value will be calculated from the grid block data.

If a positive value for the connection transmissibility factor is entered in item 8, the calculation of the denominator term will depend on whether the Kh value is set or defaulted. See item 8.

This quantity is required for calculating the connection transmissibility factor (if a zero or negative value was supplied for item 8). It will be ignored if not required.

- UNITS: mD-m (METRIC), mD-ft (FIELD), mD-cm (LAB)
- DEFAULT: Negative

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11 Skin factor

This quantity is used for the same purposes as listed for item 9. It will be ignored if not required.

Large negative skin factors can cause problems if they increase the effective wellbore radius to approach the pressure equivalent radius of the grid block. Very high values of the connection transmissibility factor may result, which could cause convergence problems. A warning message will be issued if the effective wellbore radius increases beyond half the pressure equivalent radius, or extends outside the grid block. In these circumstances, it may be preferable to change the grid block data near the well to model the physical cause of the negative skin (e.g. enhance the permeability out to a certain distance from the well). If the effective wellbore radius is increased beyond the pressure equivalent radius, the connection factor becomes negative and an error message will be issued.

- DEFAULT: 0.0

12 D-factor, for handling the effects of non-Darcy flow of free gas

A D-factor measured for the well may be entered with keyword WDFAC. It may also be entered here instead, for back-compatibility with pre-94A datasets. **ECLIPSE** will convert the well D-factor into D-factors for the connections. See the WDFAC keyword for information on how the conversion is performed. Note that the well D-factor must reflect the current number of open connections at the time it is specified.

If you wish to enter the connection's D-factor directly, you can enter it here with a negative sign. A negative sign tells **ECLIPSE** to regard it as the connection's D-factor rather than the well's D-factor. **ECLIPSE** will simply reverse its sign without applying any conversion.

- UNITS: day/ sm^3 (METRIC), day/ Mscf (FIELD), hr/scc (LAB)
- DEFAULT: "Keep the current value of the connection's D-factor"

13 Direction in which the well penetrates the grid block

'X' - the well penetrates the grid block in the X direction
'Y' - the well penetrates the grid block in the Y direction
'Z' - the well penetrates the grid block in the Z direction

In radial grids, only penetration in the Z direction is allowed.

This item is used in calculating the transmissibility factor of the connection if it was not supplied in item 8. In Cartesian grids the Peaceman formula will be used, taking the components of permeability and grid block dimensions appropriate to the direction of penetration (see "Well Inflow Performance" on page 30-1 of the "ECLIPSE 100 Technical Description"). Note that the formula assumes that the well completely penetrates a rectangular block through its centre in a direction perpendicular to two of its faces.

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This item also influences the way **ECLIPSE** orders the connections in the well. **ECLIPSE** uses the connection ordering for the wellbore head calculation, and also to determine the order in which connection flows are printed in well reports. If all connections in the well penetrate vertically (Z-direction), the connections are ordered according to depth. But if any connection is declared to be horizontal (X- or Y-direction) in item 13, **ECLIPSE** will attempt to order the connections in "heel-to-toe" fashion. It takes the heel to be the connection whose I, J coordinates are nearest the wellhead I, J set in WELSPECS items 3 and 4. If more than one connection can be a candidate for the heel, **ECLIPSE** selects the one with the minimum depth. The rest of the ordering is determined from the location and orientation of the connections. If **ECLIPSE** cannot find a unique sensible ordering (for example with a multi-lateral well), it will issue a warning message and resort to ordering the connections by depth. If the new ordering is not satisfactory, the user can override it by using the 53rd switch in the OPTIONS keyword, which forces **ECLIPSE** either to use depth ordering or to leave them in the order in which they were first input by the user. For wells that use the **ECLIPSE 200** Wellbore Friction option, the connection ordering will be determined by a separate method, using information supplied in the WFRICTN keyword.

- DEFAULT: 'Z'

14 Pressure equivalent radius, r_o

If a value > 0.0 is entered, r_o will be set to this value instead of being calculated from the grid block dimensions according to Peaceman's formula (see "Well Inflow Performance" on page 30-1 of the "ECLIPSE 100 Technical Description"). Note that the pressure equivalent radius is not used for connections in the innermost or outermost cells of a radial grid.

- UNITS: m (METRIC), ft (FIELD), cm (LAB)
- DEFAULT: Calculate r_o from Peaceman's formula

As of this writing, there are still professional differences among the industry's leading experts on the topic
of horizontal-well productivity indices.
At least one unbiased 3rd party observed that the differences relate to assumptions about boundary conditions and about field productivity versus well-cell productivity.

THE WISE SIMULATION ENGINEER WILL REQUEST OUTPUT TO CONFIRM "PROPER" HANDLING OF THE CONNECTION TRANSMISSIBILITY FACTOR.

- The calculated values of the connection transmissibility factor and Kh (if defaulted) can be examined by requesting a printout of the Schedule section keyword data (mnemonic WELSPECS in keyword RPTSCHED).
- If you wish to prevent inter-block flow (for example due to shale breaks or faults), use keyword MULTZ, MULTX etc. to set a zero transmissibility multiplier. Don't set the rock permeability to zero instead, as it is needed to calculate the connection transmissibility factor.

```
COMPDAT
 'PROD1' 6 8 1 3 'OPEN' 0 0.0  0.333 500 3.5 1E-3 'Z' /
 'PROD2' 0 0 3 3 'OPEN' 3 0.0  0.333                 /
 'PROD3' 3 5 2 2 'OPEN' 0 1*   0.333 3*            'X' /
 'PROD3' 4 5 2 3 'OPEN' 0 1*   0.333 3*            'X' /
 'INJ*'  0 0 3 3 'OPEN' 0 2.3                        /
/
```

COMPDAT Keyword, (item 13 continued to 14)

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Summary and Conclusions

This tutorial improves the author's personal productivity by serving as a memory aid that demonstrates how GeoQuest defines the well connectivity factor.

The spreadsheet J_ecl_R.xls calculates well connectivity factors for radial wells.

Most of the technical data comes from various Eclipse (Schlumberger, GeoQuest) manuals. This tutorial presents those data in a single location.

Companion topics include productivity index and well index.

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