Determination of Particular Endogenous Fires Hazard Zones in Goaf with Caving of Longwall

Magdalena Tutak 1, Jaroslaw Brodny 2
1 Silesian University of Technology, 44-100 Gliwice, Akademicka 2 Street, Poland
2 Silesian University of Technology, 41-800 Zabrze, Roosevelta 26-28 Street, Poland
magdalena.tutak@polsl.pl

Abstract. Hazard of endogenous fires is one of the basic and common presented occupational safety hazards in coal mine in Poland and in the world. This hazard means possibility of coal self-ignition as the result of its self-heating process in mining heading or its surrounding. In underground coal-mining during ventilating of operating longwalls takes place migration of parts of airflow to goaf with caving. In a case when in these goaf a coal susceptible to self-ignition occurs, then the airflow through these goaf may influence on formation of favourable conditions for coal oxidation and subsequently to its self-heating and self-ignition. Endogenous fire formed in such conditions can pose a serious hazard for the crew and for continuity of operation of mining plant. From the practical point of view, a very significant meaning has determination of the zone in the goaf with caving, in which necessary conditions for occurrence of endogenous fire are fulfilled. In the real conditions determination of such a zone is practically impossible. Therefore, authors of paper developed a methodology of determination of this zone basing on the results of modelling tests. This methodology includes a development of model of tested area, determination of boundary conditions and carrying out the simulation calculations. Based on the obtained results particular hazardous zone of endogenous fire is determined. A base for development of model of investigated region and selection of boundary conditions are the results of real tests. In the paper fundamental assumption of developed methodology, particularly in a range of assumed hazard criterion and sealing coefficient of goaf with caving were discussed. Also a mathematical model of gas flow through the porous media was characterized. Example of determination of a zone particularly endangered by endogenous fire for real system of mining heading in one of the hard coal mine was presented. Longwall ventilated in the „Y” system was subjected to the tests. For determined mining-geological conditions, the critical value of velocity of airflow and oxygen concentration in goaf, conditioning initiation of coal oxidation process were determined. For calculations ANSYS Fluent software based on finite volume method, which enable very precisely to determine the physical and chemical air and parameters at any point of tested mining heading and goaf with caving was used. Such precisely determination of these parameters on the base of the test in real conditions is practically impossible. Obtained results allowed to take early proper actions in order to limit the occurrence of endogenous fire. One can conclude, that presented methodology creates great possibilities of practical application of modelling tests for improvement of the occupational safety state in mine.

1. Introduction
Hazard of endogenous fires is one of the basic and common presented occupational safety hazards in coal mine in Poland and in the world. This hazard means possibility of coal self-ignition as the result
of its self-heating process in mining heading or its surrounding. As a result of a developing endogenous fire, the product of incomplete combustion of coal in the form of toxic carbon oxide is released into the mines atmosphere. This gas can lead to formation of atmosphere unsuitable for breathing. Additionally, in the methane seams, endogenous fire can create inflammation hazard and explosion of methane.

In recent years, in Polish hard coal mines endogenous fires were occurred the most often in the goaf of longwalls with caving. In the years 2003-2016, 66 endogenous fires occurred, from which 40 were located in goaf with caving of operating longwalls [1].

Goaf with caving are a rock debris, forming in the space after selected coal seam, as a result of caving roof rock littering over this seam. This debris is created by the chaotically, freely falling rock blocks. Degree of filling of the selected surface depends on many factors, to which among the others one can include height from which rock block are falling down (thickness of the layer being exploited or thickness of the seam), type of the roof rocks and their strength properties, as well as the distance from the front longwall and depth of mining exploitation carried out [2, 3, 4, 5, 6].

Therefore, goaf with caving create porous medium, through which flow of gases is possible, as a result of the existence empty voids (gaps between bent rock blocks). If in the exploitation process in the roof or floor layer of processed seam the coal will be left, or if in the rocks lying over this seam the patches of coal are present, as a result of the fall of roof the coal will be found in goaf and can be a source of endogenous fire. Coal left in the goaf with caving and air flowing through them with determined velocity, as well as a proper oxygen concentration are elementary conditions determining self-heating process of coal. Significant meaning has also temperatures of rock mass and of flowing gases. Therefore, it is reasonable to conclude, that endogenous fire hazard significantly depends on the parameters of air stream flowing through the goaf. This flow is a result of migration of part of ventilated air stream flowing through the longwall heading in its ventilation process.

Longwall headings can be ventilated in different ways, however the “U from boundaries type” and “Y type” in different modification are the most often used. However, independently on applied ventilation system of operating longwalls, migration from them to the goaf with caving is always present. Part of air stream can flow into the goaf along the entire length of operating longwall. However, its greatest amount gets to the goaf zone at the crossing of longwall maingate with a longwall.

Nowadays, the „Y-type” system is the second most often used ventilation system of longwall headings (Fig. 1).

Figure 1. Scheme of a longwall ventilation “Y type” system

Determination of this zone in underground conditions in practice is impossible to perform, because it is formed in inaccessible places, what precludes to carry out direct tests. However, the possibilities of its determination are created by simulation methods based on numerical modelling. These methods in recent years more and more often are used to analyse ventilation problems. They enable variant analyses of processes connected with ventilation of underground mine heading, and also in analyses of states of emergency.

In the paper there are presented results of numerical analysis, whose aim was to determine the particular hazardous zone of endogenous fires in goaf with caving of longwall heading ventilated in the “Y-type” system. For this purpose, the Ansys Fluent software based on the finite volume method was used. Application of this software enabled to precisely determine the physical and chemical air steam parameters at any point of tested mining surface, including goaf.
Based on that particular hazardous zone of endogenous fires in goaf with caving of longwall heading ventilated in the “Y-type” system was determined. Obtained results confirmed rightness of selected assumption and the effectiveness of applied research methodology. Simultaneously these results could be important source for personnel conducting preventive actions in order to reduce hazard of endogenous fires in underground mining.

2. Criterion on endogenous fire hazard
By endogenous fire we mean self-ignition of coal, caused by a process of self-heating of coal (leading to increase in temperature), and under endogenous fire hazard possibility of coal self-ignition as a result of its self-heating process in mining heading or its surroundings.

Self-heating, and in a result a spontaneous combustion of crushed coal remained in the goaf with caving of exploitation wall, occurs due to airstream flow through it with a proper velocity and oxygen concentration. Presence of oxygen is necessary for initialization of low temperature reaction of coal oxidation. During this process, heat is generated and if it is not properly carried away, temperature of coal increases, leading to its self-ignition [7, 8, 9].

The most important factor influencing on the process of heat accumulation is the velocity of air stream flowing through the goaf with caving of exploitation longwall. Results of tests indicate that critical value of air stream, causing self-heating of coal is in the range from 0.0015 to 0.02 m/s. If this velocity is small (<0.0015 m/s), then process of coal self-heating is not initialized. Similar phenomenon occurs during great velocity of air stream (>0.02 m/s), which prevent heat accumulation [7, 10, 11, 12]. Due to the velocity of air stream flowing through the goaf with caving, one can determine three zones: cooling, particular hazardous zone of endogenous fires and suffocation. Similar division can be made due to oxygen concentration in air stream flowing through goaf with caving. Laboratory tests of coal oxidation indicated that boundary value of oxygen concentration below which self-heating did not occur is equal to 8%. Therefore, it was assumed that due to the value of oxygen concentration in the air flowing through goaf with caving, particular hazardous zone of endogenous fires is presented at oxygen concentration greater or equal to 8%, whereas hypoxia zone at concentration below 8% [8, 9, 13, 14].

In Table 1 there are presented boundary values of parameters characterizing particular hazardous zone of endogenous fires in goaf with caving.

| The zone name                        | Air velocity, m/s | Oxygen concentration, % |
|--------------------------------------|-------------------|-------------------------|
| Cooling                              | 0.02 < v          | \(O_2 \geq 8\)         |
| Particular hazardous zone of endogenous fires | 0.02 \(\leq v \leq 0.0015\) | \(O_2 \geq 8\)         |
| Suffocation                          | \(v < 0.0015\)   | \(O_2 < 8\)            |

Therefore, one can formulate following criterion of hazard of endogenous fire in goaf with caving:

- the presence of crushed coal, remaining in goaf with caving prone to self-heating,
- velocity of airflow through goaf with caving,
- min. 8% of oxygen concentration in the air flowing through goaf with caving.

3. Mathematical model of gas flow
In order to determine particular hazardous zone of endogenous fires in goaf with caving, mathematical model of air stream flowing through porous medium based on below discussed dependences was developed.
A turbulent flow of viscous incompressible fluid (in this case a gas), was described by the Navier-Stokes system of equations, which together with continuity equation makes a complete system of relationships, allowing to determine pressure and field of flow velocity [15]:

- The continuity equation:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}
\]
where: \( \rho \) is density (kg/m\(^3\)), and \( t \) is time (s).

- The momentum equation:
\[
\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \tau + \rho g + F \tag{2}
\]
where: \( p \) is static pressure (Pa), \( \tau \) is the stress tensor (Pa), \( g \) is the gravitational body force (m/s\(^2\)) and \( F \) is the external body force (N).

The basis of the mathematical description of the transport process of the methane emission to the headings is a mass conservation principle related to this gas. Mathematical model of the transport, being a system of equations of advection-diffusion, which for \( i \)-th substance it takes the following form:

- The species transport equation
\[
\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \mathbf{u} Y_i) = -\nabla \mathbf{J}_i + R_i + S_i \tag{3}
\]

where: \( \mathbf{v} \) is velocity (m/s), \( Y_i \) is the local mass fraction of each species, \( \mathbf{J}_i \) is the diffusion flux of species \( i \) (kg/(m\(^2\)s)), \( R_i \) is the net rate of production of species \( i \) by chemical reaction and \( S_i \) is the rate of creation by addition from the dispersed phase plus any user-defined sources.

- The mass diffusion in turbulent flows:
\[
\mathbf{J}_i = -\left( \rho D_{i,m} + \frac{\mu}{Sc_t} \right) \nabla Y_i \tag{4}
\]

where: \( D_{i,m} \) is the mass diffusion coefficient for species \( i \) in the mixture (m\(^2\)/s), \( \mu \) is the viscosity (Pa·s) and \( Sc_t \) is the turbulent Schmidt number, 0.7.

Airflow through the goaf with caving is a flow through the porous medium. Therefore, to the equation of conservation of momentum, an additional source member \( S_i \) describing this flow was introduced:

\[
S_i = -\left( \frac{\mu}{k} + C_2 \frac{1}{2} \rho g \mathbf{v} \right) \tag{5}
\]

where: \( S_i \) is the pressure loss items defined by Darcy’s law and \( C_2 \) is the inertial resistance factor.

Loss of momentum, described by the above equation, generates pressure gradient in the porous control volumes, which is proportional to its velocity and to the square of velocity in each volume of a liquid. Flow of air stream through the exploitation longwall and segment of goaf with caving located just behind the sections of mechanical support, in which there was no full caving (determined by so-called caving step) does not correspond to laminar flow. Flow of gas streams through the excavations has turbulent character, that is, in which irregular movement of air particles occurs, and its flow parameters undergoes to unpredictable random changes in space and time.

In the presented flow analysis, the „k-ε standard” turbulence model was applied. This model describes components of the Reynolds turbulent stress tensors according to the Boussinesq’s
hypothesis. In the formula for the components of stress tensor there occur \( k \) and \( \varepsilon \) quantities. These quantities require additional two transport equations for single phase flows in a form:

\[
\frac{\partial k}{\partial t} + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_\varepsilon}{\sigma_\varepsilon} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_\varepsilon - \rho \varepsilon - Y_M + S_k \tag{6}
\]

\[
\frac{\partial \varepsilon}{\partial t} + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_\varepsilon}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon_k} \frac{\varepsilon}{k} (G_k + C_{\varepsilon_t} G_\varepsilon) - C_{\varepsilon_{\varepsilon_\varepsilon}} \frac{\varepsilon^2}{k} + S_\varepsilon \tag{7}
\]

where: \( C_{\varepsilon_k}, C_{\varepsilon_t}, C_{\varepsilon_{\varepsilon_\varepsilon}} \) are constants, \( \sigma_\varepsilon, \sigma_k \) turbulent Prandtl numbers for \( k \) and \( \varepsilon \), \( G_k \) the generation of turbulence kinetic energy due to buoyancy, \( G_\varepsilon \) the generation of turbulence kinetic energy due to the mean velocity gradients, \( Y_M \) contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, \( S_k, S_\varepsilon \) user-defined source terms. Therefore, presented model, takes into account both the flow of air stream, and the transport of gases.

4. The goafs permeability

The coefficient value of gofs permeability is determined based on the value of resistance of rock roof stratification which form the caving. The resistance of roof rock stratification is their proper loosening resistance acting against the gravity force, that is natural capability of the rock mass to oppose stratification and caving of roof rock to the heading surface (the tensile strength of the forces directed vertically). This resistance determines their tendency to going into caving state.

The resistance of roof rock stratification forming caving is calculating from dependence [16]:

\[
R_{rr} = \sum_{i=1}^{n} \frac{R_{rr_i} \cdot m_i}{\sum_{i=1}^{n} m_i} \tag{8}
\]

where: \( R_{rr} \) is resistance of roof rock stratification (Pa), \( R_{rr_i} \) tensile strength of the rock layers (Pa), \( m_i \) the thickness of layers (m).

This dependence takes into account an influence of the thickness of particular layers of roof rocks on their tendency to going into caving state.

Resistance of roof rock stratification calculated on the basis of Equation 8, enables to determine permeability coefficient of goaf with caving from Equation 9:

\[
k(x) = \frac{\mu_\varepsilon}{r_0 + ax^2}, \text{ for } 0 \leq x \leq \frac{2}{3} \cdot l \tag{9}
\]

and from dependence:

\[
k(x) = \frac{\mu_\varepsilon}{r_0 + a \left( \frac{4}{3} l - x \right)^2}, \text{ for } \frac{2}{3} \cdot l \leq x \leq l \tag{10}
\]

where: \( \mu_\varepsilon \) is the coefficient of dynamic viscosity of air (Nsm\(^{-2}\)), \( l \) the total length of the longitudinal longwalls (m), \( r_0, a \) are empirical factor depending on the mining-geological conditions goaf.

Value of empirical coefficient \( r_0 \) and \( a \) is depended on the resistance of roof rock stratification forming caving.

Value of coefficient \( r_0 \) we determine from dependence:

\[
r_0 = \frac{\mu}{k_0} \tag{11}
\]
where: \( k_0 \) is permeability coefficient of goafs behind the front of the longwall (m\(^2\)).

Value of coefficient \( a \) we determine from dependence:
\[
a = 6 \cdot 10^9 R_{trs}^{-1.74}
\]  
(12)

Value of coefficient \( k_0 \) we determine from dependence:
\[
k_0 = \frac{\mu g}{6} \cdot 10^{-10} R_{trs}^{1.44}
\]  
(13)

Presented dependences were used during determination of permeability coefficient value of goafs in modelling tests.

5. Characteristic of investigated system
The longwall B-11 in exploitation seam 358/1 is a longitudinal system with caving roof in the direction from boundary and its mining parameters are equalled:
- length of the longwall 250.0 m
- height of the longwall 1220.0 m
- transverse slope 2°
- longitudinal slope 4°

Clay slate with coal laminas and slates with coal with total thickness up to 5.9 m were deposited directly in the roof of mined seam, and above them there was deposited a layer of fine grain sandstone with thickness up to 15 m. In the seam floor there was deposited a clay slate. Value of desertification resistance of roof rocks remaining in the goaf with caving of this longwall was equal to 3.78 MPa, and longwall was ventilated in “Y-type” system. To the maingate B-11 average 1119 m\(^3\)/min of air was supplied and to the tailgate B-10 average 1029 m\(^3\)/min of air was supplied. Release of methane to the exploitation longwall amounted average to 5.4 m\(^3\)/min, and mean value of its concentration at inlet from the tailgate amounted to 0.64%. Modeling tests of the airflow through goaf with caving of this longwall was performed for its length amounted to 455 m.

6. The results and discussions
Basing on the real data a geometrical model of tested area was developed, presented together with assumed boundary conditions in a Figure 2.

![Figure 2. Geometrical model of investigated system of excavations](image)
Performed tests enabled to determine distributions of physical and chemical parameters of air stream flowing through the tested headings and goaf with caving. Distributions of air pressure, velocity, dangerous velocity and oxygen concentration in goaf with caving at distance 0.5 m from exploited seam floor were presented in Figures 3a, 4a, 5a and 6a. Distributions of air pressure, velocity, dangerous velocity and oxygen concentration in goaf with caving at distance 2.0 m from exploited seam floor were presented in Figures 3b, 4b, 5b and 6b.

**Figure 3.** Distributions of air pressure of air stream flowing through the goaf at distance 0.5 (a) and 2.0 m (b) from exploited seam floor

**Figure 4.** Distributions of air dangerous velocity of air stream flowing through the goaf at distance 0.5 (a) and 2.0 m (b) from exploited seam floor

**Figure 5.** Distributions of air dangerous velocity of air stream flowing through the goaf at distance 0.5 (a) and 2.0 m (b) from exploited seam floor
Based on the obtained results one can conclude that air flowing through the goaf with caving reaches the greatest value of velocity behind the front longwall (caving line) from the inlet side of longwall (bottom corner) and from the outlet side of longwall (upper corner). The greatest value of velocity occurs at the height of flow of 2.0 m from the floor of mined seam in the lower corner of the longwall and equals to 0.49 m/s.

Analysis of obtained distributions of oxygen concentration in the goaf with caving indicates that from side of air outlet through the longwall (bottom corner) the concentration of oxygen is smaller than from the side of air inlet to the longwall (despite the reblowing by an auxiliary ventilation device).

Based on the obtained results, characteristics of changes in velocity of air flowing through the goaf with caving (Fig. 7a) and distributions of oxygen concentrations (Fig. 7b) present in that air as a function of the distance from the front longwall were determined.

Based on determined courses one can conclude that together with an increasing distance from the face of longwall the velocity of air and oxygen concentration in goaf with caving decrease. The velocity of airflow reaches critical value (due to endogenous fires hazard) to 94 meters from caving line into the goaf. However, oxygen concentration in the air flowing the gobs reaches critical value up to 212 meters. On a base of obtained results particular hazard zone of endogenous fires was determined.
Table 2 Particular hazardous zone of endogenous fires

| Critical air velocity zone | Critical oxygen concentration zone | Particular endogeneous fires hazard zone |
|---------------------------|------------------------------------|----------------------------------------|
| 0 – 94.0 m                | 0 – 212.0 m                        | 0 – 94.0 m                             |

Based on the performed tests it was found that particular hazardous zone of endogenous fires forms just behind the front of the longwall, and its range into goaf equals to 71 m. This zone is an area in which velocity of air can cause accumulation of heat in oxidation zone (with oxygen concentration in the air of minimum 8%).

8. Conclusions
In the paper there are presented results of numerical analysis, whose aim was to determine the particular hazardous zone of endogenous fires in goaf with caving of longwall heading ventilated in the “Y” system.

Based on that particular hazardous zone of endogenous fires in goaf with caving of longwall heading ventilated in the “Y” system was determined. Obtained results confirmed rightness of selected assumption and the effectiveness of applied research methodology. Obtained results, clearly indicate that the velocity of air stream in goaf with caving is significantly dependent on their permeability and porosity. Together with increasing distance from the longwall, so decreasing porosity and permeability, velocity of air stream flowing through the goaf with caving and oxygen concentration in these goaf decrease. On the basis of obtained data, one can precisely determine range of particular hazardous zone of endogenous fires (oxidation zone), and also cooling and hypoxia zones. In the analyzed case, hazard zone includes area from the heap line (practically from mechanical support) till about 94 meters into the heap. In this area necessary criteria for initiation of self-heating and self-ignition of a coal are fulfilled. Knowledge of range of this zone has very important practical meaning.

It allows to take preventive actions, in order to prevent occurrence of endogenous fire. Obtained results indicate, that numerical methods can be successfully used for variant analyses of processes connected with ventilation of underground mine headings, including analyses connected with airflow through the goaf, and also in the analyses of emergency states, like initialization of oxidation process in favorable conditions leading to self-heating and self-ignition. Therefore, it can be assumed that simulation methods based on computational fluid dynamics (CFD) could be significant tool in improvement of the occupational safety in the mining.

Acknowledgments
This article is the result of the research project No. 06/030/BK_17/0024 „Analysis of gas flow through porous media” realized in 2017, financed by MNiSW.

References
[1] J. Kabiesz, “The state of natural and technical hazards in Polish hard coal mines in 2016”, Central Mining Institute, Katowice, 2016, pp. 62-68.
[2] J. Brodny and M. Tutak, “The impact of the flow volume flow ventilation to the location of the special hazard spontaneous fire zone in goaf with caving of operating longwalls”, 16th International Multidisciplinary Scientific GeoConference. SGEM 2016, 978-619-7105-56-8, pp. 897-904, DOI: 10.5593/SGEM2016/B12/S03.115
[3] C.O. Karacan, “A Methodology for Determining Gob Permeability Distributions and Its Application to Reservoir Modeling of Coal Mine Longwalls”, 2007 SME Annual Meeting and Exhibit, Denver, Colorado, February 25–28, preprint 07-78. NIOSHTEC-2 No. 20031652. Littleton, Colorado: Society for Mining, Metallurgy, and Exploration.
[4] A. Lisowski, “The direction of the operation longwall with caving”, Prace GIG, Komunikat nr 2001, Katowice 1959.

[5] V. Palchik, “Influence of physical characteristics of weak rock mass on height of caved zone over abandoned subsurface coal mines”, Envir.Geology, vol. 44, Issue 1, 2003, pp 92–101, DOI: 10.1007/s00254-002-0542-y.

[6] Y. J. Song, “Defending and Extinguishing Fire by Even Air Pressure in Mine”, Beijing: The Press of Coal Industry, 2002, pp. 260-262.

[7] K. Cui “Determination of Spontaneous Combustion Region in Gobs and Numerical Simulation of Air-flowing Field”, J. of Shandong University of Science and Technology, 21 (2002) pp. 88-92.

[8] C. Liu, S. Li, Q. Qiao, J. Wang and Z. Pan, “Management of spontaneous combustion in coal mine waste tips in China”, Water, Air and Soil Pollution. Volume 103, Issue 1, pp 441–444,1998 DOI: 10.1023/A:1004922620264

[9] S. Q. Yang, and R. W. Zhang, “Distribution Regularity of Spontaneous Combustion Three-Zone in Goaf of Fully-Mechanized Coal Faces”, J. of China University of Mining and Technology, 29, 2000, pp. 93-96.

[10] G. Dai, S. Zhang and M. Tang, “Determination of spontaneous combustion “three zones” in goaf of no.713 fully mechanized longwall of Qinan coal mine”, AGH J.Mining and Geoengineering vol. 36 No. 3, 2012, pp. 99-113.

[11] J. Gao and H. Wang, “Influence of Permeability Distribution on Airflow Field of Leakage in Gob”, China Saf. Sci. J.1 20 (03), 2010, pp. 81-85.

[12] J. Gao, J. Liu and X. Zhang, “Simulation Study on the Influence of Permeability on Gas Migration in Gob”, China Saf. Sci. J.1, 20 (09), 2010, pp. 9-14.

[13] S.H.G. Jiang, R.W. Zhang and K.Y. Chen, “Determination of spontaneous combustion three – zone by measuring gas consistency and temperature in goaf”, J.of China University Mining Technology. Vol. 18, issue 1, 1998.

[14] X. Zhou, “Study on spontaneous combustion and explosion characteristic and prevention and control technology with high-gas and easily-spontaneous combustion coal seam in stope”, Liaoning Technical University 2016.

[15] K. K. Veersteg, and W. Malalasekera, “An Introduction to Computational Fluid Dynamics: The Finite Volume Method”, Pearson Education 2007.

[16] J. Szlązak, “The determination of a co-efficient of longwall gob permeability”, Arch. Mining Sci. 46 (2001) 451–468.