Mathematical solutions to the multiple-fan ventilation systems

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Synopsis

In this study, graphical and mathematical methods used to determine operating points in single or multiple fan ventilation systems are summarized. The problem is mathematically formulized for parallel connected fans in which analytical solutions are not possible. For *n* number of parallel connected fans, a non-linear equation system that consists of *n* number of non-linear equations is derived. The Newton-Raphson method, which is a numerical analysis method, is adapted to solve this non-linear equation system and the solution steps are given as an algorithm. A computer program based on this algorithm is written and its applicability is proved.

Introduction

In order to achieve a required quantity of air of a desired quality in an underground mine, a fan or fans located on surface are generally used. The operating points of these fans work are one of the main parameters used in the design of ventilation networks. For a ventilation network with the total resistance of airways calculated and the location and characteristic curves for fans known, the problem of design takes the form of calculating the total quantity and distribution of air entering the mine.

In determining the total air quantity entering the mine, a graphical method to determine the system operating point is generally used. However, numerical methods can also be developed based on the principle of the graphical methods. Numerical techniques are more reliable in a comparison to graphical solutions as they are generally more accurate.

In this study, mathematical methods that can be used to define the operating points of single or multiple-fan ventilation systems are identified and the applicability of the Newton-Raphson method to multiple-fans operating in parallel is discussed.

Some assumptions and definitions

Physical, thermodynamic and aerodynamic factors affect the motion of air in underground airways. However, some simplifying assumptions can be made in predicting air flow behaviour without causing unacceptable errors in the results.

- air flow in underground airways can be described by Atkinson's Equation of Square Law;

$$h = R \cdot Q^2 \qquad [1]$$

h : pressure drop (mm water (9.8 Pa))
R : resistance of airway (kilomurgue (9.8 Ns^2/m^8))
Q : air quantity (m^3/s)

- The mine air is incompressible.
- The ventilation network consists of series and parallel segments.
- Fan curves do not have extreme points.
- The velocity head of fans are negligible.
- No stall area exists when fans operate together.
- Only pressure-quantity curves are taken into consideration from fan curves.

The pressure-quantity relationship defined as $h=R.Q^2$ for mine is a second order mathematical function. In order to show this relationship graphically, the curve drawn taking the air quantity and pressure drop as abscissae and ordinate values respectively is called 'mine characteristic curve', and is a parabola.

The graphical representation of the relationship between the pressure increase and the air quantity delivered by a fan is known as 'fan characteristic curve'. This curve is an inverted parabola described by a second degree polynomial. In this case, the pressure increase created by the fan (h_V) is formulated as follows;

$$h_v = a.Q^2 + b \cdot Q + c \text{ (mm water (9.8Pa))} \qquad [2]$$

The coefficients of this polynomial (*a, b, c*) are known as fan coefficients. These coeffi-

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cients vary for different fans and they also change for the same fan due to changes in air density fan speed and guide vain settings (Hartman[1991]).

When the characteristic curve of a mine is drawn on the same pressure–quantity coordinate system as the characteristic curve of the fan supposedly working in the concerned mine, the intersection of these curves is called the system operating point. This point defines the operating conditions of the fan for a specific mine. Abscissae of this point gives the air quantity entering the mine while ordinate indicates the pressure increase across the fan (Wallis[1983])

Solutions for single-fan ventilation systems

Graphical solution

In this solution, the characteristic curves of both the fan and the mine are drawn in the same coordinate system and the intersection coordinates is determined (Figure 1). If significant natural ventilation pressure is present in the system, the direction and the head (h_d) of the natural ventilation are primarily defined. Where the natural ventilation pressure assists the fans, the characteristic curve of the fan is increased by the value of h_d, otherwise decreased by h_d (see Figure 1). The system operating point is at the intersection of the mine's resistance and newly assigned fan curves (point B or C).

Mathematical solution

As the mine ventilation system has a single operating point, pressure drop or increase across the mine and the fan should be equal:

$$h_{mine} = h_{fan}$$

Applying Equations [1] and [2], the above Equation becomes

$$R.Q^2 = aQ^2 + bQ + c$$

Where natural ventilation is significant in the system, the Equation will take the form of

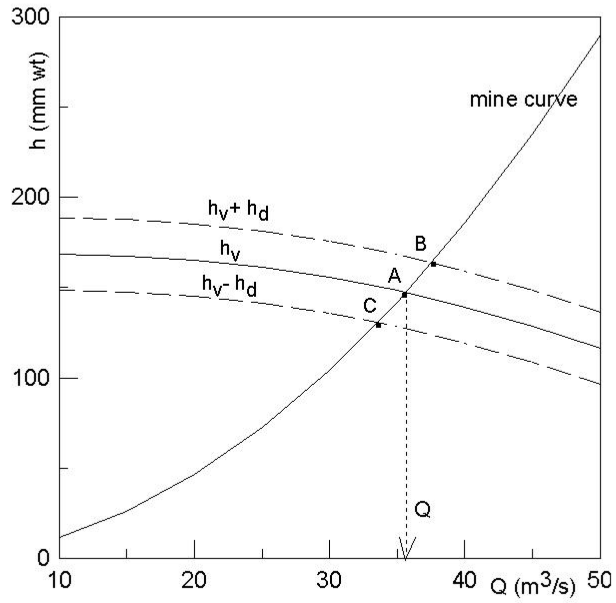

Figure 1—Operating point for single-fan ventilation system

$$R.Q^2 = aQ^2 + bQ + c \quad h_d \qquad [3]$$

Where the natural ventilation pressure is assisting the fan, h_d is added, otherwise it is subtracted. This second order Equation [3] can be written as:

$$(R - a)Q^2 - bQ - c \quad h_d = 0$$

Omitting the negative root in the above Equation, the system air flow quantity is calculated as:

$$Q = \frac{b + \sqrt{b^2 - 4.(R - a)}.(-c \pm hd)}{2.(R - a)} \qquad [4]$$

Solutions for multiple-fan ventilation systems

Large underground mines are generally ventilated using multi-fan systems. In this case, fans are operated in series and parallel configurations. A more complex and time consuming method is required to determine the total air quantity entering a mine using a multiple fan system.

Fans operating in series

The same mass flow of air is handled by fans operating in series. Fans operating in series handles the same quantity of air, but the individual fan pressures cumulatively results in the overall fan system pressure. In other words, each fan handles the same air quantity but produces only a part of the total head required (Hall[1981]).

Graphical solution

In this method, the cumulative characteristic curve of two fans operating in series is obtained by summing the pressure increase of each fan at equal air quantities. Where there is an airway between these two fans with a resistance of R_A, the system curve is decreased by the value of h_A=$R_A.Q^2$. Additionally, the system curve is either increased or decreased by the value of the natural ventilation head (h_d) when natural ventilation pressure is significant in the system (Hall[1981], Hartman[1991]). The system operating point is at the intersection of the mine's characteristic and the cumulative fan system curves (Figure 2).

Mathematical solution

The following fan laws apply in a network with two fans operating in series:

$$Q = Q_1 = Q_2 = Q_S$$
$$h_o = h_1 + h_2 = h_s$$

Q : air quantity entering the mine (m^3/s)
Q_1 : air quantity of 1st fan (m^3/s)
Q_2 : air quantity of 2nd fan (m^3/s)
Q_S : air quantity of system in series (m^3/s)
h_o : head of mine at operating point (mm water (9.8 Pa))
h_1 : head of 1st fan (mm water (9.8 Pa))
h_2 : head of 2nd fan (mm water (9.8 Pa))
h_S : head of system in series (mm water (9.8 Pa))

When there is an airway between these two fans and an effect of natural ventilation pressure, the following Equation is obtained;

$$h_o = h_1 + h_2 - h_A \text{ m } h_d \qquad [4]$$

Where h_A is the pressure drop for the airway between the fans with a resistance of R_A, and h_d is the natural ventilation

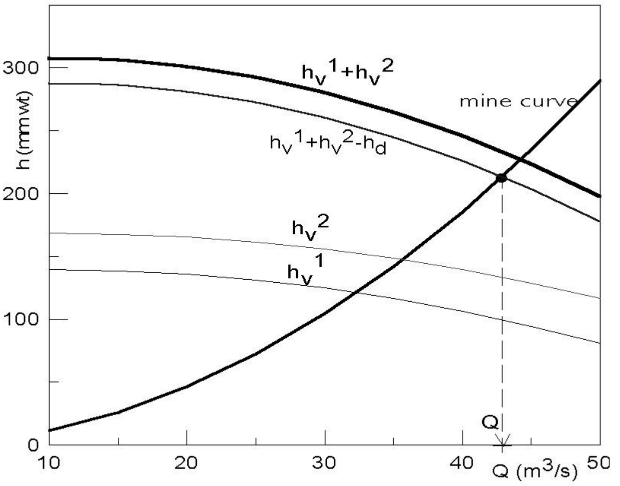

Figure 2—Graphical solution for a ventilation system with two fans operating in series

head. When Equations [1] and [2] are substituted in the previous Equation, the following Equation is obtained;

$$R.Q^2 = a_1Q^2 + b_1Q + c_1 + a_2Q^2 + b_2Q + c_2 - R_AQ^2 \mp h_d \quad [5]$$

a_1, b_1, c_1 : coefficients of 1st fan

a_2, b_2, c_2 : coefficients of 2nd fan

This second order Equation [5] can be written as:

$$\left(R - a_1 - a_2 + R_A\right)Q^2 - \left(b_1 + b_2\right)Q - \left(c_1 + c_2 \mp h_d\right) = 0$$

For this function, the numerical values of all parameters are known with the exception of Q. In this case, the problem takes the form of calculating the positive root of this second order function. The positive root defining the total air quantity entering the mine is calculated as follows;

$$\Delta = \left(b_1 + b_2\right)^2 + 4\cdot\left(R - a_1 - a_2 + R_A\right)\cdot\left(c_1 + c_2 \mp h_d\right)$$
$$Q = \frac{\left(b_1 + b_2\right) + \sqrt{\Delta}}{2.\left(R - a_1 - a_2 + R_A\right)} \quad [6]$$

When this Equation is generalized for n number of fans in series, the following is obtained;

$$\Delta = \left(b_1 + b_2 + \cdots + b_n\right)^2 + 4\cdot\left(R - a_1 - a_2 - \cdots - a_n + R_A\right)\cdot\left(c_1 + c_2 + \cdots + c_n \mp h_d\right) \quad [7]$$
$$Q = \frac{\left(b_1 + b_2 + \cdots + b_n\right) + \sqrt{\Delta}}{2.\left(R - a_1 - a_2 \cdots - a_n + R_A\right)}$$

This Equation is used to calculate the total air quantity entering the mine without using the graphical method. The result obtained is comparatively more accurate.

Fans in parallel

For mines requiring large quantities of air, it is more suitable to locate fans in parallel. In this case, fans are installed either in the same or different shafts.

At the operating point, the total head of the fan system equals the heads of the individual fans operating in parallel (Hall1981).

Graphical solution

The cumulative characteristic curve of two fans in parallel is obtained by summing the air quantity handled by each fan equal head values. Where the first fan is located in an airway with a resistance R_A and the second fan is in an alternative airway with a resistance R_B, the individual fan curves are reduced by h_A and h_B respectively. The corrected curves are then combined as explained above. Where significant natural ventilation with a head of h_d exists in the system, the associate curve is increased or decreased by the value of h_d depending on its effect. The operating point is indicated by the intersection of the mine's characteristic and the cumulative fan system curves (Figure 3).

Mathematical solution

The following fan laws apply to a fan system consisting of two fans operating in parallel;

$$h_o = h_1 = h_2 = h_s$$
$$Q = Q_s = Q_1 + Q_2$$

Where the fans are in different airways and significant natural ventilation with a head of h_d exists in the mine, the following Equation is derived;

$$h_o = h_1 - h_A \mp h_d = h_2 - h_b \mp h_d = h_s \mp h_d$$

By separating the above Equations in two parts and writing their corresponding values, the following Equations result;

$$R.Q^2 = a_1Q_1^2 + b_1Q_1 + c_1 - R_AQ_1^2 \mp h_d$$
$$R.Q^2 = a_2Q_2^2 + b_2Q_2 + c_2 - R_BQ_2^2 \mp h_d$$

Substituting Q with Q_1+Q_2 and gathering all variables into the left, the above Equations become;

$$R(Q_1 + Q_2)^2 - a_1Q_1^2 - b_1Q_1 - c_1 + R_AQ_1^2 \pm h_d = 0$$
$$R(Q_1 + Q_2)^2 - a_2Q_2^2 - b_2Q_2 - c_2 + R_BQ_2^2 \pm h_d = 0$$

In these two Equations taken as f_1 and f_2, the values of all parameters are known with the exception of Q_1 and Q_2. In this case, the problem takes the form of solving the two Equations with two unknown parameters. Once the solution

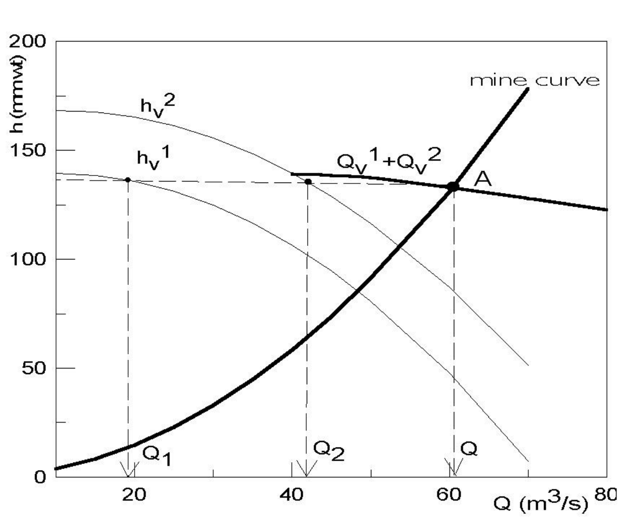

Figure 3—Graphical solution for two fans operating in parallel

has been reached, the air handled by each fan is calculated and the sum of these two values indicates the total air quantity entering the mine.

The above two second order Equations form a non-linear equation system. Analytic solution of non-linear Equation systems is difficult and it may even be impossible when the number of unknown parameters is greater than the number of equations. For the solution of this type of non-linear Equation system, it is preferable to use numerical solutions.

There are numerous mathematical methods for the solutions of non-linear Equation systems. In this study, the Newton-Raphson method (Wang and Reddy1992, Mathews1992) which is one of the most common numerical analysis methods to solve non-linear Equation systems, is used.

In the Newton-Raphson method, a Jacobien matrix of n numbers of non-linear Equation with n numbers of unknown parameters such as $Q_1, Q_2, \ldots, Q_n$ is formed. The Jacobien (J) matrix has a (nxn) dimension which is formed by the partial derivative of each Equation for each unknown parameter (Cagal1989 and Taylor1973). The J matrix for f_1 and f_2 Equations with unknown parameters Q_1 and Q_2 is formed as follows;

$$J = \begin{bmatrix} \dfrac{\partial f_1}{\partial Q_1} & \dfrac{\partial f_1}{\partial Q_2} \\ \dfrac{\partial f_2}{\partial Q_1} & \dfrac{\partial f_2}{\partial Q_2} \end{bmatrix} \qquad [8]$$

Random values are assigned to Q_1 and Q_2 and the elements of the J matrix for these random values are calculated, as well as the values of f_1 and f_2 functions. Next, the inverse of Jacobien matrix (J^{-1}) is determined by any method in Linear Algebra. By using this matrix, the values of Q_1 and Q_2 are calculated. These values are then used as the new values of Q, and the second iteration is performed. This process is continued until the difference between two consecutive iterations is lower than a pre-determined value.

The algorithm of the proposed method is summarized as follows;

Step 1: assign the value 0 to k.

Step 2: assign random values to $Q^k=(Q_1^k, Q_2^k)$ Where k designates an iteration number and not an order.

Step 3: calculate $F(Q^k) = f_1(Q_1^k, Q_2^k), f_2(Q_1^k, Q_2^k)$

Step 4: for Q^k values, form the Jacobien matrix $J(Q^k)$

Step 5: take the inverse of Jacobien matrix (J^{-1}) (In this study J^{-1} matrix is found, by using the determinant of J and adjacent matrix (J^*));

$$J^{-1} = \frac{1}{|J|} . J^*$$

Step 6: calculate the new value of Q^k vector by using the Equation given below;

$$Q^{k+1} = Q^k - J^{-1} \cdot F\left(Q^k\right)$$

Step 7: If $|Q^{k+1} - Q^k| < 0.001$, then go to Step 8 otherwise take $k=k+1$ and go back to Step 3.

Step 8: print iteration number (k), the air quantities produced by 1st and 2nd fans (Q_1^k *and* Q_2^k), total air quantity entering the mine ($Q = Q_1^k + Q_2^k$) and then stop.

For n number of fans in parallel, the same procedure will be followed, however, the dimensions of vector and matrix will be different. Q^k and $F(Q^k)$ vectors will have the dimension of n while J, J^* and J^{-1} matrices will be (nxn) dimension. A computer program based on the algorithm given above was written for n number of fans connected in parallel and its applicability is proved using an example. The results obtained are more accurate in a comparison with a graphical method.

Example solutions

The methods described in this paper are demonstrated below using numerical values.

Single-fan system

Where a fan with the coefficients a = -0.033, b = 0.686, c = 164.8 is operated in a mine with the resistance of 0.116 kilomurgue (1.137 Ns^2/m^8), the total air quantity entering the mine is found to be approximately 36 m^3/s by the graphical method (Figure 1). By using the formulation given in the mathematical method, this value is calculated as 35.64 m^3/s.

In the presence of natural ventilation acting against the ventilation system with a pressure drop of 20 mm water (196 Pa), the air quantity entering the mine is found to be approximately 33 m^3/s by the graphical method. The more accurate value calculated by the mathematical method is 33.56 m^3/s.

Two fans operating in series

Where two fans with the coefficients a_1=-0.037, b_1=0.756, c_1=135.5 and a_2=-0033, b_2=0.686, c_2=164.8 are operated in series a mine with a resistance of 0.116 kilomurgue (1.137 Ns^2/m^8), the total air quantity entering the mine is found to be approximately 44 m^3/s by the graphical method (Figure 2). By using the Equation given in the mathematical method, this value is calculated as 44.24 m^3/s. In the presence of natural ventilation acting against the ventilation system with a pressure drop of 20 mm water (196 Pa), the air quantity entering the mine is found to be approximately 43 m^3/s by the graphical method. The more accurate value calculated by the mathematical method is 42.89 m^3/s.

Two fans connected in parallel

Where two fans with the coefficients given above are operated in parallel in a mine with a resistance of 0.03636 kilomurgue (0.356 Ns^2/m^8), the total air quantity entering the mine is found to be approximately 61 m^3/s by the graphical method (Figure 3).

In order to reach the solution mathematically, it is necessary to solve non-linear Equation system. For this purpose, the algorithm of the Newton-Raphson method detailed previously is followed:

Step 1: assign k=0

Step 2: assign Q_1=20 and Q_2=20 m^3/s

Step 3: $f_1 = 0.03636(40)^2 + 0.037 * 20^2 - 0.756 * 20 - 135.5$
$f_2 = 0.03636(40)^2 + 0.033 * 20^2 - 0.686 * 20 - 164.8$

from the above Équations
f_1= -77.618 and f_2= -107.24

Step 4: The elements of Jacobien matrix are calculated as;
$J_{1,1} = 2 * R * Q_1 + 2 * R * Q_2 - 2 * a_1 * Q_1 - b_1 = 3.633$

$J_{1,2} = 2*R*Q_1 + 2*R*Q_2 = 2.909$
$J_{2,1} = 2*R*Q_1 + 2*R*Q_2 = 2.909$
$J_{2,2} = 2*R*Q_1 + 2*R*Q_2 - 2*a_2*Q_1 - b_2 = 3.543$

Step 5: The inverse of Jacobien matrix is calculated as;

$$J^{-1} = \begin{pmatrix} 0.803 & -0.659 \\ -0.659 & 0.824 \end{pmatrix}$$

Step 6:

$$Q^1 = \begin{pmatrix} 20 \\ 20 \end{pmatrix} - \begin{pmatrix} 0.803 & -0.659 \\ -0.659 & 0.824 \end{pmatrix} * \begin{pmatrix} -77.618 \\ -107.28 \end{pmatrix}$$

from above Equation $Q_1^1 = 11.629$ and $Q_2^1 = 57.128$ are calculated.

Step 7: as |11.629-20| and |57.128-20|>0.001 assign k=1 and return to Step 3.

The desired pre-determined value (0.001) is reached after 5 iterations. The Q values calculated at each iteration by the computer program developed are given below.

Here, Q_1 and Q_2 are the air quantities handled by 1st and 2nd fans respectively. In this case, the total air quantity entering the mine is calculated as 61.19 m^3/s.

Iteration	Q_1	Q_2
1	11.629	57.128
2	18.633	43.451
3	19.503	41.702
4	19.518	41.672
5	19.518	41.672

Results

The main problem in the design of ventilation networks with one or more fans is to determine the air quantity entering the mine. In order to solve this problem, the graphical methods using fan and mine characteristic curves can be utilized. However, the graphical methods are rather complex and take longer to perform.

Mathematical solutions can also be used for the determination of air quantity entering the mine. These solutions are more accurate than graphical methods and suitable for usage with computers. The mathematical formulation for a single-fan or multiple-fans operating in series are very simple and carried out by hand.

Mathematical modelling of a ventilation system with n number of fans operating in parallel, involves n number of non-linear second order equations with n number of unknown parameters. The analytical solution of this system is impossible. Therefore, it is inevitable that numerical methods will be used.

An algorithm based on the Newton-Raphson method has been developed to solve the above-mentioned problem. Following the development of this algorithm, a computer program has also been written and its applicability has been proved through examples.

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Mining reforms clear way for Australian investment in Southern Africa *

South Africa's Minister for Mines and Energy Affairs, Ms Phumzile Mlambo-Ngcuka, delivered a clear message to Australia's mining elite recently that Australian investment in Southern Africa was not only welcome but encouraged in terms of recent legislative reforms aimed at revitalizing the Republic's mining industry.

Following a three-day national mining summit held in Pretoria, Ms Mlabmo-Ngcuka impressed upon delegates at the AusiMM Southern Africa - Australia Mineral Sector Synergies Symposium in Canberra that mining in South Africa is a sunrise industry with much to learn from Australia.

The Minister said Australian investment in exploration and mining in the Republic would most likely increase due to a shift in legislation under the proposed Mineral Development Bill, which aims to open local and international access to mineral resources under a revamped system of state custodianship.

However, she was concerned that while working conditions and production levels would improve under new reforms, the South African community would miss reaping sustainable economic benefits unless a growth in secondary beneficiation industries occurred within South Africa's borders. The Minister also emphasised the need for a robust junior mining sector.

'Despite a positive trend in recent year, less than ten per cent of the minerals exported from South Africa leave the country in a beneficiated form,' the Minister said.

'The remaining 90 per cent can be subjected to a value adding process, but this is not yet done, leaving room for many new investment opportunities.'

Given that the location chosen to process minerals - whether locally or shipped to a foreign port - was based on economic factors, and therefore fell largely outside the government's legislative framework, Ms Mlambo-Ngcuka pointed to incentive schemes which provided concessions for mineral processing operators.

'We would like to see more companies whose speciality and expertise is in beneficiation investing and operating in South Africa,' Ms Mlambo-Ngcuka said.

'In fact, our incentive schemes are much more in favour of those kinds of companies than of those who are involved just in mining.'

Evidence that Southern African mining was now a sunrise industry was reinforced by Anglo Gold CEO, Bobby Godsell, who said the industry had moved from the morgue, to intensive care and now the recovery ward over the past five years.

'We are in the middle of ambitious programs to completely re-skill our workforce and to re-engineer our workplaces, with progressive introduction of technologies that will improve both safety and productivity,' he said.

'Mining is among the most technically challenging of any jobs, and can and should be high tech. We have made far too little use of technology in general and information technology in particular.'

Mr Godsell said the adoption of new technology was an important factor in establishing mining as the centrepiece of the new South African economy.

Much of this technology had originated from Australia through AMIRA International, the Julius Kruttschnitt Mineral Research Centre and the Centre for Mining Technology and Equipment.

'Whilst companies will compete in many areas, it is also possible for both companies and industries to co-operate in the development of new technology,' Mr Godsell said.

JKMRC Director Professor Tim Napier-Munn said Southern Africa's platinum industry was a timely example of how strategic alliances built on mineral processing R & D was influencing the way in which the industry was beginning to embrace emerging technologies.

Run by the University of Queensland's Julius Kruttschnitt Mineral Research Centre and brokered by AMIRA International, the 'P9' Project had proved so successful that every major Southern African platinum producer was represented, along with several other companies from other sectors, Professor Napier-Munn siad.

Since the mid-1990s the project had forged strong links with the University of Cape Town, particularly in the science of flotation and, more recently, comminution (rock breakage).

'P9 continues to break all records for a project of its type, with funding worth nearly $2 million a year from 40 companies in five countries, including 16 from South Africa,' Professor Napier-Munn said.

'The way in which P9 has emerged as an important formal link between Australian and Southern African mineral processors could provide the template for similar ventures between the two nations.'

Mr Godsell said that just as large-number mathematics and rocket science have transformed the world of futures trading and derivatives, so the advances of these science should impact on many other areas of mining.

Placing recent advances in information technology within the same context as advances in traditional geo-sciences, Mr Godsell said efficient capture and manipulation of information had every bit as much application to extracting on average seven or eight grammes of gold from each ton of rock mined at depth of two or three kilometres as it did to any e-commerce business.

Prominent Australian mining identity Mr Joseph Gutnick said during his announcement at the Symposium of a US$500 million Capital Growth Resources Fund that too much emphasis had been placed on 'dot.com' mania as an investment choice, rather than as a tool for the mining industry.

'Instead of trying to compete with dot.coms, we are saying, let's raise money via a less conventional route and use our expertise to create a portfolio of minerals projects and provide average returns to our investors,' he said.

Like Mr Godsell and Professor Napier-Munn, Mr Gutnick agreed that strategic alliances had become very attractive in the resources sector lately as companies recognized they needed technical and/or financial assistance to discover new orebodies and develop projects.

'The concept of helping each other so that both can improve their net position is a concept that is catching on fast.'

AusIMM Canberra Branch chairman, Mr John Bain, said convenor Mr Peter Hancock had developed a symposium which explored potential synergies between Australia and Southern Africa.

'It was obvious that the symposium had evoked passionate arguments encouraging Southern African mineral exploration in Australia, and likewise for Australian mining companies to spread their activities to Southern Africa,' Mr Bain said.

'The whole sector of Southern African mining was represented at the symposium including mining union officials, company CEO's and politicians—in fact the whole spectrum of mining in the region was represented at the highest level.'

Mr Bain said the South African High Commission's support for the symposium had helped strengthen the relationships between the respective countries' mining and minerals enterprises, and reinforced the bonds of friendship between the nations.

Also speaking at the event were Zimbabwean Minister of Mines, Environment and Tourism, Simon Moyo, Director and founding partner of SRK International Oskar Steffen, Delta Gold and Zimplats Managing Direcor and CEO, Terry Burgess, and Iscor Australia Managing Director, Kowie Strauss.. ◆

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* *Issued by: David Goeldner, Communication Coordinator for the Julius Kruttschnitt Mineral Reseach Centre, and a former journalist with Australian Provincial Newspapers.*