Published as: A.D.S. Gillies. A probabilistic method for mine heat prediction. *Proceedings, 3rd U S Mine Ventilation Symposium*, Society of Mining Engineers, Oct. 1987, pp.145-151.

Chapter 19

A PROBABILISTIC METHOD FOR MINE HEAT PREDICTION

Dr.A.D.S. Gillies

Senior Lecturer in Mining Engineering,
University of Queensland, Brisbane,
Queensland, AUSTRALIA.

ABSTRACT

The provision of a suitable working environment in deep level mines requires the accurate prediction of the ventilation heat load. Mathematical models for predicting strata heat load have been under development since the 1930's and 1940's. Computer models for predicting this and other mine heat sources have been developed and refined over the last 20 years. Some empirical studies have occurred and there is an increased emphasis on the importance of underground studies.

Any theoretically or empirically determined predictive method must of necessity make assumptions. Underground space with its irregular configurations and rough wall surfaces cannot be described by simple mathematical expressions. Some heat loads, such as machinery, may occur intermittently while others such as the influence of water evaporation are very difficult to quantify accurately.

Current popular models for predicting mine heat load have been surveyed. In testing some of these it is often found that each estimates significantly different quantitative values for the expected load in a particular underground space under study. These differences are explained by the assumptions, simplifications and omissions implicit in each of these models. It would be easier to estimate conditions at any point if heat flow into mine air passageways could be described by simple equations with associated statistically-based confidence ranges. Use of probability distributions to indicate confidence ranges allows any heat level estimate to be expressed as a range of values with limits for maximum and minimum expected values. This approach allows many of the limitations of the popular predictive models to be overcome. A heat prediction method using this approach has been developed based on Monte Carlo simulation and tested on mine data from a number of operations.

Heat flow levels which can be predicted by simple equations supported by probability distributions allow the engineer flexibility in adjusting a predictive model to the underground characteristics appropriate to the mine site under study. The influence of all heat sources present in the mine opening must be included. Prediction methods must be updated as mining systems and machinery change with time. Heat sources interact with one another and the system must therefore be understood in its entirety.

INTRODUCTION

Many authors have written about and developed models for explaining heat exchange in mine tunnels, development ends and stopes (Goch and Patterson (1940), Starfield and Dickson (1967), Starfield (1969), Gooch (1973), Whillier and Ramsden (1975), Starfield and Bleloch (1983), the McPherson heat flow program described by von Glehn (1984), Hemp (1985) and Ouederni, Deliac and Cassini (1985)). Further, empirical studies on mine heat exchange have been undertaken by Wiles and Quilliam(1959), Hemp (1966), Hemp (1967), Lambrechts (1967), Hemp (1969), Hemp and Deglon (1979) and Gillies and Alexander (1987). Some of these empirical approaches propose equations for heat level prediction.

Most of these methods pay considerable attention to heat exchange from both wet and dry rock surfaces. In this analysis, the predictive methods must, of necessity, make assumptions. Underground space with its irregular configurations, rock surfaces of varying texture and with water present at different temperatures from point to point cannot be described in exact terms by simple mathematical expressions. The importance of other heat sources, such as machinery and explosives has not been analysed in detail in many of the methods. Heat output from these sources may occur intermittently and these variations with their consequent effects on local air temperature influence heat flow from nearby rock surfaces.

In a comparative study, a number of currently popular prediction methods for determining mine heat load have been tested against observed changes occurring in a number of mine tunnels and development airways. It was concluded from this exercise that heat pick up values estimated by the different methods can vary significantly.

Theoretical methods for predicting heat load have been largely adapted from an approach proposed by Goch and Patterson (1940); a manual mathematical method using Fourier Numbers to calculate heat exchange.Many methods developed since about 1960 rely on computers to ease mathematical calculations in this approach. Differences in estimated heat pick up can be explained by the assumptions, simplification and omissions implicit in each. Reliable usage of the methods demands accurate knowledge of parameters such as airway dimensions, airflow velocity and temperature, rock surface heat flow coefficient and airway wetness. The nature and competence of rock and the mine use and drainage of water mean that these last two parameters can be difficult or impossible to accurately establish.

Difficulties in the use of these methods due to the inability to measure some data reliably and the simplifying assumptions inherent in each approach could be overcome if heat flow into an incremental mine tunnel length could be described by giving a range of value estimates rather than a point value. This range approach would allow statistically based confidence levels to be used to enhance the value of the heat load estimate. Further heat flow into a mine air passageway could be described by a simple equation with associated statistically based confidence ranges. Use of probability distributions across the confidence ranges allows any heat level estimate to be expressed as a range of values with limits for maximum and minimum expected values. This approach allows many of the limitations of the more popular predictive methods to be overcome.

The heat level and psychrometric conditions at any point in a mine are directly influenced by heat pick up in the mine ventilation network feeding air to that location. Points of interest in the mine may include stopes, development ends, maintenance bays and travelled airways and it is likely that the intake air network will be made up of a number of branches. Air may be delivered as a single stream or split to a mine point as occurs in coal operations or some mixing may have occurred in the intake air as occurs in many metalliferous mines. In determining heat load at a point, the heat pick up value or equation and its associated statistically based confidence range in all intake branches needs to be considered. A heat prediction method using this approach has been developed based on the Monte Carlo simulation technique. A study has been undertaken to test the method against mine heat load data from a number of operations.

Heat flow levels which can be predicted by simple equations supported by probability distributions allow the engineer flexibility in adjusting a predictive model to the underground characteristics appropriate to the mine site under study. Heat sources interact with one another and the system must therefore be understood in its entirety.

HEAT PREDICTION METHODS

Mine heat prediction methods in popular use attempt to estimate the flow of heat from wet or dry rock surfaces into the mine atmosphere and normally consider the influence of other heat sources in a separate calculation. Heat flow from the wall rock into an airway is extremely complex, departing from steady state heat transfer theory. Flow is considerably higher during the initial period after a mine opening is excavated than several years after when steady state conditions have developed. Prediction methods used in the study are briefly discussed in this section.

Goch and Patterson (1940) presented numerical solutions in tabular form for integrals developed to give the temperature inside the rock at any time and at any distance from a cylindrical tunnel boundary and the rate of heat flow across a unit area of the bounding surface. Their solutions are found from a complicated Bessel function integral involving the use of Fourier numbers. Starfield (1966) and Starfield and Dickson (1967) modified the Goch and Patterson tables to take into account varying surface heat transfer coefficients in calculating the surface temperature of the tunnel. With this approach, the effect of evaporating water from wet surfaces can be estimated. The modified approach to take account of wet surfaces requiring use of tabulated data and manual mathematical calculations has been used in the study.

Some assumptions important to the method are as follows:

1. Rock properties must be consistent.
2. Tunnel air temperature variations (climatic influences, machinery) are not accounted for.
3. An airway incremental length has an average age.
4. Non circular tunnel shapes were not considered.
5. Wetness was assumed to be distributed evenly around the tunnel perimeter.
6. The convective heat transfer coefficient is representative of both heat convection and radiation to air.
7. Average surface temperatures are used for heat transfer calculations.

The various predictive computer methods in popular usage substantially rely on mathematical solutions derived by Goch and Patterson and so understanding of these assumptions is important to their implementation.

The Ramsden method (Whillier and Ramsden, 1975) is based on the use of a simple relationship which was developed from a least squares fit to heat flow results derived from repeated runs of the Starfield (1969) computer program. The Ramsden Airway equation takes the following form:

$$Q = 5.57\ (\text{W.F.} + 0.255)\ (\text{VRT}-\text{D.B.})(\text{CF}) \ \ldots\ldots\ (1)$$

with

$$\text{CF} = (\text{PERIM}/12)^{0.437}(\text{AGE}/3)^{-0.147}(k/5.5)^{0.853} \ldots\ (2)$$

Q = heat pick-up, kW/100 m length of airway
W.F. = wetness factor, zero for a dry airway and 1 for a very wet airway.
VRT = virgin rock temperature, ^{o}C
D.B. = dry-bulb temperature, ^{o}C
CF = correction factor size, age, rock type
PERIM = perimeter of airway, metres
AGE = age of the airway, years
k = thermal conductivity of the rock, W/m^{o}C

The equation was proposed for use with tunnels of age greater than 100 days and so should be used with care in areas such as development ends.

The McPherson method (McPherson, 1984) is computer based and relies on an algorithm "Normtempgrad" which calculates the normalised temperature gradient into the rock. Von Glehn (1984) upgraded the program to a flexible interactive form. The program predicts increases in air temperature and humidity along mine airways directly. In the program calculations, surface heat transfer coefficient is calculated by an equation using data from underground measurement.

The Hemp approach (Hemp 1985) is a computer based tunnel heat calculation method which can be performed on a hand held calculator such as a Hewlett-Packard 41CV. Use of the program is designed for maximum simplicity and it is claimed to be accurate for tunnel properties which give a Fourier Number greater than 3 and so correspond to an age of about one month. The program is interactive but does not request rock surface heat transfer coefficients.

These four heat prediction methods have been found in the study to give significant variation in values for heat pick up along a test set of mine tunnels and development end sections. The differences between the empirically determined heat flow and that predicted by the four methods has been examined, and the Monte Carlo simulation technique applied to establish estimates of heat levels at points in a mine network which can be supported by statistically based confidence limits.

MONTE CARLO SIMULATION TECHNIQUE

Standard statistics books detail how estimated parameter value ranges which are described using probability distributions can be combined in a series of mathematical steps so that the final result (in this case additional heat loads) is given as a range of values with an appropriate confidence level statement. The method involves an approach referred to as the Monte Carlo simulation technique and its previous use in a mining application has been described by Bennett, Thompson, Quiring and Toland (1970).

APPLICATION

The proposed method for predicting heat load at a point was tested by the following steps.

1. Empirical data establishing heat pick up along a number of mine tunnels (through airways and development ends) was gathered.
2. Heat pick up for these same mine tunnels was estimated using the prediction methods of Goch and Patterson, Ramsden, McPherson and Hemp.
3. Heat pick up values (from empirical and prediction determinations) were compared for a particular tunnel, a range of possible values determined and a probability distribution assigned.
4. Heat load at a point in a mine was established by inputting heat pick up values as a probability distribution for all mine tunnels carrying air to the point into a Monte Carlo simulation computer program. Program output expresses heat load as a range. Heat load pick up through a mine network is normally additive (assuming the effects of air pressure changes are not important) although cooling units would have their refrigeration power expressed as a fixed value or range which is subtracted from mine heat load.
5. The final determination for heat load is expressed as a range of values with calculated standard deviation and so allows confidence limits to be assigned to a restricted expression of the range.

EXAMPLES

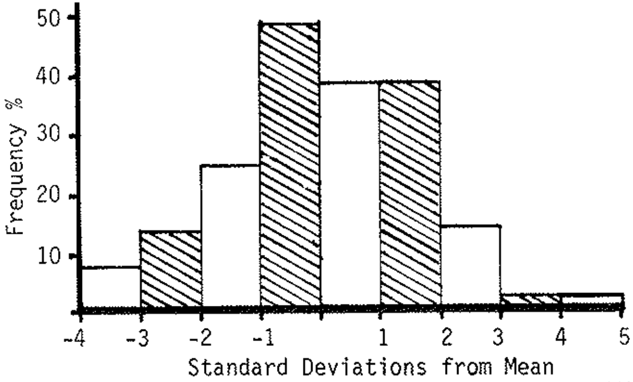
In order to illustrate use of the method by example, empirical heat pick up data from three sections of a single development end tunnel (Gillies & Alexander, 1987) and four mine airways (Anderson, 1980) were examined. Characteristics of these tunnel sections are given in Table 1. Heat pick up by the mine air established from empirical and predictive methods is set down in Table 2.

The assigning of probability distributions to the range of values established for each tunnel section is undertaken by examining their scatter on graph paper. Table 3 shows the ranges of heat pick up values divided into increments with associated levels of probability assigned.

Application of the proposed technique can be seen by examining examples of simple mine networks which lead to a point where mine heat load information is needed. Two examples using the tunnel section information are given.

Example 1

Air quantity of 15.7 m^3/s passes along airway 1; some is lost through leakage and 12.1 m^3/s passes through the adjoining airway 4. The airflow divides and 7.9 m^3/s moves through the development and tunnel sections. The additional heat load as the air is delivered at the development end face can be found by running the Monte Carlo simulation program after the air mass flow through airways has been adjusted to account for the heat load in the air that leaves the network before reaching the development end face. The additional heat load at the development end face is shown as a distribution function in Figure 1.



Mean = 122.9 kW, Standard Deviation = 7.5 kW

FIG.1 Probability Distribution for Example 1.

TABLE 1. SOME CHARACTERISTICS OF TEST TUNNEL SECTIONS.

Tunnel Section	WB/DB Temperature Inlet °C	Outlet °C	Atm. P. kPa	Flow m^3/s	L m	Perim. m	W.F.* %	Age Yrs.	Depth m	VRT °C	Rock Type	Cond. W/m°C	Density kg/m^3	Specific Heat J/kg°C
Dev.End AB	30.0/34.7	31.0/34.6	108.8	7.9	200	12.5	13.2	0.16	2,540	43	Quartzite	5.5	2670	920
Dev.End BC	29.0/34.3	30.0/34.7	108.9	7.9	200	12.5	12.2	0.33	2,540	43	Quartzite	5.5	2670	920
Dev.End CD	28.0/33.7	29.0/34.3	109.0	7.9	200	12.5	8.6	0.5	2,540	43	Quartzite	5.5	2670	920
Airway 1	20.4/29.9	20.8/29.2	103.0	15.7	192	11.7	8	0.1**	464	37	Siltstone	3.0	2600	920
Airway 2	19.5/33.5	21.4/36.3	105.0	2.5	288	13.0	2	20	580	40	Shale/ Dolomite	5.5	2750	920
Airway 3	28.8/32.5	29.1/33.4	105.7	12.7	252	15.5	8	15	696	43	Dolomitic Shale	4.1	2750	920
Airway 4	19.9/33.5	20.6/34.3	107.5	12.1	120	15.1	8	10	870	45	Shale/ Dolomite	5.5	2750	920

* Footwall Wetness Factor
**Closed off tunnel recently re-opened

TABLE 2. HEAT PICK UP ALONG TUNNEL SECTIONS FROM EMPIRICAL AND PREDICTIVE DETERMINATIONS

Tunnel Section	Empirical	Goch and Patterson		Ramsden		McPherson		Hemp		Average Difference to Empirical
	kW	kW	%diff. to emp.	kW	%diff. to emp.	kW	%diff. to emp	kW	%diff. to emp.	%
Development End AB	42.5	43.4	+ 2	41	- 4	39.8	- 6	32.6	-25	- 8
Development End BC	37.7	40.4	+ 7	37.4	- 1	33.6	-11	30.2	-20	- 6
Development End CD	36.3	37.1	+ 2	36.0	- 1	33.0	- 9	29.6	-19	- 7
Airway 1	26.2	28.3	+ 8	18.0	-31	21.0	-20	22.7	-13	-14
Airway 2	15.7	29.3	+87	22.3	+42	15.0	- 4	13.5	-14	+28
Airway 3	12.5	26.3	+108	26.9	+116	18.0	+44	22.9	+83	+88
Airway 4	29.7	28.6	- 4	18.4	- 38	13.0	-56	16.6	-44	-36

TABLE 3. TUNNEL PICK UP RANGES AND ASSIGNMENT OF PROBABILITY DISTRIBUTIONS

Tunnel Section	Heat Pick Up Range kW	Probabilities Assigned to Range Increments Upper Line - Increment Mean Lower Line - Probability						
Development End AB	32.6 - 43.4	31.25 0	33.75 0.2	36.25 0	38.75 0.2	41.25 0.3	43.75 0.3	46.25 0
Development End BC	30.2 - 40.4	28.75 0	31.25 0.2	33.75 0.2	36.25 0.2	38.75 0.2	41.25 0.2	43.75 0
Development End CD	29.6 - 37.1	26.25 0	28.25 0.2	31.25 0	33.75 0.2	36.75 0.6	38.75 0	
Airway 1	18.0 - 28.3	12.5 0	17.5 0.2	22.5 0.4	27.5 0.4	32.5 0		
Airway 2	13.5 - 29.3	7.5 0	12.5 0.4	17.5 0.2	22.5 0.2	27.5 0.2	32.5 0	
Airway 3	12.5 - 26.9	7.5 0	12.5 0.2	17.5 0.4	22.5 0.2	27.5 0.2	32.5 0	
Airway 4	13.0 - 29.7	7.5 0	12.5 0.2	17.5 0.4	22.5 0	27.5 0.4	32.5 0	

The skew distribution shows a mean heat load addition of 122.9 kW with a standard deviation of 7.5 kW. Further analysis indicates that there is a 90% confidence that the heat load will lie within 3 Standard Deviations of the mean or within the range 100.4 kW to 145.4kW. As an example, air entering the network at the initial specified temperature of 20.4 w.b., 29.9 d.b. would have a Sigma Heat increase of 13.5 kJ/Kg and be delivered to the development end face at 24.3 w.b., 29.9 d.b. (assuming d.b. temperature remains constant).

Example 2

The same air quantity of 15.7 m^3/s in Example 1 passes along airway 1. The air divides, 2.5 m^3/s passes along airway 2, 12.7 m^3/s along airway 3 and some is lost through leakage. Air from these two airways remixes and then 7.9 m^3/s passes through a chiller of 30 kW capacity before passing along the development end tunnel sections to the working face. Adjusting for heat load that leaves the network system, the additional heat load is shown as the function in Figure 2.

The distribution indicates a mean heat load addition of 109.7 kW with Standard Deviation of 5.9 kW. There is a 90% confidence that the heat load will lie within 3 Standard Deviations of the Mean or within the range 92.0 kW to 127.4 kW. The air entering the network at the initial specified temperature of 20.4 w.b., 29.9 d.b. would have a Sigma Heat increase of 12.0 kJ/Kg and be delivered to the development and face at 24.0 w.b., 29.9d.b. (assuming d.b. temperature remains constant).

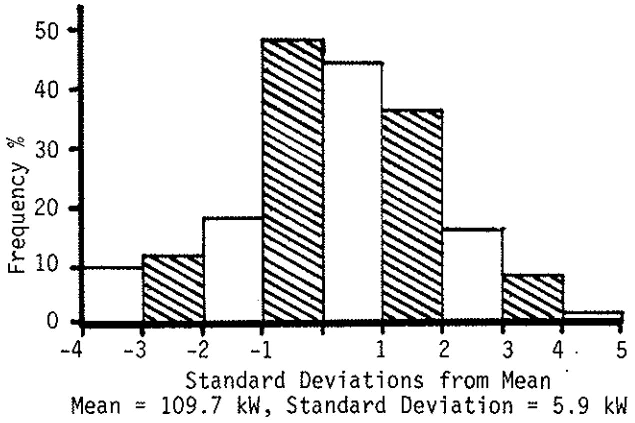


FIG.2 Probability Distribution for Example 2.

DISCUSSION

A method for using the Monte Carlo simulation technique to predict mine heat load has been illustrated by the use of two ventilation network examples. Comparison of tunnel heat pick up values from empirical determinations with those gained from prediction methods demonstrated the variance or disparity that may occur in results from the different approaches. The planning engineer when faced with prediction methods which give dissimilar results has difficulty in selecting the best approach.

The proposed approach allows information from as many available prediction techniques and any empirical determinations to be utilised. In many cases, empirical determination may not be available and so all modelling will be based on prediction techniques. This should not unduly limit accuracy of the technique as the mine tunnel examples given demonstrate that some prediction approaches overestimate heat load in comparison with empirical determinations, and some underestimate. There is no question, however, that empirical data should be used wherever available.

The results of the exercises demonstrate that the heat load at a particular mine point can be predicted with the result given as a range with associated confidence level. The two examples given demonstrate a 90% confidence that on average the heat load value will lie within 18% of the mean predicted value. With the uncertainties of the underground environment, is it likely that we can expect better precision than this?

Once the tunnel heat pick up characteristics of a particular mine have been understood, the procedure may be able to be simplified through the use of an appropriate simple equation supported by probability distributions. The Ramsden model is an example of a simple equation which is conceptually easy to understand. An appropriate equation for each tunnel type in a mine network may be formulated. This approach allows the engineer most flexibility in adjusting a predictive model to the underground characteristics in the particular situation under study. It also allows the influence of other heat sources present in the mine opening to be included. Prediction methods must be updated as mining systems and machinery change with time. Heat sources interact with one another and the system must therefore be understood in its entirety.

CONCLUSIONS

A technique has been outlined for predicting mine heat loads with increased confidence. The approach relies on the use of one or more of the presently popular heat load prediction methods and the use of a Monte Carlo simulation technique to allow heat load at a mine point to be specified across a range of probable occurrence within confidence limits.

The use of the technique has been discussed and some examples tested to illustrate application. Comparison of the various available tunnel heat methods demonstrates that significant variance may occur in predicted values between the different methods. The method proposed relies on statistical techniques to enhance the value of heat load predictions within the mine ventilation network.

ACKNOWLEDGEMENT

The paper has been prepared within the Department of Mining and Metallurgical Engineering of the University of Queensland and the support of this institution is acknowledged. Mr.Stephen Garrone is thanked for his assistance in the study while a student at the University of Queensland.

REFERENCES

Anderson, J.M., 1980. "Thermal Conductivity Measurements in Established Mine Airways", B.Sc. (Hons.) Thesis, University of Nottingham, England (unpublished).

Bennett, H.J., Thompson, J.G., Quiring H.J. and Toland, J.E., 1970. "Financial Evaluation of Mineral Deposits Using Sensitity and Probabilistic Analysis Methods, U.S. Bureau of Mines IC8495.

Gillies, A.D.S. and Alexander N.A., 1987. "The Development End Heat Load", Journal South African Institute of Mining and Metallurgy (submitted for publication).

Goch, D.C. and Patterson, H.A., 1940. "The Heat Flow Into Tunnels". Journal of the Chemical, Metallurgical and Mining Society of South Africa, Vol.41. pp.117-128.

Gooch, C.D., 1973. "Heat Flow Into the Developing Tunnel". Chamber of Mines of South Africa Research Report 3/73.

Hemp, R., 1966. "Air Temperature Increase in 53 Haulage East, Crown Mines Ltd." Internal report, Rand Mines Limited.

Hemp, R., 1967. "Heat Flow in Drives - Measurements at Six Sites at Harmony Gold Mining Company Ltd." Internal report, Rand Mines Limited.

Hemp, R., 1969. "Heat Flow Measurements at Libenon Gold Mining Company Ltd." Internal Report, Rand Mines Limited.

Hemp, R., 1985. "Air Temperature Increases in Airways", Journal Mine Ventilation Society of South Africa; pp.1-8; 13-20.

Hemp, R. and Deglon, P., 1979. "A Heat Balance in a Section of a Mine. Proc. Second International Mine Ventilation Congress, SME, pp.523-533.

Lambrechts, J.de V., 1967. "Prediction of Wet Bulb Temperature Gradients in Mine Airways". Journal South African Institute Mining and Metallurgy. Vol.67, pp.595-610.

McPherson, M.J., 1984. "Mine Ventilation Planning in the 1980's. International Journal of Mining Engineering, 2, pp.185-227.

Ouederni, M.A., Deliac, E.P. and Cassini, P., 1985. "Modelling and Prediction of Climatic Conditions Conditions in a Deep Level Development Tunnel". Proc. Second U.S. Mine Ventilation Symposium, SME, pp.489-498.

Starfield, A.M., 1966. "Tables for the Flow of Heat into a Rock Tunnel with Different Surface Heat Transfer Coefficients". Journal South African Institute Mining and Metallurgy, Vol.66, pp.692-694.

Starfield, A.M. 1969. "A Rapid Method for Calculating Temperature Increase Along Mine Airways" Journal South African Institute of Mining and Metallurgy, Vol.70, pp.77-83.

Starfield, A.M., and Dickson, A.J. 1967. "A Study of Heat Transfer and Moisture Pick up in Mine Airways. Journal South African Institute of Mining and Metallurgy, Vol.68, pp.211-234.

Starfield, A.M. and Bleloch, A.L. 1983. "A New Method for the Computation of Heat and Moisture Transfer in a Partly Wet Airway". Journal South African Institute of Mining and Metallurgy, Vol.83, pp.263-269.

Von Glehn, F., 1984. "A User's Manual for the Computer Program 'Airway' for Calculating Heat Pickup in Mine Airways". (McPherson program), Chamber of Mines of South Africa Research Report 48/84.

Whillier, A. and Ramsden, R. 1975. "Sources of Heat in Deep Mines and the Use of Mine Service Water for Cooling". Proc.International Mine Ventilation Congress. The Mine Ventilation Society of South Africa.

Wiles, G.G. and Quilliam, J.H., 1959. "Some Temperature Gradients Observed in Specially Selected Underground Airways", Journal South *African Institute Mining and Metallurgy*,Vol.59, pp.360-368.