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J. of Fire Prot. Engr., 1 (2), 1989, pp 63-76

Stansted Terminal Building and Early Atrium Studies

Dr. R. A.Waters
Ove Arup & Partners
13 Fiyzroy Street
London WIP 6BQ England*

SUMMARY

The paper demonstrates how field modelling techniques can be used to understand smoke control strategies during the design phase of major buildings.

The use of animation techniques that combine smoke and people movement results, for a particular fire scenario, to produce a computer driven animated colour portrayal of an evacuation is discussed.

The design of public spaces in commercial buildings has undergone vast changes in the last two decades. The harbingers of these changes have been the modern atrium and the large covered space. The Hyatt Regency Hotel, Atlanta, U.S.A., contained the first modern atrium and since then there have been many other examples. In the United Kingdom the Lloyd's Building, Leadenhall St., London contains a prestigious atrium. Stansted's Airport Terminal Building, Essex, England will contain a large uncompartmented passenger concourse of 32,000 m^2. In recent years such spaces have increased both in size and the range of activities that take place within them.

In the United Kingdom the regulations have been formulated to cover all aspects of traditional building design. Anomalies occur in the regulations pertaining to fire and smoke management when they are applied both to new complex building forms and conventional buildings used in an unconventional manner. In these situations, smoke generation and spread models can be used to estimate what will happen in the event of a fire. In the future results from these types of models will be used to obtain clarification of the regulations. This paper details two projects: smoke and escape studies for the Stansted Airport Terminal Building, and a study of smoke flow in an atrium - we have allied the latter to the atrium of the Lloyd's building of which we have detailed knowledge.

Communication between the groups involved in designing and checking a building is always a major problem. Ove Arup and Partners have begun to tackle this problem in fire engineering by using computer generated colour graphics to present the results of calculations in an easily understandable form, as will be illustrated in this paper.

MODELLING TECHNIQUES

The modelling of smoke and air movement within buildings can be carried out with an ever increasing number of calculation methods. Broadly speaking these fall into three categories:

- simple fluid dynamic models for predicting particular flow features - for example algebraic equations to calculate the spread and velocity changes in a smoke plume
- models capable of predicting global smoke movement in a variety of different enclosures
- complex models that provide detailed smoke and air movement estimates inside one or two enclosures.

Each category of model is of importance to the building designer, because to a large extent they provide complementary predictions. The results of any model, of course, can only be as good as the information fed in.

The simple models give "ball-park" data on

* *Now a Director of Computational Dynamics, Ltd., Olympic House, 317 Latimer Road, London W106RA.*

important features. If they indicate that there will be no smoke management problems, further calculations may be unnecessary.

Global smoke movement predictions can be obtained with zonal models. These often contain semi-empirical engineering relationships to account for particular phenomena, for example fire and plume development. These models provide excellent results when the engineering relationships embodied in them apply to the problem being solved and results of unknown quality when they do not.

Detailed smoke and air movement predictions can only be obtained with field models. The enclosure being examined is divided into a series of inter-connecting cells and the flow equations solved in each cell. Field models are very powerful, giving assessments of air and smoke movement, temperature and species concentrations throughout the space. However, they are difficult to use and can take a long time to work. They can provide design data on smoke movement and management in the new types of buildings being evolved by architects, developers and technocrats.

FIELD MODELS

Several different types of field models have been used to carry out the predictions detailed in this paper. Below we have briefly described the fundamental structure common to all these models. The steady state differential equations solved all have the form:

$$\frac{\partial}{\partial x}(\rho U\phi)+\frac{\partial}{\partial y}(\rho V\phi)+\frac{\partial}{\partial z}(\rho W\phi)= \\ \frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_\phi\frac{\partial\phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_\phi\frac{\partial\phi}{\partial y}\right)+S_\phi+BF \qquad (1)$$

The values taken by ϕ when this equation represents continuity, momentum and enthalpy/concentration are detailed in Table 1. (In this instance the velocity, V, is in the vertical direction).

These equations represent the steady state laminar or turbulent flow of air. In them the effective viscosity, μ_{eff}, is equal to the sum of the turbulent, μ_t and laminar viscosity, μ_l.

The field models we have used solve the partial differential equation for continuity, momentum and any scalar property. These equations are reduced to algebraic relationships by integrating them over a typical cell. Pressure predictions are obtained from a pressure correction relationship which works on the principle that the correction is sufficient to produce velocity changes that satisfy continuity. The SIMPLE practice[1] was used to solve the resultant algebraic equations.

	ϕ	Γ_ϕ	S_ϕ	BF
Continuity	1	0	0	0
Horizontal momentum	U	μ_{eff}	$-\frac{\partial P}{\partial x}+\frac{\partial\left(\mu_{eff}\frac{\partial U}{\partial x}\right)}{\partial x}+\frac{\partial\left(\mu_{eff}\frac{\partial V}{\partial x}\right)}{\partial y}+\frac{\partial\left(\mu_{eff}\frac{\partial W}{\partial x}\right)}{\partial z}$	0
Vertical momentum	V	μ_{eff}	$-\frac{\partial P}{\partial y}+\frac{\partial\left(\mu_{eff}\frac{\partial U}{\partial y}\right)}{\partial x}+\frac{\partial\left(\mu_{eff}\frac{\partial V}{\partial y}\right)}{\partial y}+\frac{\partial\left(\mu_{eff}\frac{\partial W}{\partial y}\right)}{\partial z}$	$\rho Bg\theta$
Lateral momentum	W	μ_{eff}	$-\frac{\partial P}{\partial z}+\frac{\partial\left(\mu_{eff}\frac{\partial U}{\partial z}\right)}{\partial x}+\frac{\partial\left(\mu_{eff}\frac{\partial V}{\partial z}\right)}{\partial y}+\frac{\partial\left(\mu_{eff}\frac{\partial W}{\partial z}\right)}{\partial z}$	0
Enthalpy or **Concentration**	h or c	Γ	0	0

Table 1: Values of ϕ, Γ_ϕ, S_ϕ and BF

Fire Modelling Techniques

At present simple models are used to represent the fire. The simplest represent the fire as a heat release. This technique has the advantages of being easy to apply and corresponds to the way fires are usually assessed in the United Kingdom. A more complex model assumes that the fire can be represented by a one step chemical reaction of the type:

$$\text{Fuel} + \text{Oxidant} \rightarrow \text{Product} \quad (2)$$

with the fuel and air combining in stoichiometric proportions to produce a single product. The effect of turbulent mixing on the reaction rate of the fuel can be assessed with an eddy break up model - after Spalding *et.al.*[2] and Magnussen *et.al.*[3] This technique is far more complex than the heat release analogy and for cases involving complex reactions will not be very accurate.

Turbulence

Turbulent effects in the fire, plume and air contained by the enclosure are normally represented by either algebraic or two equation models which predict the turbulent viscosity μ_t. Launder and Spalding[4] have reviewed the construction and performance of these models.

Two of the most often used algebraic models are:

$$\mu_t = \text{Factor (Laminar Viscosity): Factor} > 1 \quad (3)$$

or

$$\mu_t = \max.(\text{Factor} \times [\text{Local Velocity}], \text{Laminar Viscosity}) \quad (4)$$

Algebraic models have the advantage of being both easy to apply and solve. Their major disadvantage is that they only accurately apply to a few flow situations; when they do not apply the results will be of an unknown quality

The major advantage of the two equation turbulence models is that they are far more general, however, this does not mean they can be applied to all flow situations. The major disadvantage is that they are quite difficult to use and solve. We have used both types of models in the projects presented in this paper.

Stansted Passenger Terminal Building

Stansted Airport was selected by the United Kingdom's government to be London's third airport. Both Heathrow and Gatwick do not have sufficient capacity to deal with the projected passenger demand of the 1990s.

Stansted Airport is situated in the heart of the Essex countryside. The airport is about 40 miles from the centre of London. Fast rail links will mean that travel time from the capital will be approximately half-an-hour. The current airport deals with national and intercontinental flights and handles about 1 million passengers per annum (mppa). The new airport facilities have been designed to handle 8 million passengers per annum and can be extended to deal with 15 million passengers per annum.

The main enhancement to the airport is the new terminal building. The client (British Airport's Authority) appointed Foster Associates as architects, Ove Arup and Partners as structural and fire engineers, and undertook mechanical and electrical design with their own staff. The total cost of the development is $200,000,000.

The general layout of the terminal building is shown in Figure 1, and an elevation is shown in Figure 2. Service equipment is predominantly situated in the undercroft. The single storey passenger concourse is on one level, is largely uncompartmented, has a height of 13 m and a floor area of approximately 32,000 m^2. This concourse has been designed to provide:

- An uninterrupted flow of travellers to and from the aeroplanes.
- A high degree of flexibility for future alterations of passenger facilities

The roof is of lightweight construction and supported on regularly positioned lightweight space frame columns at 36 m centres. The lower portion of these columns supports passenger communications equipment and the mechanical devices for heating and cooling the terminal. Above 2 m these columns are relatively open,

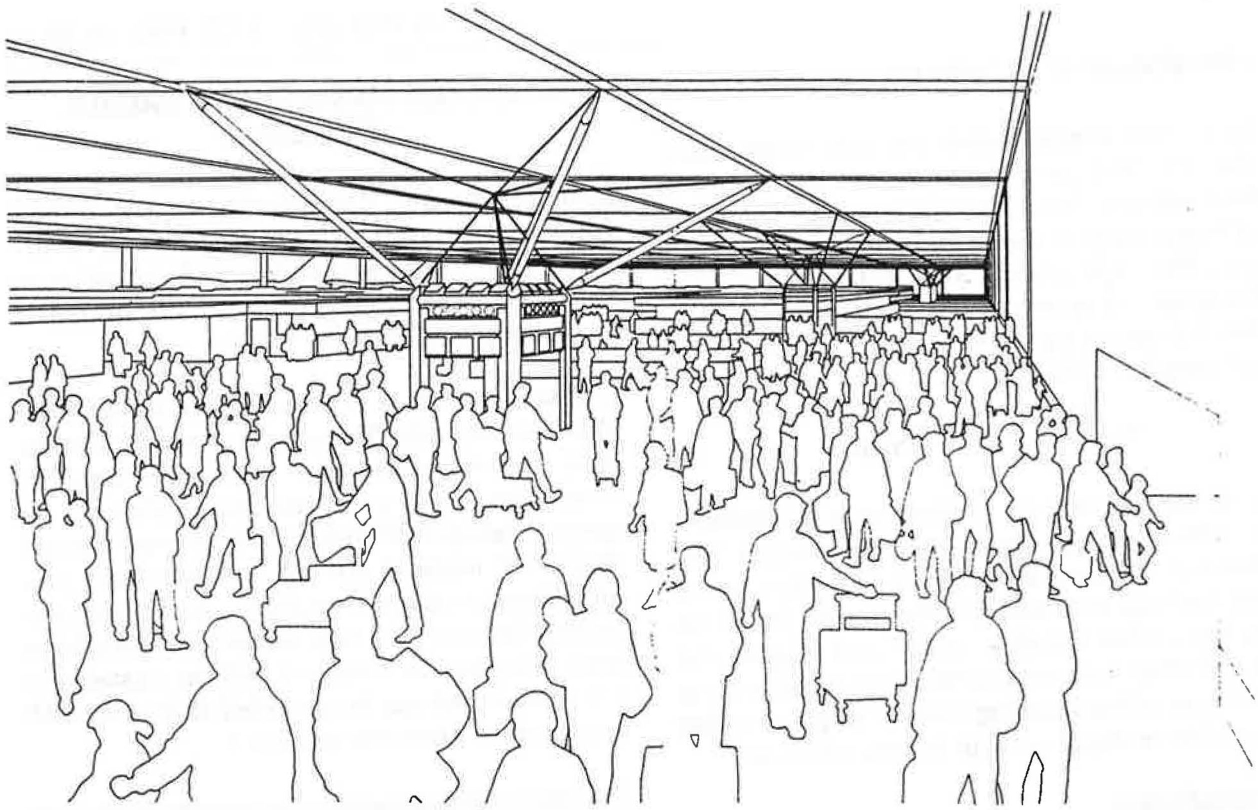

Figure 1. View of Concourse.

and thus unobtrusive to both the eye and any air or smoke movement that occurs within the concourse.

Fire Engineering

To allow the concourse to have a high degree of flexibility for future alterations many passenger facilities, such as duty free shops, banks and cafés, are open-sided cabins. Enclosed cabins are provided for private offices and kitchens. The aim is to prevent smoke and heat from a fire in one of these cabins entering the main circulation areas of the concourse.

The open-sided cabins are provided with their own fire detection and smoke extraction facilities. Sprinklers will limit the growth and spread of a fire until the fire fighting services arrive. The smoke extract system will draw the majority of smoke generated by the fire directly out of the building – as shown in Figure 3a.

In the event of a fire in an enclosed cabin smoke will be extracted by operating the mechanical air systems in a non-recirculating mode – as shown in Figure 3b.

The remainder of the concourse has been allocated to passenger movement waiting areas and baggage reclaim, and is considered to be relatively a safe area. In the event of a fire, passengers will escape from the building along their normal movement patterns, to the air and landside of the buildings and by a protected staircase to the road that bisects the undercroft. The escape routes are illustrated in Figure 4.

Ove Arup and Partners were commissioned to carry out smoke and people movement studies for various fire scenarios to understand how the evacuation of people would proceed in the event of a fire.

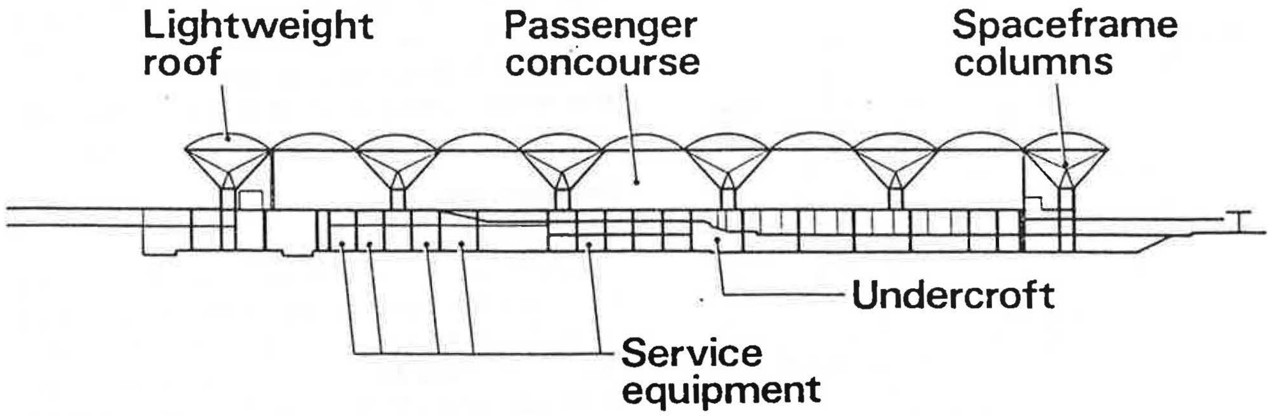

Figure 2. Elevation of Concourse.

Previous Approaches and Present Contribution

The method of assessing fire risks in buildings is well documented. Briefly, the size and growth rate of a fire can be obtained from published statistical data, and the probable movement of smoke estimated using published design methods. The published guides are not directly applicable to the Stansted Concourse, and calculation techniques have been used to estimate smoke movement. Zonal techniques were not used, because they embodied "rule of thumb" laws about smoke movement which were not applicable to this type of building.

A field model was used to estimate smoke spread. Considerable research work has been done into establishing the scope and accuracy of field modelling techniques when predicting smoke spread. In the United Kingdom the Fire Research Station (F.R.S.) has developed a research code called Jasmine. This has been tested in a large number of applications. Good comparisons between predicted and experimental results have been reported in small tests cells[5], hospital wards[6], transportation tunnels[7] and fires in the open[8]. Smoke movement in the passenger compartment of aircraft is being studied by Markatos *et.al.*[9]. The effect of sprinkler sprays on smoke and air movement is being studied by Markatos and Hoffman[10]. Independently, Lockwood *et.al.*[11],

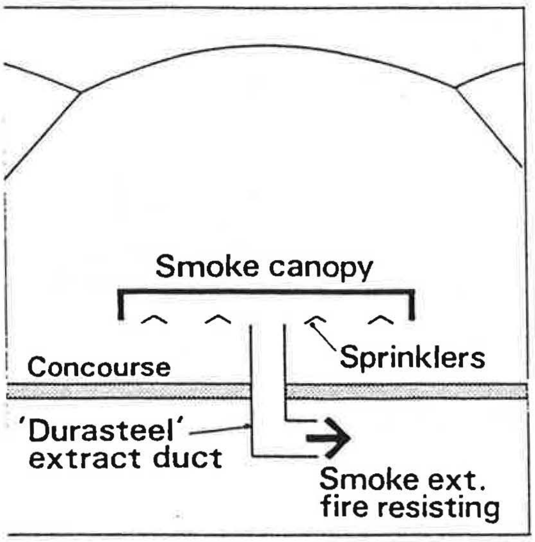

Figure 3a. Open cabin.

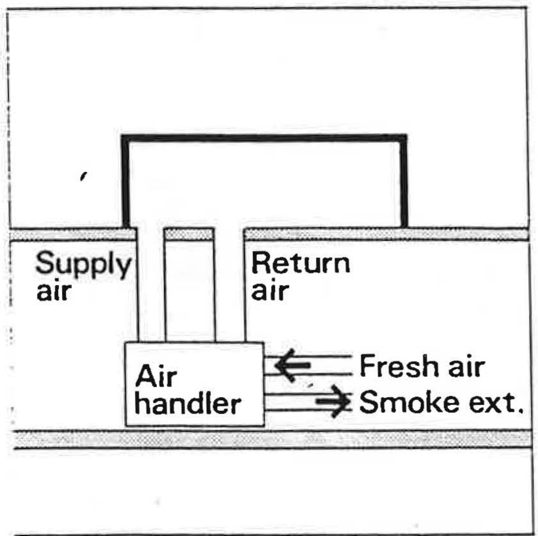

Figure 3b. Enclosed cabin.

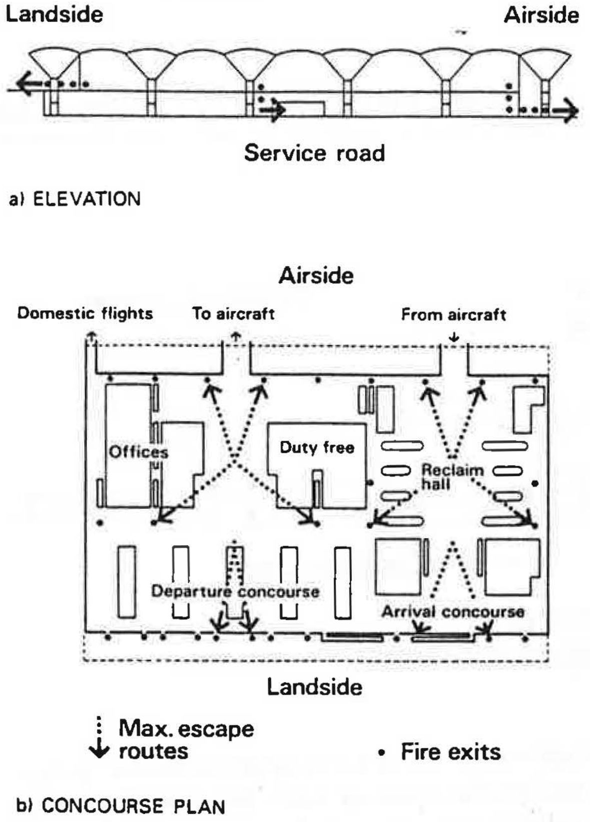

Figure 4. Means of escape.

Yang *et.al.*[12,13], at the University of Notre Dame, and Morita and Kawagoe[15], at Tokyo University, have carried out smoke movement studies with different types of field models.

The field modelling technique developed and tested by the Fire Research Station was used to predict smoke movement with time. Ove Arup & Partners have developed a similar code. However, the F.R.S. code was used because we believed that this would make evaluation of the results by the regulatory authorities as simple as possible.

Problem Description

A number of scenarios were considered and two are described here. In each the fire occurs at ground level at the center of the passenger concourse, without failure of any smoke extract system occurring. In both situations we were interested in assessing smoke spread with time. In these simulations we assumed that the walls, roof and floor of the building were adiabatic and that the turbulent viscosity of the air was constant at 200 and then 400 times the laminar value.

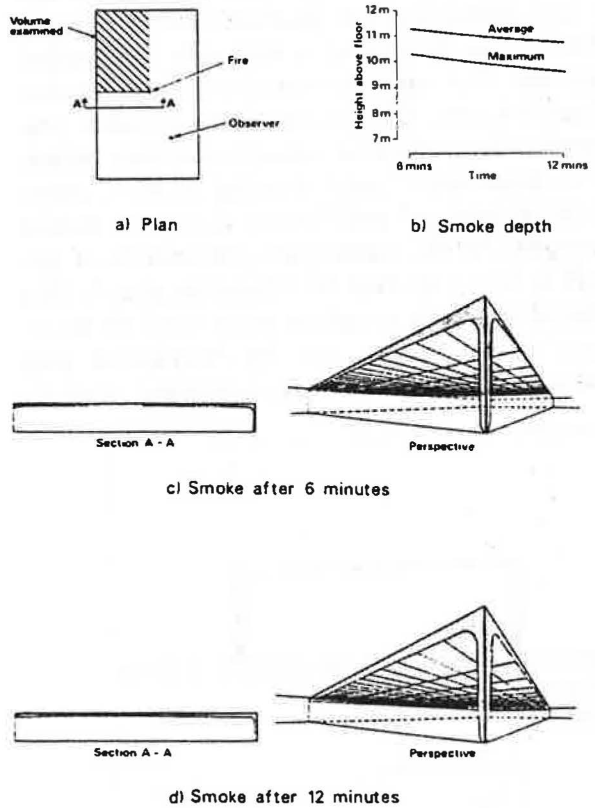

Figure 5. Sample results of first fire scenario.

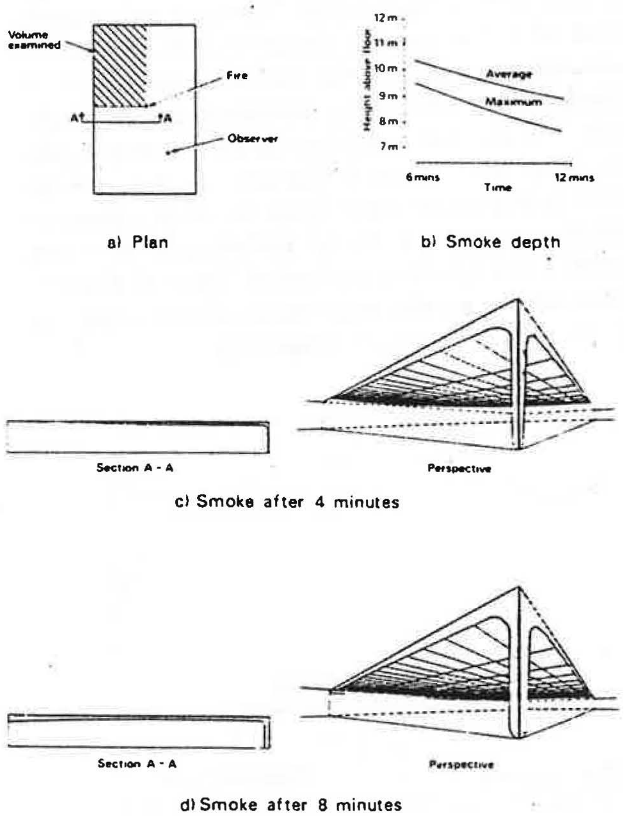

Figure 6. Sample results of second fire scenario.

The fire load and heat output have been taken as being equivalent to a fire load of 20 kg/m^2 of wood with a burning time of 20 minutes and a heat output of 13 MJ/kg. The initial fire area was taken as 3 m^2, and the fire area was assumed to double every four minutes. In the first scenario the final area was 9 m^2 after which it remained constant. This represents a fire beginning at detection, with fire growth limited to an area of 9m^2 by firefighting action. At this phase the fire is under control but not extinguished. In the second scenario the fire was allowed to continue doubling in area every four minutes, assuming there was no fire fighting. This represented a fire completely out of control which in these circumstances is an unlikely event.

The part of the concourse simulated is shown shaded in Figure 5a. The grid spacing was non-uniform with grid lines more closely spaced in the vicinity of the fire – typically eighty or twenty-four thousand cells were used in the simulation. The fire was modelled as a heat source. We used a temperature contour of 4°C above ambient temperature to denote the smoke boundary.

Results and Discussion

Sample results for the first fire scenario are shown in Figure 5 – they show the edge of the smoke, where visibility is estimated at 5-10 m, at 6 and 12 minutes after fire detection. The smoke edge reached the long wall of the building between 4 and 6 minutes after fire detection and the short wall about 12 minutes after detection. The lower edge of the smoke layer does not enter the habitable zone. Shown in Figure 5b are plots of the average and maximum smoke depths.

Results for the second scenario are shown in Figure 6. The views and criterion for determining the region where the smoke predominated are unchanged from the first simulation. The results show the situation 4 and 8 minutes after fire detection. The smoke layer reaches the long wall of the concourse at about 4-6 minutes after detection, and the short wall at about 10 minutes. The time to reach the short wall is less than in the previous simulation, because in this case the fire continued to grow in output power throughout the simulation. Again the lower edge of the smoke does not reach head height. The average and maximum smoke depths are shown in Figure 6b.

Escape

Measurements have been made of the walking speeds of passengers in the baggage reclaim area of an existing airport (to be published by M. Law of Ove Arup and Partners). It was considered that in the event of an emergency evacuation passengers would move slowest in the baggage reclaim area at speeds no slower than they would exhibit under normal conditions.

Measurements were taken of the time taken by passengers to move, with their baggage, from the baggage collection point to the exit. Although the passenger sample was not selected on any statistical basis it did contain young and old single persons, and groups of two or more that contained either predominately young or old people. The times recorded included pauses to adjust baggage on trolleys, greeting and saying goodbye to friends, and in one instance changing contact lenses.

Nominal and actual walking speeds and the gathering time were calculated – the results are summarized in Table 2. Nominal speeds were calculated for the most direct distance to the exit, and actual walking distance on the real distance travelled.

The most crowded population density during the measurements was estimated to be 1.5 person/m^2.

		Single Person	Groups	All
Median Nominal Speed	(m/s)	1.04	0.8	0.85
Median Walking Speed	(m/s)	1.08	0.89	0.92
Median Gathering Up time	(sec)	22	47	39

Table 2: Walking Speeds

A computer program was written to assess the way in which passengers were likely to evacuate the concourse – assuming they moved in the way measured in the baggage reclaim area. The concepts behind the program were as follows:

- A population density of 1.5 persons/m^2 was set
- A gathering up, or pause time, of 30 seconds was assumed after fire detection
- The passengers that would use one fire exit were distributed randomly within the U.K. regulatory distance from that exit.
- The speed at which the passengers would move was generated randomly, with the constraint that the assumed passenger population had to have the same speed distribution as that measured for groups of passengers.

The program was run several dozen times. It was found that there was a high probability of it taking passengers 4 to 5 minutes to evacuate the terminal. This is about twice times the design escape time given in the U.K. regulations

Closure

A field modelling technique has been used to model the three dimensional movement of air and smoke in the passenger concourse of an airport building in two different scenarios. The first corresponded to a growing fire at the centre of the concourse which was limited by fire protection measures to an area of 9 m^2. In the second scenario the fire was allowed to grow. We have predicted at least 6 to 7 metres of air above floor level 10 minutes after fire detection; and a maximum evacuation time of some 4.5 minutes after fire detection. From these results we deduced that passengers will be able to safely evacuate the concourse.

The smoke movement predictions from the first fire scenario have been computationally combined with the people movement predictions to produce an animated coloured representation of the evacuation. We have found that animated representations of results considerably enhance communication between the grouips involved in designing and checking a major building.

ATRIA

The modern atrium has evolved over the last two decades, particularly in the United States where dramatic and lively social areas have been produced. Examples of such building forms are Crystal Court, Minneapolis, U.S.A. Peachtree Plaza Hotel, Atlanta, U.S.A. and Eaton Centre, Toronto, Canada.

In the United Kingdom the atrium concept has been enthusiastically embraced and some fine buildings produced. However, the building regulations and current practice have restricted U.K. design. Ove Arup & Partners have begun examining different smoke management scenarios in atria, by using computer based models to understand what problems exist and how they can be overcome.

Regulations

Currently there are no statutory requirements for the removal of smoke from atria. The now disbanded Greater London Council produced a series of recommendations which now have no legal force.

These recommendation provided for a comprehensive protection of the surrounding offices from a fire in the atrium. However, they often resulted in a sterile design. For example:

- The requirement to have offices above the 3rd level separated from the atrium by glazing can result in a tube-like appearance.
- The requirement to have low fire loads on the atrium floor can result in barren empty floor spaces.

The recommendations also made no allowance for the fact that escape from the space might be completed during the initial growth period of a fire. In the regulations the concept was to design for a steady state maximum fire of 5 MW.

Having recognized the need for more flexibility and that small or medium sized fires are equally relevant to safety, Ove Arup & Partners have begun to postulate different fire scenarios and investigate their effect. We have studied a space similar the atrium of the Lloyd's Building, Leadenhall Street, London, England. The reason for this is that we intimately understand the fabric, climatic effects and air movement in this space during normal use.

Lloyd's Building

The Lloyd's building is situated in the city of London and houses the underwriters and other member of Lloyd's. The architects of this building were Richard Rogers and Partners, and the consulting engineers were Ove Arup & Partners

The main building is a rectangular block measuring 68.4 m x 46.8 m in plan. The lower ground level contains public areas and the reinstated Old Library. Above this is an enclosure called the Room, which is double height, and above this level are 12 galleries built as rings around the atrium – as shown in Figure 7a. The first six galleries completely ring the atrium, but above that the galleries are cut back to suit the right of light of adjacent buildings. The atrium measures 34.2 m x 11.6 m in plan and has a barrel shaped roof.

The smoke extracts for the atrium are positioned just below the barrel vault. In the event of a fire they will extract air and smoke from the atrium at six air changes per hour; make up air being provided at low level.

Initially underwriting will be confined to the Room and the three galleries above it. In order to conform to Lloyd's rules, which require all underwriting to be carried out in a single space, the Room and the three galleries above it are open onto the atrium. Circulation between these areas is by escalators that criss-cross the atrium. Provision has been made for expansion of the underwriting area to the sixth gallery.

A typical gallery floor plan is shown in Figure 7b. A high level ceiling zone carries lighting, air extract devices, fire detectors and sprinklers; the concrete floor slab is a fire barrier.

Six satellite towers, labelled T1 to T6 in Figure 7b, surround the building. Satellites T1, T3 and T5 are for circulation and escape and comprise a lobby, four high speed external passenger lifts, a staircase, toilet capsule and service riser. Towers T2, T4 and T6 are fire fighting and escape satellites. T4 and T6 contain a fireman's lift, staircase and service riser; satellite T2 contains an additional external goods lift.

Previous Work and Present Contribution

As part of the design brief Ove Arup & Partners conducted an environmental study of the atrium with external conditions corresponding to summer and winter. Simple aerodynamic calculations and predictions with a field model were used to estimate air movement inside the atrium[15].

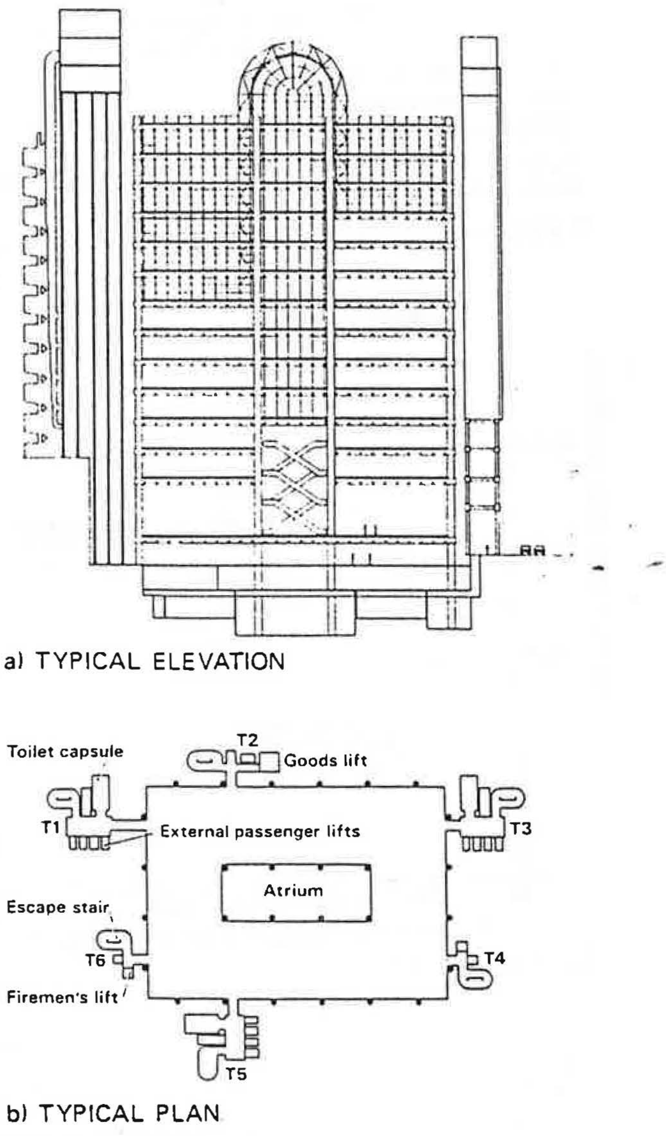

Figure 7. Lloyds Building.

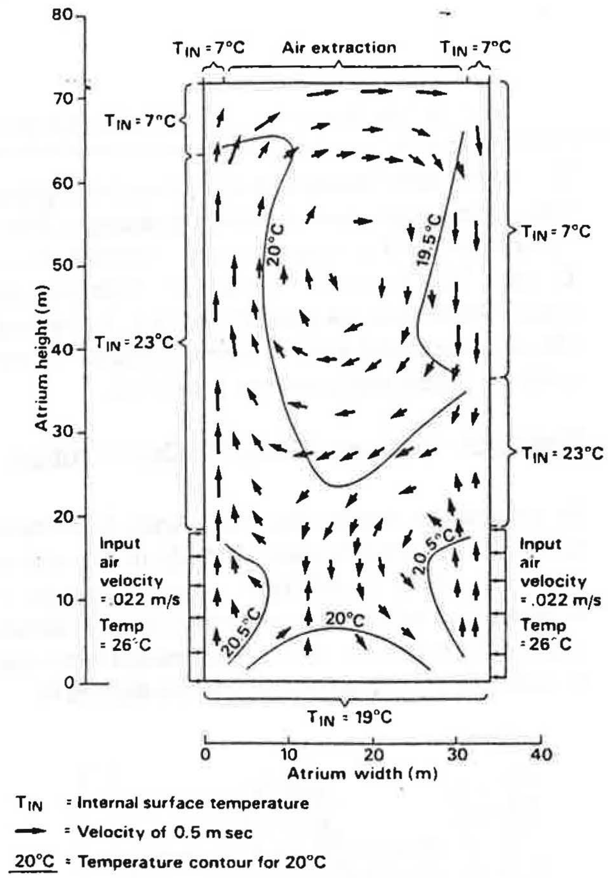

Figure 8. Velocity and temperature fields in the longitudinal slice.

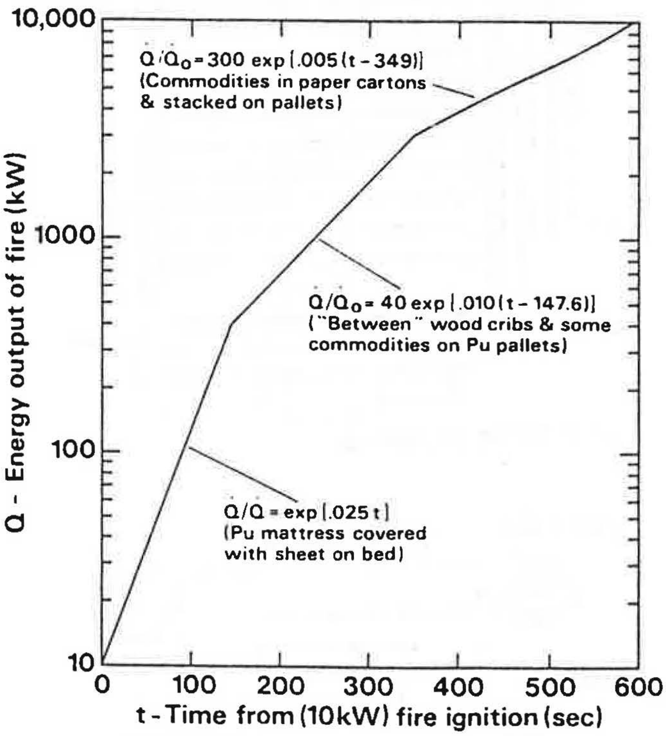

Figure 9. Design fire.

We calculated that on a winter's day cold downdraughts from the high level southerly glazing created a large re-circulation loop that approximately spread from the top of the atrium to the fifth galley level. A sample result for a slice through the atrium measuring 34.2 m wide is shown in Figure 8. This slice represents the situation corresponding to offices up to the sixth and twelfth galleries on alternate sides of the atrium. The loop is characterized by a slow moving center and fast moving edges where air speeds of up to 0.74 m/s occur. In summer we calculated that conditions were dependent on the ventilation strategy. Under certain circumstances a temperature stratification of the order 10-15°C between the top and bottom of the space could occur.

The building was completed in 1986, and our commissioning engineers have monitored air movement patterns and found them similar to those predicted. We therefore had some confidence in using field models to study the various smoke management scenarios in the atrium, with a small fire at ground level and existing air movement and stratification effects inside the atrium. Further, these were the only types of model with sufficient flexibility to take account of the internal climatic effects detailed above. We decided to start with the simplest possible simulation to test the adequacy of our modelling technique. This corresponded to a small growing fire at the center of the atrium floor and a still stratified environment within it. The forced smoke extract was switched on 120 seconds after the fire has started.

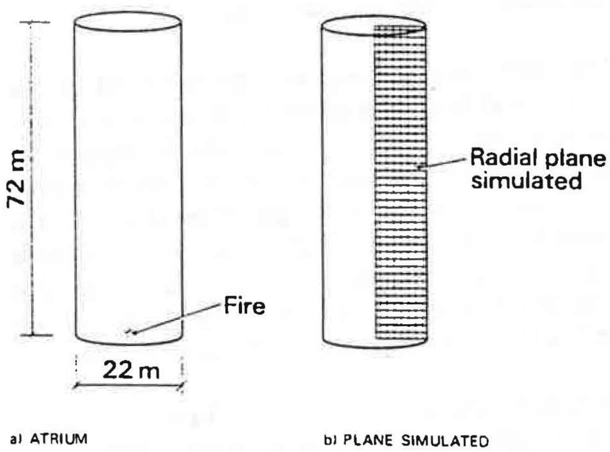

Figure 10. Atrium simulation.

Problem Description

The fire was assumed to grow in the way detailed by Cooper's data – the fire's output with time is reproduced in Figure 9. The flame height of the fire was assessed from Zukoski[16] equation detailed below.

$$Z = 0.23\,\dot{Q}^{2/5} \qquad (5)$$

The heat output was uniformly spread over the fire volume.

We assumed that there was a linear vertical temperature gradient – the temperature at floor level was 23°C and at the top of the atrium the temperature was 43°C. At the start of the fire the air in the atrium was stationary.

The turbulence of the air in the atrium was estimated by solving the two equation model for turbulent kinetic energy and dissipation proposed by Launder *et.al.*[4]. The differential equations for kinetic energy, k and dissipation ε have the same form as Equation 1, but with the values of ϕ Γ_ϕ and S_ϕ taking the values given in Table 3.

In these equations:

$$G = \mu_t\left(2\left[\left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial V}{\partial y}\right)^2 + \left(\frac{\partial W}{\partial z}\right)^2\right] + \left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z}\right)^2\right) \qquad (6)$$

$$G_B = \frac{\beta_g\, v_t}{\sigma_t}\frac{\partial \theta}{\partial y} \qquad (7)$$

and

$$\theta = T - T_{ref} \qquad (8)$$

The constants normally take the following values:

$C_1 = 1.44$; $C_2 = 1.92$; $C_D = 0.09$; $\sigma_k = 1.0$

Buoyancy generated turbulence has been allowed for by following the practice outlined by Rodi[17].

We intended modifying the constants C_D and σ_t to the settings recommended by Rodi[17]; these enable the spread and velocity changes in a buoyant plume to be accurately predicted. However, the solver used in the field model would not allow these corrections to be fully implemented. So we concentrated on modifying C_D which appeared to be the most important correction parameter; after investigation we selected 0.13 - which gave the best approximate fit to plume data used by Rodi.

The atrium simulated is shown in Figure 10a. It has a diameter of 22 m and height of 72 m. A field model was used to predict the flow pattern on the radial plane shown in Figure 10b. The grid spacing used was non-uniform with grid lines more closely spaced in the vicinity of the fire – typically nine hundred or three and half thousand cells were used. A temperature contour of 0.25°C above local ambient temperature was used to distinguish between smoke and air. We estimate that the criterion gives a smoke edge with an optical density of the order 0.03.

Results on Discussion

Sample results at 40 and 180 seconds after igni-

	ϕ	Γ_ϕ	S_ϕ	Buoyancy Effects
Kinetic energy	k	$\frac{\mu_{eff}}{\sigma_k}$	$G-\rho\varepsilon$	G_B
Dissipation	ε	$\frac{\mu_{eff}}{\sigma_k}$	$\frac{\varepsilon(C_1 G - C_2 \rho e)}{k}$	$\frac{\varepsilon C_1 G_B}{k}$

Table 3. Value of ϕ, Γ_ϕ and S_ϕ

tion are shown in Figures 11 and 12 respectively.

At 40 seconds the fire size is approximately equivalent to 0.1 MW and the smoke plume has risen some 20 m into the atrium. After 180 seconds the fire size is approximately 1 MW and the smoke plume has stratified at some 30 m above floor level. In both figures we have mapped the location of extremely light smoke – we estimate one could see 20-30 m through it. At this stage the smoke extract system has been on for forty seconds, and has begun to pull the smoke upwards. It should be noted that the bulge at the top of the stratified layer is caused by hot gaseous plume from the fire having sufficient vertical momentum to push through the stratified layer. Cooper[18] has investigated this phenomena, and obtained similar qualitative results with a physical model that used salt water.

Closure

The presented results indicate the model's ability to qualitatively predict smoke movement in an environment which is in motion or contains thermal gradients. The next phase of the study is to carry out detailed comparison with experimental data.

We have already noticed that algebraic plume

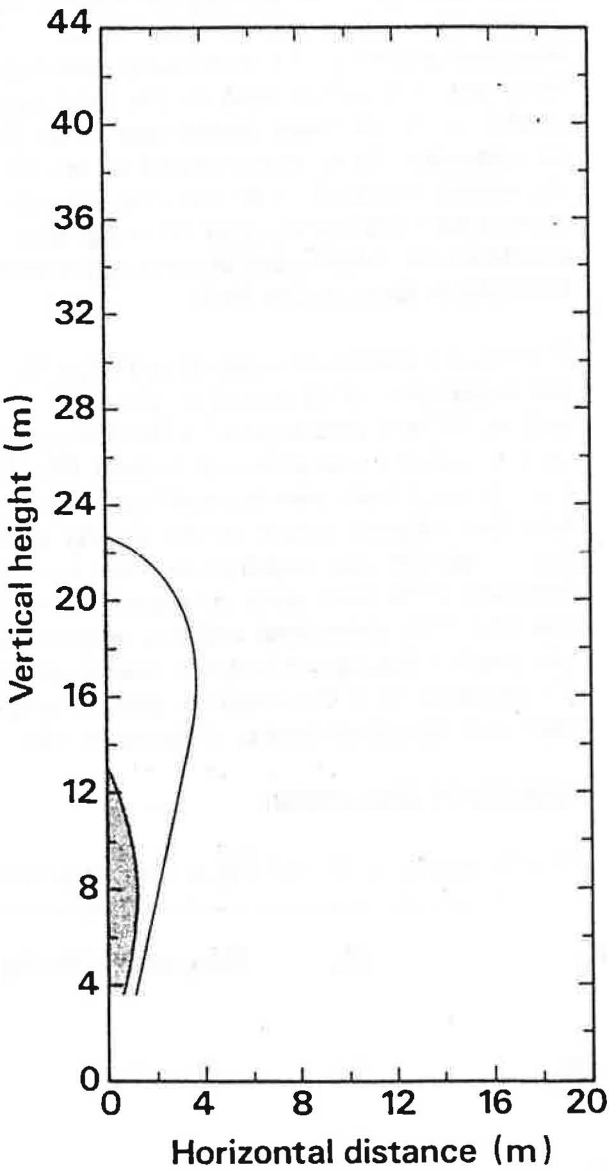

Figure 11. Edge of smoke after 40 seconds.

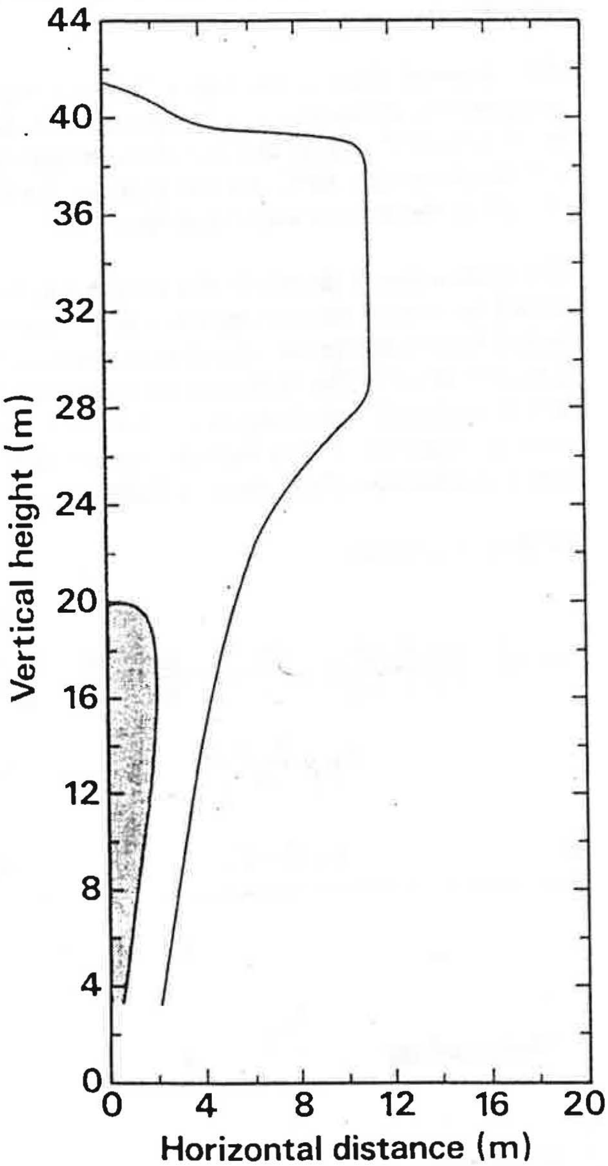

Figure 12. Edge of smoke after 180 seconds.

stratification equations, for example Equation (9) by Briggs[19], may not work correctly in atria when the plume nearly fills the atrium.

$$H = \frac{5\,F^{0.25}}{G^{0.375}} \qquad (9)$$

The reason for this is that these types of equation assume that the air entrained into the plume is at local ambient temperature. Once the atrium is full as shown in Figure 12, hot air from the plume is entrained back into the plume, making this assumption invalid.

Conclusions

The important advantages accruing from the use of field models are as follows. Their fundamental fluid and thermodynamic basis means that they can be applied to a variety of different building applications with confidence that no "rule of thumb" assumptions will invalidate their use. Design changes can be relatively easily embodied into them. The predicted results give designers and engineers a qualitative insight into the movement of air and smoke.

Acknowledgement

The author acknowledges the help of Ms. M. Law of Ove Arup & Partners; without her enthusiasm, advice and great knowledge of the science of fire engineering the presented work could not have been carried out.

The author also thanks Mr. G. Cox, Fire Research Station, England, and Professor N.C. Markatos, NTU Athens, Greece, for their advice and help.

Nomenclature

BF Body force term
F – Plume Froude number
G – Plume Grashof number
g – Gravity
H – Maximum plume rise
k – Turbulent kinetic energy
T – Temperature
P – Pressure
U – Steady state horizontal velocity
V – Steady state vertical velocity
W – Steady state lateral velocity
x – Horizontal co-ordinate
y – Vertical co-ordinate
z – Lateral co-ordinate
Z – Flame height
β – Coefficient of cubical expansion
σ – Dissipation temperature difference (i.e. $T - T_{ref}$)
θ – Viscosity
μ – Dynamic viscosity
ρ – Density

Subscripts
eff Effective
t Turbulent
k kinetic

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