HONG KONG MASS TRANSIT RAILWAY

Conceptual Development of the Environmental Control System for the Hong Kong Mass Transit Railway

by W.W. Hitchcock, Ph.D.
Parsons Brinckerhoff Quade & Douglas, Inc.
New York

and D.E. Driver, Director of Operations
Drake and Scull Engineering Ltd.
Hong Kong

February, 1977

Drake & Scull Engineering Ltd
(Incorporated in the UK)
20th Floor, World Trade Centre, 280 Gloucester Road, Hong Kong. Telephone: 5-760411. Telex: HX75673. Cables: Scull Hongkong

Background

The control of environment in the underground portions of fixed guideway mass transit systems has in recent years come to the fore as a significant systemwide element. Today's generation of high-performance, air-conditioned rolling stock produces large quantities of heat which, if not properly dealt with, lead to patron discomfort and possibly even distress. The transit system proposed for Hong Kong presents factors which make proper engineering of the Environmental Control System (ECS) even more critical. Not only does Hong Kong experience severe temperature and humidity ambient conditions for many months of the year, but the urban railway is being designed to carry almost twice the maximum passenger loading of other comparable systems (Ref. 1).

The Hong Kong Mass Transit Railway Corporation (MTRC) recognised the potential consequences of an uncertain ECS, both in terms of reduced ridership and patron safety. This recognition led to the commissioning of Drake & Scull Engineering Ltd. in association with Parsons Brinckerhoff Quade and Douglas Inc. to undertake a study of ECS performance goals and alternative engineering solutions leading to positive recommendations on the most viable and economical concept for that portion of the Mass Transit Railway known as the Modified Initial System (MIS) (Ref. 2).

Implementation of this two-month Initial Design Study (IDS) was on a team basis, utilizing experienced professionals in the fields of subway environmental analysis, equipment design and performance, automated controls, and plant design and construction. Detailed, quantitative analyses of alternative ECS concepts were made possible by the use of latest state-of-the-art techniques as reflected in the Subway Environmental Design Handbook (Ref. 3) and the Subway Environment Simulation (SES) computer model (Ref. 4), developed and verified during an ambitious four year research program sponsored jointly by the United States Department of Transportaion and the the American Public Transit Association, which represents the operating transit agencies in North America.

The IDS comprised three distinct phases of work:

* **ECS Performance Goals,** including recommendations for air temperature, humidity and velocity criteria in the underground stations and tunnels during normal and emergency operating conditions.

Analysis of Alternative Engineering Solutions, including detailed performance analysis of three alternative ECS concepts under normal conditions and emergencies, and recommendation of the best concept.

* **Mechanical Systems Development,** including the development of preliminary functional specifications for major equipment required by the best ECS concept.

ECS performance goals

The objective of the ECS is to provide for the comfort and safety of people and protection of equipment. Generally stated, the ECS should maintain temperature and humidity within prescribed tolerances, achieve effective control of air flow (both velocity and direction), air quality, and air pressure transients, protect against condensation, and operate at acceptable noise levels in stations, tunnels and to the external environment. ECS performance goals were developed for a range of train operating conditions in the Hong Kong subway including:

***Normal (Rush Period) Operations—**
8-car trains operating at 2-minute headways; no train delays in tunnels.

***Congested Operation—**
8-car trains delayed briefly in tunnels before entering a station due to peak rush period traffic delays.

***Train Emergency Operation—**
Up to two 8-car trains, loaded to crush capacity, delayed in a tunnel for a prolonged period of time (on the order of 30 minutes).

*** Serious Emergency Operation—**
Emergency involving an 8-car train disabled in a tunnel and requiring evacuation with the presence of fire and smoke.

In the underground stations, environmental design conditions for normal operations were based on consideration of physiological comfort. These conditions were developed using a method for computing Relative Warmth Indices (RWI) described in the Subway Environmental Design Handbook Volume I (Ref.3). The RWI technique enables the development of a histogram which traces the comfort aspects of the transient environment experienced by passengers moving from the outside through the subway station concourse to the train platform and entering a train. The RWI method considers passenger activity and its duration, taking into account metabolic rate, insulation of clothing (clo value), total air velocity (ambient plus activity induced), air dry bulb temperature and humidity and mean incident radiant heat. In this manner, the unique transitional aspects of short-term exposure can be accounted for in setting comfort criteria.

An engineering application of the RWI method to the Hong Kong subway produced design conditions for the concourse and platform which fell between outside ambient conditions and the conditions to be maintained within the trains by on-board air conditioning, providing an increasing sensation of comfort for the passengers as shown by the illustrative histogram of Figure 1. It is important to note that the values shown by Figure 1 were established only for the purposes of the IDS. The final choice of appropriate comfort criteria may be subject to other factors, including the level of comfort in the subway in comparison with competing transportation modes, energy conservation, and capital and operating cost comparisons.

In the subway tunnels, the concern is for maintenance workers in the tunnels, passengers on board trains in the event of a failure of the on-board air conditioning system and, in the event of a serious emergency, for passengers who may be required to detrain into the tunnel environment. If the tunnel environment is not adequately controlled, people within the tunnel will be exposed to substantial risk to health as can be demonstrated by an evaluation of physiological stress.

Figure 2, based on data in the ASHRAE Handbook of Fundamentals (Ref. 5) and adjusted to reflect anticipated metabolic rates, air velocities, etc. of people in the tunnel environment, demonstrates the factors which influence physiological stress. Considering the regions identified as "Uncomfortably Warm" and "Intolerable", one of the most noteworthy observations is the sensitvity of physiological stress to humidity. Note, for example, that for the outside ambient design conditions established for the IDS, the environment becomes uncomfortably warm at a dry bulb temperature of approximately 92F, while at station platform design humidity the uncomfortably warm region is reached at 103F dry bulb. The difference in these temperatures is even greater when entering the intolerable region, emphasizing the need to properly control the tunnel environment in Hong Kong's humid climate.

In addition to considerations of physiological stress in the tunnels, it is also importment to insure that the environment does not compromise the proper operation of equipment. This applies to the signalling systems, transformers, etc. but of more direct concern to passenger safety is the operation of the on-board air conditioning system. When loaded trains are stopped in tunnels, the high rate of heat generation can lead to substantially elevated temperatures along side the train(s). According to manufacturer's data, when the inlet air temperature to the on-board A/C condenser exceeds a value on the order of 115F, the cooling capacity of the A/C unit is degraded, leading to uncomfortable or possibly dangerous conditions within the train. Thus it is important that the ECS performance precludes the eventuality of such excessive temperature levels.

Historic events have shown that serious emergency conditions involving fire and smoke within an underground rapid transit system can lead to tragic consequences involving loss of life and property when not properly managed. An essential requirement is that the amount of combustibles within the system be kept to a minimum. However, even a well engineered transit car contains construction materials equivalent to hundreds of gallons of petrol in heat content. Given the essential elements of a fire — fuel, oxygen and a heat source in the form of large quantities of electrical energy consumed at high current levels and large quantities of mechanical energy dissipated as friction — it is essential that effective strategies be formulated to deal with the eventuality of serious emergency situations. The ECS is only one factor in a comprehensive plan to deal with fire emergencies. Fire prevention, accident survival and emergency response disciplines must all be brought to bear. The objectives of ECS emergency ventilation procedures are as follows:

* Provide a safe and reliable evacuation route from trains and stations.

* Provide predictable air flow movements and control of smoke.

* Provide control of air temperatures.

* Provide directives easily understood and implemented by operating personnel.

Proper development of an ECS which meets these objectives must include evaluation of such disparate phenomena as the buoyant stratification and movement of heated air and its impact on fan-induced air flows, and the severe environment to which ECS components may be subjected. A comprehensive study of a range of possible serious emergency situations and proper ECS operating modes is required for the development of a procedures manual for operating personnel.

Design Conditions

	Deg. Fdb	Deg. Fwb
Outside	90	82
Concourse	86	76
Platform	83	74
Train	80	71

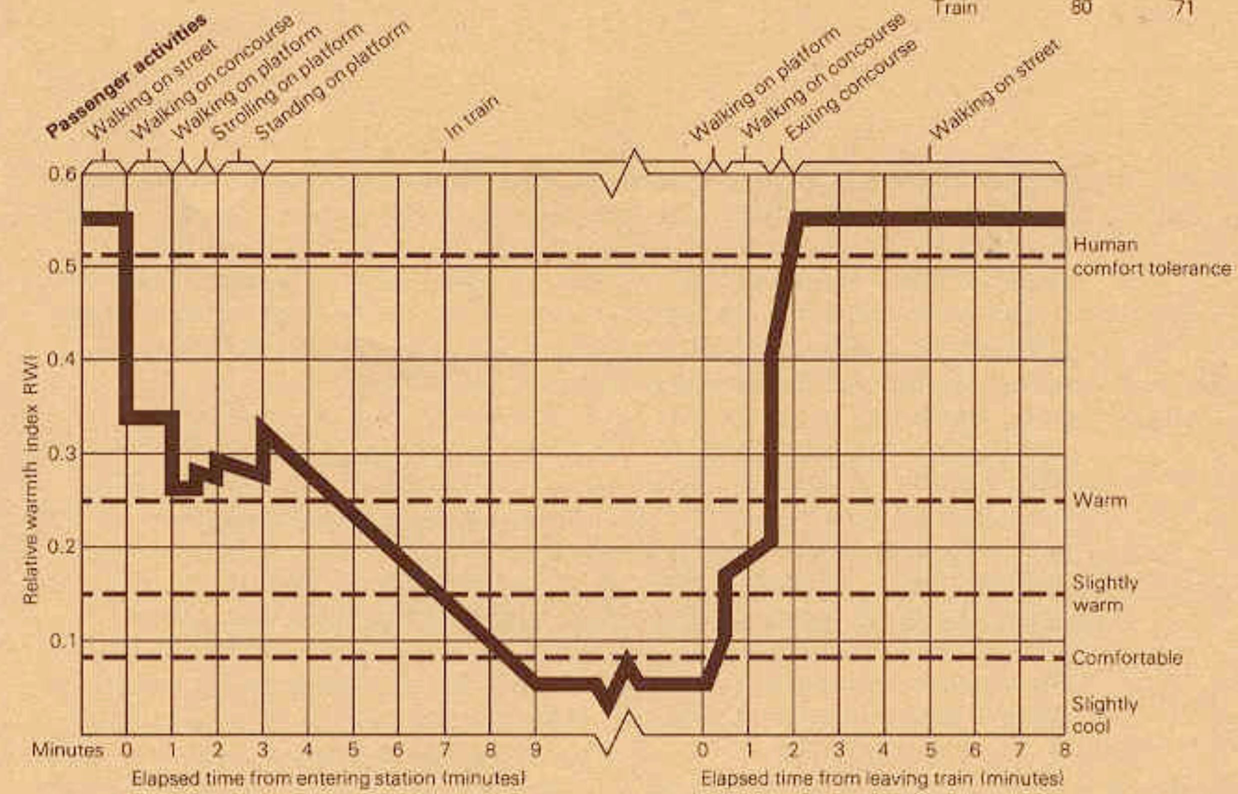

Figure 1
Relative warmth histogram in subway system: Evening rush period

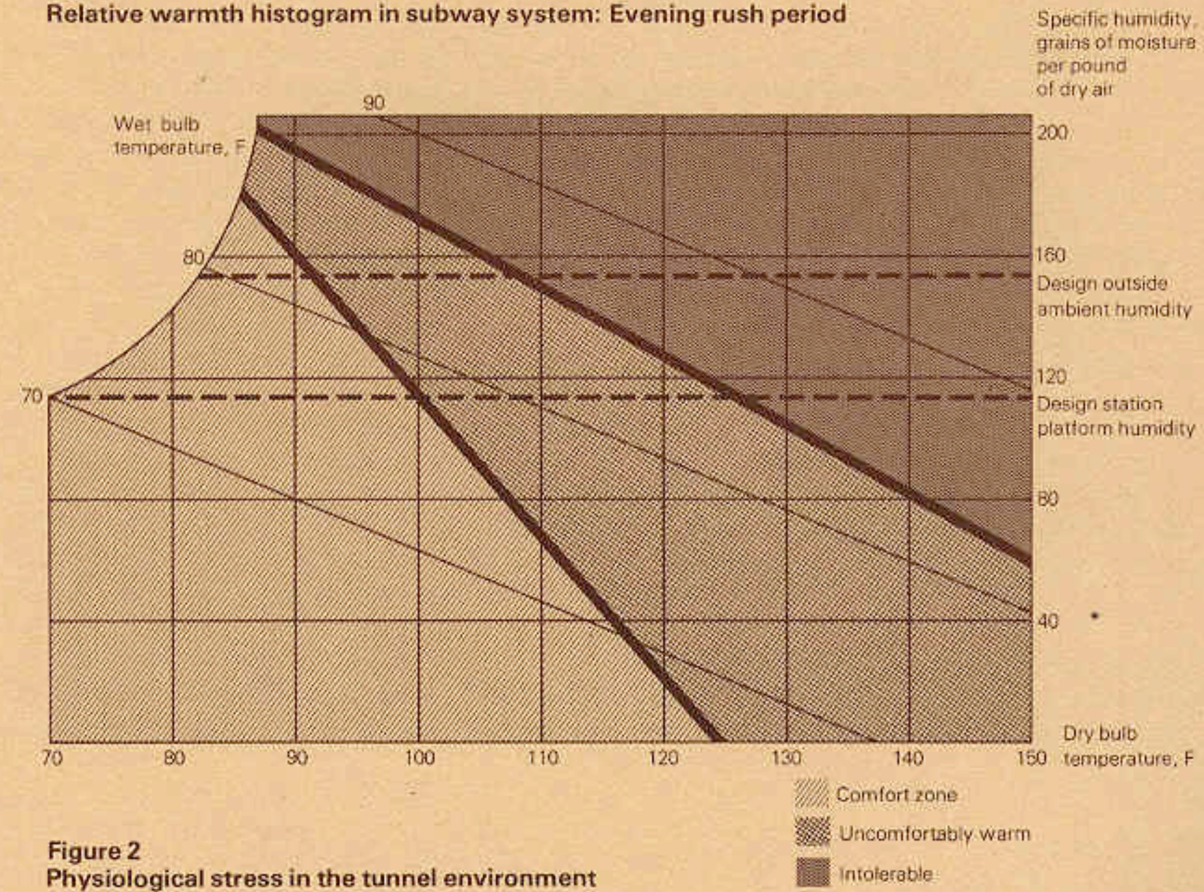

Figure 2
Physiological stress in the tunnel environment

Alternative concepts

As would be be noted in a review of ECS schemes used by underground rapid transit systems around the world, there are numerous ways in which mechanical equipment, ventilation shafts and the like can be applied to affect the underground environment. This review also would illustrate that in many systems the environment leaves something to be desired, particularly during the heat of the summer. One of the main reasons for this situation has been the lack of analytical methods for scientifically engineering the ECS.

The basic complexity which defied analysis in the past is the transient, dynamic nature of the subway environment and the factors which influence it. The operation of trains through the system causes large magnitude "piston-effect" air flows which interact continuously, convecting train-borne heat throughout the system. In turn, the heat content of the air is affected by the subway structures and surrounding earth, a phenomenon known as the "heat sink" effect.

Recognition of these complexities and the lack of fundamental knowledge on subway environmental control lead to the development of the SES program, a unique engineering tool for evaluating in detail the combined dynamic effects on environment of an operating subway and proposed ECS. If mechanical cooling of stations is to be used to help control the environment, the SES translates the calculations of dynamic environment into refrigeration plant capacities required to achieve specified design conditions and provides readings of the resulting air velocities, temperatures, humidities and heat sink conditions throughout the subway. The SES not only enables evaluation and comparison of alternative ECS concepts, but also provides information essential to proper functional specification and design of ECS equipment, cooling load distribution and the like. Verified through comprehensive field tests on operating properties in the United States and Canada, the SES computer model was selected as the principle analytical tool for the IDS engineering evaluation of alternative concepts.

The objective of this evaluation was the identification and development of an ECS concept which met the performance goals set forth and required the lowest capital expenditure and operating costs. Each of the concepts considered was constrained as to the location of ventilation shafts, fixed previously by land acquisition, civil design and the progressing construction program. Generally, these shafts connecting the subway tunnels to the surface are positioned near the ends of each station with one shaft serving each of the trackways.

Because of the conceptual nature of the IDS objective, the study focused on a limited region of the MIS, comprising Lok Fu, Wong Tai Sin and Diamond Hill stations and adjoining tunnels (see Figure3). Particular emphasis was placed on

Wong Tai Sin, being centrally located in the study area. A preliminary engineering review lead to the identification of three basic ECS concepts to be compared:

*** Open System Concept**

The first concept was a conventional ECS configuration utilizing, for normal operations, a station air-conditioning supply system and a station trainway extraction system to remove train-borne heat at the source. No fans were used in the tunnels, and natural ventilation through open vent shafts via train piston action was unrestrained.

***Station Isolation Concept**

This concept employed, in addition to station air conditioning and trackway extraction, a novel and sophisticated air curtain device at all station/tunnel portals to limit the exchange of tunnel and station air. The tunnels were ventilated by train piston-action with outside air drawn through the shaft behind a train and exhausted through the shaft ahead.

***Closed System Concept**

This concept is similar to the open system, except that natural piston action ventilation is precluded by maintaining dampers in the shafts in a fully closed position. With this concept, the tunnel air is cooled and dehumidified to a degree during normal operations by the train-induced flow of conditioned station air into the tunnel sections.

The open system concept was included in the IDS to confirm intuitive expectations that, with the severe summer ambient conditions in Hong Kong, a conventional ECS employing open tunnel vent connections would not be attractive. The study findings confirmed this supposition: the station cooling load due to the natural flow of outside air into the system through the open shafts was on the same order as the heat generated by trains, and was about ten times greater than the corresponding load for the closed system configuration.

The station isolation system seems an obvious solution to this situation. However, SES analysis showed the tunnels, ventilated with ambient air and heated by train operations, to be well into the "uncomfortably warm" stress region even during normal operations. During congested and train emergency situations, tunnel conditions extended significantly into the "intolerable" stress zone.

The Closed System ECS concept proved to be the engineering solution to the established performance goals. Properly implemented, this concept will achieve effective control of temperature and humidity throughout the subway, protect

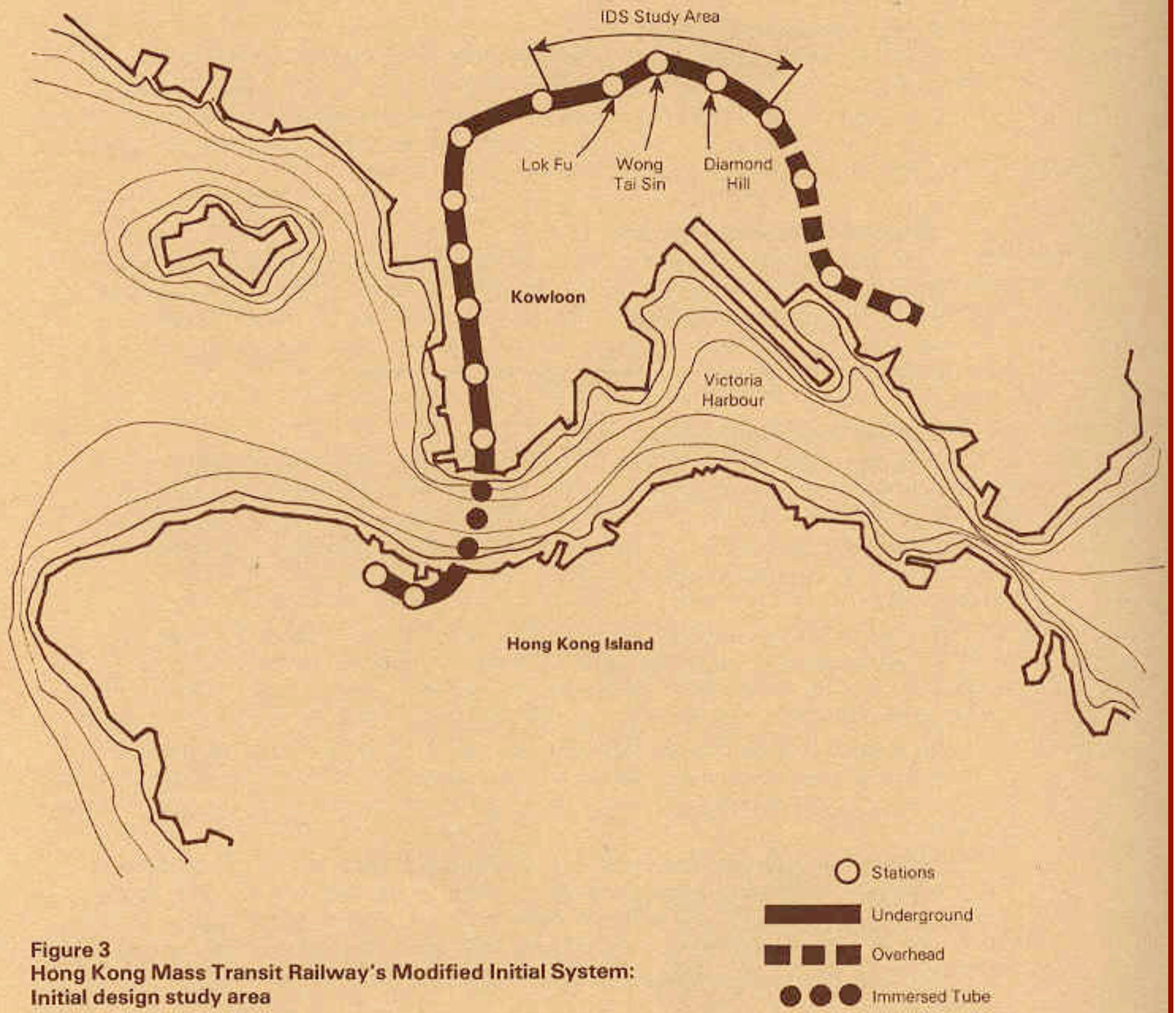

Figure 3
Hong Kong Mass Transit Railway's Modified Initial System: Initial design study area

against condensation and operate at acceptable noise levels. Furthermore, this concept takes full advantage of normally occurring phenomena within the subway, such as train-generated piston-action air flow and the ground heat sink effect around tunnels.

During normal operations, the tunnels are cooled by the station air drawn into the tunnels by train piston-action producing conditions within the comfort region shown on Figure 2. In turn, the heat convected into the station by air flow comprises tunnel heat (from trains, power rail and lighting, which is not absorbed by the heat sink) and the heat content of ambient air drawn through the entranceways by train piston-action. The latter effect is reduced, particularly during rush hour operations, by the air flow recirculation at the ends of each station between the approach and departure tunnels. This air flow behaviour is graphically depicted by Figure 4, which shows typical SES-computed air flows at one end of Wong Tai Sin station during 2-minute headway operations. The accompanying train situation diagram on this figure enables detailed analysis of the cause and effect of the train-induced air flow.

Positive control of tunnel environment during congested and train emergency operations when the piston-action ventilation is unreliable requires an additional ECS component – the impulse fan system (IFS). The IFS, a possible configuration of which is shown by Figure 5, is an adaptation of the induction fan system used for the longitudinal ventilation of some road tunnels. The principal difference in the IFS, to be accounted for by proper design, is the much higher tunnel air flow resistance occasioned by the blockage of one or two stopped trains. By proper sizing of the IFS relative to the heat generated by trains stopped in the tunnels, the tunnel environment can be directly controlled without compromising the integrity of the closed system.

Serious emergency ventilation requires the use of the ventilation shafts and fans to control the movement of heated air and smoke and expel this vitiated air from the subway environment. Axial fan and bypass damper arrangements in each of the ventilation shafts represent an obvious solution to the requirement. With this approach the fans should be fully reversible to accommodate the spectrum of conceivable emergencies. A drawback of this approach is the large number of fans which must be activated to produce sufficient flow of outside air through a tunnel occupied by a stalled train. Since the fan-induced air flow seeks the path of least resistance, most of the flow is through empty tunnels and station stanceways, and the fan-induced air flow must be many times greater than the flow required past the stalled train. An alternative arrangement which overcomes this drawback involves the use of a multi-purpose IFS, capable of supplying either subway air or outside air, and possibly acting as a conventional exhaust fan as well. Such a system would require fewer fans overall, but would involve extensive use of motorized dampers. Such alternatives as the multi-purpose IFS should be carefully weighed during the final design of the ECS.

Other attributes possible with the Closed System concept include:

*The ability to pre-cool tunnel sections, thus controlling and improving heat sink characteristics.

*The ability to provide partial cooling from adjacent stations in the event of a temporary plant breakdown or localized power failure.

*Proper filtration of all supply air to the system (with the exception of entranceway infiltration), thus substantially reducing maintenance of station finishes and tunnel sections and prolonging equipment life.

Associated with the Closed System ECS are unique features which must be considered carefully in finalizing the capacity of station plants. In contrast with the open systems used in more temperate climates, where outside air can be used to remove a portion of the subway heat gains and limit system temperature rise, the heat generated within the closed system must either be removed by the heat sink effect of the structures and surrounding earth or by the ECS. The heat sink effect can be controlled and maximized within limits by proper operation of the ECS. However, if the station refrigeration plant is undersized even when full practical use is made of the heat sink, the excess heat within the system will produce a serious degradation of environment — an "insulated-box" behavior. Alternatively, proper sizing of the station plant can produce near-optimum conditions system-wide.

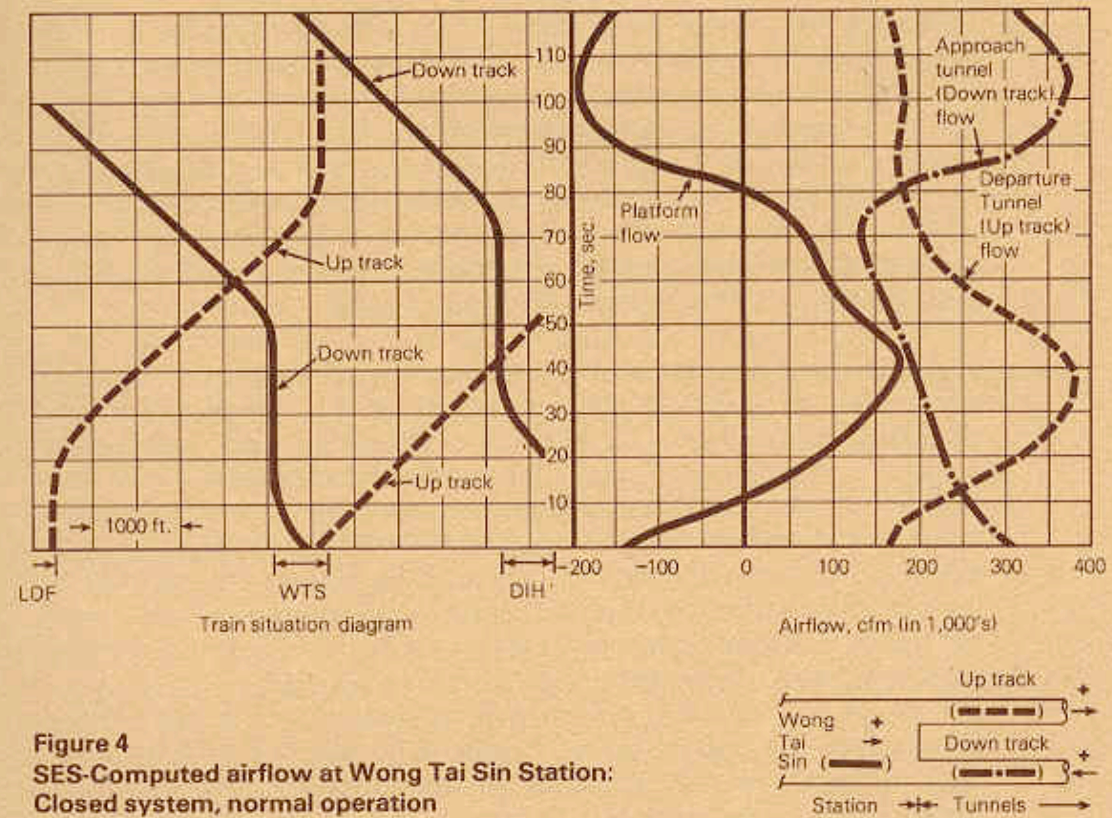

Figure 4
SES-Computed airflow at Wong Tai Sin Station: Closed system, normal operation

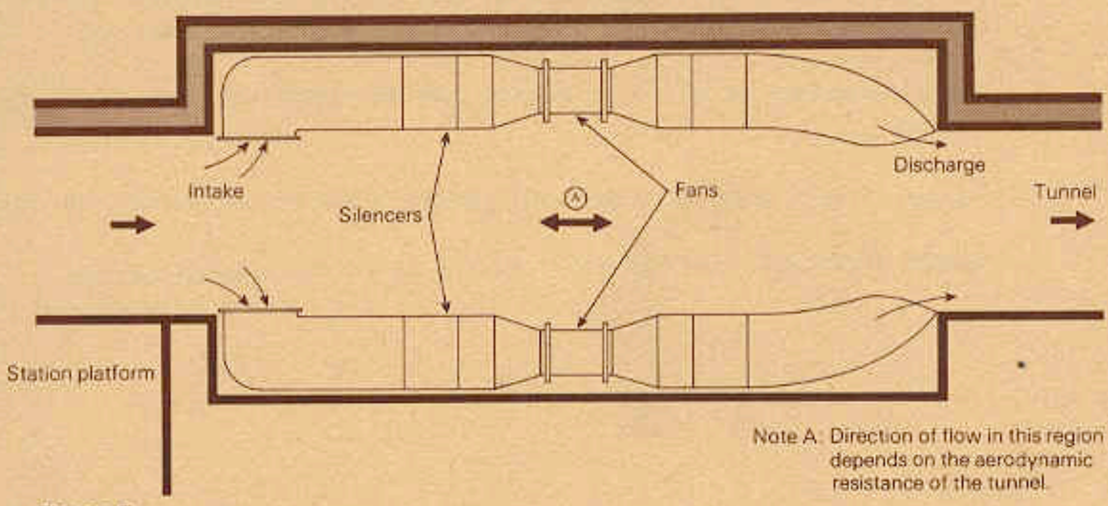

Figure 5
Impulse fan system schematic

Mechanical systems and control

Following selection of the Closed System ECS, the Initial Design Study proceeded with the development of preliminary functional specifications for the major equipment items. Refrigeration plant capacity was estimated for Wong Tai Sin Station, along with the pressure and flow requirements of the fans required by the Closed System ECS, and a preliminary exercise was implemented to evaluate the adequacy of the mechanical equipment rooms as well as impacts on the ongoing civil construction program. For the station mechanical plant, general process flow diagrams were formulated showing the arrangement and operating modes required of the equipment.

The findings of this task showed, for example, the benefits of an exhaust system which extracts air in the vicinity of heat producing equipment on board trains stopped in the stations. During summer operations, this "trackway exhaust system" can be used to reduce the net internal refrigeration load in the station, hence the required conditioned supply air volume, by significantly reducing the encroachment of train heat on the station platform envelope (see Ref. 6 for further amplification). The trackway exhaust system has the added benefits of providing the train air-conditioning condensers with cooler air while the train is stopped in the station and reducing the station air temperature swings associated with the movement of trains. The evaluation also showed that because of the high heat content of the outside air during the summer months, the total refrigeration coil load would be considerably lower if the trackway exhaust air were routed to the coil side of the refrigeration plant rather than exhausted from the station to be replaced with outside air make-up. In addition, this ECS component should have the capability to exhaust to the outside during cooler months of the year.

As the above example suggests, the study of ECS configuration and operating modes documented the need for considerable flexibility in order to:

*take full advantage of the previously identified potential attributes of the Closed System ECS,

*utilize "free cooling" to maximum advantage during cooler months of the year,

*perform properly over the wide range of train operating conditions.

Given these far-reaching ECS requirements, the advantages of centralized monitoring and control are clear. The number and combinations of mechanical sub-systems to meet the operating requirements make manual control unattractive, and the interactions among these subsystems throughout the subway, an inherent feature of the Closed System, render local control impractical. The routine decisions required for the proper, energy efficient operation of the ECS during normal train service can be centralized and automated, thus reducing demands on the operating staff and facilitating trouble-shooting of mechanical equipment failures. In emergency situations, the centralized facility enables trained personnel with an overview of the status of the entire system to make rational decisions regarding appropriate ECS operation.

Concept to installation

The IDS served to identify the best ECS for the Hong Kong subway, but much work remains in the successful translation of this concept into a detailed working design and installation. While the stations in the study area are of a two-track, center platform arrangement, several other stations are single-track, over/under arrangements; three track stations, or multi-level stations providing for future expansion of the system. Similarly, fully half of the interstation tunnels of the MIS are complicated by scissor crossovers and the like which provide for aerodynamic and thermodynamic intercommunication, and the immersed tube beneath Victoria Harbour deserves special attention. Thus, successful interpretation of the Closed System concept on a site-specific basis throughout the MIS requires a thorough engineering evaluation. Some of the major considerations are as follows:

*Special provisions may be required in some stations (e.g. over/under track arrangements) to adequately handle approach/departure tunnel air recirculation and prevent draughty and uncomfortable station conditions.

*Conditioning of the air recirculating between approach and departure tunnels by proper design of the station supply air distribution system is important to tunnel heat sink performance, controlled tunnel conditions, and proper operation of the station plants.

*Special provisions may be required in tunnels with crossover connections; those terminating at portals; or which are particularly long, to achieve acceptable tunnel environment, preserve the integrety of the Closed System, and avoid excessive heat burdens on the connected stations.

*Operational flexibility in the ECS design and control systems to achieve specified daily and annual operations cycles is essential to successful functioning of the Closed System and controlled behaviour of the tunnel heat sink. In addition, adjacent stations should be able to "share" the load, thus avoiding the possibility of intolerable conditions caused by partial plant failure.

*Proper selection of cooling coils and controls, given the recirculation of trackway ventilation air to the coil side of the refrigeration plant, will avoid "slugging" which degrades chiller performance as well as station environment.

*Proper design of the impulse fan installations will avoid the problems of performance, excessive power requirements and excessive noise generation.

Proper sizing of the ECS equipment is on a par with proper site-specific design interpretations in importance. Equipment sizing must be based on precisely specified subway operations, yet in the case of a new system such as Hong Kong's such key parameters as patronage estimates, passenger loadings and even train operation and frequency must be estimated without the benefit of actual operating experience. For the Closed System configuration over 80% of the station plant refrigeration capacity traces directly to patronage estimates and train operations. The actual patronage and train operations will undoubtedly vary from the theoretical forecasts that formed the basis of design and it may therefore be prudent to make provisions in the initial installation for future increase in station plant capacity without disturbing revenue earning operations.

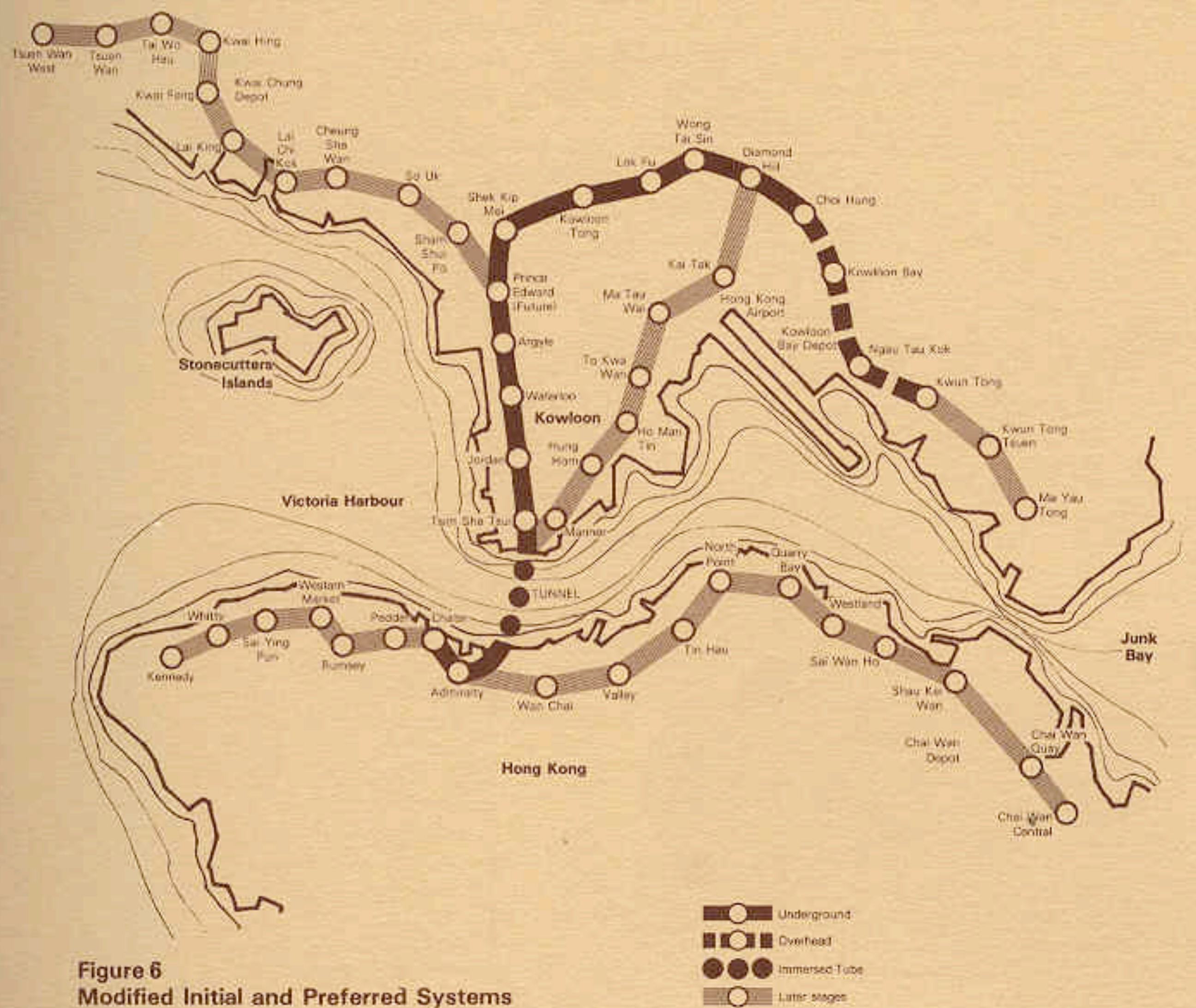

Figure 6
Modified Initial and Preferred Systems

Conclusions

The Closed System ECS has been selected by the Mass Transit Railway Corporation for implementation in the underground portion of the Modified Initial System. Properly engineered and operated, this ECS will provide fully for the comfort and safety of patrons and the protection of equipment.

Although the Closed System is conceptually simple and straightforward, the overall performance of the ECS is tied closely to the coordinated functioning and interaction of all of the ECS components. These components are linked in the Closed System to a degree never before encountered in subway environmental control by the direct, unattenuated aerodynamic and thermodynamic communication among the stations and tunnels. As a consequence, such normally occuring phenomena as train-generated piston-action air flow and ground heat sink effect assume major roles in the ECS performance and can cause adverse cascading effects unless they are accurately anticipated and employed to advantage.

References

1. Ridley, T.M. "Mass Transit Comes to the Tropics," **The Railway Gazette International,** January 1976.

2. Coulson, C.R. "Planning of the Initial System of the Hong Kong Mass Transit Railway," **Hong Kong Engineer,** Vol. 4, NO. 3, June 1976.

3. Associated Engineers, a Joint Venture of Parsons, Brinckerhoff, Quade & Douglas, Inc., Kaiser Engineers and DeLeuw, Cather & Co., **Subway Environmental Design Handbook Volume I. Principles and Applications,** Second Edition, U.S. Department of Commerce, National Technical Information Service No. PB-254 788, March, 1976.

4. Associated Engineers, A Joint Venture, **Subway Environmental Design Handbook Volume II, Subway Environmental Simulation Computer Program** (SES), U.S. Department of Commerce, NTIS No. PB-254-789, Parts 1-3, October, 1975.

5. **ASHRAE Handbook of Fundamentals.** American Society of Heating, Refrigerating and Air-Conditioning engineers, Inc., New York, 1972.

6. Hitchcock, W.W. "The use of Underplatform Ventilation Systems in the Control of Subway Thermal Environment," **ASHRAE Transactions** (to be published) February, 1977.