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ASSESSMENT OF THE IMPACT OF DIPPED GUIDEWAYS ON URBAN RAIL TRANSIT SYSTEMS

VENTILATION AND SAFETY REQUIREMENTS

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ABSTRACT

This report documents a study performed by Kaiser Engineers to evaluate the ventilation and fire safety requirements for subway tunnels with dipped profiles between stations as compared to subway tunnels with level profiles. This evaluation is based upon computer simulations of four tunnel configurations with normal train operations and an additional computer simulation of a train fire emergency condition. Each of the tunnel configurations evaluated was developed from characteristics that are representative of modern transit systems. No attempt was made to optimize the ventilation and train operational aspects for each tunnel configuration. Rather, only the parameters describing tunnel size and profile between stations were varied. The results of the study indicate that: 1. The level tunnel system required about 10% more station cooling than dipped tunnel systems in order to meet design requirements. 2. The emergency ventilation requirements are greater with dipped tunnel systems than with level tunnel systems. Although mid-tunnel fan shafts are not essential for emergency ventilation, their elimination should come only after full consideration of: the additional station fan capacity needed to provide the same airflow capability, the loss of a potential evacuation route, and the increased sensitivity of the emergency ventilation procedure to fan failure. 3. Further study should be made of train performance on a dipped guideway system, and the possible penalities for deviations from the preferred acceleration and braking zones.

TABLE OF CONTENTS

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I. INTRODUCTION

In March, 1981, the Jet Propulsion Laboratory (JPL) requested that Kaiser Engineers conduct a study to evaluate the ventilation and fire safety requirements for subway tunnels with dipped profiles between stations as compared to subway tunnels with level profiles. This study was one of four studies being sponsored by JPL to evaluate in detail certain key aspects of subways constructed using the dipped guideway concept.

A description of the dipped guideway or Gravity Assisted Rapid Transit (GART) concept can be found in the report "Alternative Concepts for Underground Rapid Transit Systems" prepared by the JPL in March, 1977 for the U.S. Department of Transportation, #DOT-TST-77-31.

The dipped guideway concept or dipped profile tunnels offer the potential for large savings in energy costs in high-performance underground rail mass-rapid-transit systems. However, before this type of system can be fully considered for any particular transit application, the operating cost and other advantages must be weighed against the potential problems that may be inherent to dipped profile tunnels. For this study Kaiser Engineers considered the impacts on ventilation of a dipped profile tunnel. With a dipped profile, there would be less train braking heat released into the tunnels than with a level profile because the trains would be braking on an upgrade. This indicates a savings in ventilation costs with the dipped profile tunnel. During a train fire emergency condition, buoyant effects of hot air would be greater in dipped profile tunnels than in level tunnels. This indicates an extra ventilation cost with the dipped profile tunnel in order to be able to fully control the movement of air. The study discussed here addresses both normal ventilation as well as ventilation during a train fire emergency for the level and dipped profiles, single and double track tunnels.

II. TECHNICAL DISCUSSION

A. Approach

The study was performed using the Subway Environment Simulation (SES) computer program. This program simulates aerodynamic and thermodynamic conditions in subway systems. The parameters that characterize the physical and operational attributes of a transit system were selected for computer input. Subway tunnel geometries, train characteristics, and operating conditions were selected as representative of a modern transit system. The specific key parameters are discussed in the following section. These parameters were used to develop an SES computer model for each type of system being evaluated.

In all, four computer models were developed for the normal ventilation portion of the study. The four models corresponded to the four tunnel configurations (between stations) that were considered:

1. Two single track tunnels, level profile
2. Two single track tunnels, dipped profile
3. Double track tunnel, level profile
4. Double track tunnel, dipped profile

In terms of ventilation, the single track tunnels could be considered as side by side or over/under.

In determining the performance characteristics for the normal train operation, we made use of Kaiser Engineers' Transit Operational Model (TOM) computer programs. The TOM programs compute information such as train travel times, average speed, acceleration, and energy consumption.

A separate SES computer model was developed to examine a train fire emergency situation. For this condition, we modeled a single track tunnel system with a dipped profile with no mid-tunnel fan shafts. The fire was located near the lower portion of the downgrade and the fans were operated in such a way as to move air downhill past the fire. This condition was thought to be the most demanding on the ventilation system's capabilities. The SES computer program was used to estimate air temperature and airflows for fire conditions corresponding to low heat release and high heat release.

Although we did not model alternative train fire locations, our past experience on this subject is extensive enough to justify a manual analysis of the alternative locations. It is important to note that ventilation is only one aspect of fire safety and other aspects such as evacuation and fire-fighting are not directly addressed in this report.

B. Computer Models

1. Parameter Selection

The parameters chosen to characterize the four types of systems being modeled were selected from data representative of modern transit systems. In order to have comparable results between the dipped and level systems, certain parameters that may ordinarily be varied to achieve optimization, were held constant. Such parameters include maximum train velocity, train motor characteristics, train synchronization, station to station travel times, steady state heat sources, wall surface temperatures and fan types. This type of parameter selection, although not optimized for each case, produces results that can be useful in a general sense for comparative analysis.

a. Physical Parameters (See Table A)

The geometric configurations for the four computer models are shown in Figure 1. The station spacing is 5,000 feet in each model. A uniform station spacing for each model was chosen so that it would not be necessary to determine the sensitivity of air flows and temperature distributions to station spacing. The length of station platform is 300 feet, long enough to accommodate a four-car train. This is the alternative platform length considered in the JPL report reference in the Introduction. Typical tunnel characteristics such as area, perimeter and roughness were chosen using the Subway-Environmental Design Handbook as a guide and were compared with values commonly found in modern mass transit systems.

Surge chambers (tunnel with enlarged cross sectional area at ends of station which reduce air velocities into the station) and fan shafts are located on each end of the stations. The fan shafts can serve as ventilation shafts when the fans are not operating. Mid-tunnel fan shafts were included in the normal train operation runs to show their effect on air temperature and air velocity control. Fan operation in the mid-tunnel shafts was not utilized during the normal train operation runs, they only served as vent shafts.

The ambient air temperature was set at 90oF which is characteristic of the Los Angeles area in July. Wall surface temperatures were set a few degrees cooler than the air temperature due to the cooling effect of the surrounding soil.

b. Operational Parameters (See Table B)

Four-car trains on 120 second headways were modeled. With 5,000-foot station spacing and a 10% grade for 1,000 feet, a 70 mph maximum train velocity was chosen. This selection was based upon results of the TOM programs. Basic variables for these programs are train performance (acceleration, deceleration, maximum speed), train length, weight (including passengers), and propulsion system characteristics (traction motor torque and current as functions of speed). With the variables used as shown in Table B, we evaluated the maximum speed allowed between stations. Train speeds of 55, 70, and 75 mph were analyzed. It was found that trains could not reach 75 mph on a level profile with 5,000-foot station spacing. The 70 mph maximum train velocity could be reached on the level profile.

A comparison was then made between a maximum train velocity of 70 mph with 120 second headways and 55 mph maximum train velocity with 90 second headways. (Trains operating at 70 mph at 90 second headways cannot always maintain a safe braking distance on the dipped profile system.) The results of the TOM runs indicated that the 70 mph/120 second headway would produce a higher heat loading.

With the parameters described in Table B, the station to station travel time for the level system was 76.8 seconds with no coasting allowed. In order to have equal travel times on the dipped system, coasting was allowed. The train begins coasting before the approach grade and begins braking after the top end of the grade, 260 feet before the station stop point. This type of operation produced a station to station travel time of 73.0 seconds. This 3.8 second travel time difference was not eliminated due to the extensive effort that is required to "fine tune" train performance with the SES program. Toward the end of the study, a 76.6 second travel time was simulated with the double track dipped tunnel system. The results of that simulation were the basis for the conclusions regarding variations in travel time.

The car and motor characteristics are typical of modern subway transit vehicles. They use solid state "chopper" control of the DC traction motors.

2. Ventilation Criteria

The ventilation requirements were determined by applying the criteria for environmental control to the characteristics of the system. The criteria defines the degree of control for two separate conditions as discussed below.

a. Normal Operating Conditions

During normal summer operating conditions the environmental control criteria chosen was to maintain station temperatures at ambient and neither allow air velocities in the stations to exceed a peak of 1,000 fpm nor to exceed 500 fpm on the average. In order to satisfy this criteria mechanical cooling was used in the stations and fans were used for under platform exhaust and for ventilation at the ends of the stations. Additional ventilation was obtained through the use of mid-tunnel vent shafts.

b. Fire Emergency Conditions

Ventilation requirements for a fire emergency are based on three criteria.

1) Ventilation must provide a safe evacuation route from the train. To be considered a safe evacuation route, airflow must be maintained in the direction opposite to passenger movement, without possibility of reversal.

2) Ventilation must be able to dissipate heat generated by the fire so that air temperatures do not become excessive. This criterion considers both the fan capacity and the mode of fan operation that produces the most airflow past the fire. The greater the airflow, the lower the average air temperatures will be for a given size of fire.

3) Stations not on the evacuation route must be kept free of smoke and heat. This criteria addresses the safety of patrons within the system who are not involved in the train evacuation.

Based upon those criteria we did a manual heat balance to estimate the required fan capacities, ventilation shaft sizes and mechanical cooling loads.

3. Simulation Description

The subway system models consist of six stations bounded by seven tunnel segments for a total system route distance of 36,000 feet. For an accurate evaluation of airflows and temperatures in a specific region of interest within a subway, it was necessary to develop a model of a somewhat larger portion of the system so that the specific region of interest would not be influenced by boundary conditions. Based on previous studies we decided that six stations with seven route segments would be most appropriate for this study.

The SES program provides a second-by-second simulation of the operation of the trains and mechanical equipment in a subway. A simulation time of 720 seconds was used. This time allows several trains to pass through the system in both directions and allows a steady-state aerodynamic/thermodynamic pattern to be established.

III. RESULTS

A. Normal Operating Conditions

1. SES Computer Output Description

The SES program has been designed to provide output readings of the maximum, minimum, and average values for system air velocities, temperatures, and humidities during any preset time intervals. Although a simulation can extend over any period of subway operation, the primary focus of the SES program is on short-term simulations such as the peak rush hour, when there is often an extreme deterioration of the subway environment.

Instantaneous values of airflows, air velocities, air temperatures, humidity ratios and train operational data were printed every 30 seconds for time intervals 0-240 seconds and 480-720 seconds. Outputs every 10 seconds were received during the 240-480 second time interval. Train operational data includes train location, speed, acceleration rate, air drag, tractive effort, motor current, braking resistor grid temperatures, and power heat loss rejection. The 10-second time interval was useful in verifying train operation characteristics against the results from the TOM programs that were used to develop these characteristics.

A summary output every 120 seconds was used to obtain average values of air velocity, air temperature and airflows. The summary output also included average sensible heat gains (losses) within a particular area of interest. This summary interval is equal to the headway chosen and provides a verification that cyclic patterns of aerodynamic conditions are occurring and approach steady-state.

2. Data Analysis Preparation

We have prepared several figures and tables for use in this report based on the data produced by the computer simulation. The figures graphically illustrate the comparisons between the level and the dipped profile tunnels and between the single and double track tunnels.

Figure 1 shows a portion of the system geometry of all the systems modeled. It illustrates one tunnel section and two stations. For each model, the rest of the system consists of an extension of the configuration shown in Figure 1. The stations and tunnel sections are labeled for reference purposes.

Figure 2 was prepared to graphically represent the difference in piston action between the single and double track tunnels. Figures 3 to 6 show air velocity as a function of time at the stairwell entrances of the stations. Figures 3 and 4 represent all four tunnel configurations with opposing trains entering the stations 20 seconds apart (Station A in Figure 1). Figures 5 and 6 have opposing trains entering the stations 60 seconds apart (Station B in Figure 1).

Tables A and B are the tabulation of physical and operational parameters as described earlier. Table C gives average values of station temperatures, stairwell air velocities, and relative warmth indices in the station for a particular instant of time for comparative analysis of patron comfort. Table D is a summary of heat loss through mid-line vent shafts which indicates their effectiveness in removing heat from the system in addition to decreasing airflows in the tunnels during normal train operating conditions.

3. Air Temperature

The subway station and tunnel air temperatures were analyzed to determine the effect of train operations for each modeled subway configuration. After several trains had passed through the system and an apparent steady-state condition was reached, the resultant air temperatures were reviewed and the following conclusions were reached:

a. The single track dipped tunnel was cooler than the single track level tunnel and the double track dipped tunnel was cooler than the double track level tunnel. This was expected and can be attributed to the less heat given off by the trains on the dipped systems due to less train braking energy to be dissipated.

b. The single track level tunnel was cooler than the double track dipped tunnel. This occurs even though the trains operating on the level system produce more heat to be dissipated than trains on the dipped system, and can be understood from the wall heat sink comparison between the two. The tunnel perimeter to area ratio is larger for the single track tunnel than the double track tunnel. This results in more wall surface area which in turn produces a greater heat sink effect. Also, in the case of the single track tunnel (level or dipped) the airflow is always in one direction (See Figure 2). This is not true for the double track tunnels. Train synchronizations in double track tunnels inhibit "new" air from entering the system which is therefore a deterrant to cooling the system. In viewing Figure 2, the airflow is predominantly to the north as defined in Figure 1. This can be explained by the fact that the fans in Station A draw air from section 1 (1A and 1B) in addition to drawing air down the stairwells in Station A. Ideally, with no train movement, air would be drawn in the mid-line vents and then split to the north in sections 1 (1A and 1B) and to the south in sections 2 (2A and 2B). With the single track tunnel the train piston action always moves air to the north, adding to the fan induced flow. With the double track tunnel a south bound train moves air to the south, overcoming the north bound flow as it passes through Section 1.

c. The mid-line vent shafts (with no fan operation) were a factor in removing heat from the system except in the single track dipped tunnel system (See Table D). With the parameters that we selected, the mid-line vent actually added heat to the single track dipped tunnel system. Ambient air at 90°F and an 88°F wall surface temperature had been assumed. Since for the single track dipped tunnel the average tunnel air temperatures did not exceed 90oF, the ambient air was heating up the tunnels when it was drawn in the mid-line vent shafts.

d. Average station temperatures for the different systems are summarized in Table C. Parameters that influence the station temperatures include heat given off by the trains, underplatform exhaust effectiveness, sensible and latent heat in the station, station mechanical cooling, station ventilation and the degree to which the station is open to the ambient air. Underplatform exhaust effectiveness was estimated at 80% while the train is stopped and 60% when the train is entering or exiting the station. The amount of sensible and latent heat, mechanical cooling, and ventilation capacity are shown in Table B. The stairwells cross sectional areas are 320 square feet. Opening up the stations more reduces the ventilation requirements to maintain ambient conditions. However, it is a less controllable system because the station conditions are more suseptible to changes in ambient conditions.

The small differences in average station temperatures can be looked at in terms of the addition or reduction in mechanical cooling required in order to achieve the design temperature of 90°F. These values expressed in tons (12,000 BTUH) for Station A are shown in Table C. It should be noted that the underplatform exhaust effectiveness is constant for all simulations. This in effect means that there is more heat removal for the level profile tunnels than for the dipped profile tunnels. If the airflow rate for both systems are the same, the level tunnel systems get more efficiency from their under platform exhaust than the dipped profile systems.

4. Air Velocity

Air velocity in the stairwells at the stations were compared between the systems with different opposing train synchronizations. Figures 3 and 4 are based upon opposing trains entering station A 20 seconds apart. Figures 5 and 6 show air velocity as a function of time in the stairwells at Station B. Station B has opposing trains entering the station 60 seconds apart. The lower portion of the graph is for air coming into the station through the stairwells and the upper values are for air going out the stairwells. The graphs are shifted towards air coming into the station because the station fans are operating in the exhaust mode pulling air down the stairwells.

There is very little difference in stairwell velocity in Figures 3 and 4 for all four systems analyzed. With trains entering and exiting the station at close time intervals, tunnel geometries do not significantly affect stairwell air velocities. Since the opposing tunnels on both sides of the stations have trains entering or exiting in them, the least resistive path for airflow is into or out of the stairwells. The air velocity in the stairwells due to train piston action is cumulative when both trains are leaving or entering the station. This is shown by the change in slope on the graphs at 280 to 290 and 400 to 410 seconds. These are the times corresponding to the train which leaves the station 20 seconds after the first train has left.

In Figures 5 and 6 where opposing trains enter or exit station B 60 seconds apart, different air velocity profiles are developed. The difference is between airflows in single track and double track tunnels. Air velocity comparisons between level and dipped profile tunnels do not yield a significant difference in the stairwells. However, the single track tunnel (Figure 5) shows an airflow directional change that does not occur with the double track tunnel (Figure 6).

The higher piston action associated with the single track tunnel system is evidenced more with this type of train synchronization than with the 20 second deviation associated with Station A. Airflow in a single track tunnel is more independent of train synchronization than airflow in a double track tunnel. Airflow interference reduces air velocities in double track tunnels and therefore less air is pushed out the stairwells.

In Figures 5 and 6 the airflow cycle is one half of the cycle in Figures 3 and 4. This shows that the airflows due to train piston action are quasi-independent for Station B and cumulative for Station A. This results in lower peak air velocity values in the stairwells in Station B.

Average air velocities in the stairwells are shown in Table C. These velocities can be reduced if the stations are more open to the outside. Also, it is important to note that the station fans usually do not operate in the winter or anytime the stations can be cooled by ambient air. Figures 3 through 6 would be symmetrical about the time axis if the fans were not operating.

In all cases modeled, the mid-tunnel ventilation shafts were effective in reducing the movement of air into the stations by reducing the piston effect of the trains.

5. Patron Comfort

Relative Warmth Index (RWI) was computed to compare patron comfort for each system and is shown in Table C. The dipped profiles had lower air temperatures and thus lower RWI.

B. Fire Emergency Conditions

Train Fire emergency conditions were analyzed both manually and by use of the SES computer program. The manual analysis involved a determination of the effects of tunnel profile on emergency ventilation requirements based upon previous emergency ventilation studies. The computer analysis involved the modeling and simulation of a specific train fire condition.

The following discussion documents both the manual and computer assisted analysis. It first defines the criteria for evaluating the effectiveness of an emergency ventilation procedure, then describes the alternative ventilation procedures that can be used for different fire conditions, and then explains how the tunnel profile would influence the ventilation requirements.

Ventilation requirements for a train fire emergency are based on three criteria stated previously. First, the ventilation equipment must be capable of providing a safe evacuation route from the train. To be considered a safe evacuation route, airflow must be maintained in the direction opposite to passenger egress without possibility of reversal during the evacuation. Secondly, heat generated by the fire must be dissipated so that air temperatures do not become excessive. Although it is not practical to provide sufficient fan capacity to keep temperatures in all portions of the tunnel below 140°F (an upper limit tolerable to humans), both the fan capacity and modes of fan operation must be chosen so that air temperatures can be kept below levels that produce spontaneous combustion of carborne materials. The greater the airflow, the lower the average air temperatures will be for a given size of fire. The third criterion is for stations not on the evacuation route, to be kept free of smoke and heat. This criterion addresses the safety of patrons within the system who are not initially involved in the train fire incident.

The emergency ventilation requirements for several different tunnel configurations were evaluated. A dipped tunnel profile was compared to a level tunnel profile with consideration given to both double track tunnel and single track tunnel configurations. For each of these four configurations, a basic ventilation system of end of station fans was compared with an alternative ventilation system which consisted of mid-tunnel fan shafts as well as end of station fans. Two fire locations were considered, one being a train fire within a station and the other a train fire in mid- tunnel. In terms of emergency ventilation these two train fire locations are representative of any possible train fire emergency situation.

In general, for a train fire within the station, an all exhaust mode of fan operation will produce the most desirable airflow pattern. With this mode of fan operation, all fans in the system are operated in the exhaust mode. This ventilation procedure draws fresh air down the station entrances, through the station and out the fan shafts. A clear evacuation route can be established out the station entrances. Hot, smokey air is taken out the station fan shafts. An alternative mode of fan operation where the fans at one end of the station are operated in the supply mode and the fans on the other end of the station are operated in the exhaust mode (push-pull mode of fan operation) can possibly move more air past the fire, but cannot always maintain a flow of fresh air in the station entrance.

For a train fire within a station, all three emergency ventilation criteria can be met without inclusion of mid-tunnel vent shafts by installing station fans of adequate capacity. The tunnel profile between stations will not influence this situation unless station fans are of considerably different capacities at each station. In this case hot air could move through a station and in to the tunnel beyond. With a dipped tunnel this would produce a buoyant effect. With a level tunnel there would be no buoyant effect. The addition of mid-tunnel fans enhances the ventilation system in several ways. For the same fan capacity in each fan shaft, a greater quantity of air can be drawn across the fire, reducing temperature build-up and further diluting the smoke. Greater velocities can be expected down the station entrances thereby reducing the risks of air reversal. Infiltration of hot smokey air, into the adjacent stations is reduced since the mid- tunnel shaft provides an additional path out of the system. The ventilation system will be less sensitive to the loss of a fan.

Special consideration must be given to train fires within a station which is at or near a portal. In this case, the air drawn from the portal can short circuit the station fans and significantly effect the station airflow pattern. Reversal of air up the station entrances can occur preventing a clear evacuation route from being established. Installation of closable emergency doors to block the portal can eliminate this short circuiting.

For mid-tunnel train fires the push-pull mode of fan operation is generally preferred. This ventilation procedure creates airflow past the train fire by operating all fans on one side of the fire in supply while all fans on the opposite side of the fire are operated in the exhaust mode. A safe evacuation route in a direction opposite the airflow is established.

For level tunnels the direction of the push-pull must be selected based upon the train location relative to stations and points of egress - either emergency exits or cross passages to adjacent tunnels. The guidelines for ventilation in this situation are: move smoke and hot air across the fewest people, clear the shortest evacuation route, and move smoke and hot air away from the most crowded stations. (In single track tunnels evacuation in two directions may be required in order to minimize the total evacuation time. In this case it might be better to operate the ventilation fans so as to clear the longest evacuation route. This will move smoke and hot air along the shorter evacuation route. Consequently, the route must be short in an absolute sense - through a cross passage - or the use of the two routes will be no better than a slower evacuation using one clear route.) When these guidelines are considered with the three emergency ventilation criteria described earlier, a preferred mode of fan operation can be selected for each train location based upon assumptions regarding fire location on the train and train patron loading.

For a dipped profile tunnel, the direction of push-pull fan operation is chosen following the same guidelines as established for the level tunnel. However, with the possibility of strong buoyant effects, the emergency ventilation guidelines and criteria may conflict. (Shortest evacuation distance may be uphill which means hot air must be pulled downhill against the buoyant effect.) In this case it is necessary to determine if the alternative directions of airflow can be maintained at a sufficient magnitude to satisfy the air temperature and no airflow reversal criteria.

The push-pull mode of fan operation uphill past a fire is assisted by the buoyant effect of the fire. The use of station fans only is not a problem provided they are of sufficient capacity to move the desired amount of air past the fire train even if there is no assistance from buoyancy (smoke only fire).

The push-pull mode of fan operation downhill past a fire is the most demanding on the ventilation system. This ventilation procedure (with no mid-tunnel fan shafts) was simulated using the SES computer program. This procedure may be preferable to movement of air uphill for the case where evacuation downhill would force the passengers to pass directly by the fire, or if smoke and heat infiltration into the uphill station would cause more of a hazard than the longer evacuation route uphill. The results of the computer simulation showed that the 130,000 cfm station fans could not maintain a flow of air down hill past a fire once the fire grew to major proportions. Figures 7 and 8 are for this case and show the airflows past the fire for the low heat and high heat release rates respectively.

Based upon the computer simulation results and assuming that the tunnel walls are quite warm (the fire has been burning for some time), that the train is about half way down the 10% grade, that the fire heat release rate is 60,000,000 BTUH, and that the minimum desirable air velocity is 650 fpm, the airflow past the fire must be at least 130,000 cfm in order for a reversal not to occur. This requires an airflow when there is no fire to be about 190,000 cfm. With the single track tunnel configuration, this requires a station fan capacity of about 500,000 cfm. This is 370,000 cfm more than the baseline station fan capacity of 130,000 cfm. Hotter fires and higher tunnel blockage by the train would increase the cfm of the station fans required to control air flow. By comparison, if midtunnel fan shafts are used, a nominal capacity of about 180,000 cfm would be required at both the station fan shafts and at the mid-tunnel shafts in order to move enough air past this type of fire to prevent reversal.

For double track tunnels (400 square feet) the pressure required to move air past a fire is about one-fourth that required to move the same amount of air through a single track tunnel. However, the buoyancy would be the same for the same size fire and air flow in either type of tunnel. Assuming conditions like those assumed for the single track tunnel, the ventilation fans must be able to move an airflow of at least 260,000 cfm past the fire to prevent a reversal when the fire reaches major proportions. This requires an airflow of about 340,000 cfm when there is no fire. Station fans with capacities of about 400,000 cfm would be required to provide this flow. This is 270,000 cfm more than the baseline station fan capacity of 130,000 cfm.

With mid-tunnel fan shafts in the double track tunnel, a nominal capacity of about 280,000 cfm would be required both at the stations and at the mid-tunnel fan shafts to move enough air past the fire to prevent an airflow reversal.

Emergency ventilation capabilities are not the only factors to be considered when evaluating the feasibility of not using mid-tunnel ventilation shafts. Additional factors to be considered are: the loss of a potential evacuation/access route; the spread of smoke through the system; and the ability to design an emergency ventilation system less sensitive to the loss of a fan.

It should be noted that the above mentioned fan capacities are based upon the specific configuration of the system under study. Other grades, tunnel areas, station entrance sizes, etc. all influence the specific values. The relative comparison between capacities with and without mid-tunnel fan shafts should be valid.

IV. CONCLUSIONS

From the abundance of data that was produced for this study the following conclusions are thought to be the most significant.

1. Less ventilation equipment is required to maintain design conditions with a dipped tunnel system than with a level tunnel system. One way the difference in ventilation equipment can be quantified is as a difference in mechanical cooling capacity. For this study the dipped tunnel system requires about 10% less mechanical cooling than the level tunnel system.

2. A single track, level tunnel system can require less ventilation equipment to maintain design conditions than a double track dipped tunnel system. This difference appears to be sensitive to the specific train operation and specific system design. The double track tunnel system receives fewer air changes due to train operation than the single track tunnel system. Therefore the double track tunnel system is at a disadvantage when an "open system" ventilation design concept (which relies heavily on air changes with outside air for cooling) is being considered.

3. Station entrance air velocities are more independent of train operation in a single track tunnel system than in a double track tunnel system. The peak entrance air velocities are about the same in either case.

4. Train operation on the dipped tunnel system must be carefully tailored to the profile in order to obtain the most benefit. There can be significant penalties to pay in terms of energy consumption or heat loads if the trains are not allowed to accelerate on the downgrade or brake on the upgrade.

5. The greater the heat loads in a system, the more efficient the ventilation equipment will be if it provides air changes rather than mechanically cooled air. For example, under platform exhaust equipment working with a 90°F design temperature will remove 33% more heat if the air it removes is 110°F rather than 105°F.

6. For train fires in stations, an all exhaust mode of fan operation can be used to provide adequate ventilation for evacuating patrons. This is true whether the system is a level system or a dipped system. In either case, mid-tunnel fan shafts are not necessary as long as there are fans at the ends of each station that continue to operate during the emergency.

7 For a train fire emergency in a tunnel, a dipped tunnel system is more difficult to adequately ventilate than a level tunnel system. This is due to the buoyancy effect of hot air on the grade in the dipped system which makes it more difficult to move air downhill. Although it may be possible to provide adequate ventilation during a tunnel train fire emergency on a dipped system without mid-tunnel fan shafts, the airflow capacity of the station fans required to achieve this objective is substantial. The effects of mid-tunnel fan shafts are more pronounced with a single track tunnel system than with

the double track tunnel system. In the single track tunnel system the use of station fans only can allow air to bypass the tunnel with the train and flow through the adjacent tunnel.

8. The use of mid-tunnel ventilation shafts is valuable in several respects. In all but the single track dipped system the mid-tunnel vents provide a means of reducing heat in the tunnels. During a train fire emergency, the use of the mid-tunnel ventilation fans makes the overall ventilation scheme less sensitive to the loss of a fan, and the ventilation shaft can provide an evacuation route for patrons.

9. There are other measures that can be taken to enhance fire safety during a train fire emergency in addition to emergency ventilation. These include the reduction of the fire load on the vehicles, the addition of cross passages from one single track tunnel to another and the provision for fire barriers such as closable doors that can reconfigure the tunnel aerodynamic network in order to make the ventilation equipment most effective.

10. There is no significant difference between the single track over-under and side-by-side tunnel configurations in terms of ventilation. The cummulative effects of train induced airflows in stairways will be the most notable difference. For either type of tunnel configuration, the stairway air velocities must be evaluated based upon the expected train operations and ventilation design.

V. RECOMMENDATIONS

Although the dipped guideway system does show that it can reduce the ventilation requirements as compared to the level system, further evaluation of this concept should be considered in order to determine the sensitivity of this savings in ventilation requirements to variations of the train operations. Furthermore, this concept of reducing the ventilation requirement should be compared to alternative concepts such as the use of train screens in stations, as well as other ways of isolating the station from the tunnel portions of the system such as the use of air or water curtains.

The need for mid-tunnel ventilation shafts makes the dipped system much less appealing because of the costs involved in constructing such a shaft. The mid-tunnel fan is primarily needed for train fire emergency ventilation. It would be worthwhile to investigate use of impulse fans for mid-tunnel ventilation since they do not require a shaft to the surface.

VI. APPENDIX

OF POOR QUALITY

TABLE A PHYSICAL PARAMETERS

Section Type	Length (ft.)	Cross Section Area (ft^2)	Perimter (ft.)	Initial Temperatures °F Dry Bulb	Wet Bulb	Wall* Surface
All Stations	300	1000	184	80	68	78
Single Track Tunnel, Level or Dipped Profile	4600	197	51	90	70	88
Double Track Tunnel, Level or Dipped Profile	4600	400	80	90	70	88
Surge Chamber, Single Track Tunnels, Level or Dipped Profile	50	992	139	80	68	78
Surge Chamber, Double Track Tunnel, Level or Dipped Profile	50	900	120	80	68	78
All Fan Shafts	60	200	55	80	68	78
Mid-Line Vents Level Profile	60	200	50	90	70	88
Mid-Line Vents Dipped Profile	160	200	50	90	70	88
All Stairwells	120	320	72	80	68	78

*Although surrounding soils temperatures are much lower, this temperature represents the expected wall surface temperature for the given initial air temperature when the heat transfer rates of air to wall and wall to soil are considered.

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Table B.--Operational Parameters

Train Characteristics:

Maximum Velocity	70 mph
Acceleration Rate	3 mph/s
Deceleration Rate	3 mph/s
Headway	120 sec.
Station Dwell	25 sec.

Car Characteristics:

Number of Cars/Train	4
Number of Motors/Car	4
Length	75 ft.
Perimeter	38 ft.
Frontal Area	100 sq. ft.
Weight, Empty	36 tons
Weight, Full (standing)	48.5 tons
Heat Rejection/Car	260,000 BTU/hr.

Propulsion Characteristics:

Traction Motor	1462-A, 325 Volts DC
Wheel Diameter	28 in.
Gear Ratio	5.4
Supply Voltage	650 volts
Maximum Tractive Effort at Wheel	3600 lbs.

Fan Nominal Capacity: 130,000 cfm at each end of each station for both double track and single track tunnels

Steady State Heat Loads:

Stations	Sensible (BTU/hr)	Latent (BTU/hr)
Patrons	56,250	117,000
Lights	419,000	
Third Rail (2 Tracks)	66/ft.	
Fare Collection	70,400	
Escalatcrs	381,750	
Agent Area	8,536	
Mechanical cooling	-947,200	-117,000
Single Track Tunnel:		
Lights	6.8/ft.	
Third Rail (Level)	33/ft.	
Third Rail (Dipped)	23/ft.	
Double Track Tunnel and All Surge Chambers:		
Lights	10.2/ft.	
Third Rail (Level)	66/ft.	
Third Rail (Dipped)	46/ft.	

TABLE C

AVERAGE STATION TEMPERATURES AND STAIRWELL VELOCITIES

TUNNEL TYPE	PROFILE TYPE	AVERAGE STATION TEMPERATURES (°F)		AVERAGE STAIRWELL VELOCITIES, (FPM)				RELATIVE WARMTH INDEX STATION B	
				INFLOW		OUTFLOW			
		A	B	STA. A.	STA. B.	STA. A.	STA. B	SITTING	WALKING
Single Track	Level	90.5 (+4.0)*	90.5	603	571	117	41	.23	.31
Single Track	Dipped	89.7 (-2.5)*	89.7	610	590	108	54	.20	.30
Double Track	Level	92.0 (+15.0)*	90.9	536	769	98	n/a	.27	.34
Double Track	Dipped	90.7 (+4.7)*	90.0	571	803	112	n/a	.22	.31

*Change in mechanical cooling (Tons = 12,000 BTUH) to achieve 90°F design temperature.

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TABLE D

HEAT LOSS SUMMARY THROUGH MID-LINE VENTILATION SHAFTS

TUNNEL TYPE	PROFILE TYPE	TRAIN SYNCHRONIZATION[1]	AIRFLOW (CFM) OUTFLOW	AIRFLOW (CFM) INFLOW	HEAT LOSS BTU/HR OUTFLOW	HEAT LOSS BTU/HR INFLOW	TOTAL HEAT LOSS BTU/HR.
Single Track[2]	Level	n/a	40,300	83,300	14,250	57,800	72,050
Single Track[2]	Dipped	n/a	41,800	87,700	800	-6,050[3]	-5,250[3]
Double Track	Level	0	36,800	131,900	71,700	932,800	1,004,500
Double Track	Dipped	0	36,600	136,300	33,500	609,800	643,300
Double Track	Level	40/80	25,800	96,000	56,800	517,300	574,100
Double Track	Dipped	40/80	37,700	93,000	46,400	253,700	300,100

[1] Difference in time (seconds) when opposing trains pass mid-line vent shaft location.

[2] One Tunnel only

[3] Indicates heat gain

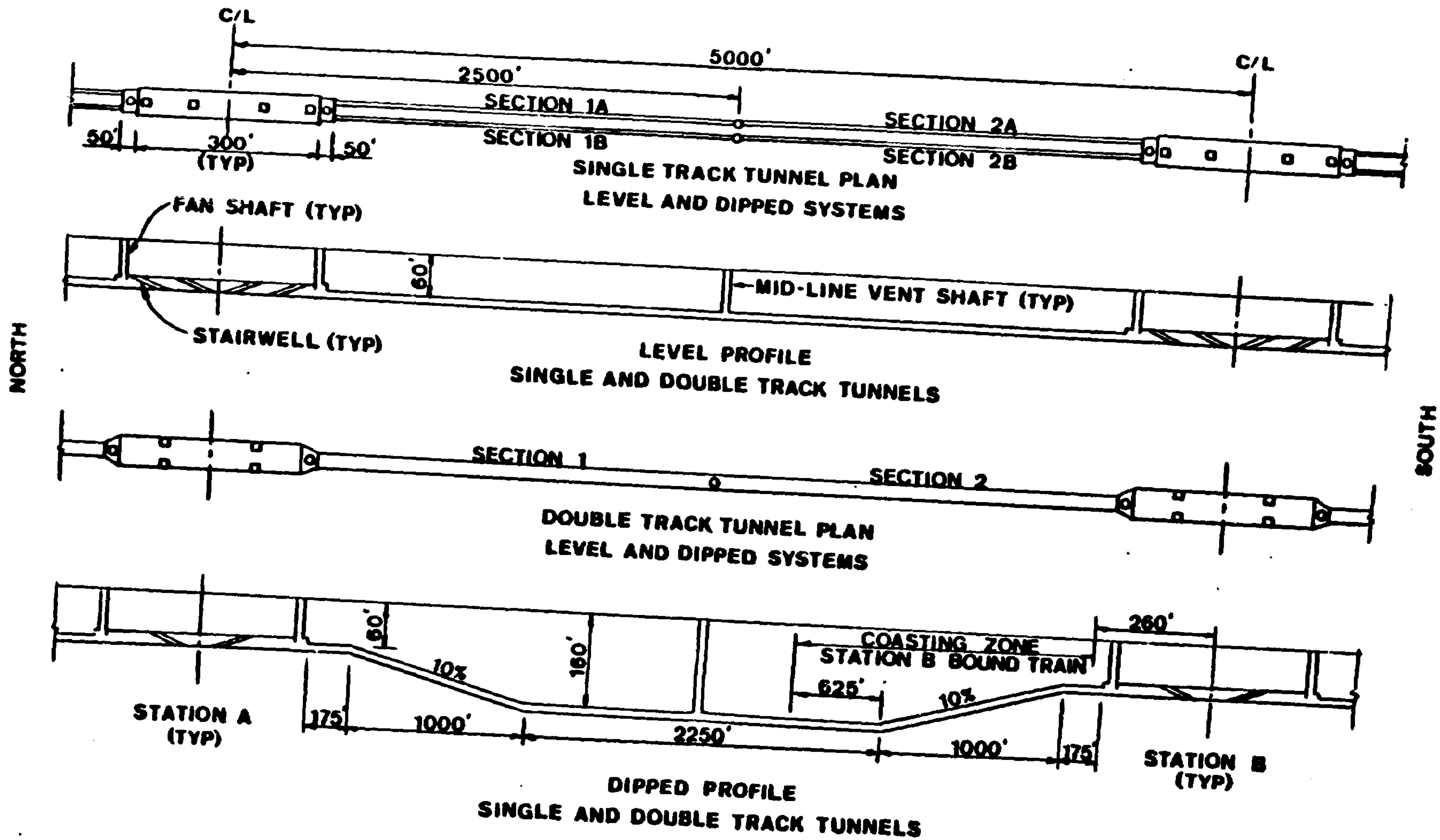

FIGURE 1
SYSTEM GEOMETRY

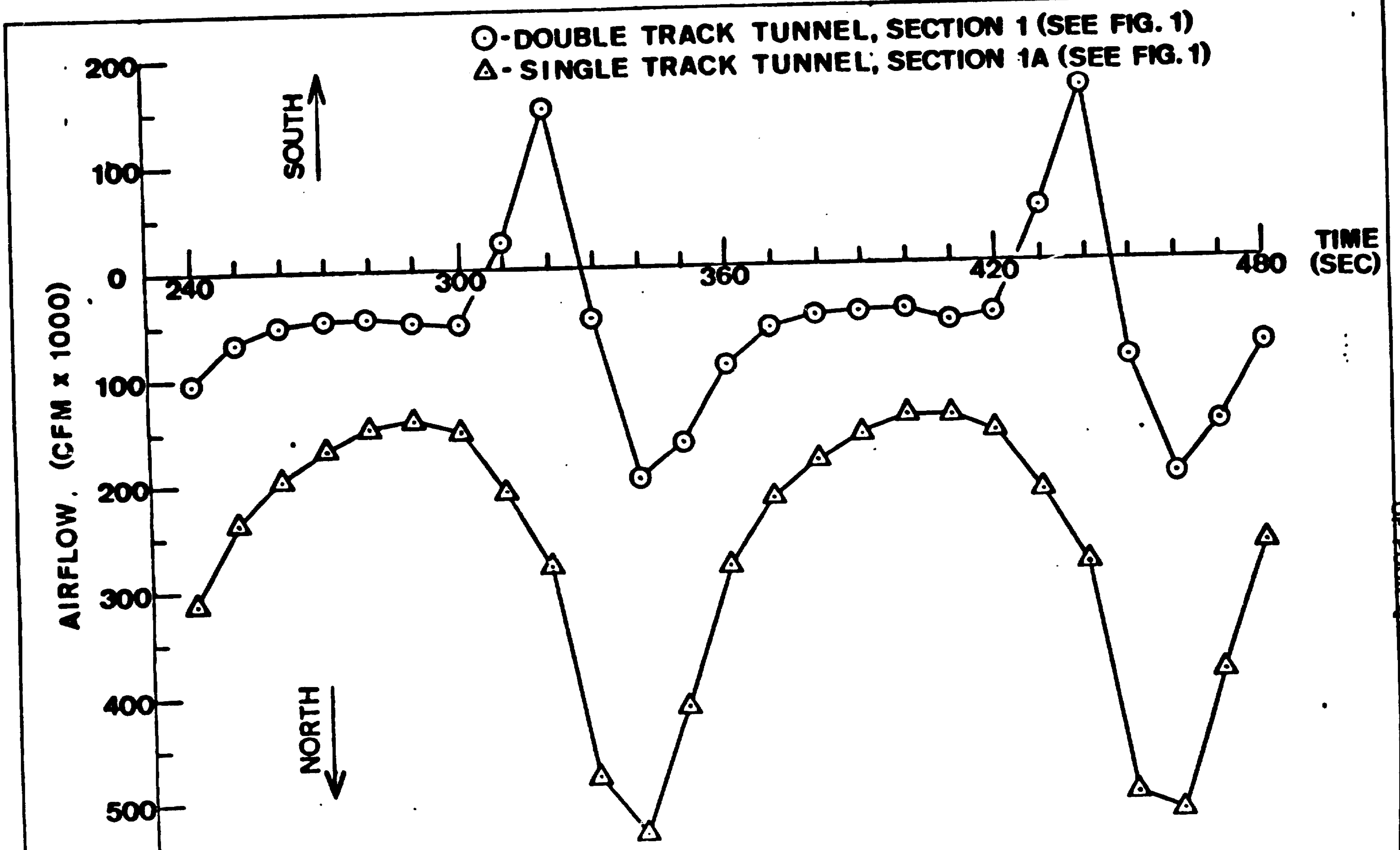

FIGURE 2
AIRFLOW COMPARISON OF DIPPED PROFILES

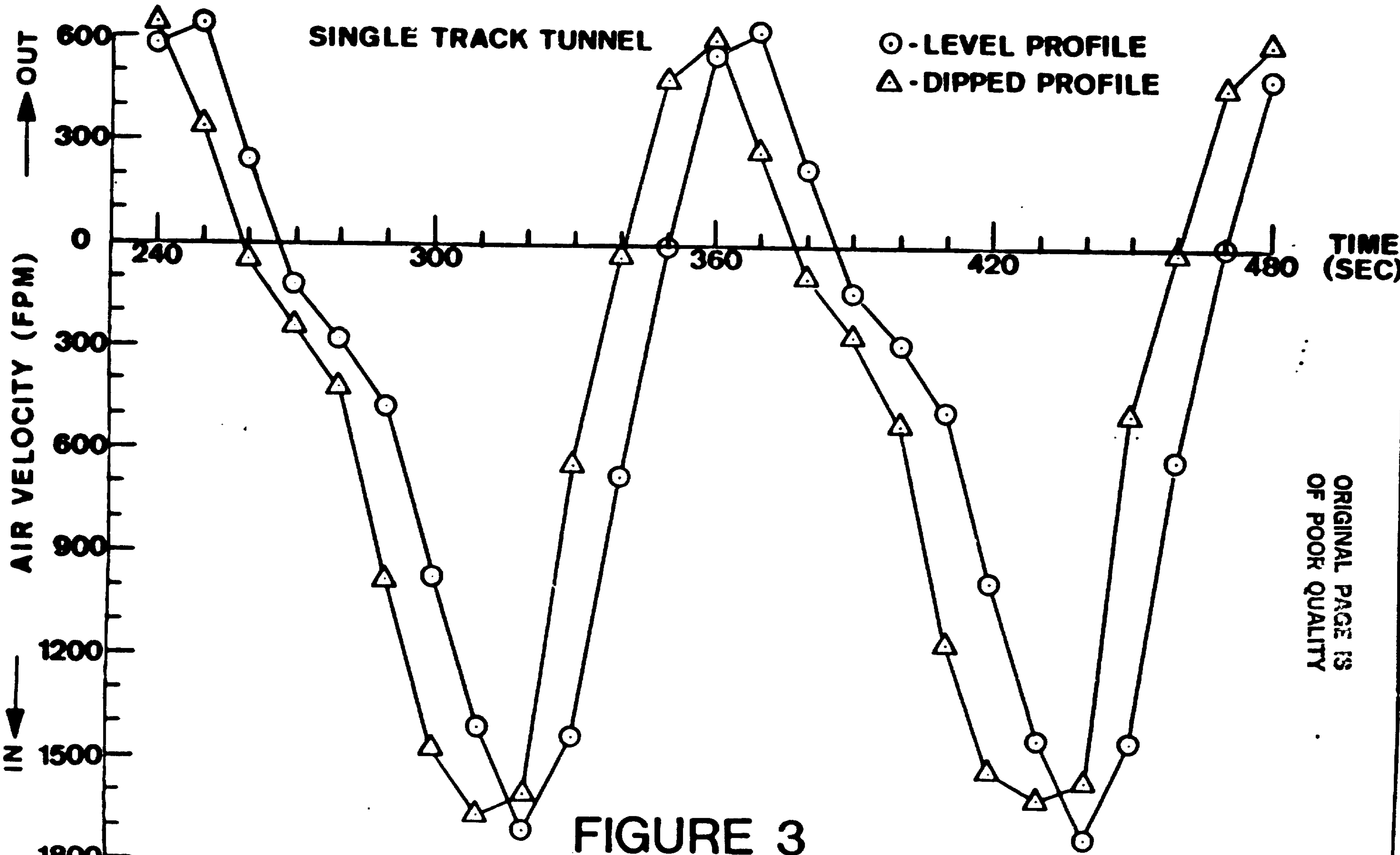

FIGURE 3
AIR VELOCITY COMPARISON IN STAIRWELLS
STATION A (SEE FIG. 1)

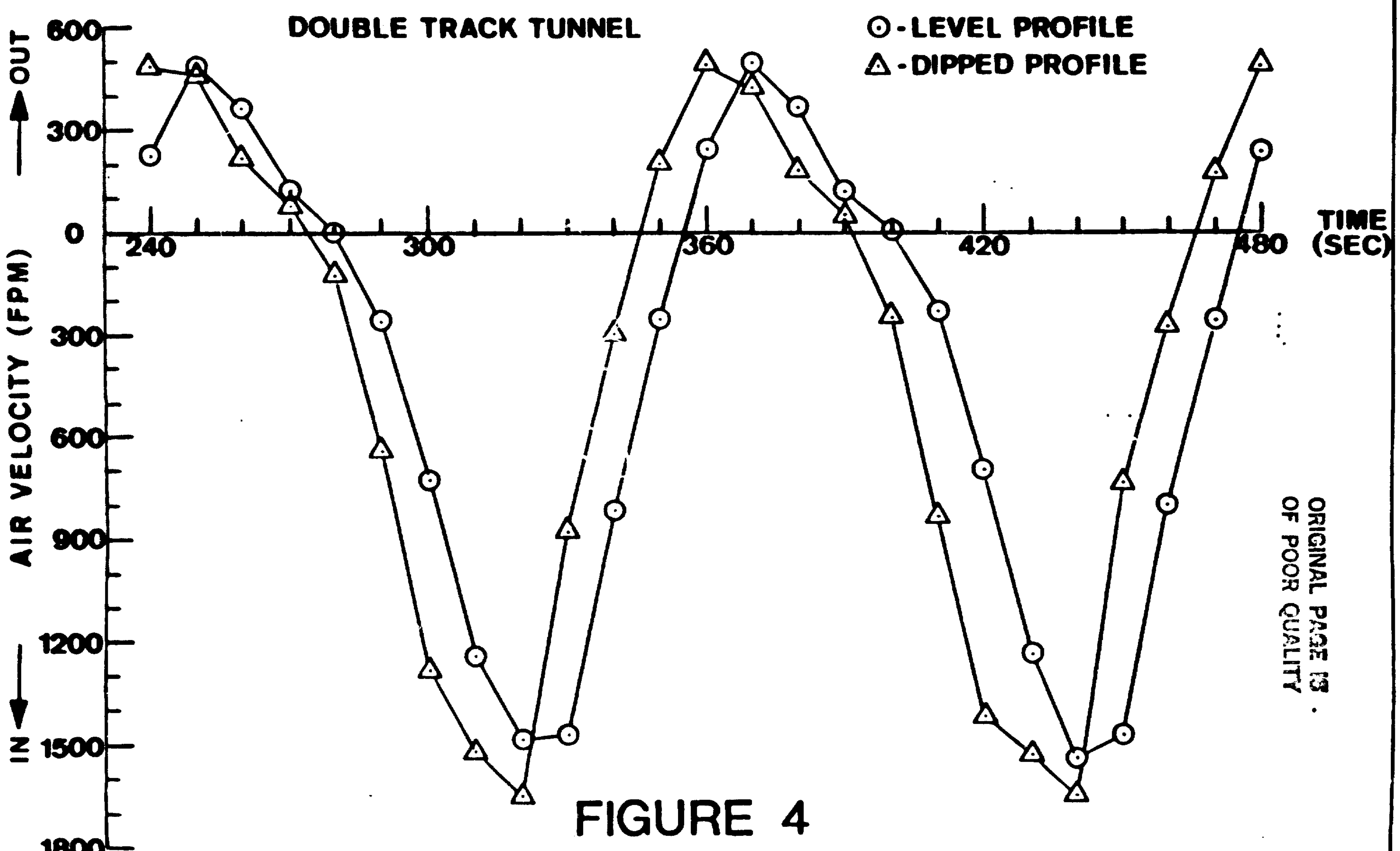

FIGURE 4
AIR VELOCITY COMPARISON IN STAIRWELLS STATION A (SEE FIG. 1)

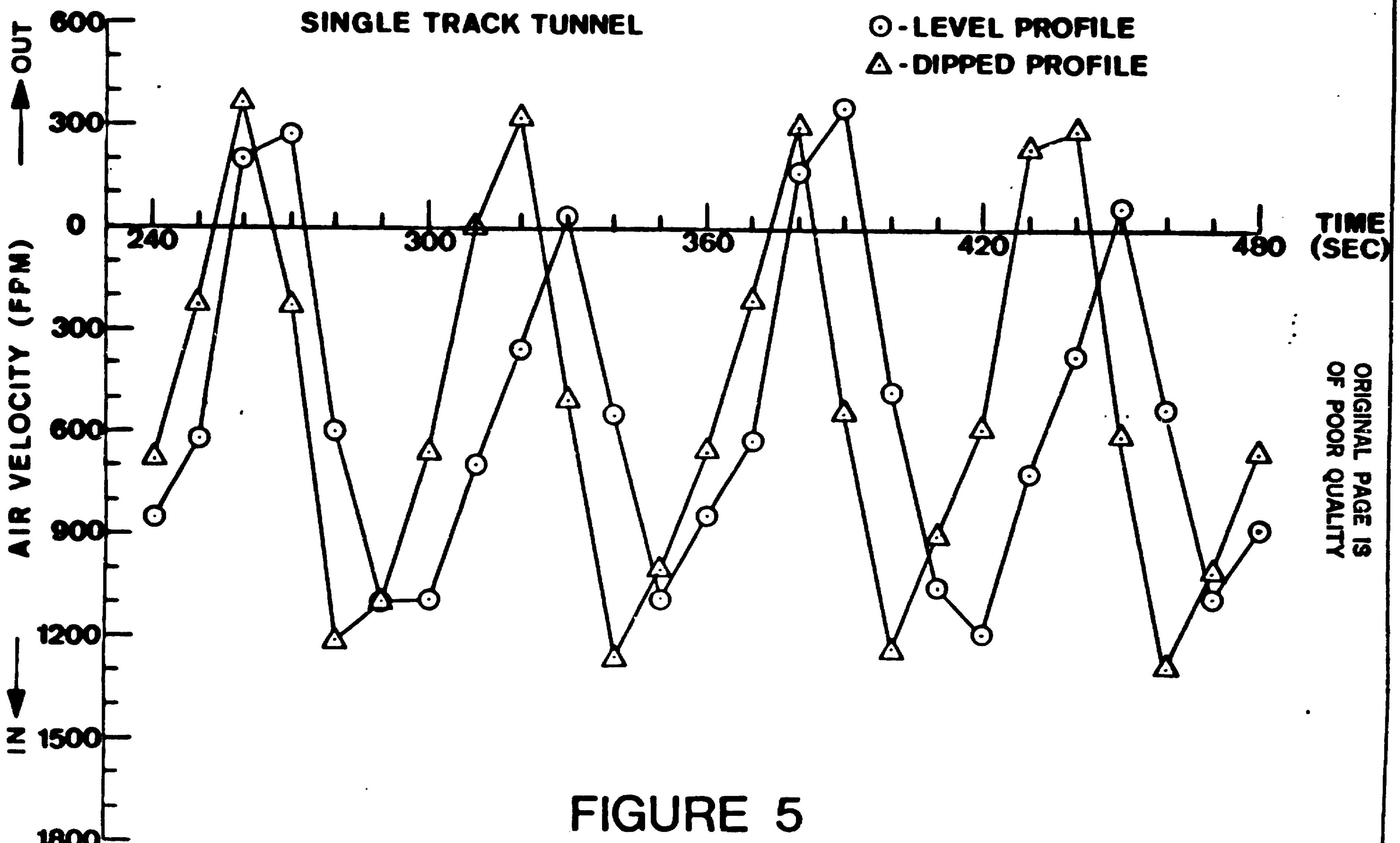

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FIGURE 5
AIR VELOCITY COMPARISON IN STAIRWELLS
STATION B (SEE FIG.1)

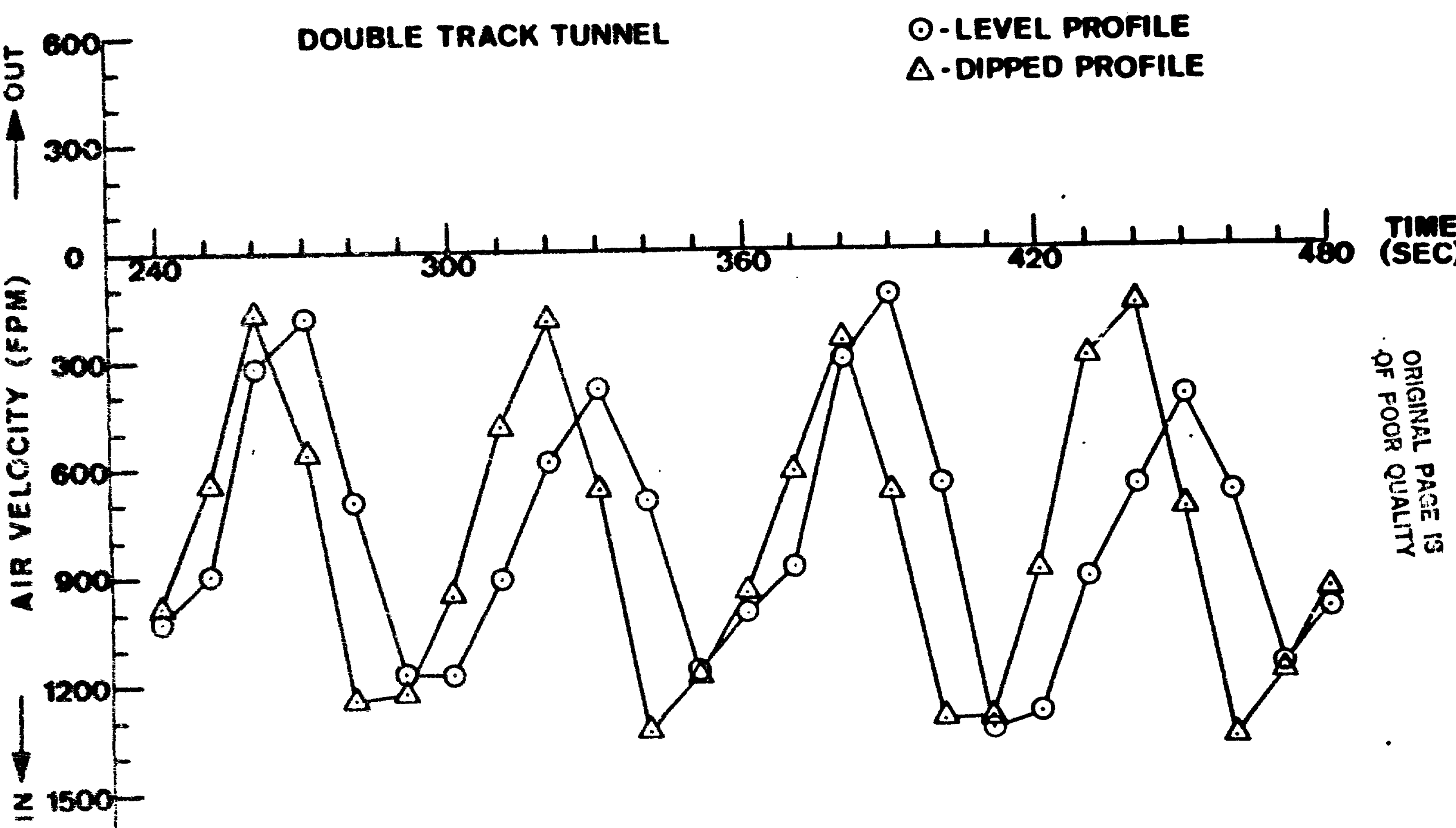
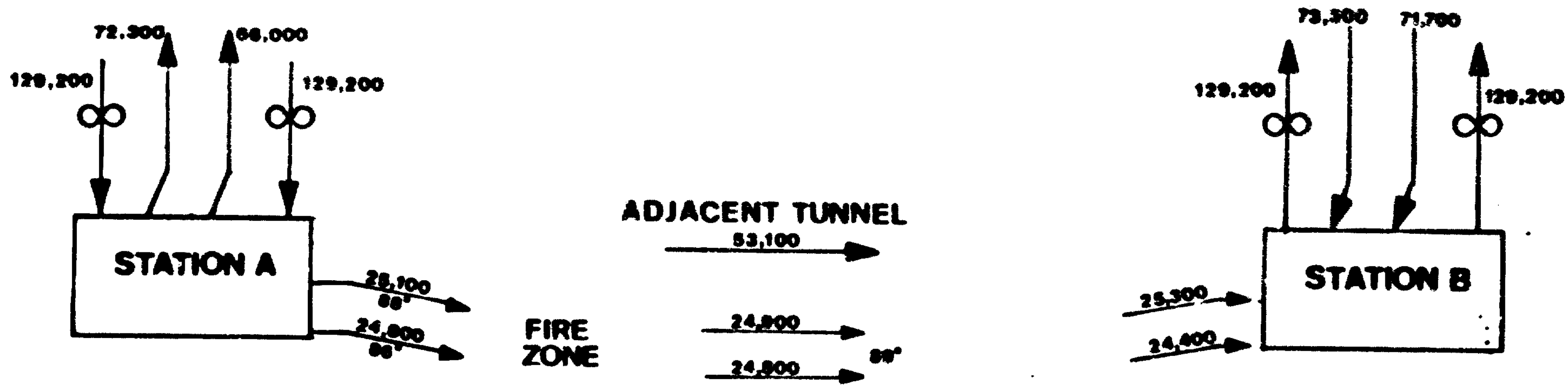


FIGURE 6
AIR VELOCITY COMPARISON IN STAIRWELLS
STATION B (SEE FIG. 1)

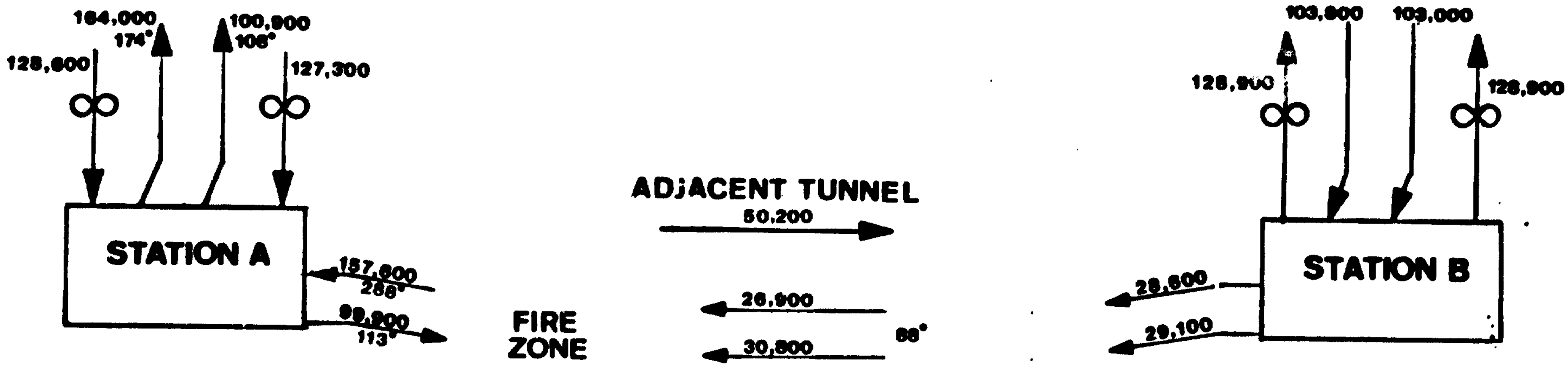


BEFORE FIRE - SMOKE ONLY

FIGURE 7

LOW HEAT FIRE RELEASE

AIRFLOWS (CFM) AND TEMPERATURES (ºF)



6 MINUTES AFTER START OF 60,000,000 BTU PER HR FIRE

FIGURE 8

HIGH HEAT FIRE RELEASE

AIRFLOWS (CFM) AND TEMPERATURES (°F)