SOUTHERN CALIFORNIA RAPID TRANSIT DISTRICT

METRO RAIL PROJECT

OPERATIONAL IMPACTS OF POWER SYSTEM FAILURES

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1.0 INTRODUCTION

1.0 INTRODUCTION

The Southern California Rapid Transit District (SCRTD) is presently in the final stages of designing the electrical power distribution system, including both traction power and auxiliary power, for the Metro Rail project. To maximize the dependability of the Metro Rail system, the SCRTD asked Booz, Allen to study alternative power system configurations and analyze the effects of power system failures.

1.1 PURPOSE AND OVERVIEW OF THE PROJECT

The purpose of the model, and of this report, is to estimate the operational reliability of various power system configurations. Metro Rail, in common with heavy rail rapid transit systems in general and underground systems in particular, is potentially subject to service disruptions as a result of outages of electrical power. Even a localized loss or reduction of traction power can prevent or impede the movement of trains. Loss or impairment of stations auxiliary power will not only interfere with station operations but in underground systems may also affect train movements and public safety. For example, if power is not available for smoke control ventilation, trains should be prohibited from proceeding into the affected section of tunnel even though traction power may be available. Of course, the degree to which any power outage impacts the rail system as a whole depends not only on the extent of the outage but also on its duration.

Thus, it is necessary to maximize power system reliability within the context of components which inherently are less than perfectly reliable, and within cost constraints. The solution lies in configuring the system as a network that contains redundant or backup elements.

The need to examine the reliability of a number of alternative power system networks, taking into account the complexities of potentially interacting individual failures, ruled out hand calculation of reliability estimates. This was especially true since it was known that sensitivity analyses would need to be addressed. In view of this, a power system reliability model was developed for use on an IBM Personal Computer. The computer code for the model is provided in the Appendix. The model involves two primary modules:

- A module that provides a detailed "library" of the characteristics and configurations of the system elements.

- The basic analytical module that: identifies all potential failures of system elements; evaluates occurrence probabilities and durations; categorizes potential effects on train status and station status; and displays summarized results.

The reliability model was designed to make it relatively easy to change system design and expand or modify the library of system element characteristics. This was done to facilitate future evaluations of alternatives and sensitivity factors.

The model does not take capital or operating costs into account, and thus cannot be used on its own as a source for power system design recommendations.

The reliability model used in this analysis considers the Metro Rail power system to be composed of the following types of elements:

- Sources - the utilities supplying power. The main, and in some configurations the only, source will be the Department of Water and Power (DWP); limited use will also be made of Southern California Edison (SCE) power.

- Receiving stations - the utility yards which serve as the interface between high voltage transmission lines and local area feeders.

- Feeders - the lines carrying power from receiving stations to traction power substations and auxiliary power substations.

- Traction power substations - combinations of switchgear, transformers, rectifiers, and auxiliary equipment, providing direct current (dc) power for the trains.

- Auxiliary power substations - similar equipment providing standard alternating current (ac) power at voltages suitable for loads such as ventilation and illumination.

"Downstream" (load-side) electrical equipment that is common to all potential power system configurations, such as the third rail, is excluded from the model. Any equipment which is not specifically mentioned is included in the categories listed above. For example, the reliability of transmission lines from a source to a receiving station is considered as part of receiving station reliability.

The model is designed to consider any potential failure of a single system element and any combination of independent failures of two elements. Since the number of such combinations increases rapidly as the number of elements increases, model running time can become substantial for large configurations. However, geographically remote pairs of failures generally do not interact, so that the number of outages tends to increase linearly rather than geometrically with configuration size. Thus, full analysis of large configurations usually is not necessary.

For each outage (single failure or pair), the model follows the propagation of effects down to the load side of each substation; thus, the failure of a single receiving station serving as the only supply point for a number of substations is recognized as resulting in loss of output at all of these substations. The number, degree, duration, and geographic relationships of power losses among substations then define the ultimate impact on train and station status.

Input to the model includes the expected number and duration of power outages sustained per year by each system component. These values are used to determine each component's contribution to the frequency and duration of service impairment incidents, by train and station status categories.

The model output for any given configuration consists of a simple matrix display of the number and duration of service impairment incidents in each of several categories. These categories are defined in the next chapter. Examples of model output will be found in Chapters 4.0 and 5.0.

A separate project associated with the planning of Metro Rail involved a survey of other North American transit systems. That survey identified a number of specific trends in power system design, as well as some interesting observations on system reliability. The survey findings will be discussed later in this report, and comparisons will be made with the results of this analysis. However, one finding is of immediate interest. It seems that no other transit system has ever undertaken to develop such precisely quantified estimates of power system reliability as have been developed in this report.

1.2 REPORT ORGANIZATION

Chapter 2.0, which follows, provides a simple explanation of the components which will make up the electrical power system for the Metro Rail. The chapter also discusses the assumptions built into the model description of each configuration.

Chapter 3.0 summarizes the analyses of some alternative power system configurations that were explored before the specific Metro Rail configurations were defined.

Chapters 4.0 and 5.0 examine the results of the reliability analysis. Chapter 4.0 discusses the results in terms of the power system design decided upon for the three Metro Rail configurations, and provides a brief comparison with reliability of other rail transit systems.

Chapter 5.0 summarizes the results of the numerous sensitivity analyses performed both in arriving at the power system designs described in Chapter 4.0, and in subsequent validity tests of those designs.

2.0 OVERVIEW OF THE POWER SYSTEM AND KEY ASSUMPTIONS

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Prior to examining the results of the analysis, it is necessary to understand the ground rules of the analysis. Section 2.1, which follows, provides a layman's explanation of power system functions and components. Section 2.2 then provides a discussion of the key assumptions used in the analysis.

2.1 OVERVIEW OF THE POWER SYSTEM

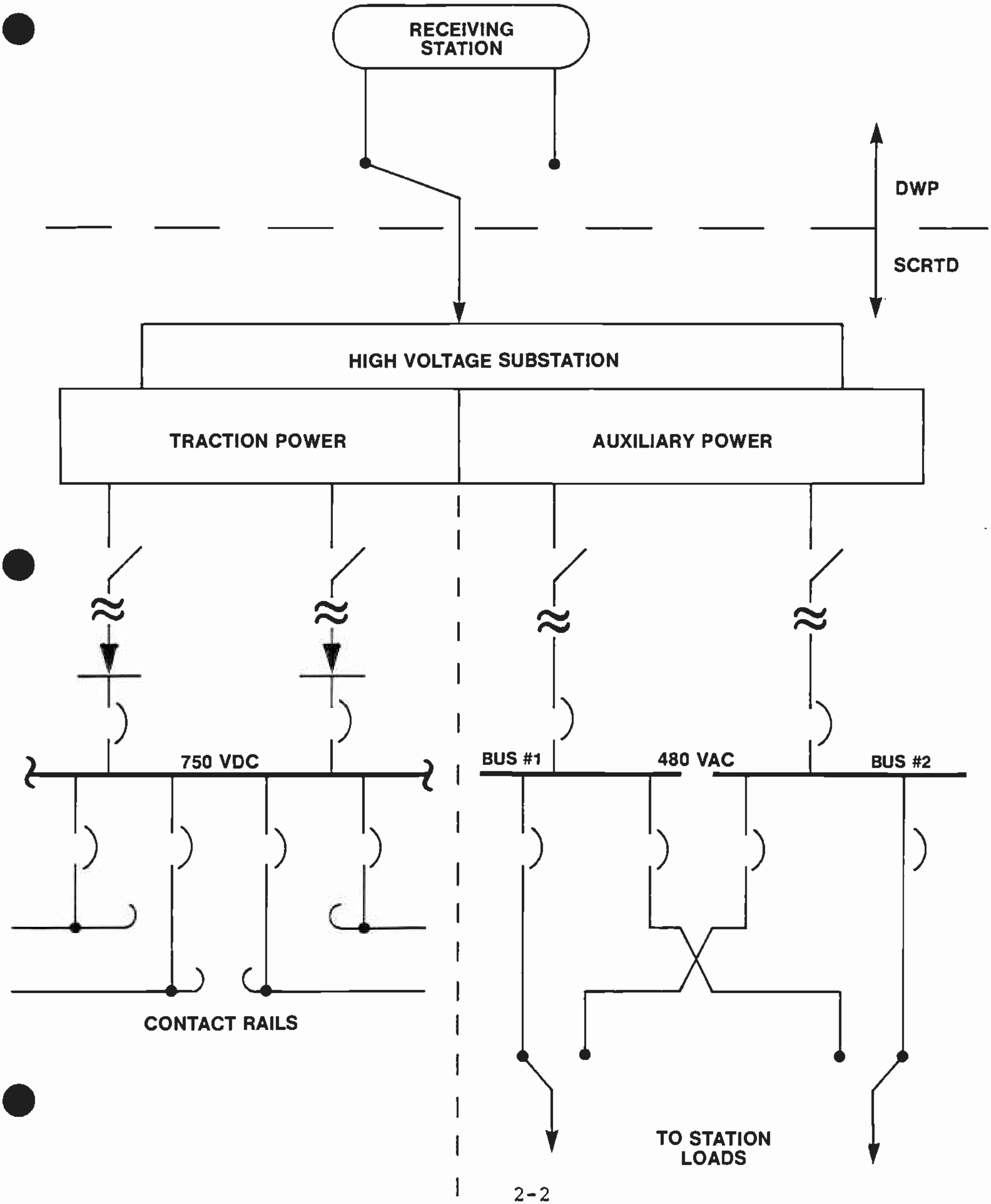
For the purposes of this study, the Metro Rail power system consists of elements to be supplied by the Southern California Rapid Transit District (SCRTD), the Los Angeles Department of Water and Power (DWP), and possibly Southern California Edison (SCE). For modeling purposes, it is not important where the boundaries lie; usually, feeder transfer switches and upstream elements will belong to the DWP or SCE and all elements downstream, including substations, will belong to the SCRTD.

The model includes all the elements shown in Exhibit 2-1. On the downstream side, the power system is, for modeling purposes, considered to end at the outputs of the traction power (TP) substations, up to and including 750 volt switchgear and contact rail feeder cables; and at the auxiliary power (AP) substations, up to and including low voltage transfer switches. The operational impacts of power system failures are regarded as completely defined by power availability status at these outputs. In turn, the status is defined by:

- The number of TP and AP substations having less than nominal power output available
- The level of each less-than-nominal power output
- The geographical relationship among the affected substations (when more than one substation is affected)

EXHIBIT 2-1

ELEMENTS INCLUDED IN THE POWER SYSTEM MODEL



- The duration of the power availability impairment.*

Impaired power availability may have operational impacts on trains, stations, or both. The following impacts have been defined:

- Trains

  - Reduced Performance: Slightly longer run times; some increases in crowding in trains and at stations.

  - Impaired Performance: Significant delays and longer run times; severe crowding.

  - Restricted: Train operation not required by Design Criteria. However, some minimal level of train movement may be possible.

- Stations

  - Discomfort: Poor ventilation; escalators inoperable.

  - Unavailable: Some portions of line not usable; trains not allowed to operate by procedure.

Exhibit 2-2 displays the relationships between power availability status and operational impacts.

For modeling purposes, the Metro Rail power system will consist of elements of four kinds: sources, receiving stations, feeders, and substations. These elements are defined and described below.

2.2.1 Sources

A source may be a local power plant, switching stations, or any other node directly upstream of one or more receiving stations.

For purposes of this analysis, all sources were assumed to have perfect reliability. This was based on the SCRTD's belief that there is no point in attempting to base Metro Rail reliability estimates

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* Power outages are characterized as less than one minute in duration (XSHORT), one to five minutes (SHORT), five to fifteen minutes (LONG), or more than fifteen minutes (XLONG).

EXHIBIT 2-2
Operational Impacts of Power Availability Status

Power Availability Status	Operational Impacts: Trains				Operational Impacts: Stations		
	Normal	Reduced	Impaired	Restricted	Normal	Discomfort	Unavailable
One TP Substation Affected							
1/2 Power	X				X		
0 Power		X			X		
Two Adjacent TP Stations							
1/2 + 1/2		X			X		
1/2 + 0			X		X		
0 + 0				X	X		
Outside 2 of 3 Adjacent TP Substations							
1/2 + 1/2	X				X		
1/2 + 0		X			X		
0 + 0			X		X		
Three Adjacent TP Sub-stations (Any Combination of Levels)				X	X		

EXHIBIT 2-2
Operational Impacts of Power Availability Status

	Operational Impacts						
	Trains				Stations		
Power Availability Status	Normal	Reduced	Impaired	Restricted	Normal	Discomfort	Unavailable
One AP Substation @ Passenger Station							
1/2 Power	X					X	
0 Power			#	*			X
Two AP Substations @ Passenger Stations							
1/2 + 1/2	X					X	
1/2 + 0			#	*			X
0 + 0			#	*			X
AP Substation @ Midline Vent							
1/2	X				X		
0			#	*	X		

NOTES: # = Applies if duration is not more than 5 minutes.
* = Applies if duration is more than 5 minutes.

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upon predictions of source failures which affect many other users besides the SCRTD. In any case, as has been shown on other transit systems around the country, source failures are rare.

2.1.2 Receiving Stations

A receiving station is a facility from which one or more Metro Rail substations and, usually, other customers are supplied. For purposes of determining outage frequencies and durations, a receiving station was considered to include the transmission lines, switchgear, etc., connecting it to its source.

A receiving station was also assumed to be either fully operational (all-up) or completely down. If it is all-up, it has the capacity to meet the power demands of all feeders connected to it.

2.1.3 Feeders

A feeder is a connection between a receiving station and a traction power substation, an auxiliary power substation, or both. A limited feeder is one of two lines which together have the capacity to meet the power demands of the substation(s) connected to them. Limited feeders are generally shared with other power users.

A dedicated feeder would serve only Metro Rail, and would have the capacity to meet the full power demands of the substations(s) connected to it. A system feeder is a tunnel backup cable which connects multiple substations (auxiliary, traction power, or both) and is designed to provide full or partial power to several, but not necessarily all, of these substations at the same time.

2.1.4 Substations

Traction and auxiliary power substations are the facilities at which power is actually to be made available for system use. Traction power is direct current (dc); auxiliary power is alternating current (ac). For purposes of analysis, a substation includes all hardware between feeder(s) and loads. Metro Rail power substations will generally be located at or near passenger stations.

The model treats power substations differently from other system elements in that some substations have the potential for three states: all-up, half-up, or down.

Five potential substation designs have been identified. They are defined in terms of their transformer connections and capacities, as follows:

1. A single transformer, with full capacity to handle the power loads connected to it

2. Paired transformers wired in parallel, each with full capacity to handle the load

3. Paired transformers, wired in parallel, each with half capacity

4. Paired transformers, separately fed, each with full capacity

5. Paired transformers, separately fed, each with half capacity.

Configurations 1, 2 and 4 have two possible states (all-up or down). Configurations 3 and 5, however, have three states (all-up, half-up, or down).

2.2 KEY ASSUMPTIONS

In order to control the complexity of this potentially unwieldy analysis, a number of simplifying assumptions were agreed upon by the SCRTD staff. However, should it be desirable for future analyses, the model has the capacity of evaluating the impact of changing most of these assumptions, as discussed below and in Chapter 5.0. All major assumptions used in the analysis to date are discussed below by category.

2.2.1 General

The inherent reliability of most individual electrical components is sufficiently high that in a system of such relatively small size as the Metro Rail system, multiple independent failures are unlikely. In addition, due to the geometric progression of possible events presented by an increasing number of independent failures, a thorough analysis of potential impacts quickly reaches a point of diminishing returns in the trade-off between analytical effort and useful results. Thus it was decided early in the analysis that there was no need to consider the possibility of any more than two independent failures in the power system at any one time.

This assumption was incorporated in the model logic. It presents an analytical difficulty only when considering a power system which incorporates backup generators, which tend to be less reliable than most power system components and which, by definition, are not called upon until other failures have occurred. This situation was considered on an exception basis in the analysis.

2.2.2 Sources

Both the DWP and SCE are potential sources of power for Metro Rail. Each undoubtedly has somewhat different reliability characteristics. But as was discussed earlier, for purposes of this analysis each source was regarded as perfectly reliable. However, should the capability ever be needed, the model can evaluate multiple sources, with different levels of reliability.

2.2.3 Receiving Stations

Available DWP information suggests that long receiving station outages occur approximately once per 200 receiving-station-years. Very short outages (for example, those that clear automatically after reclosing of circuit breakers) are undoubtedly much more frequent; the total frequency has been taken to be higher by a factor of 100. The model input assumes that 99 percent of all outages are in the very short category, while the expected number per year is 0.5 for a single receiving station. These values may be changed in the model, and may be specified differently for each power source, if desired. The assignment of specific receiving stations to Metro Rail power requirements is tentative and subject to change.

2.2.4 Feeders

DWP data for 1981 and 1982 indicate an outage frequency for limited feeders of 0.72 per feeder-year and an average outage duration of 57 minutes. However, year-to-year variations in the distribution of outage durations are substantial. Also, data from other utilities suggest that a substantially larger number of very brief outages should be anticipated. In response to these observations, the estimates used in the model assign 90 percent of the outages to the less-than-1-minute (self-clearing) category and 5 percent each to the 1-to-5 minute (clearable remotely by the utility) and very long (requiring dispatch of repair crews) categories. The total frequency is increased so that the average annual outage duration is about the same as in the DWP data.

Dedicated feeders are expected to have a lower failure frequency, since they are generally in better condition and less subject to outage as a result of other customers' problems. They are also expected to have a higher proportion of very short duration failures, due to their better isolation capability. System feeders should have an intermediate frequency of failure occurrence, since they are longer but better-protected than limited feeders.

2.2.5 Substations

It is expected that most traction and auxiliary power substations will consist of paired transformers and ancillary equipment (e.g., rectifiers) coupled with common elements (e.g., low-voltage switchgear). If the paired portions do not each have the capacity to handle the substation's full load, such substations have two levels of failed states. That is, if one of the paired transformers were to fail, the substation would provide half power; if both transformers failed, the substation would be completely out.

However, to make a complete determination of substation output status, it is also necessary to identify input feeder status and capacities, since feeders do not necessarily provide full power. Thus a feeder may be operational but provide only half power. If substation branches (traction or auxiliary power) are fed by separate feeders, the analysis gets even more complex.

A rigorous analysis of the complex interactions involved here would not only increase computer program complexity, but would also substantially increase execution time. The model therefore allows only one level of failed state and disregards the geometric interactions. Since the most likely failed state in a dual-path configuration is a one-path failure, the allowed output status for failed substations is taken as 1/2; occurrence frequency probabilities have been modified to compensate for the different ways in which this impacts the different substation configurations.

Single transformer traction power substations are expected to experience .34 failures per year; dual transformer substations should experience approximately double that failure rate. In either case, over 90% of these failures will be associated with rectifiers, which tend to be self-clearing. Many of the remaining failures will be responsive to manual intervention (restoration of trips). It is estimated that 50% of traction power substation outages will be in the less than one minute (XSHORT) category, 40% in the 5 to 15 minute category (LONG), and the remainder in the over 15 minute category (XLONG).

The expected number of failures per year for a dual-path auxiliary power substation is approximately 0.026. The probabilities of short-duration outages are much lower for auxiliary power substations; this is due to a very small proportion of self-clearing and a smaller proportion of outages that are correctable by simple manual intervention. It is estimated that 2 percent of the outages are in the shortest (XSHORT) category, 18 percent LONG, and the balance XLONG.

3.0 ANALYSES OF SOME BASIC ALTERNATIVE CONFIGURATIONS

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Early in the study, the SCRTD identified a number of basic alternative power system designs. Each of these alternatives was applied to a simple three passenger station system. Reliability analyses could not be conducted on such a small system because some effects of power outages may involve as many as three traction power substations. To ensure validity, the basic alternatives were expanded to a six passenger station application and the reliability model used to evaluate each alternative. This chapter will describe each alternative configuration and the results of the analyses.

3.1 STANDARD DWP SERVICE CONFIGURATION

Exhibit 3-1 shows the standard DWP service configuration. Power is distributed at 34.5 kv from the receiving stations. The 34.5 kv feeders are shared with other customers. This design may cause cascading outages when, for example, one customer brings down one feeder and all other customers on that line subsequently transfer to other feeders, causing them to overload.

3.2 DUAL INDEPENDENT FEEDS, SHARED SERVICE CONFIGURATION

Exhibit 3-2 shows this configuration which requires the utility to provide a feeder to each Metro Rail substation from two different receiving stations.

3.3 MULTIPLE DEDICATED FEEDER CONFIGURATION

Exhibit 3-3 shows this configuration which uses dedicated feeders running along the Metro Rail tunnel to distribute power to the substations.

3.4 SINGLE DEDICATED FEEDER CONFIGURATION

Exhibit 3-4 shows this configuration which is basically the standard DWP arrangement with an additional receiving station supplying a dedicated feeder along the Metro Rail tunnel.

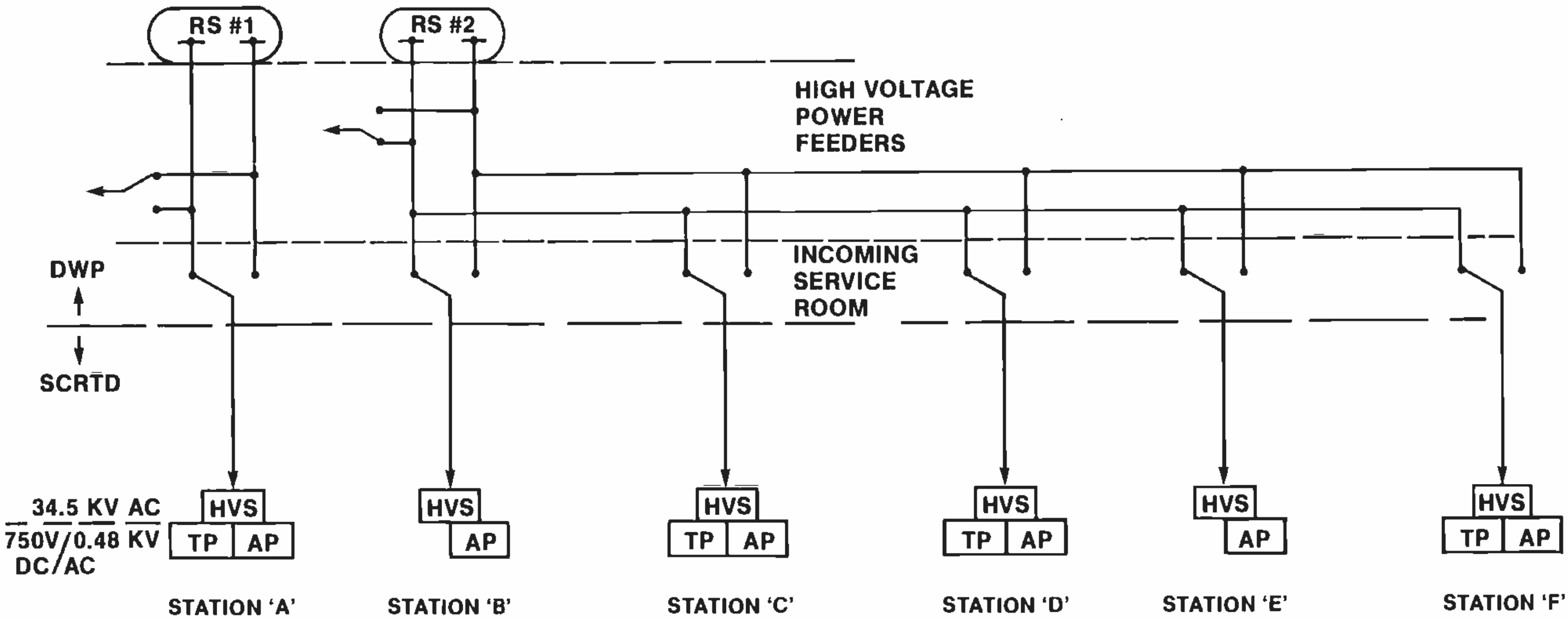

EXHIBIT 3-1
DWP Standard Service Configuration

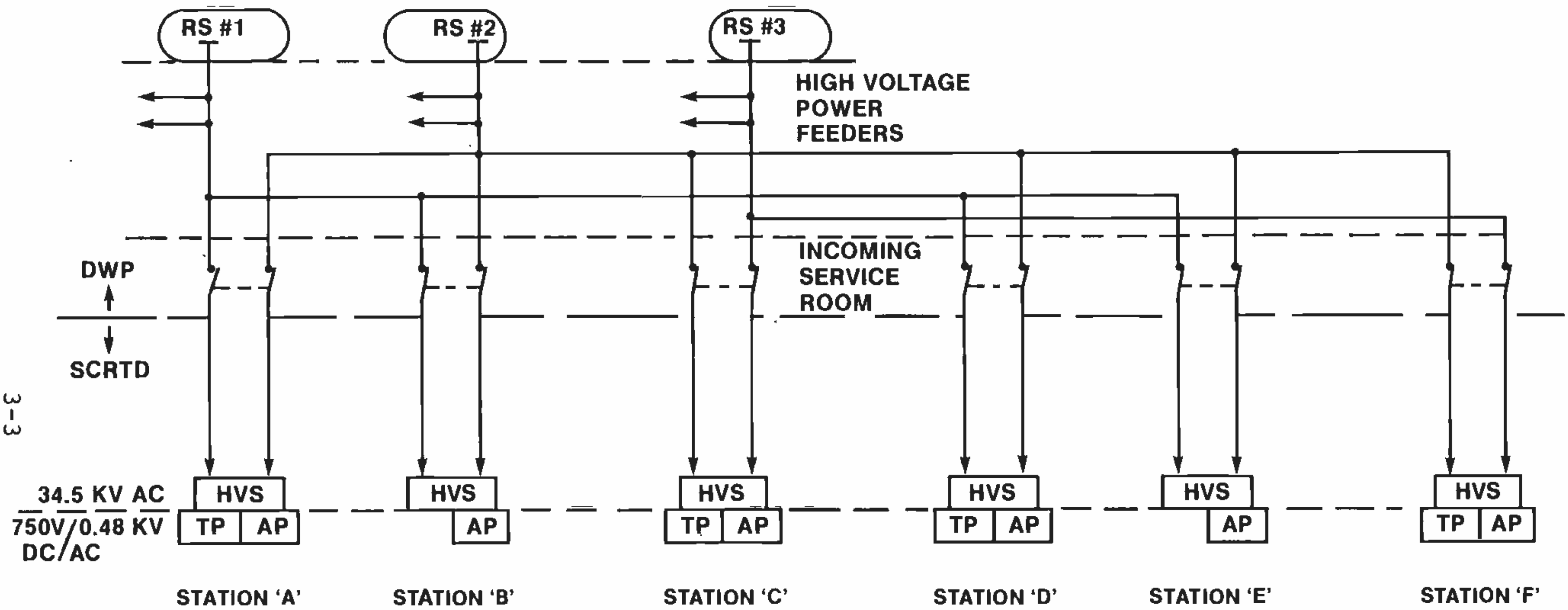

EXHIBIT 3-2
Dual Independent Feeds, Shared Service Configuration

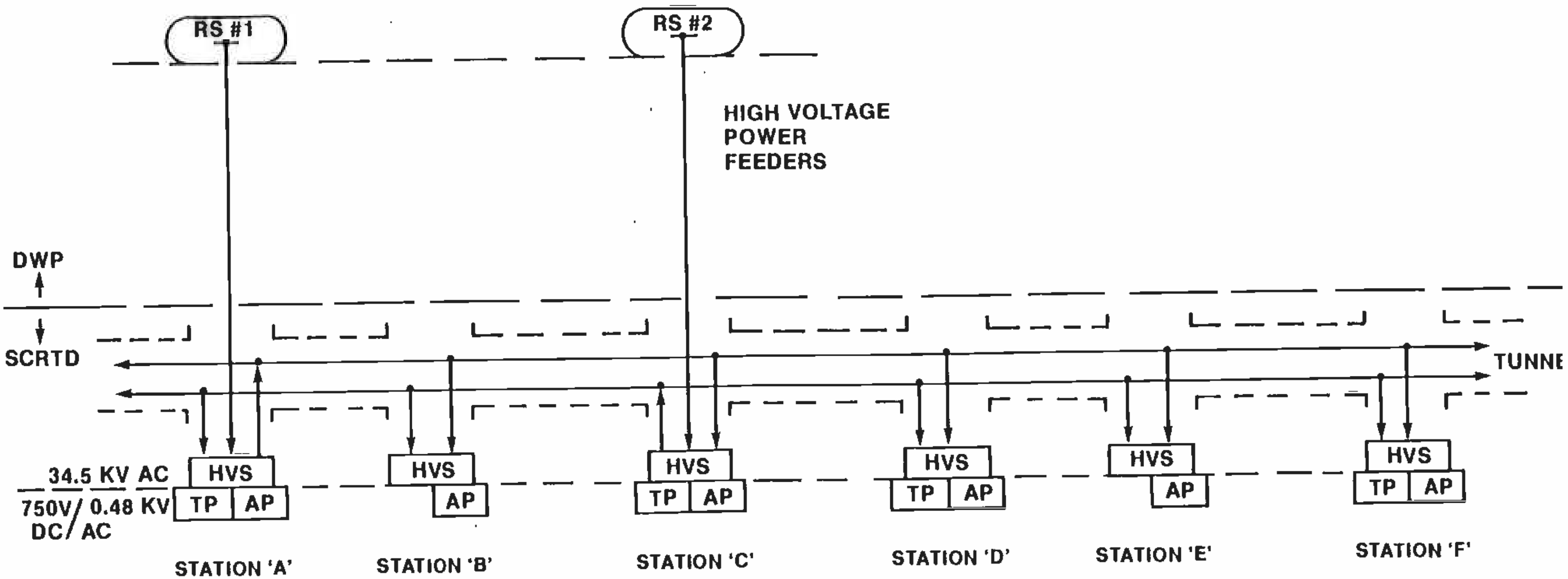

EXHIBIT 3-3
Multiple Dedicated Feeder Configuration

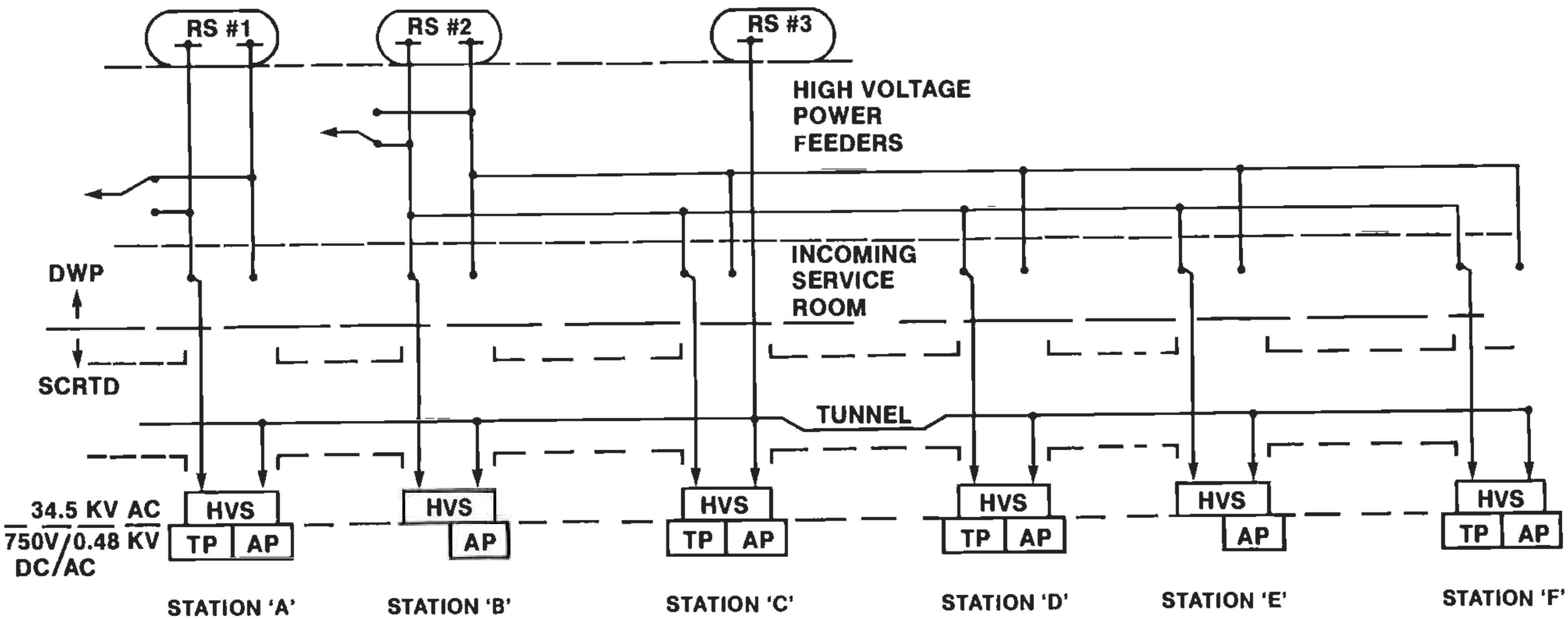

EXHIBIT 3-4
Single Dedicated Feeder Configuration

3.5 STANDBY GENERATOR CONFIGURATION

This configuration, shown in Exhibit 3-5, uses standby generators to supply auxiliary power substations. While this represents a low cost alternative, it also provides little improvement in the dependability of train operations and has a high impact on the design of Metro Rail facilities.

3.6 RESULTS OF THE ANALYSES

The results of the reliability analyses are shown in Exhibit 3-6. The standard DWP service was the least reliable, with an average of 113 minutes/year impaired train service, 308 minutes/year when the trains are stopped, and 421 minutes/year when the stations cannot be used. Two configurations, multiple dedicated feeders and the single dedicated feeder, offer the most reliable Metro Rail service with negligible effects on the system performance. Of these alternatives, the single dedicated feeder was preferred because it provides the lowest capital costs and uses a largely standard DWP arrangement.

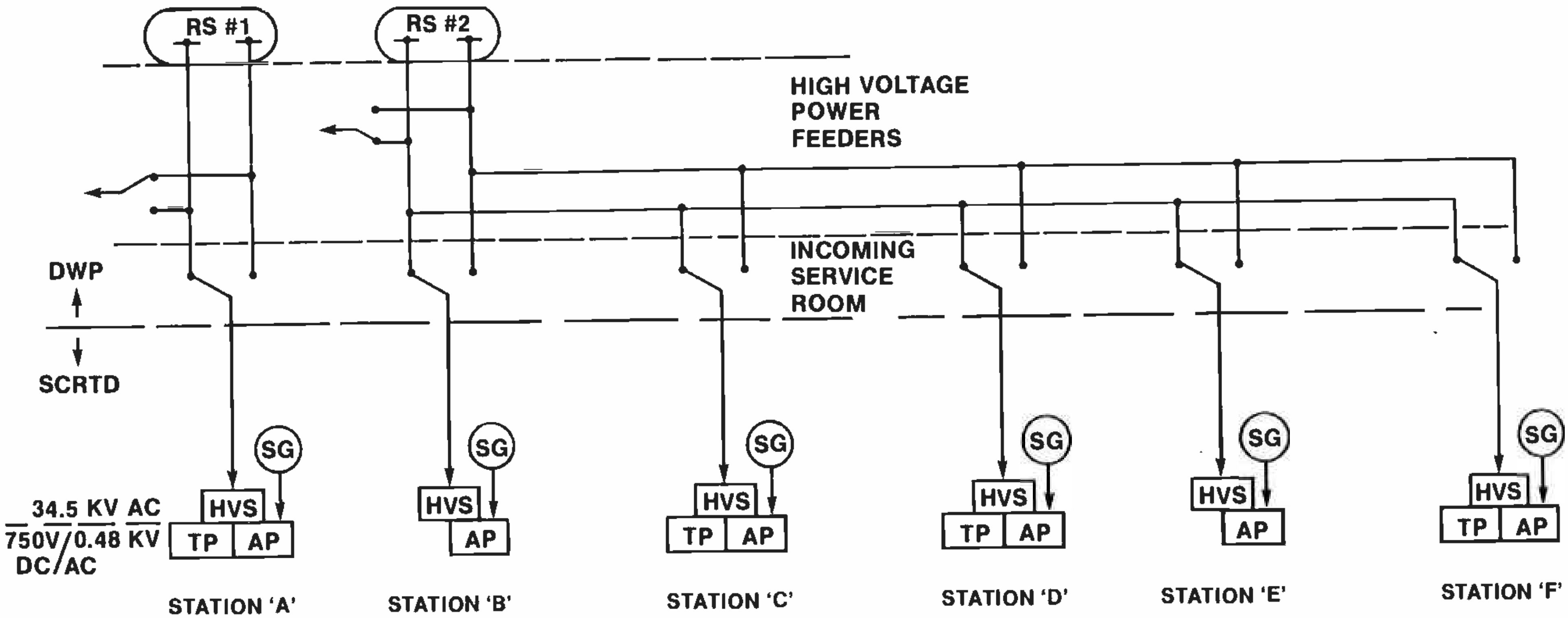

EXHIBIT 3-5
Standby Generator Configuration

EXHIBIT 3-6
Results of the Reliability Analyses of Alternative Configurations

Configuration	Cumulative Disruptions Per Year (Minutes)*		
	Operations		Stations
	Impaired	Restricted	Unavailable
Standard DWP Service	113	308	421
Dual Independent Feeders, Shared Service	13	32.4	45.4
Multiple Dedicated Feeder	0	0	0
Single Dedicated Feeder	0	0	0
Standby Generator	0.4	1.3	1.7

* Zero values correspond to less than 0.1 minute per year.

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4.0 EVALUATION OF BASELINE POWER SYSTEM DESIGNS

4.0 EVALUATION OF BASELINE POWER SYSTEM DESIGNS

In December of 1984, after considerable preliminary analysis, the SCRTD designated power system designs for the three Metro Rail configurations then being considered for initial operation. The three configurations consist of a 4-mile system, an 8.8-mile system, and an 18.6-mile system (see Exhibit 4-1). In this chapter, the power systems designated for each configuration are described and then the model analysis of system reliability is discussed.

4.1 THE 4-MILE CONFIGURATION

The 4-mile configuration would incorporate five stations, plus a maintenance/storage yard. It would extend from Union Station to Wilshire Boulevard at Alvarado.

The power system proposed for the 4-mile configuration is portrayed schematically in Exhibit 4-2. Relying exclusively on the DWP as a power source, the system would incorporate three receiving stations. One receiving station would service only the yard, another only Union Station, and the third the remaining passenger stations. Each receiving station would be linked to traction and auxiliary power substations by means of switchable limited feeders. Partial capacity backup for safety-related auxiliary power would be provided by a system feeder located in the train tunnel.

Results of an analysis of the four-mile configuration by the computer model are presented in Exhibit 4-3. In summary, the results indicate that total system outages (other than any caused by a possible DWP system outage) are extremely unlikely. Very brief (less than one minute) train stoppages can be expected, on an average, of once every other year. Modest train delays due to power reductions or interruptions can be expected to occur on an average of 20 times a year, with an accumulated total of approximately 50 minutes of less than normal service throughout the course of a year. Interruptions to passenger station lighting and ventilating power would be extremely rare, due largely to the system feeder backup provided.

Southern California Rapid Transit District
Metro Rail Project
TOTAL 18.6 MILES

STATIONS
1. UNION STATION
2. CIVIC CENTER
3. 5TH/HILL
4. 7TH/FLOWER
5. WILSHIRE/ALVARADO
6. WILSHIRE/VERMONT
7. WILSHIRE/NORMANDIE
8. WILSHIRE/WESTERN
9. WILSHIRE/CRENSHAW
10. WILSHIRE/LA BREA
11. WILSHIRE/FAIRFAX
12. FAIRFAX/BEVERLY
13. FAIRFAX/SANTA MONICA
14. LA BREA/SUNSET
15. HOLLYWOOD/CAHUENGA
16. HOLLYWOOD BOWL
17. UNIVERSAL CITY
18. NORTH HOLLYWOOD

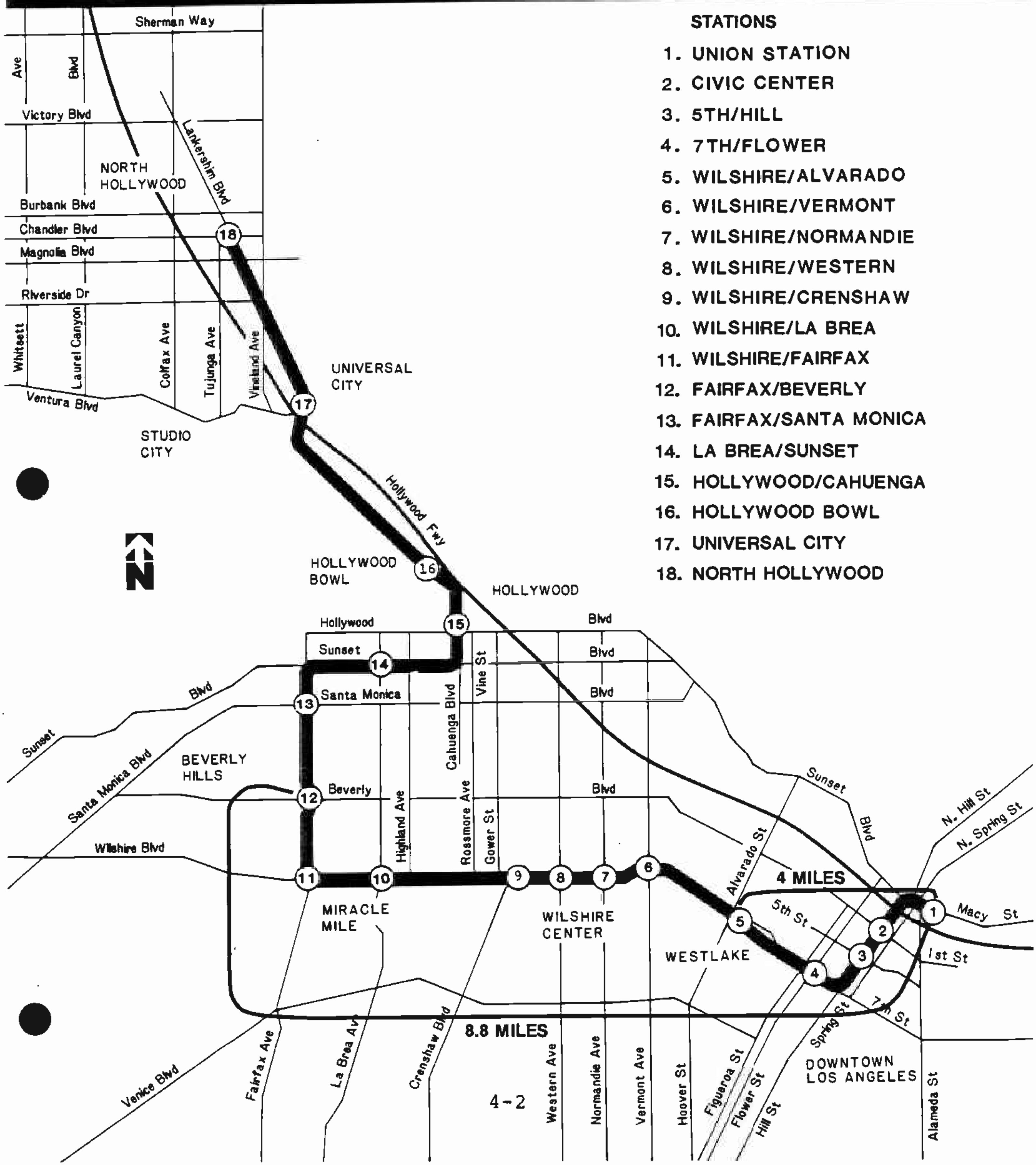
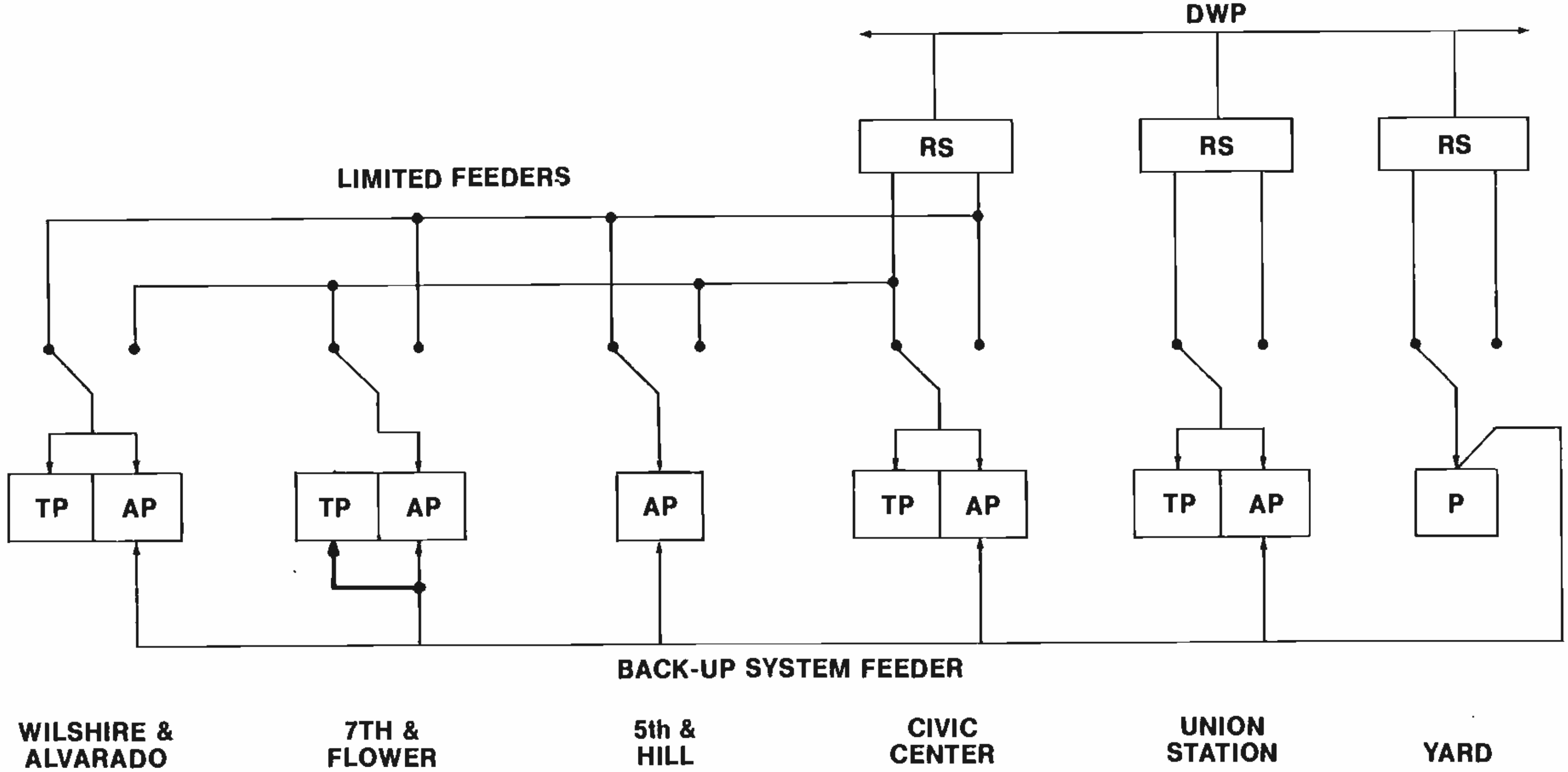


EXHIBIT 4-2

POWER SYSTEM SCHEMATIC

4 MILE CONFIGURATION



RS=RECEIVING STATION
TP=TRACTION POWER
AP=AUXILIARY POWER

EXHIBIT 4-3
Results for 4-Mile Configuration

Status		Average Incidents Per Year					Average Duration
Trains	Stations	XShort	Short	Long	XLong	Total	Minutes/Year
Reduced	Normal	19.4	1.54	1.14	1.09	23.2	58.4
Normal	Discomfort	<.01	<.01	.012	.052	.1	1.7
Reduced	Discomfort	<.01	<.01	<.01	<.01	<.01	0.0
Restricted	Normal	.50	<.01	<.01	<.01	.51	0.4
Restricted	Unavailable	<.01	0.0	0.0	<.01	<.01	0.0
Reduced	All Cases					23.2	58.4
Restricted	All Cases					.5	0.4
All Cases	Discomfort					.1	1.7
All Cases	Unavailable					<.01	0.0

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4.2 THE 8.8-MILE CONFIGURATION

The 8.8-mile configuration would incorporate 12 passenger stations, extending from Union Station out to Beverly Boulevard at Fairfax Avenue. The proposed power system for the configuration is portrayed schematically in Exhibit 4-4. As with the 4-mile system, this one would also rely entirely on the DWP as a source, and would incorporate one receiving station servicing only the yard and another exclusively for Union Station. The remainder of the passenger stations would be serviced by one of two other receiving stations.

As with the 4-mile configuration, each passenger station would have separate traction and auxiliary power substations, except for one station in each group of five which would only have an auxiliary power substation. Backup power in the 8.8-mile configuration would be designed somewhat differently. In the first place, there would be a separate receiving station with a dedicated feeder servicing the backup system feeder. In the second place, backup power would be provided not only for auxiliary passenger station power, but at one station in each group of five, for traction power as well.

Results of the model analysis for the 8.8-mile configuration are presented in Exhibit 4-5. As with the shorter configuration, the results indicate that serious disruptions of service would still be extremely unlikely, although very short train stoppages would increase to approximately one per year. As would be expected, modest train delays or station inconvenience due to limited power reductions or interruptions would also occur more frequently on an 8.8-mile system than a 4-mile system. Train delay incidents would be expected to occur perhaps once a month, but 85% of such delays would self-clear in less than a minute. In total, approximately 80 minutes per year of some form of power service reliability problem could be expected.

4.3 THE 18.6-MILE CONFIGURATION

The 18.6-mile configuration would incorporate 21 stations extending from Union Station to North Hollywood.

The proposed power system for the configuration is portrayed schematically in Exhibit 4-6. This power system design is similar to those discussed previously in terms of:

- Receiving stations that would service groups of four to six passenger stations (or mid-line air vents)

EXHIBIT 4-4

POWER SYSTEM SCHEMATIC
8.8 MILE CONFIGURATION

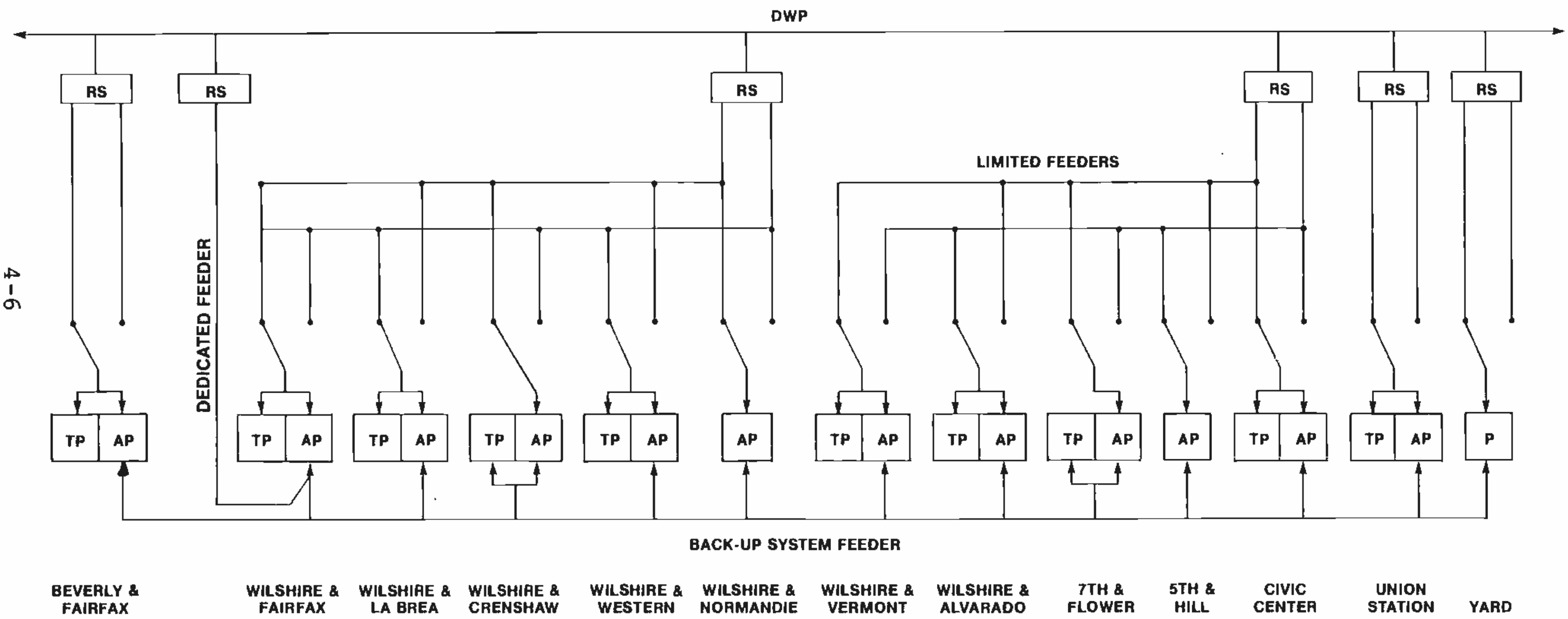

EXHIBIT 4-5
Results for 8.8-Mile Configuration

Status		Average Incidents Per Year					Average Duration
Trains	Stations	XShort	Short	Long	XLong	Total	Minutes/Year
Reduced	Normal	37.2	2.44	1.96	2.20	43.8	111.5
Normal	Discomfort	.01	<.01	.028	.013	.05	4.0
Reduced	Discomfort	<.01	<.01	<.01	<.01	<.01	0.0
Restricted	Normal	.99	0.0	0.0	.01	1.0	0.8
Restricted	Unavailable	<.01	0.0	0.0	<.01	<.01	0.0
Reduced	All Cases					43.8	111.5
Restricted	All Cases					1.0	0.8
All Cases	Discomfort					.05	4.0
All Cases	Unavailable					<.01	0.0

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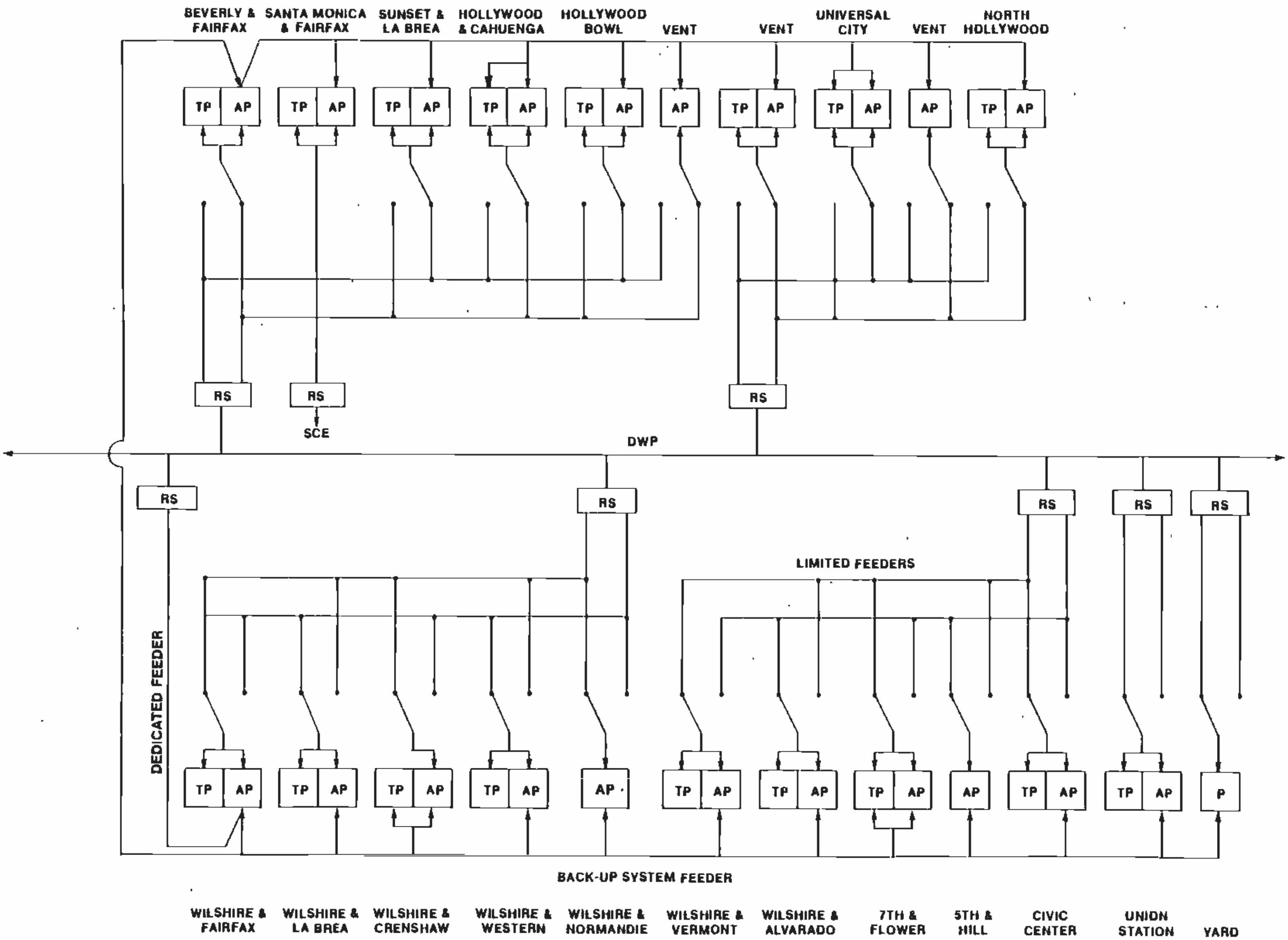
EXHIBIT 4-6

POWER SYSTEM SCHEMATIC

18.6 MILE CONFIGURATION



4-8

- Separate receiving stations dedicated to servicing Union Station and the yard.

- A system feed located in the tunnel that would provide backup power to all auxiliary substations, in addition to one of the traction substations serviced by each receiving station.

As with the 8.8-mile configuration, the tunnel backup cable would be serviced by a dedicated receiving station and feeder. The 18.6-mile configuration would differ from the two shorter configurations in that a combination of DWP and SCE power sources would be used.

Results of the model analysis of the 18.6-mile configuration are presented in Exhibit 4-7. The pattern is highly consistent with that observed for the shorter configurations. The magnitude of the numbers is larger, simply because the system is longer and thus contains more operating elements. In summary:

- Catastrophic outages of all service are not expected, unless the DWP source system experiences such a failure.

- Brief (less than one minute) train stoppages or significant slowdowns will occur on an average of once every six months; longer stoppages will be rare.

- Power outages affecting auxiliary power at one or more passenger stations will occur on an average of once every five years; these will tend to be relatively long outages (more than 15 minutes). However, these will almost always be partial outages, maintaining emergency ventilation capability.

- Modest train service slowdowns will occur on an average of once every week or so; however, 85% of these slowdowns will be so brief as to be virtually imperceptible to riders.

4.4 COMPARISON WITH OTHER TRANSIT SYSTEMS

In order to take maximum advantage of lessons learned by the planners and operators of other rail transit systems around the country, the SCRTD commissioned an extensive survey of those systems. Many valuable lessons relating to power system design and operating practices were learned. The information gained is discussed in detail in other SCRTD publications.

EXHIBIT 4-7
Results for 18.6-Mile Configuration

Status		Average Incidents Per Year					Average Duration
Trains	Stations	XShort	Short	Long	XLong	Total	Minutes/Year
Reduced	Normal	54.7	3.29	2.91	3.24	64.1	163.5
Normal	Discomfort	.017	<.01	.042	.019	.08	6.1
Reduced	Discomfort	<.01	<.01	<.01	<.01	<.01	0.0
Impaired	Normal	1.00	<.01	0.0	.01	1.0	0.8
Restricted	Normal	1.00	0.0	0.0	.01	1.0	0.8
Restricted	Unavailable	<.01	0.0	0.0	<.01	<.01	0.0
Reduced	All Cases					64.1	163.5
Impaired	All Cases					1.0	0.8
Restricted	All Cases					1.0	0.8
All Cases	Discomfort					.08	6.1
All Cases	Unavailable					<.01	0.0

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For purposes of this report, however, two important observations can be made. First, that prior to this project, no transit system has made an effort to model power system reliability or to predict it with any degree of mathematical precision. Second, that the reliability patterns predicted here for any of the initial system configurations compare quite favorably with the experience of transit systems that have been in operation for some years.

The responses from the thirteen systems participating in the survey ranged from three which have never experienced a significant outage, to one which has experienced one "major" outage every three years plus two local substation outages per year (the duration was not noted). Two others have experienced total outages for an extended period, as a result of regional power blackouts.

The majority of the systems, however, "have experienced infrequent power outages, most of short duration and with limited effect on system operation."*

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* Survey of Electric Power Systems for North American Rail Rapid Transit Properties; Metro Rail Transit Consultants; July 1984; Question 18.

5.0 SENSITIVITY ANALYSIS

5.0 SENSITIVITY ANALYSIS

The analysis leading up to the designation of power system designs for the alternative Metro Rail configurations, as described in the previous chapter, involved an extensive series of sensitivity analyses. Further analyses have been conducted subsequent to the designation of power system designs, in an effort to identify potential improvements. Some of these analyses are discussed in this chapter.

5.1 SYSTEM FEEDER BACKUP

The importance of this system feeder backup was tested in two ways by analyzing the impact on the 18.6-mile Metro Rail configuration of:

- Eliminating the backup for traction power substations
- Extending it to cover all traction power substations as well as auxiliary power substations.

Results of this two-part analysis have been presented in Exhibits 5-1 and 5-2. They should be compared with the results in Exhibit 4-7.

The comparison reveals that eliminating the traction power backup would result in:

- Twice as many restricted train incidents (although the vast majority would still be of minimal duration)
- A small increase in the number of, and total time spent in, reduced train service incidents.

In other words, the impact of eliminating the traction power backup feeder would be a significant, but not catastrophic, increase in train and station service interruptions.

In contrast, the positive impacts of providing comprehensive backup capability with a system feeder are striking. Serious incidents would be virtually eliminated, and reduced train service incidents would drop from

EXHIBIT 5-1
Sensitivity Analysis: No System Feeder Backup

Status		Average Incidents Per Year					Average Duration Minutes/Year
Trains	Stations	XShort	Short	Long	XLong	Total	
Reduced	Normal	59.1	3.01	2.31	3.55	68.0	168.1
Normal	Discomfort	.017	<.01	.042	.19	.2	6.1
Reduced	Discomfort	<.01	<.01	<.01	<.01	<.01	0.0
Restricted	Normal	1.99	0.0	0.0	.02	2.0	1.6
Restricted	Unavailable	<.01	0.0	0.0	<.01	<.01	0.0
Reduced	All Cases					68.0	168.1
Restricted	All Cases					2.0	1.6
All Cases	Discomfort					.2	6.1
All Cases	Unavailable					<.01	0.0

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EXHIBIT 5-2

Sensitivity Analysis: Comprehensive System Feeder Backup

Status		Average Incidents Per Year					Duration
Trains	Stations	XShort	Short	Long	XLong	Total	Minutes/Year
Reduced	Normal	11.5	1.01	2.91	.99	16.4	67.7
Normal	Discomfort	.017	<.01	.042	.19	.25	6.1
Reduced	Discomfort	<.01	0.0	<.01	<.01	<.01	0.0
Impaired	Unavailable	<.01	<.01	0.0	0.0	<.01	0.0
Restricted	Unavailable	<.01	0.0	0.0	.01	<.01	0.0
Reduced	All Cases					16.4	67.7
Impaired	All Cases					<.01	0.0
Restricted	All Cases					<.01	0.0
All Cases	Discomfort					.25	6.1
All Cases	Unavailable					<.01	0.0

more than one per week to, on an average, one every three weeks.

Based solely on reliability evidence, adding full backup capability to all power substations by means of a dedicated system feeder appears to have promising potential for improving overall Metro Rail reliability. However, it may not be justifiable economically.

5.2 SENSITIVITY ANALYSIS OF MODEL ASSUMPTIONS

The computer model of power system reliability which was used for this project incorporated a number of assumptions of reliability factors for specific system components. These were discussed in Chapter 2.0.

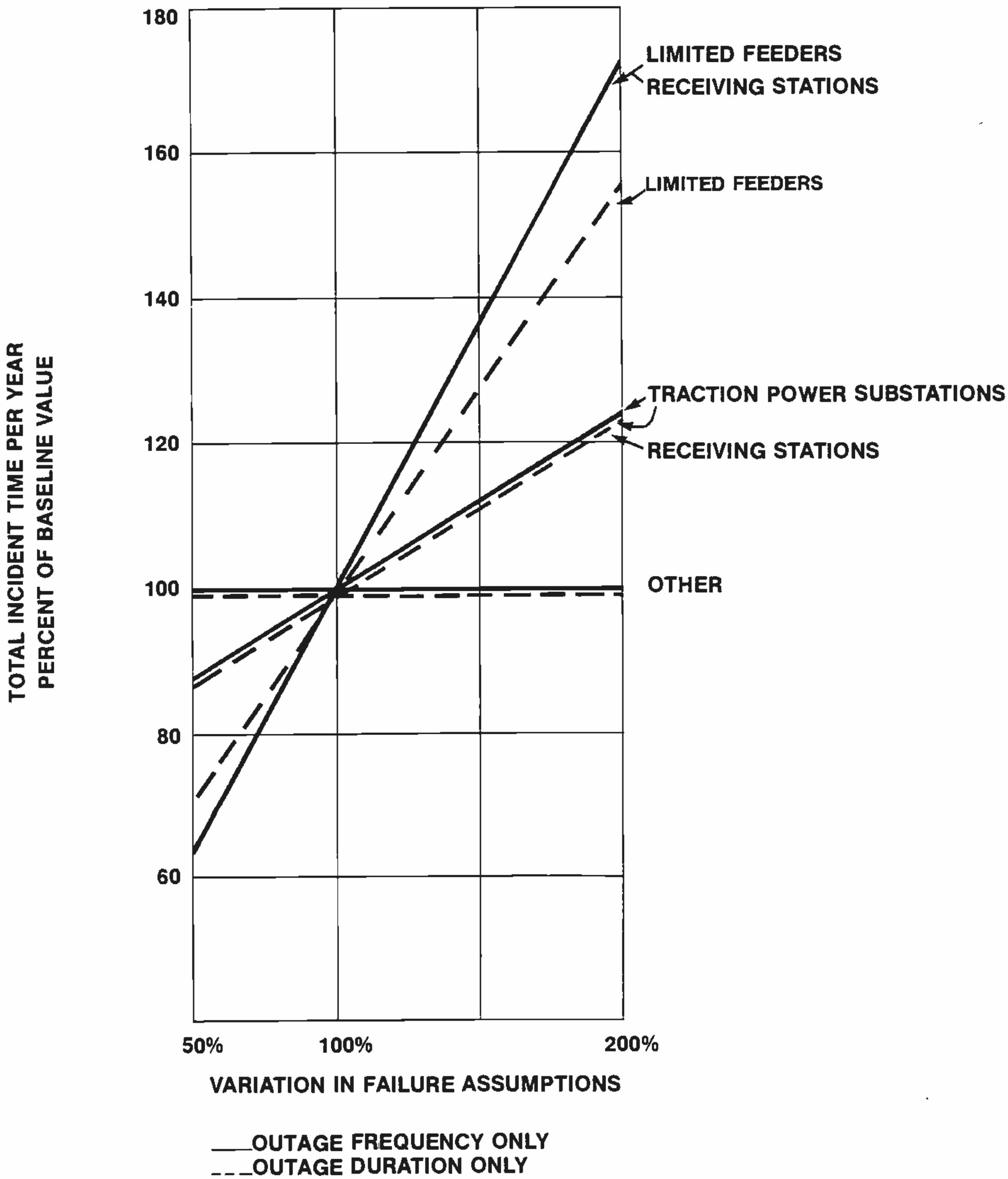
Most of the assumptions were well documented, all were subjected to intensive expert review, and the net result is a scenario which is considered a reasonable representation of reality. However, any assumption is subject to question, so it was considered desirable to test the sensitivity of output results to changes in key assumptions. This sensitivity analysis was performed on the 4-mile Metro Rail configuration results.

The impact on train service is demonstrated in Exhibit 5-3. The intersection point of the three lines represents the number of minutes per year of power outage incidents, as predicted by the model, using all the built-in estimates for individual component reliability. Each solid line demonstrates the percentage impact on the total time spent in any less-than-normal train service category, as the frequency of individual component failures varies from 50% to 200% of the baseline value. For example, if the frequency of traction power substation incidents is reduced to 50% of the baseline value assumed in the model, the average annual duration of the outages is reduced to approximately 88% of the value estimated for the 4-mile system. In addition, the impact of the duration assumptions on the number of minutes per year of power outage incidents was also assessed. For all duration categories except the extra-short, the proportion of incidents in each category was varied from 50% to 200% of the modeled value. Dashed lines in Exhibit 5-3 represent the results of the sensitivity analysis of the duration assumptions. The relationships are very nearly linear over the 50%-200% range.

Exhibit 5-3 indicates equal sensitivity with respect to outage frequency effects for limited feeders and receiving stations. There is an important difference: outage of limited feeders results in reduced train status, which is more common but less serious than the stopped train status that typically results from receiving station

EXHIBIT 5-3

IMPACT ON TRAIN SERVICE
OF VARIATIONS IN RELIABILITY ASSUMPTIONS



outage. Traction power substation outages also result in reduced train status. Some additional sensitivities probably would become apparent if more than two independent failures were considered simultaneously; however, the associated probabilities are sufficiently small to be considered negligible.

Exhibit 5-4 displays the impact on passenger station services of increasing the frequency and duration of auxiliary power substation outages. Increased outages of any other component, including receiving stations, have no impact, due to the backups built into the system specifically for auxiliary power.

Two cautionary notes must be made in interpreting the results of this analysis. First, recall that this study was restricted to analyzing impacts of no more than two independent failures at one time, due to the low probability of more complex failures and the high cost of analyzing them. Second, note that this particular sensitivity analysis looks at the impact of increasing the frequency or duration of failures of only one system component at a time. Again, more complex failures are of no practical concern.

Sensitivity analyses such as this one can have at least two purposes:

- To determine whether the baseline analytical results are sufficiently "robust," that is, sufficiently insensitive to estimation uncertainties to support confident decision making

- To help identify favorable trade-offs, in this case, between investment cost and service dependability.

Robustness appears to have been established, in that even if critical assumptions of component failure rates and duration were to be off by a factor of 200%, the impact on the system would be no worse than proportional (station auxiliary power) and in most cases much less than proportional.

Trade-off analysis requires information beyond the output of this sensitivity analysis, primarily cost information and management judgment as to the relative importance of the frequency and duration of various types of reliability problems. From a trade-off standpoint, the results of the sensitivity analyses provide guidance and tools, not final answers.

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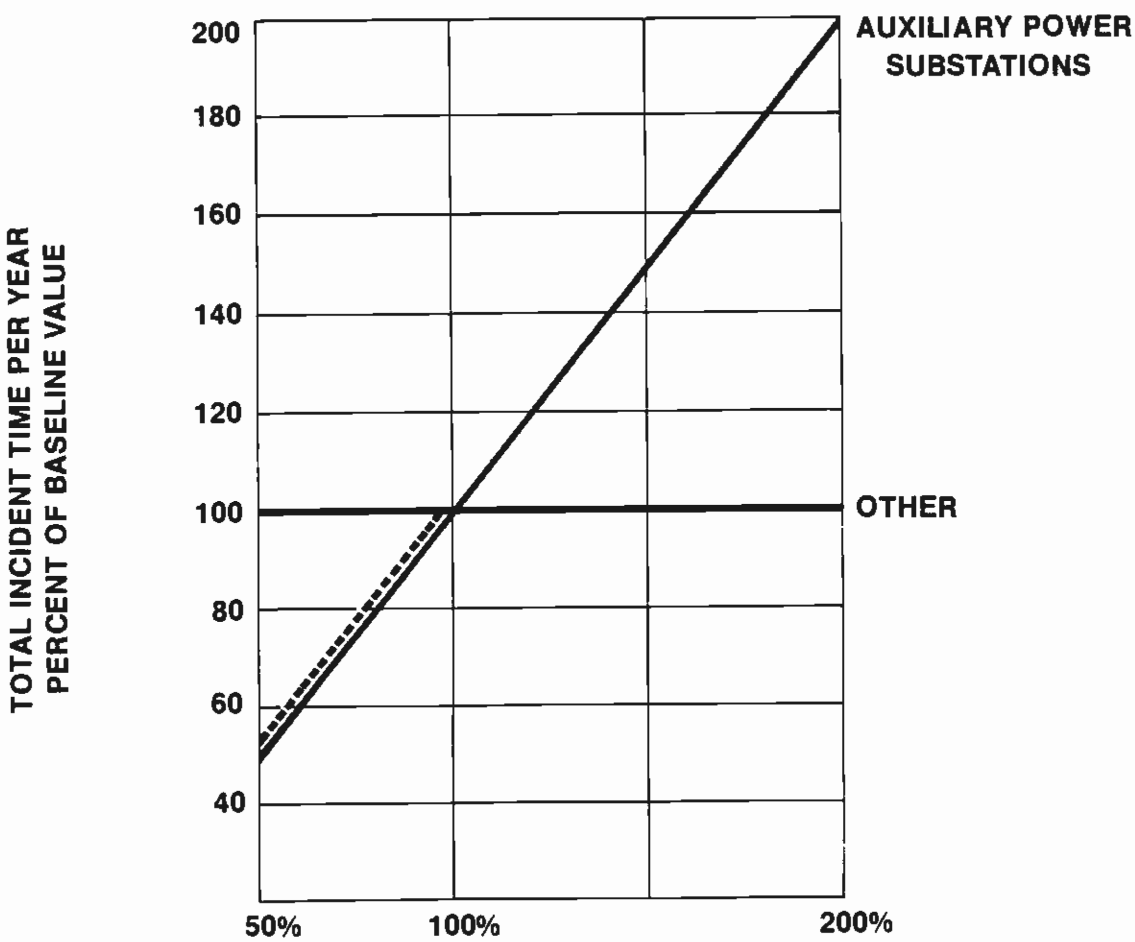
EXHIBIT 5-4

IMPACT ON PASSENGER STATION SERVICE
OF VARIATIONS IN RELIABILITY ASSUMPTIONS



VARIATION IN FAILURE ASSUMPTIONS

____OUTAGE FREQUENCY ONLY
___OUTAGE DURATION ONLY
(EVALUATION ABOVE 100% INFEASIBLE)

APPENDIX

```
2 READ DAT$
4 LPRINT
6 LPRINT USING "socpow2A using datafile &";DAT$
8 LPRINT
10 DIM ASTAT(25),DT%(50,25),DA%(50,25),E(115),FE(11),FT%(50),FSTAT(50),FP(3,11),
ID%(115)
20 DIM NT%(50),NA%(50),NL%(50),NN%(115),O%(50),P(3,115),P1(10,2),P2(10,2),P3(10,
2),PE(11)
30 DIM P4(10,2),PP(3,11),RE(4),RN$(11),RP(3,4),RS%(11),RSTAT(11),RT%(11),S$(11),
ST%(5),SN$(5),SSTAT(5),SE(3),SP(3,3),STT(5)
35 DIM TT%(50),TTN$(25),TA%(50),TTA$(25),T%(115),TRT(7),TSTAT(25),T$(11)
40 READ NST%                                           'NO. OF SOURCE TYPES
50 FOR I%=1 TO NST%
60 READ SE(I%),SP(1,I%),SP(2,I%),SP(3,I%)              'EXP. FAILS/YR. DUR. PROBS
70 NEXT I%
80 READ NRT%                                           'NO. OF RS TYPES
90 FOR I%=1 TO NRT%
100 READ RE(I%),RP(1,I%),RP(2,I%),RP(3,I%)
110 NEXT I%
120 READ NFT%                                           'NO. OF FEEDER TYPES
130 FOR I%=1 TO NFT%
140 READ FE(I%),FP(1,I%),FP(2,I%),FP(3,I%)
150 NEXT I%
160 READ NPT%                    'NO. OF SUBSTATION TYPES (AP & TP COMBINED)
170 FOR I%=1 TO NPT%
180 READ PE(I%),PP(1,I%),PP(2,I%),PP(3,I%)
190 NEXT I%
200 READ NS%                                'no. of sources
210 FOR I%=1 TO NS%
220 READ ST%(I%),SN$(I%)
230 NEXT I%
240 REM st=source type, sn=source name
300 READ NR%                                'no. of receiving stations
310 FOR I%=1 TO NR%
320 READ RT%(I%),RN$(I%),RS%(I%)
330 NEXT I%
340 REM rt=rs type, rn=name, rs=source
400 READ NF%                    'no. of feeders; enter system feeders in data last
410 FOR I%=1 TO NF%
420 READ FT%(I%),O%(I%),NT%(I%),NA%(I%)
430 IF NT%(I%)=0 THEN 470
440 FOR J%=1 TO NT%(I%)
450 READ DT%(I%,J%)
460 NEXT J%
465 REM dt=jth destination tp of ith feeder;enter in data in increasing distance
order
470 IF NA%(I%)=0 THEN 510
480 FOR J%=1 TO NA%(I%)
490 READ DA%(I%,J%)
500 NEXT J%
505 REM da=jth destination ap of ith feeder
510 IF FT%(I%)<>1 THEN 530                        'not system feeder
```

```
520 READ NL%(I%)              'no. of substations that can be fed by ith feeder
530 NEXT I%
600 READ NNT%                               'no. of tp substations
610 FOR I%=1 TO NNT%
620 READ TT%(I%),TTN$(I%)
630 NEXT I%
635 REM tt=type of tp substation, ttn=name of its location
700 READ NNA%                               'no. of ap substations
710 FOR I%=1 TO NNA%
720 READ TA%(I%),TTA$(I%)
730 NEXT I%
735 REM ta=type of ap substation, tta=name of its location
1000 REM this routine assigns consecutive numbers to all system elements
1005 FOR I%=1 TO NS%
1010 T%(I%)=ST%(I%)      't% is to be used to bypass unfailable items (=0)
1020 NN%(I%)=1                              'item is a source
1030 ID%(I%)=I%                             'source index is i%
1032 E(I%)=SE(ST%(I%))
1034 P(1,I%)=SP(1,ST%(I%))
1036 P(2,I%)=SP(2,ST%(I%))
1038 P(3,I%)=SP(3,ST%(I%))
1040 NEXT I%
1050 FOR I%=1 TO NR%
1060 T%(I%+NS%)=RT%(I%)
1070 NN%(I%+NS%)=2                          'item is a receiving station (rs)
1080 ID%(I%+NS%)=I%                         'rs index is i%
1082 E(I%+NS%)=RE(RT%(I%))
1084 P(1,I%+NS%)=RP(1,RT%(I%))
1086 P(2,I%+NS%)=RP(2,RT%(I%))
1088 P(3,I%+NS%)=RP(3,RT%(I%))
1090 NEXT I%
1100 FOR I%=1 TO NF%
1110 T%(I%+NS%+NR%)=FT%(I%)
1120 NN%(I%+NS%+NR%)=3                      'item is a feeder
1130 ID%(I%+NS%+NR%)=I%                     'feeder index is i%
1132 E(I%+NS%+NR%)=FE(FT%(I%))
1134 P(1,I%+NS%+NR%)=FP(1,FT%(I%))
1136 P(2,I%+NS%+NR%)=FP(2,FT%(I%))
1138 P(3,I%+NS%+NR%)=FP(3,FT%(I%))
1140 NEXT I%
1150 FOR I%=1 TO NNT%
1160 T%(I%+NS%+NR%+NF%)=TT%(I%)
1170 NN%(I%+NS%+NR%+NF%)=4                     'item is a tp substation
1180 ID%(I%+NS%+NR%+NF%)=I%                    'tp substation index is i%
1182 E(I%+NS%+NR%+NF%)=PE(TT%(I%))
1184 P(1,I%+NS%+NR%+NF%)=PP(1,TT%(I%))
1186 P(2,I%+NS%+NR%+NF%)=PP(2,TT%(I%))
1188 P(3,I%+NS%+NR%+NF%)=PP(3,TT%(I%))
1190 NEXT I%
1200 FOR I%=1 TO NNA%
1210 T%(I%+NS%+NR%+NF%+NNT%)=TA%(I%)
```

```
1220 NN%(I%+NS%+NR%+NF%+NNT%)=5                    'item is an ap substation
1230 ID%(I%+NS%+NR%+NF%+NNT%)=I%                   'ap substation index is i%
1232 E(I%+NS%+NR%+NF%+NNT%)=PE(TA%(I%))
1234 P(1,I%+NS%+NR%+NF%+NNT%)=PP(1,TA%(I%))
1236 P(2,I%+NS%+NR%+NF%+NNT%)=PP(2,TA%(I%))
1238 P(3,I%+NS%+NR%+NF%+NNT%)=PP(3,TA%(I%))
1240 NEXT I%
1290 GOSUB 2000
1300 T$(1)="REDUCED"
1310 T$(2)="NORMAL"
1320 T$(3)="REDUCED"
1330 T$(4)="IMPAIRED"
1340 T$(5)="IMPAIRED"
1350 T$(7)="IMPAIRED"
1360 T$(8)="STOPPED"
1370 T$(9)="STOPPED"
1380 T$(10)="STOPPED"
1390 S$(1)="NORMAL"
1400 S$(2)="DISCOMFORT"
1410 S$(3)="DISCOMFORT"
1420 S$(4)="NORMAL"
1430 S$(5)="DISCOMFORT"
1440 S$(7)="UNAVAILABLE"
1450 S$(8)="NORMAL"
1460 S$(9)="DISCOMFORT"
1470 S$(10)="UNAVAILABLE"
1500 LPRINT                                          'DISPLAY ROUTINE
1510 LPRINT
1520 LPRINT "                                                        RESULTS"
1530 LPRINT "      STATUS                        OCCURRENCES PER YEAR
DURATION"
1540 LPRINT "TRAINS      STATION(S)     XSHORT      SHORT      LONG        XLONG    M
INUTES/YR"
1550 LPRINT
1600 FOR J%=1 TO 10
1610 IF J%=6 THEN 1670
1620 TRST1=.5*P1(J%,1)+3*P2(J%,1)+10*P3(J%,1)+30*P4(J%,1)
1622 TRST2=.5*P1(J%,2)+3*P2(J%,2)+10*P3(J%,2)+30*P4(J%,2)+TRST1
1625 IF TRST2=0 THEN 1670
1630 LPRINT USING "\        \    \             \";T$(J%),S$(J%)
1640 LPRINT USING "      1 INDEP. FAILURE    ##.##^^^^   ##.##^^^^   ##.##^^^^   ##.#
#^^^^   ####.#";P1(J%,1),P2(J%,1),P3(J%,1),P4(J%,1),TRST1
1650 LPRINT USING "1 or 2 INDEP. FAILURES   ##.##^^^^   ##.##^^^^   ##.##^^^^   ##.#
#^^^^   ####.#";P1(J%,1)+P1(J%,2),P2(J%,1)+P2(J%,2),P3(J%,1)+P3(J%,2),P4(J%,1)+P4
(J%,2),TRST2
1660 LPRINT
1665 GOSUB 6300                                 'time accumulation subroutine
1670 NEXT J%
1680 LPRINT
1690 LPRINT
1700 LPRINT "TRAIN STATUS                        MINUTES/YEAR"
1710 LPRINT
1720 LPRINT "  REDUCED"
1730 LPRINT USING "      1 INDEP. FAILURE                ####.#";TRT(1)
1740 LPRINT USING "1 or 2 INDEP. FAILURES                ####.#";TRT(2)
1750 LPRINT "  IMPAIRED"
```

```
1760 LPRINT USING "      1 INDEP. FAILURE                   ####.#";TRT(3)
1770 LPRINT USING "1 or 2 INDEP. FAILURES                   ####.#";TRT(4)
1780 LPRINT "  STOPPED"
1790 LPRINT USING "      1 INDEP. FAILURE                   ####.#";TRT(5)
1800 LPRINT USING "1 or 2 INDEP. FAILURES                   ####.#";TRT(6)
1810 LPRINT
1820 LPRINT "STATION STATUS"
1830 LPRINT
1840 LPRINT "  DISCOMFORT"
1850 LPRINT USING "      1 INDEP. FAILURE                   ####.#";STT(1)
1860 LPRINT USING "1 or 2 INDEP. FAILURES                   ####.#";STT(2)
1870 LPRINT "  UNAVAILABLE"
1880 LPRINT USING "      1 INDEP. FAILURE                   ####.#";STT(3)
1890 LPRINT USING "1 or 2 INDEP. FAILURES                   ####.#";STT(4)
1900 LPRINT
1910 LPRINT
1990 GOTO 9999
2000 REM failure identity assignment routine (1, 2 at a time)
2005 TOT%=NS%+NR%+NF%+NNT%+NNA%
2010 FOR I%=1 TO TOT%
2020 IF T%(I%)=0 OR E(I%)=0 THEN 2160                      'unfailable item
2030 GOSUB 3000
2040 IF I%=TOT% THEN 2160                         'only 1 failure possible
2050 FOR I1%=I%+1 TO TOT%
2060 IF T%(I1%)=0 OR E(I1%)=0 THEN 2140
2070 GOSUB 3000
2140 NEXT I1%
2150 I1%=0
2160 NEXT I%
2190 RETURN
3000 GOSUB 6000
3030 IF I%>NS%+NR% THEN 3200                 'no failure above feeder level
3040 IF I%>NS% THEN 3100                     'no failure at source level
3050 FOR I9%=1 TO NS%
3060 IF I9%<>I% AND I9%<>I1% THEN 3080 'unfailed source
3070 SSTAT(I9%)=0
3080 NEXT I9%
3100 FOR I9%=1 TO NR%
3110 IF SSTAT(RS%(I9%))=0 THEN 3140          'source of this rs has failed
3120 IF NN%(I%)=2 AND ID%(I%)=I9% THEN 3140 'rs has failed (1st failure)
3122 IF NN%(I1%)=2 AND ID%(I1%)=I9% THEN 3140 'rs has failed (2nd failure)
3130 GOTO 3150
3140 RSTAT(I9%)=0
3150 NEXT I9%
3200 REM this routine handles both feeder and substation failures
3205 FOR I9%=1 TO NF%
3210 IF RSTAT(O%(I9%))=0 THEN 3240           'rs of this feeder has failed or no
power
3220 IF NN%(I%)=3 AND ID%(I%)=I9% THEN 3240 'this feeder is first failure
3222 IF NN%(I1%)=3 AND ID%(I1%)=I9% THEN 3240 'this feeder is second failure
3230 GOTO 3250
3240 FSTAT(I9%)=0
3250 IF FSTAT(I9%)=0 THEN 3490
3260 IF FT%(I9%)=1 THEN 3400            'system feeder
3270 IF NA%(I9%)=0 THEN 3310                'no ap on this feeder
```

```
3272 IF NN%(I%)=5 AND ID%(I%)=DA%(I9%,1) AND TA%(ID%(I%))<3 THEN 3310 'fully
failed substation
3273 IF NN%(I1%)=5 AND ID%(I1%)=DA%(I9%,1) AND TA%(ID%(I1%))<3 THEN 3310 'fully
failed substation
3274 IF NN%(I%)=5 AND ID%(I%)=DA%(I9%,1) THEN 3304 'substation failed to half
capacity
3275 IF NN%(I1%)=5 AND ID%(I1%)=DA%(I9%,1) THEN 3304 'substation failed to half
capacity
3280 ASTAT(DA%(I9%,1))=ASTAT(DA%(I9%,1))+FSTAT(I9%)
3290 IF ASTAT(DA%(I9%,1))<=1 THEN 3310
3300 ASTAT (DA%(I9%,1))=1                    'correction for unneeded feeder
3302 GOTO 3310
3304 ASTAT(DA%(I9%,1))=.5
3310 IF NT%(I9%)=0 THEN 3490                       'no tp on this feeder
3312 IF NN%(I%)=4 AND ID%(I%)=DT%(I9%,1) AND TT%(ID%(I%))<3 THEN 3490 'fully
failed substation
3313 IF NN%(I1%)=4 AND ID%(I1%)=DT%(I9%,1) AND TT%(ID%(I1%))<3 THEN 3490 'fully
failed substation
3314 IF NN%(I%)=4 AND ID%(I%)=DT%(I9%,1) THEN 3344 'substation failed to half
capacity
3315 IF NN%(I1%)=4 AND ID%(I1%)=DT%(I9%,1) THEN 3344 'substation failed to half
capacity
3320 TSTAT(DT%(I9%,1))=TSTAT(DT%(I9%,1))+FSTAT(I9%)
3330 IF TSTAT(DT%(I9%,1))<=1 THEN 3490
3340 TSTAT(DT%(I9%,1))=1                          'correction for unneeded feeder
3342 GOTO 3490
3344 TSTAT(DT%(I9%,1))=.5
3350 GOTO 3490
3400 K9%=NA%(I9%)
3410 IF NA%(I9%)>=NT%(I9%) THEN 3430     'chooses larger of two as bound on loop
3420 K9%=NT%(I9%)
3430 GOSUB 4000                          'system feeder subroutine, first pass
3440 IF FSTAT(I9%)=0 THEN 3490
3450 GOSUB 4000                            'system feeder subroutine, second pass
3490 NEXT I9%
3500 GOSUB 4500
3590 RETURN
4000 FOR K1%=1 TO K9%                              'system feeder subroutine
4010 IF FSTAT(I9%)=0 THEN 4280
4020 IF NA%(I9%)<K1% THEN 4100             'exhausted ap substations, this feeder
4030 IF NN%(I%)=5 AND ID%(I%)=DA%(I9%,K1%) AND TA%(ID%(I%))<3 THEN 4200  'feeder
 out from here on
4040 IF NN%(I1%)=5 AND ID%(I1%)=DA%(I9%,K1%) AND TA%(ID%(I1%))<3 THEN 4200     '
feeder out from here on
4042 IF NN%(I%)=5 AND ID%(I%)=DA%(I9%,K1%) THEN 4054   'half-failed
4044 IF NN%(I1%)=5 AND ID%(I1%)=DA%(I9%,K1%) THEN 4054 'half-failed
4050 Q1=1-ASTAT(DA%(I9%,K1%))              'current deficit, this substation
4052 GOTO 4060
4054 Q1=.5-ASTAT(DA%(I9%,K1%)) 'current deficit relative to .5 limit (half-
failed status)
4060 IF Q1<.1 THEN 4100                                 'no demand here
4070 ASTAT(DA%(I9%,K1%))=ASTAT(DA%(I9%,K1%))+.5
4080 FSTAT(I9%)=FSTAT(I9%)-.5
```

```
4100 IF NT%(I9%)<K1% THEN 4280          'exhausted tp substations. this feeder
4110 IF NN%(I%)=4 AND ID%(I%)=DT%(I9%,K1%) AND TT%(ID%(I%))<3 THEN 4280
4120 IF NN%(I1%)=4 AND ID%(I1%)=DT%(I9%,K1%) AND TT%(ID%(I1%))<3 THEN 4280
4122 IF NN%(I%)=4 AND ID%(I%)=DT%(I9%,K1%) THEN 4134
4124 IF NN%(I1%)=4 AND ID%(I1%)=DT%(I9%,K1%) THEN 4134
4130 Q1=1-TSTAT(DT%(I9%,K1%))           'current deficit, this substation
4132 GOTO 4140
4134 Q1=.5-TSTAT(DT%(I9%,K1%)) 'current deficit relative to .5 limit
4140 IF Q1<.1 THEN 4280                         'no demand here
4150 TSTAT(DT%(I9%,K1%))=TSTAT(DT%(I9%,K1%))+.5
4160 FSTAT(I9%)=FSTAT(I9%)-.5
4190 GOTO 4280
4200 FSTAT(I9%)=0
4280 NEXT K1%
4290 RETURN
4500 TSC%=0                             'TP STATUS COUNT
4510 APSC%=0
4520 FOR I9%=1 TO NNT%-2
4530 IF TSC%=3 THEN 4700
4540 IF TSTAT(I9%)+TSTAT(I9%+1)+TSTAT(I9%+2)<1 THEN 4650
4550 IF TSTAT(I9%)=0 AND TSTAT(I9%+1)=0 THEN 4650
4560 IF TSTAT(I9%+1)=0 AND TSTAT(I9%+2)=0 THEN 4650
4570 IF TSC%>=2 THEN 4700
4580 IF TSTAT(I9%)+TSTAT(I9%+2)=0 THEN 4670
4585 IF TSTAT(I9%)+TSTAT(I9%+1)+TSTAT(I9%+2)=1 THEN 4670
4590 IF TSTAT(I9%)+TSTAT(I9%+1)=.5 THEN 4670
4600 IF TSTAT(I9%+1)+TSTAT(I9%+2)=.5 THEN 4670
4610 IF TSC%>=1 THEN 4700
4620 IF TSTAT(I9%)=0 OR TSTAT(I9%+1)=0 OR TSTAT(I9%+2)=0 THEN 4690
4630 IF TSTAT(I9%)+TSTAT(I9%+1)=1 THEN 4690
4635 IF TSTAT(I9%)+TSTAT(I9%+1)+TSTAT(I9%+2)<3 THEN 4690
4640 IF TSTAT(I9%+1)+TSTAT(I9%+2)=1 THEN 4690
4645 GOTO 4700
4650 TSC%=3
4660 GOTO 4700
4670 TSC%=2
4680 GOTO 4700
4690 TSC%=1
4700 NEXT I9%
4710 MSC%=0                               'presence of disabled midline ap
4720 FOR I9%=1 TO NNA%
4730 IF ASTAT(I9%)=1 THEN 4840
4740 IF APSC%=3 THEN 4840
4750 SN$=LEFT$(TTA$(I9%),3)               'first 3 characters of name
4760 IF SN$="MID" THEN 4820
4770 IF ASTAT(I9%)=.5 THEN 4800
4780 APSC%=3
4790 GOTO 4840
4800 APSC%=1
4810 GOTO 4840
4820 IF ASTAT(I9%)=.5 THEN 4840
4830 MSC%=1
4840 NEXT I9%
4850 OUTC%=0                                     'outcome identifier
```

```
4900 IF APSC%=0 AND TSC%=0 AND MSC%=0 THEN 5440      'no effect
4910 IF APSC%=3 AND TSC%=3 THEN OUTC%=10: GOTO 5100
4920 IF TSC%=3 AND APSC%=1 THEN OUTC%=9: GOTO 5100
4930 IF TSC%=3 THEN OUTC%=8: GOTO 5100
4940 IF APSC%=3 THEN OUTC%=7: GOTO 5100
4950 IF MSC%=1 THEN OUTC%=6: GOTO 5100
4960 IF TSC%=2 AND APSC%=1 THEN OUTC%=5: GOTO 5100
4970 IF TSC%=2 THEN OUTC%=4: GOTO 5100
4980 IF TSC%=1 AND APSC%=1 THEN OUTC%=3: GOTO 5100
4990 IF TSC%=0 AND APSC%=1 THEN OUTC%=2: GOTO 5100
5000 OUTC%=1
5100 IF I1%>0 THEN 5170
5110 I8%=1                                        'one primary failure
5120 E1=P(1,I%)*E(I%)          'EXP. NO./YR, SHORTEST DURATION
5130 E2=(P(2,I%)-P(1,I%))*E(I%)          'NEXT HIGHER DURATION
5140 E3=(P(3,I%)-P(2,I%))*E(I%)        'NEXT HIGHER DURATION
5150 E4=E(I%)-(E1+E2+E3)                   'LONGEST DURATION
5160 GOTO 5300
5170 I8%=2                                        'two primary failures
5180 T1=P(1,I%)/120+(P(2,I%)-P(1,I%))/20+(P(3,I%)-P(2,I%))/6+(1-P(3,I%))
5182 IF NN%(I%)=3 AND NN%(I1%)=3 THEN 5450       'both are feeders
5185 REM ABOVE IS EXP. DUR. OF FIRST FAILURE, BELOW SECOND
5190 T2=P(1,I1%)/120+(P(2,I1%)-P(1,I1%))/20+(P(3,I1%)-P(2,I1%))/6+(1-P(3,I1%))
5200 E0=(T1+T2)*E(I%)*E(I1%)/8760                 'TOTAL EXP. NO. PER YEAR
5210 IF T2<T1 THEN 5240
5220 I7%=I%
5230 GOTO 5250
5240 I7%=I1%
5250 E1=P(1,I7%)*E0
5260 E2=(P(2,I7%)-P(1,I7%))*E0
5270 E3=(P(3,I7%)-P(2,I7%))*E0
5280 E4=E0-(E1+E2+E3)
5300 IF OUTC%=6 THEN 5370
5310 P1(OUTC%,I8%)=P1(OUTC%,I8%)+E1
5320 P2(OUTC%,I8%)=P2(OUTC%,I8%)+E2
5330 IF OUTC%=7 THEN 5420
5340 P3(OUTC%,I8%)=P3(OUTC%,I8%)+E3
5350 P4(OUTC%,I8%)=P4(OUTC%,I8%)+E4
5360 GOTO 5440                                    'end of case
5370 P1(4,I8%)=P1(4,I8%)+E1
5380 P2(4,I8%)=P2(4,I8%)+E2
5390 P3(4,I8%)=P3(4,I8%)+E3
5400 P4(4,I8%)=P4(4,I8%)+E4
5410 GOTO 5440
5420 P3(10,I8%)=P3(10,I8%)+E3
5430 P4(10,I8%)=P4(10,I8%)+E4
5440 RETURN
5450 IF FT%(ID%(I%))<>FT%(ID%(I1%)) OR FT%(ID%(I%))<>2 THEN 5190 'not both are
limited feeders
5460 IF DT%(ID%(I%),1)=DT%(ID%(I1%),1) AND DT%(ID%(I%),1)<>0 THEN 5480 'same
destination tp
5470 IF DA%(ID%(I%),1)<>DA%(ID%(I1%),1) OR DA%(ID%(I%),1)=0 THEN 5190 'not same
destination ap
5480 E0=E(I1%)/4                        'p(second feeder out given first out)=.25
5490 GOTO 5240
```

```
6000 FOR I9%=1 TO NS%
6010 SSTAT(I9%)=1
6020 NEXT I9%
6030 FOR I9%=1 TO NR%
6040 RSTAT(I9%)=1
6050 NEXT I9%
6060 FOR I9%=1 TO NF%
6080 IF FT%(I9%)=1 THEN 6130
6090 FSTAT(I9%)=1                              'dedicated feeder
6100 GOTO 6135
6110 FSTAT(I9%)=1                              'limited feeder
6120 GOTO 6135
6130 FSTAT(I9%)=NL%(I9%)                       'system feeder
6135 NEXT I9%
6140 FOR I9%=1 TO NNT%
6150 TSTAT(I9%)=0
6160 NEXT I9%
6165 REM substation status initialized at 0
6170 FOR I9%=1 TO NNA%
6180 ASTAT(I9%)=0
6190 NEXT I9%
6200 RETURN
6300 IF J%=2 THEN 6500                         'trains normal
6310 IF J%<>1 AND J%<>3 THEN 6350              'not reduced
6320 TRT(1)=TRT(1)+TRST1
6330 TRT(2)=TRT(2)+TRST2
6340 GOTO 6500
6350 IF J%<4 OR J%>7 THEN 6390                 'stopped
6360 TRT(3)=TRT(3)+TRST1
6370 TRT(4)=TRT(4)+TRST2
6380 GOTO 6500
6390 TRT(5)=TRT(5)+TRST1
6400 TRT(6)=TRT(6)+TRST2
6500 IF J%=1 OR J%=4 OR J%=8 THEN 6590         'stations normal
6510 IF J%=7 OR J%=10 THEN 6550                'unavailable
6520 STT(1)=STT(1)+TRST1                       'discomfort
6530 STT(2)=STT(2)+TRST2
6540 GOTO 6590
6550 STT(3)=STT(3)+TRST1
6560 STT(4)=STT(4)+TRST2
6590 RETURN
```

```
2 READ DAT$
4 LPRINT
6 LPRINT USING "datafile &";DAT$
8 LPRINT
10 DIM ASTAT(25),DT%(50,25),DA%(50,25),FT%(50),FSTAT(50),FP(3,11)
20 DIM NT%(50),NA%(50),NL%(50),O%(50),P(3,115),P1(10,2),P2(10,2),P3(10,2)
30 DIM P4(10,2),PP(3,11),RE(4),RP(3,4),ST%(5),SN$(5),SSTAT(5),SE(3),SP(3,3)
35 DIM TT%(25),TTN$(25),TA%(25),TTA$(25),TSTAT(25)
40 READ NST%                                              'NO. OF SOURCE TYPES
50 FOR I%=1 TO NST%
60 READ SE(I%),SP(1,I%),SP(2,I%),SP(3,I%)                 'EXP. FAILS/YR, DUR. PROBS
70 NEXT I%
80 READ NRT%                                              'NO. OF RS TYPES
90 FOR I%=1 TO NRT%
100 READ RE(I%),RP(1,I%),RP(2,I%),RP(3,I%)
110 NEXT I%
120 READ NFT%                                             'NO. OF FEEDER TYPES
130 FOR I%=1 TO NFT%
140 READ FE(I%),FP(1,I%),FP(2,I%),FP(3,I%)
150 NEXT I%
160 READ NPT%                     'NO. OF SUBSTATION TYPES (AP & TP COMBINED)
170 FOR I%=1 TO NPT%
180 READ PE(I%),PP(1,I%),PP(2,I%),PP(3,I%)
190 NEXT I%
200 READ NS%                                   'no. of sources
210 FOR I%=1 TO NS%
220 READ ST%(I%),SN$(I%)
230 NEXT I%
240 REM st=source type, sn=source name
300 READ NR%                                   'no. of receiving stations
310 FOR I%=1 TO NR%
320 READ RT%(I%),RN$(I%),RS%(I%)
330 NEXT I%
340 REM rt=rs type, rn=name, rs=source
400 READ NF%                      'no. of feeders; enter system feeders in data last
410 FOR I%=1 TO NF%
420 READ FT%(I%),O%(I%),NT%(I%),NA%(I%)
430 IF NT%(I%)=0 THEN 470
440 FOR J%=1 TO NT%(I%)
450 READ DT%(I%,J%)
460 NEXT J%
465 REM dt=jth destination tp of ith feeder;enter in data in increasing distance
order
470 IF NA%(I%)=0 THEN 510
480 FOR J%=1 TO NA%(I%)
490 READ DA%(I%,J%)
500 NEXT J%
505 REM da=jth destination ap of ith feeder
510 IF FT%(I%)<>1 THEN 530                                'not system feeder
520 READ NL%(I%)               'no. of substations that can be fed by ith feeder
530 NEXT I%
600 READ NNT%                                  'no. of tp substations
610 FOR I%=1 TO NNT%
620 READ TT%(I%),TTN$(I%)
630 NEXT I%
635 REM tt=type of tp substation, ttn=name of its location
700 READ NNA%                                  'no. of ap substations
```

```
710 FOR I%=1 TO NNA%
720 READ TA%(I%),TTA$(I%)
730 NEXT I%
735 REM ta=type of ap substation, tta=name of its location
1000 LPRINT
1010 LPRINT "by feeder"
1020 LPRINT
1030 LPRINT "no. type source   rs      tp                ap"
1040 LPRINT
1050 FOR I%=1 TO NF%
1060 LPRINT USING "##   ##     \ \       \\      \          \      \              \";I%,FT%(
I%),SN$(RS%(O%(I%))),RN$(O%(I%)),TTN$(DT%(I%,1)),TTA$(DA%(I%,1))
1070 J%=2
1080 IF NT%(I%)<J% AND NA%(I%)<J% THEN 1120
1090 LPRINT USING "                                    \          \      \              \";TTN$(DT
%(I%,J%)),TTA$(DA%(I%,J%))
1100 J%=J%+1
1110 GOTO 1080
1120 LPRINT
1130 NEXT I%
1140 LPRINT
1200 LPRINT "by substation"
1210 LPRINT
1220 LPRINT                    "traction power"
1225 LPRINT "substation       feeders"
1230 LPRINT
1240 FOR I%=1 TO NNT%
1250 LPRINT TTN$(I%),
1260 FOR J%=1 TO NF%
1270 FOR K%=1 TO NT%(J%)
1280 IF DT%(J%,K%)<>I% THEN 1300
1290 LPRINT J%,
1300 NEXT K%
1310 NEXT J%
1320 LPRINT
1330 LPRINT
1340 NEXT I%
1350 LPRINT
1420 LPRINT                    "auxiliary power"
1425 LPRINT "substation       feeders"
1430 LPRINT
1440 FOR I%=1 TO NNA%
1450 LPRINT TTA$(I%),
1460 FOR J%=1 TO NF%
1470 FOR K%=1 TO NA%(J%)
1480 IF DA%(J%,K%)<>I% THEN 1500
1490 LPRINT J%,
1500 NEXT K%
1510 NEXT J%
1520 LPRINT
1530 LPRINT
1540 NEXT I%
1550 LPRINT
1570 LPRINT
1590 GOTO 9999
```

```
8000 DATA prmos
8010 REM 12/7/84 9-mile configuration
8100 REM no. of source types (dimensioned for 3)
8102 REM "type 0" is not entered via data, automatically is unfailable
8110 DATA 2
8115 REM by type: exp. fails/yr, cum. probabilities for xshort, short, long
8120 DATA 0,.25,.6,.95
8130 DATA 0,.1,.5,.8
8135 REM when exp. is 0, other values are not used but dummies must be in data
8200 REM no. of rs types (dimensioned for 4)
8210 DATA 2
8220 DATA .5,.99,.99,.99
8230 DATA .5,.99,.99,.99
8300 REM no. of feeder types (dimensioned for 11)
8310 DATA 3
8312 REM type 1 is system feeder, type 2 limited feeder; any additional system
8314 REM or limited types with nonzero exp fails/yr require changes in socpow
8316 REM program at statements 510, 3260, 5450, 6080
8320 DATA 10,.8,.9,.96
8330 DATA 14.4,.9,.95,.95
8340 DATA 4,.95,.98,.98
8400 REM no. of substation types (dimensioned for 11, ap & tp combined)
8410 DATA 10
8415 REM types 1 & 2 are single-thread & fail to zero capacity; all others fail
8416 REM to half capacity.  any additional types intended to fail to zero
require changes in socpow program at statements 4040, 4042, 4110, 4120
8420 DATA .344,.5,.5,.9
8430 DATA .019,.02,.02,.2
8440 DATA .68,.5,.5,.9
8450 DATA .026,.02,.02,.2
8460 DATA .34,.5,.5,.9
8470 DATA .013,.02,.02,.2
8480 DATA 1.02,.5,.5,.9
8490 DATA .039,.02,.02,.2
8500 DATA .68,.5,.5,.9
8510 DATA .026,.02,.02,.2
9000 REM no. of sources (dimensioned for 5)
9010 DATA 1
9015 REM source type, name
9020 DATA 1,DWP
9100 REM no. of receiving stations (dimensioned for 11)
9110 DATA 5
9115 REM rs type, name, source
9118 DATA 1,H,1
9120 DATA 1,K,1
9130 DATA 1,D,1
9140 DATA 1,P,1
9150 DATA 1,A,1
```

```
9200 REM no. of feeders (dimensioned for 50)
9205 DATA 25
9210 REM feeder type, origin, no. tp's, no. ap's, all tp destinations, all ap
9215 REM destinations; feeder capacity (no. of substations) last (sys fdrs only)
9218 REM system feeders must be at end of feeder data
9220 DATA 2,1,1,1,1,1
9225 DATA 2,1,1,1,1,1
9230 DATA 2,3,1,1,2,2
9235 DATA 2,3,1,1,2,2
9240 DATA 2,3,1,1,3,3
9245 DATA 2,3,1,1,3,3
9250 DATA 2,3,0,1,4
9255 DATA 2,3,0,1,4
9260 DATA 2,3,1,1,5,5
9265 DATA 2,3,1,1,5,5
9270 DATA 2,3,0,1,6
9275 DATA 2,3,0,1,6
9280 DATA 2,4,1,1,6,7
9285 DATA 2,4,1,1,6,7
9290 DATA 2,4,1,1,7,8
9295 DATA 2,4,1,1,7,8
9300 DATA 2,4,0,1,9
9305 DATA 2,4,0,1,9
9310 DATA 2,4,0,1,10
9315 DATA 2,4,0,1,10
9320 DATA 2,4,1,1,9,11
9325 DATA 2,4,1,1,9,11
9330 DATA 2,5,1,1,10,12
9335 DATA 2,5,1,1,10,12
9340 DATA 1,2,2,12,4,8,2,1,3,4,5,6,7,8,9,10,11,12,14
9500 REM no. of tp substations (dimensioned for 25)
9510 DATA 10
9520 REM tp type, name (use uppercase "MID" to lead vent names)
9525 DATA 5,F/B
9530 DATA 5,W/F,5,W/LB,5,W/C,5,W/W,5,W/V,5,W/A,5,7/F,5,CC,5,US
9700 REM no. of ap substations (dimensioned for 25)
9710 DATA 12
9720 REM ap type, name (use uppercase "MID" to lead vent names)
9725 DATA 6,F/B
9730 DATA 6,W/F,6,W/LB,6,W/C,6,W/W,6,W/N,6,W/V,6,W/A,6,7/F,6,5/H,6,CC,6,US
9999 END
```