A SYSTEMS ENGINEERING APPROACH TO POWER SYSTEMS IN REMOTE REGIONS

by

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Report submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
MASTER OF ENGINEERING
in
Systems Engineering

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November 1, 1991
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ACKNOWLEDGEMENTS

I would like to extend my thanks and appreciation to Dr. Rahman for his time and assistance with this project and to the Appalachian Power Company for its generous support. Above all I wish to thank my wife Diane, who has stood by me these last three years and whose encouragement and assistance have been invaluable.

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INTRODUCTION

There are many remote regions in the world today in both advanced and developing countries that do not have electric power available. Electricity can be a powerful force for change in rural areas. It can improve the quality of life for the people, economically and socially. The purposes of this design project are to demonstrate why a systems approach is well suited to the problem of electric power systems in remote areas and how it can be applied. In the first part of this report the systems approach and the systems engineering process in general will be described. In the second part this process will be tailored to the problem of power systems in remote areas. This process will then be applied to a specific case in the final part. This paper follows closely the systems engineering format as described in *System Engineering And Analysis* by B.S.Blanchard and W.J.Fabrycky. [1]

THE SYSTEMS APPROACH

A system is a set of interrelated parts acting in an organized manner toward a common goal such that the whole is greater than the sum of its parts. Its design and operation will influence the demands it must accommodate.

The systems approach is a way of solving a problem or meeting a need. The systems approach has four characteristics. The first is that it takes a holistic approach to the problem. It recognizes that technological considerations alone are insufficient. The solution must also take into account the social, political, economic, and environmental factors that will impact on how well the system meets the needs of society. The second is that it uses innovation instead of evolution to develop solutions to the problem. It is a top-down approach. Instead of building on existing methods it uses modern, sophisticated techniques in conjunction with the traditional scientific approach to come up with creative and innovative answers. Thirdly, the systems approach is an interdisciplinary approach. It integrates the expertise of many specialties in science, engineering, economics, business, management, and other fields. Last, the systems approach is concerned with the system life cycle. The life cycle begins with the identification of need or desire and ends with the retirement and disposal of the system at the end of its useful life. The systems approach considers how all phases of the life cycle affect the system.

THE SYSTEMS ENGINEERING PROCESS

Systems engineering is the application of the systems approach to solving complex problems that involve technology. It can also be described as an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies in a near-optimal manner the full range of requirements for the system. [3]

There are six steps that are performed during the system life cycle. These are system planning (conceptual design), system engineering (preliminary system design), system design (detail design), system production and/or construction, system utilization and support, and system retirement. These steps are shown in Figure 1.

The system life cycle and the system engineering process begin with a definition of need. This is a broad statement explaining why the system is needed or wanted.

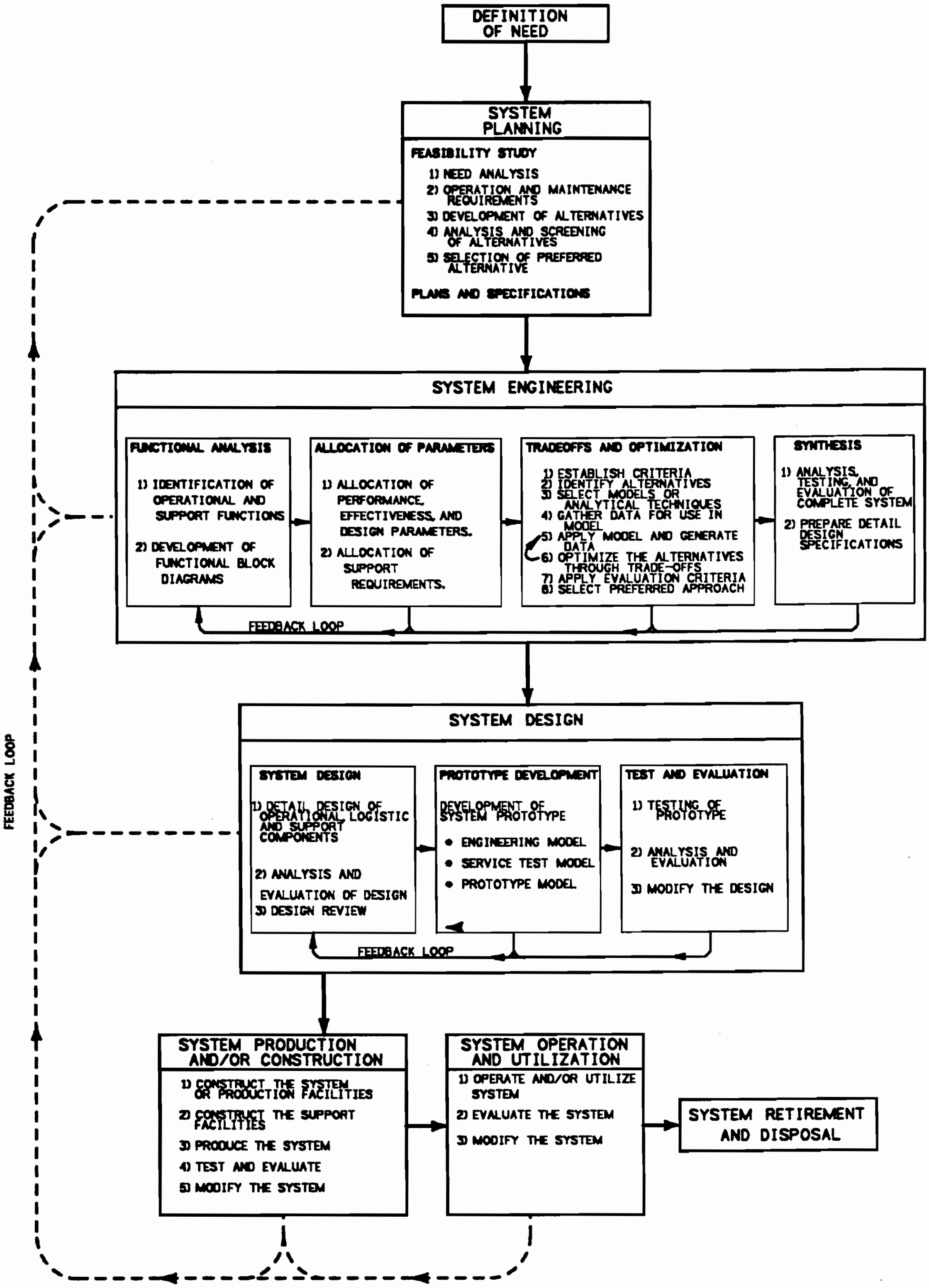

Figure 1 The System Life Cycle

The system planning step is broken down into two stages. The first is a feasibility study which does five things:

1) it analyzes the needs,
2) it defines the operational and support requirements necessary to satisfy these needs,
3) it identifys possible alternatives that will meet these requirements,
4) it screens and evaluates the most likely candidates,
5) and it selects a preferred approach.

The second is the preparation of the system specifications which state the operational and support requirements for the system as a whole. The specifications serve as a guide to the engineers and designers. Some areas that the specifications might address include the following:

1) General description of the system and its function.
2) Operational requirements.
3) Maintenance concept.
4) System functional diagrams and functional interfaces.
5) Performance characteristics.
6) Physical characteristics.
7) Effectiveness characteristics.

8) Design characteristics--reliability, maintainability
9) Construction
10) Logistic support
11) Design documentation
12) Quality Assurance provisions

The next step is system engineering. In this step the system specifications are developed into detailed qualitative and quantitative design requirements. This is done through an iterative process of functional analysis, allocation of requirements, trade-off and optimization, and synthesis.

Functional analysis is the process of describing all the activities necessary to carry out the systems mission. It is a hierarchical method that begins with the primary functions and decomposes them into subfunctions and their subordinate subfunctions. It is done for both operational and support functions. Breaking down the system by its functions helps assure that all aspects of the system are considered and adequately defined and what functions have common elements that can be packaged together in hardware/software assemblies. The basic tool of functional analysis is the functional flow diagram. The functional analysis is done down to the level where initial packaging concepts can be visualized.

After the system is broken down into packages the operational and support requirements are allocated to each. The packages can be broken down further into units, assemblies, subassemblies, and so on. The requirements are also broken down among the levels. The requirements can be allocated in the form of a stated level with a tolerance band to allow flexibility in meeting them.

There is usually more than one approach that will satisfy the operational and support requirements for each functional package. The process of trade-offs and optimization begins. In this process alternative approachs are developed and analyzed. They are evaluated for how well they satisfy the allocated requirements and either rejected, modified, or accepted. This is an iterative process that continues until all functional packages have been optimized. A flow chart of this process is shown in Figure 2.

Synthesis is putting all the preferred optimized functional packages together and determining how well they work as a complete system. Synthesis has been achieved when sufficient trade-offs and preliminary design have been accomplished to confirm and assure the completeness of system performance and design requirements allocated for detail design. Synthesis can be tested either through an analytical model or through the development of a physical model. The end result is a set of detailed specifications that will guide the designers.

The system design phase follows next. This is also an iterative process of detail design, model development, and the testing and evaluation of the model. The goal of the design phase is to progress from the detailed specifications describing the subsystems, units, assemblies, down to the level needed to produce or construct the system and operate and support it. Its end product is the design documentation such as equipment specifications and detail drawings and software. The detail design is again tested and evaluated either through the use of analytical models or a physical prototype model.

In the system production/construction step the system is physically created following the design developed in the previous step. There is a feedback loop to the previous steps to allow for changes that might be required or desirable during production or construction.

The system utilization and support step involves the operation, maintenance and administration of the system. Again a feedback loop exists to allow the system to change in response to changing needs or as the result of operating or maintenance experience.

Finally when the system has reached the end of its useful life it must be retired and disposed of. This system engineering process is also guided by the system management approach. Using this approach a project management plan is developed to effectively plan the people, equipment, material, time, and money to implement the system

This has been a brief overlook at the systems engineering process. More detailed information can be found in the references. [1][2][3] In the next section this general process will be tailored to the problem of electric power systems in remote regions.

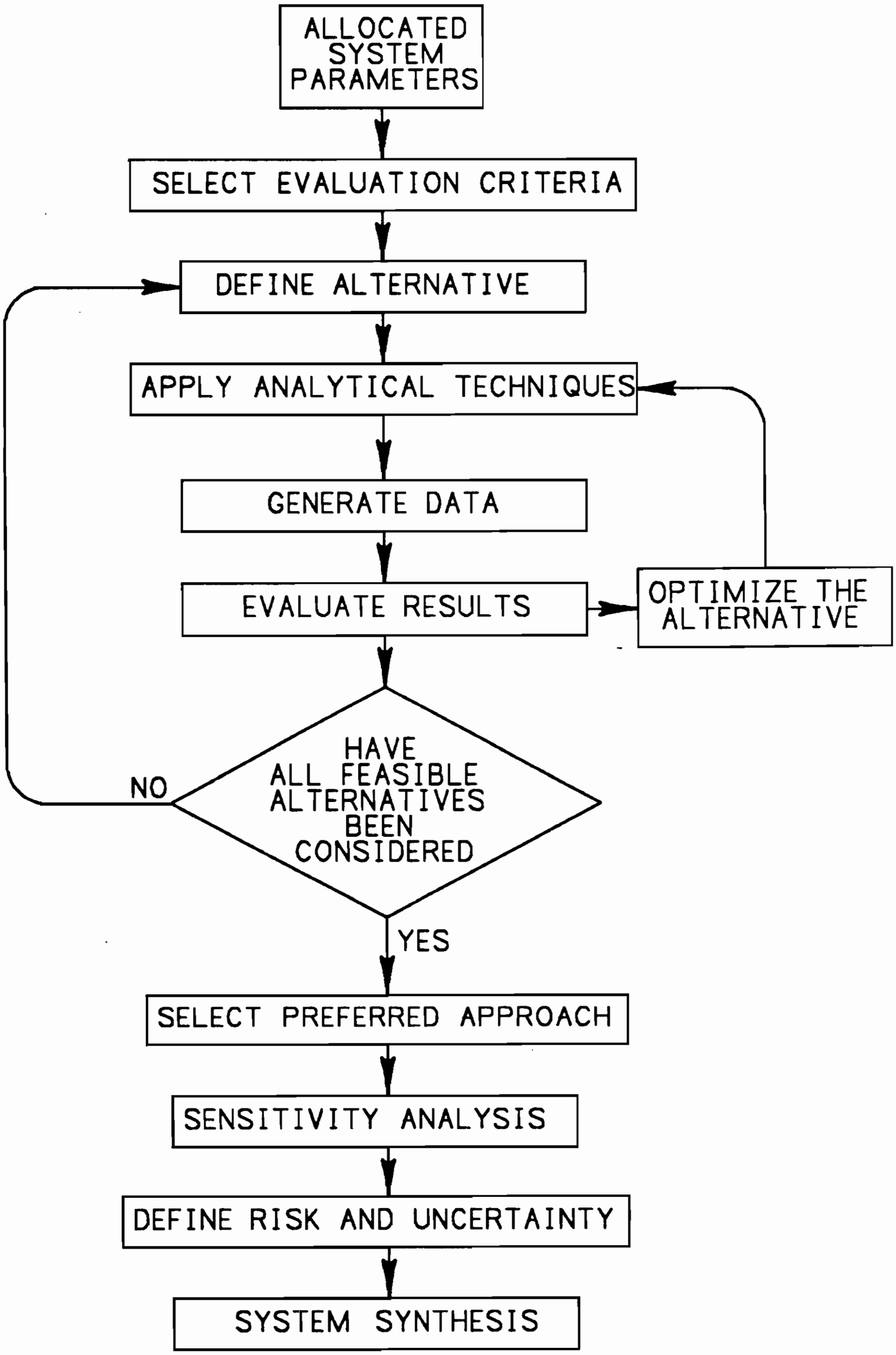

FIGURE 2
TRADE-OFF AND OPTIMIZATION PROCESS

THE SYSTEMS ENGINEERING APPROACH TO REMOTE POWER SYSTEMS

The purpose of this part of the project is to tailor the general systems engineering process to the problem of power systems in remote areas.

It was stated in the previous section that there are six steps in the system engineering process. In this part the planning and engineering phases will be developed in a general manner for remote power systems. These steps and guidelines can then be followed for any power system.

Definition Of Need

The systems engineering process begins with the definition of need. Electricity is a very useful form of energy. In remote areas it can greatly improve the quality of life in several ways. As a light source it provides clean, bright light. It can be used for heating and cooking replacing other fuels such as wood, oil, gas, and coal. Electric machines can greatly improve the way things are done by increasing productivity and making difficult or time consuming tasks quicker and easier. It can also be used to power electronics such as radio and television. A power system is an integrated system of generation, transmission, and distribution that is designed and operated to deliver power efficiently, economically, and safely. This is in contrast to the generation and utilization of electricity by each individual consumer. A system can improve the reliability and economy of electric power over individual generation. Thus the first step in the process is to determine if electrification is desirable.

System Planning

There are two parts to the system planning process. The first is to prepare a feasibility study and the second is to develop plans and specifications. The feasibility study begins with an analysis of the need. The need or desirability of electric power was defined in rather broad terms previously. The need analysis will determine the amount of electric power and energy needed. The basic load model is the load duration curve (LDC) which is the cumulative probability distribution of the demand. The LDC can be developed using other models such as an end-use, econometric, time trend, or weather sensitive models. These models are described in the references. [8] A causal model which relates the supply and the demand to a wide range of political, social, and economic factors can also be used to determine the system requirements.

Once the needs have been established the system requirements can be determined. Both operational and support requirements will have to be established. Typical requirements for a power system are listed below. These requirements are general in nature and serve as a guide that can be used in specific cases.

System Operational Requirements

Mission Definition: The electric power system is to provide adequate, reliable, economical, quality electric power in a safe manner.

Performance Characteristics:

Frequency - This is to be determined based on the specific circumstances. Two frequencies are standard 50 and 60 Hz. The choice will depend on the country where the system will be installed. Direct current systems , while possible, are generally not a practical choice.

Transmission and Distribution Voltages - These are to be determined based on the specific circumstances. Industry standards should be used. Some standard transmission and distribution voltages are:

120/240	single phase
480	(277Y)
4160	(2400Y)
12.47kv	(7200Y)
34.5kv	(19920Y)
69kv	
138kv	

Operational Deployment: This is the geographic area the system is to serve. The things that need to be identified are load centers and the types of loads, the location of resources, and the transportation system.

Operational Life Cycle: The anticipated lifetime of the system. Typically a lifetime of 30 to 40 years can be assumed.

Utilization Requirements: Typically the power system will be required to function 24 hours a day, 365 days a year.

Effectiveness Factors: Effectiveness factors are grouped in five categories; adequacy, reliability, economic, quality, and manability.

Adequacy: The adequacy of a power system is its capability to supply the power requirements of consumers, taking into account scheduled and unscheduled outages. The system must be able to meet the power and energy demands of the customers. One widely used measure is the Loss-Of-Load-Probability or LOLP. This is a measure of the probability that there will be insufficient generation to serve the demand. An accepted value for a utility is .1 days per year or .00027. For a remote area a higher value can be chosen.

Reliability: The reliability of a power system is the degree to which the performance of the elements in the power system result in power being delivered to consumers within accepted standards and in the amount desired. Thus adequacy is part of reliability. Reliability is measured in terms of the frequency, duration and magnitude of interruptions. There are four types of interruptions on power systems; forced, scheduled, momentary, and temporary. A forced interruption is caused by emergency conditions directly associated with a component that requires that the component be taken out of service immediately. A scheduled interruption results when a component is taken out of service at a selected time. A momentary interruption is limited by the time required for automatic switching devices to restore service. A temporary interruption is limited by the time required for manual switching to restore service. With the exception of momentary outages these outages will affect the reliability.

In general terms reliability is given by the equation $R(t) = e^{-t/mtbf}$ where MTBF is the mean time between failure and its reciprocal is the failure rate. A power system as a whole usually fails on a daily basis. These are most often short outages affecting a handful of customers. Thus the reliability of an entire power system is quite low but the reliability as seen by the individual customer can be high. Many methods of measuring reliability have been developed. [6] Three will be described here. An overall measure of the systems reliability is the availability which is computed as follows:

Availability (Index of Reliability)=

$$\frac{\text{(total customer-hrs/yr)} - \text{(total customer-hrs interrupted/yr)}}{\text{(total customer-hours/yr)}}$$

Availability should be in the range of 95-99%.

Other measures from an individual customer standpoint can also be used. Examples are the customer interruption frequency index (CIFI) and the customer interruption duration index (CIDI). The CIFI is the average number of interruptions per customer per year. The CIDI is the average duration of the interruptions. Other reliability measures are mean time between maintenance (MTBM), mean time to repair (MTTR), mean corrective maintenance time (MCT), mean preventive maintenance time (MPT), and mean logistic delay time (LDT). The systems engineer will have to decide what criteria will be used.

Quality: Quality of electricity is measured by four factors of which frequency and voltage are the primary considerations for remote power systems the others being voltage flicker and harmonics.

Voltage Fluctuations. Normal loading .975-1.05 p.u.
Emergency loading .93-1.06 p.u.
Frequency Fluctuations +/- .5 Hz

Economic: The life cycle costs of a power system include five types of expenses. These are engineering and design costs, construction costs, energy production costs, operation, maintenance, and support costs, and retirement and disposal costs. One common utility method of economic evaluation is the annual revenue requirement method. It uses the annualized capital costs and annual expenses to determine the revenue required to operate the system. The annual revenue required can be presented in several ways. It can be expressed as a lump sum, a per customer amount, or on a kilowatt-hour rate. This revenue requirement can be used as a figure-of-merit to determine the cost-effectiveness of the power system. The question needs to be addressed how much is the consumer willing to spend to have electricity.

Manability: Manability is the number and skill levels of personnel required to operate, maintain, support, and administer the system. In a remote area with a small population a large number of people cannot be devoted to running the power system. The number of people required and their skill levels must be established. One method is to classify the skills required into three skill levels such as basic, intermediate and high. A basic skill level is needed for jobs requiring heavy physical labor or clerical work. The ability to read and write at a ninth grade level and to follow instructions is required. Typical positions might be groundman or clerk. An intermediate skill level requires more training and more specialized skills. Typical positions might be equipment operators, journeymen linemen, or technicians. A high skill level requires 2 - 4 years of college and the ability to supervise others and make decisions regarding system operations and maintenance. Engineers, technicians and managers would fall in this category.

Environment - The operating environment of the system needs to be completely described. Some of the factors are as follows:

Climate: Precipitation (rain, snow, ice); Temperature (average and extremes); Solar Radiation; Wind speed (average and maximum)

Topography: Elevations, steepness of terrain; river systems

Geology: Soil types, seismic acitivity

System Maintenance Concept

Five factors need to be considered to develop a systems maintenance concept. They are what is to be repaired, what types of maintenance actions will be required, where it is to be done, who is to do it, and what tools and equipment will be needed. These requirements for a power system are shown in Table 1. Other decisions such as the location of the maintenance facilities and the repair-or-replace policy should also be decided as part of the maintenance concept.

Table 1
Maintenance Requirements

		Crew Class	Location	Functions
Plants -	building and land improvements	D	1	1,5,6
	structures	C,D	1	1,5,6,7
	mechanical systems	A,B,C,D	1,2,3	1-7
	electrical systems	A,B,C,D	1,2,3	1-7
	control systems	A,B	1,2	1-7
Stations -	buildings and land improvements	D	1	1,5,6
	structures	C,D	1	1,5,6,7
	buswork	C,D	1	1,5,6,7
	transformers	B	1,2,3	1-7
	circuit breakers	B	1,2,3	1-7
	capacitors & reactors	B	1,2	1-7
	switches & fuses	C	1,2	1-7
	arresters	B,C	1	1,2,7
	relays & controls	A,B	1,2	1-7
	metering equipment	A,B,C	1,2	1-7
	communication	A,B,C	1,2	1-7
Transmission Lines				
	right of ways	D	1	1,5
	structures	D	1	1,5,6,7
	insulators	C,D	1	1,5,7
	conductors	C,D	1	1,6,7
Distribution Lines				
	right of ways	D	1	1,5
	structures	D	1	1,5,6,7
	insulators	C,D	1	1,5,7
	conductors	C,D	1	1,6,7
	switches	C	1,2	1-7
	reclosers	B,C	1,2	1-7
	transformers	C	1,2	1-7
	regulators	B,C	1,2	1-7
	arresters	C	1	1,2,7
	meters	A,B,C	1,2	1-7

Crew Classes
A - Engineer(s) with meters, tests sets, and hand tools in a car.
B - Technician(s) with meters, test sets, and hand tools in a car.
C - Linemen with hand and power tools in bucket and equipment trucks.
D - Unskilled laborers with hand and power tools in an equipment truck.

Location
1 - Site maintenance is performed at the equipments installed location.
2 - Shop maintenance is performed by removing the equipment (or a part of it) to the nearest system facility.
3 - Factory maintenance is performed by shipping the equipment (or a part of it) to the factory for repairs.

Maintenance Functions
1 - Inspection
2 - Testing
3 - Calibration
4 - Operation
5 - Cleaning
6 - Repair
7 - Replacement

The third goal of the feasibility study is to identify configurations that will meet the system requirements within the technical and resource restraints. There are two alternative configurations that should be considered. The first is to build whatever lines are necessary to serve the region from an established grid. The second is to build a system in the region that is independent of a central grid. Both alternatives employ mature technologies. The preferred approach may be obvious and detailed evaluation may mot be necessary at this point. The last step in the feasibility study is to choose the between these two alternatives.

The final part of the planning phase is to develop the system plans and specifications which will be used to guide the design process. It should describe the functional configuration and physical characteristics of the system and the operation and maintenance requirements. Typical plans and specifications for a power system might include the following:

1. General description.
2. Operational specifications
    a) hours of operation
    b) life span
    c) deployment
    d) environment
3. Maintenance specifications
4. Performance specifications
    a) frequency

    - b) voltages
5. Effectiveness specifications
    - a) capacity
    - b) reliability
    - c) quality
    - d) cost
    - e) manability
6. Design specifications
    - a) maintainability
    - b) transportability
    - c) interchangeability
    - d) manability
    - e) safety
    - f) expandability
7. Construction specifications
8. Support specifications
9. Documentation specifications

System Engineering

After the plans and specifications have been drawn up the system engineering process moves into the engineering phase. The goal of engineering is to transform the plans and specifications into a blueprint that the designers can convert into construction documents.

The first step is a functional analysis. A functional analysis is a functional description of the system and all facets of system development and operation. A function is a specific and discrete action required to achieve a given objective. Functions are identified and functional flow diagrams are generated. Functional flow diagrams are prepared down to the level necessary to establish the needs of the system and so packaging concepts can be visualized. Typical functions of a power system are listed below. The operation and maintenance functions are broken down to the second level.

Top Level Functions
1.0 Define system requirements
2.0 Design the power system (generating plants, lines, and stations)
3.0 Design the support system (facilities necessary for the operation and control, maintenance, logistic, and administrative functions)
4.0 Construct the power system
5.0 Construct and furnish operation and control facilities
6.0 Construct and furnish maintenance and logistic facilities

- 7.0 Construct and furnish administrative facilities
- 8.0 Operate the power system
- 9.0 Maintain the power system
- 10.0 Administer the power system

First Level Functions

- 1.0 Define System Requirements
  - 1.1 Define the Need for Electric Power
  - 1.2 Prepare Feasibility Study
  - 1.3 Prepare Plans and Specifications

- 2.0 Design the Power System
  - 2.1 Engineer the system
  - 2.2 Design the system

- 3.0 Design the Support System
  - 3.1 Engineer the Support System
  - 3.2 Design the Support System

- 4.0 Construct the Power System
  - 4.1 Construct the Generation Stations
  - 4.2 Construct the Transmission System
  - 4.2 Construct the Distribution System

- 5.0 Construct and Furnish the Operation and Control Facilities
  - 5.1 Construct the Facilities
  - 5.2 Acquire and Install the Control and Communication Equipment

- 6.0 Construct and Furnish the Maintenance and Logistics Facilities
  - 6.1 Construct Maintenance Shops and Offices
  - 6.2 Acquire and Install Equipment

- 7.0 Construct and Furnish the Administrative Facilities
  - 7.1 Construct Administrative Buildings
  - 7.2 Acquire and Install Equipment

- 8.0 Operate Power System
  - 8.1 Monitor System Conditions
  - 8.2 Automatically Protect Personnel and Equipment from Abnormal Conditions
  - 8.3 Communicate Data to and from O&C Center
  - 8.4 Control Power Flow
  - 8.5 Generate Power
  - 8.6 Transmit Power
  - 8.7 Distribute Power

- 9.0 Maintain System

9.1 Identify Maintenance Need
9.2 Schedule Maintenance
9.3 Prepare Equipment For Maintenance
9.4 Perform Maintenance Action
9.5 Verify That Maintenance Action Was Successful
9.6 Return to Service
9.7 Complete Maintenance Report

10.0 Administer System
10.1 Supervise the overall system operation
10.2 Hire and train personnel
10.3 Collect revenues from customers
10.4 Purchase material and equipment

Second Level Functions
8.1.1 Monitor the system conditions
8.1.2 Activate alarm signals

8.2.1 Surge arresters operate
8.2.2 Relays operate
8.2.3 Fuses operate

8.3.1 Send data, signals, voice to the O&C center
8.3.2 Interpret data and signals and decide on control action
8.3.3 Send instructions to operator

8.4.1 Operate control mechanism
8.4.2 Apply control signal
8.4.3 Control devices operate

8.5.1 Generate real power
8.5.2 Generate reactive power

8.6.1 Transform voltage level
8.6.2 Transmit power
8.6.3 Regulate power flow
8.6.4 Transform voltage level

8.7.1 Distribute power
8.7.2 Regulate power flow
8.7.3 Transform voltage level
8.7.4 Meter power use

9.1.1 Perform Visual Inspection
9.1.2 Receive Alarm
9.1.3 Receive Test Results
9.1.4 Monitor System Conditions
9.1.5 Follow Maintenance Schedule

9.2.1 Assemble Personnel, Equipment, and Materials

9.2.2 Schedule with O&C Center

9.3.1 Install Spare
9.3.2 Switch to Backup
9.3.3 Isolate Equipment
9.3.4 Leave Equipment In Service

9.4.1 Perform Necessary Maintenance Actions

9.5.1 Perform Visual Inspection
9.5.2 Perform Tests
9.5.3 Operate Equipment

9.6.1 Return Equipment to Service

9.7.1 Submit a Report of Maintenance Action
9.7.2 Compile the Report into a Maintenance Database

These functions can be shown graphically in the functional flow diagrams. Functional Flow diagrams for the top and first levels are shown in Figures 3a-c.

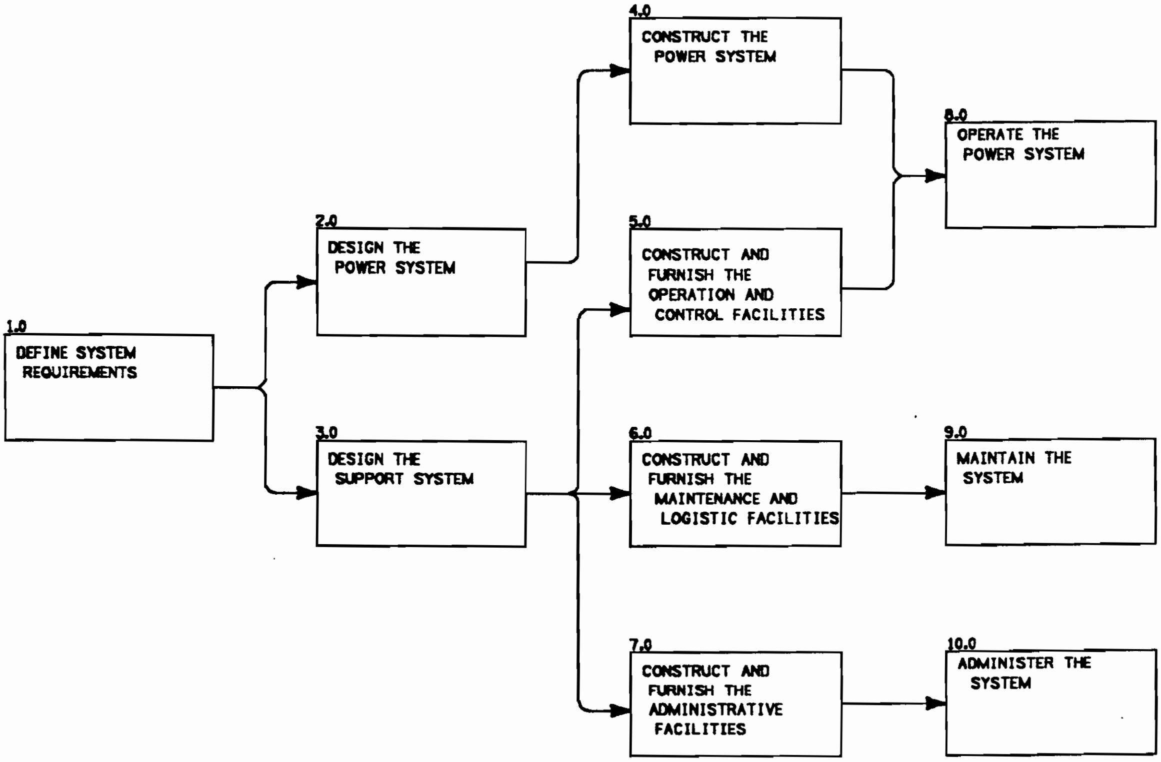

Figure 3a
Top Level Functional Flow Diagram

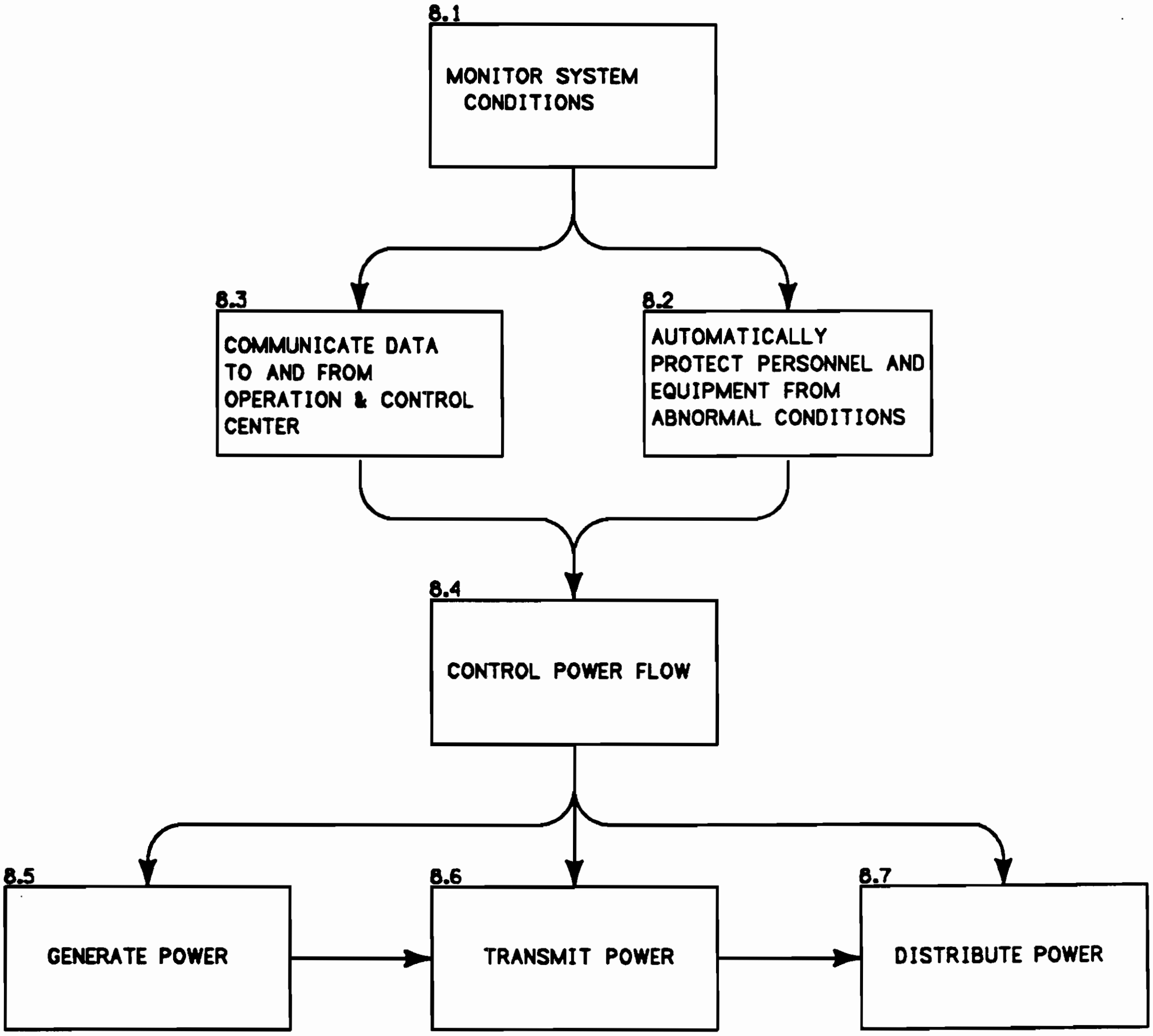

Figure 3b
First Level Operational Functional Flow Diagram

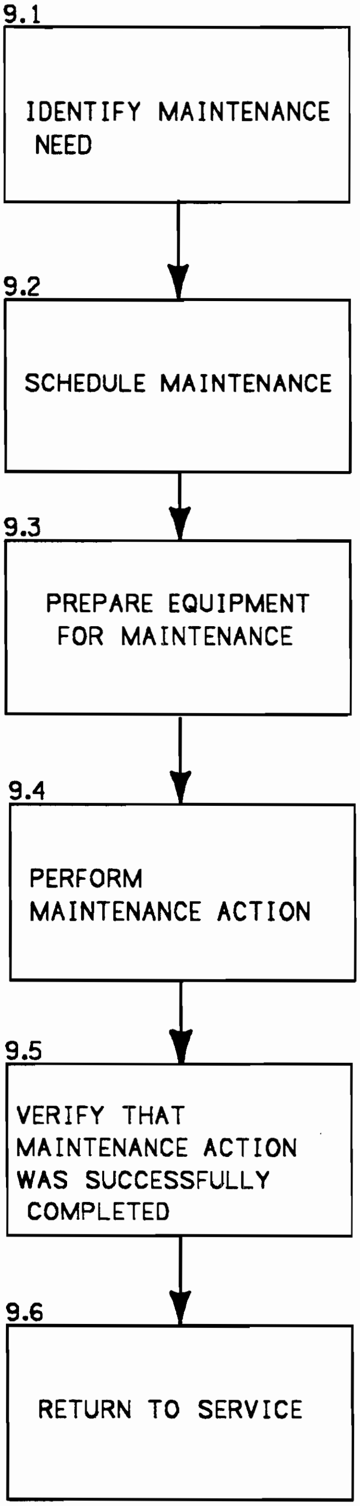

Figure 3c
FIRST LEVEL MAINTENANCE FUNCTIONAL FLOW DIAGRAM

After the functions are defined to at least the third level, the power system is broken down into packages so that requirements and resources can be allocated to each. These packages or subsystems will be subdivided into units, assemblies, and subassemblies. An example of a functional packaging scheme is shown in Figure 4. In this diagram the system is broken down first into five subsystems: generation, transmission, distribution, operation and control, and support. The generation subsystem is divided up by the generating plants and each plant is further divided up into its units. The units are then broken down into components. The transmission subsystem is divided up into the substations and the lines connecting them. The distribution subsystem is divided up into the substation and the distribution circuits out of each substation. The transmission and distribution subsystems will likely share portions of the stations.

Once all the subsystems, units, and assemblies are defined the system parameters are allocated to each. An example of a resource allocation table is shown in Table 2. The allocation of requirements is an iterative process of trial-and-error. It may require several attempts to allocate the requirements initially and then these may be modified as a result of the engineering and design work done later. The process of trade-offs, optimization, and evaluation of alternatives begins once a packaging scheme has been developed and the requirements have been allocated. The following is a list of tools and analytical techniques that can be used to develop the alternatives and to generate the data to evaluate them.

- Econometric Models
- Financial Simulation Models
- Economic Evaluation Models
- Energy Assessment Models
- Production Cost Models
- Economic Dispatch Models
- Environmental Impact Studies
- Load Flow Models
- Short Circuit Models
- Reliability Models
- Contingency Analysis
- Maintainability Analysis
- Human Factors Analysis
- Logistic Support Analysis
- Sensitivity Analysis
- Risk and Uncertainty Analysis

These models are described in detail in the references listed. [1,7-23] It is up to the systems engineer to decide what models will be used. There are several techniques that can be used to evaluate the alternatives such as a weighted scoring system or the analytical hierarchy process. These techniques are described in the references. [15]

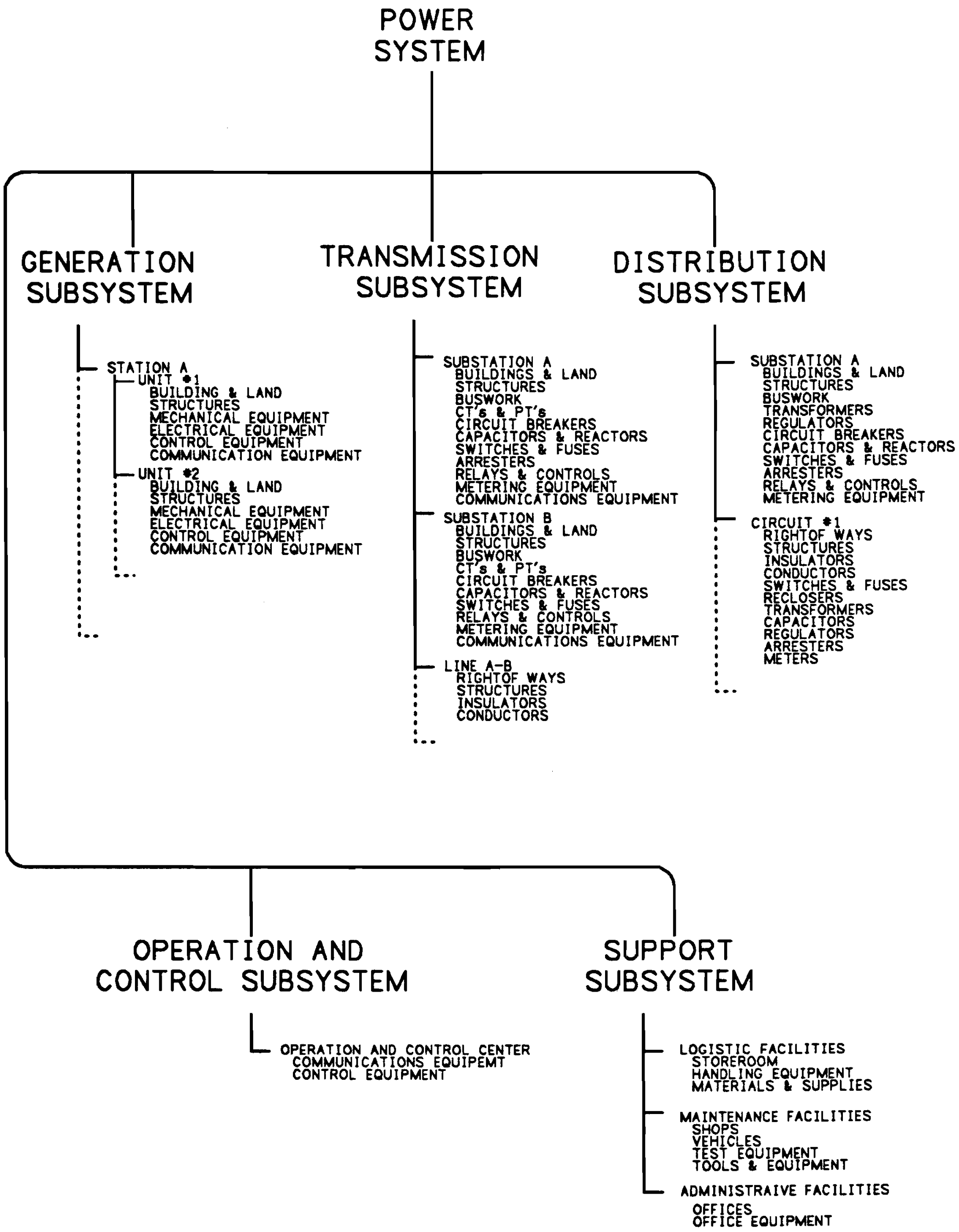

Figure 4

Functional Packaging Scheme

Table 2
REQUIREMENT ALLOCATION TABLE

PACKAGE	RELIABILITY		COST		MANHOURS		
	REL.	AVAIL.	$/YEAR	$/KWH	BASIC	INTER.	HIGH
SYSTEM							
GENERATION SUBSYSTEM							
STATION A UNIT #1 BUILDING & LAND STRUCTURES MECHANICAL EQUIPMENT ELECTRICAL EQUIPMENT CONTROL EQUIPMENT COMMUNICATION EQUIPMENT							
TRANSMISSION SUBSYSTEM							
SUBSTATION A BUILDINGS & LAND STRUCTURES BUSWORK CT's & PT's CIRCUIT BREAKERS CAPACITORS & REACTORS SWITCHES & FUSES ARRESTERS RELAYS & CONTROLS METERING EQUIPMENT COMMUNICATIONS EQUIPMENT LINE A-B RIGHTOF WAYS STRUCTURES INSULATORS CONDUCTORS							
DISTRIBUTION SUBSYSTEM							
SUBSTATION A BUILDINGS & LAND STRUCTURES BUSWORK TRANSFORMERS REGULATORS CIRCUIT BREAKERS CAPACITORS & REACTORS SWITCHES & FUSES ARRESTERS RELAYS & CONTROLS METERING EQUIPMENT CIRCUIT #1 RIGHTOF WAYS STRUCTURES INSULATORS CONDUCTORS SWITCHES & FUSES RECLOSERS TRANSFORMERS CAPACITORS REGULATORS ARRESTERS METERS							
OPERATIONS SUBSYSTEM							
COMMUNICATIONS EQUIPEMT CONTROL EQUIPMENT							
SUPPORT SUBSYSTEM							
LOGISTIC FACILITIES STOREROOM HANDLING EQUIPMENT MATERIALS & SUPPLIES MAINTENANCE FACILITIES SHOPS VEHICLES TEST EQUIPMENT TOOLS & EQUIPMENT ADMINISTRAIVE FACILITIES OFFICES OFFICE EQUIPMENT							

System synthesis is putting all the pieces together and verifying that the system will function as desired. Synthesis is tested through the use of the analytical models listed above. Contingencies can be evaluated to determine if the system will operate with various loads, and line or generator outages. System stability can also be evaluated. Once synthesis is achieved detailed specifications can be written to guide the designers in the detailed design of the system. For a power system the detailed specifications can include one line diagrams, operating notes, location plans, right-of way maps, and equipment specifications among the documentation.

It is important to remember the iterative, feedback nature of the systems engineering process. At any stage as more insight is gained into the system the previous work can be changed. System synthesis can have an impact on the functional flow diagrams and start the process on a new round.

It was stated in the first part that a system management approach would be used to implement the system. A project management plan should be developed for the system. The plan will be used to guide the planning, engineering, design, construction, and testing of the system. This plan includes the following five parts:

1) A work breakdown structure
2) An organization chart
3) A schedule
4) A budget
5) Control procedures and documents

Every task necessary to implement the system should be defined and organized in a tree structure. This work breakdown structure provides a framework for dividing the total project up into manageable tasks. It forms the basis for the schedule and the budget. The organization chart should describe who is responsible for what and to whom. The schedule is used to manage people, equipment, material, and time. The budget is concerned with controlling the money spent on the project. In order to communicate the progress documents and procedures have to be set up to monitor the budget and the schedule and report it so that variances can be detected and appropriate action taken. Additional information on system management can be found in the references. [1,2,28]

THE SPRUCE MOUNTAIN POWER SYSTEM

Introduction

The subject area for this design project is a region of the Allegheny Highlands in West Virginia as shown in Figure 5. U.S.G.S. topographic maps which show more details of the region are included in the back. This area presently consists of small farms with logging, mining, and gas production being the major industries. There are several small communities in the area linked by a good road system. A modern power transmission and distribution system already serves this area from an interconnected network. In order to treat this area as a remote region lacking a power system many assumptions were made. The geographic data was used from this area but population, economic, and other factors have been altered slightly to simulate an isolated mountainous region. This simulated region is described as follows.

The Spruce Mountain region is a rugged mountainous area of the Alleghenies. It encompasses approximately 400 square miles. The region is heavily forested with hardwood species dominating at the lower elevations and spruce forests higher up. Only small areas have been cleared for crops and pastures. Fish and wildlife are abundant in this region.

The population of 3000 people reside on small farms and in five communities: Bemis, Durbin, Whitmer, Dry Fork, and Cherry Grove. These communities serve as centers for commerce, government, social services, schools, and community activities. The principal industries are agriculture, timber production, and limestone quarrying. There is a spur railroad line up to Bemis and the road network consists of well maintained dirt and gravel roads. At present there is no electric power system in the region. Wood, oil, and gas are the fuels used for light, heat, and power. The oil and gas are imported into the region.

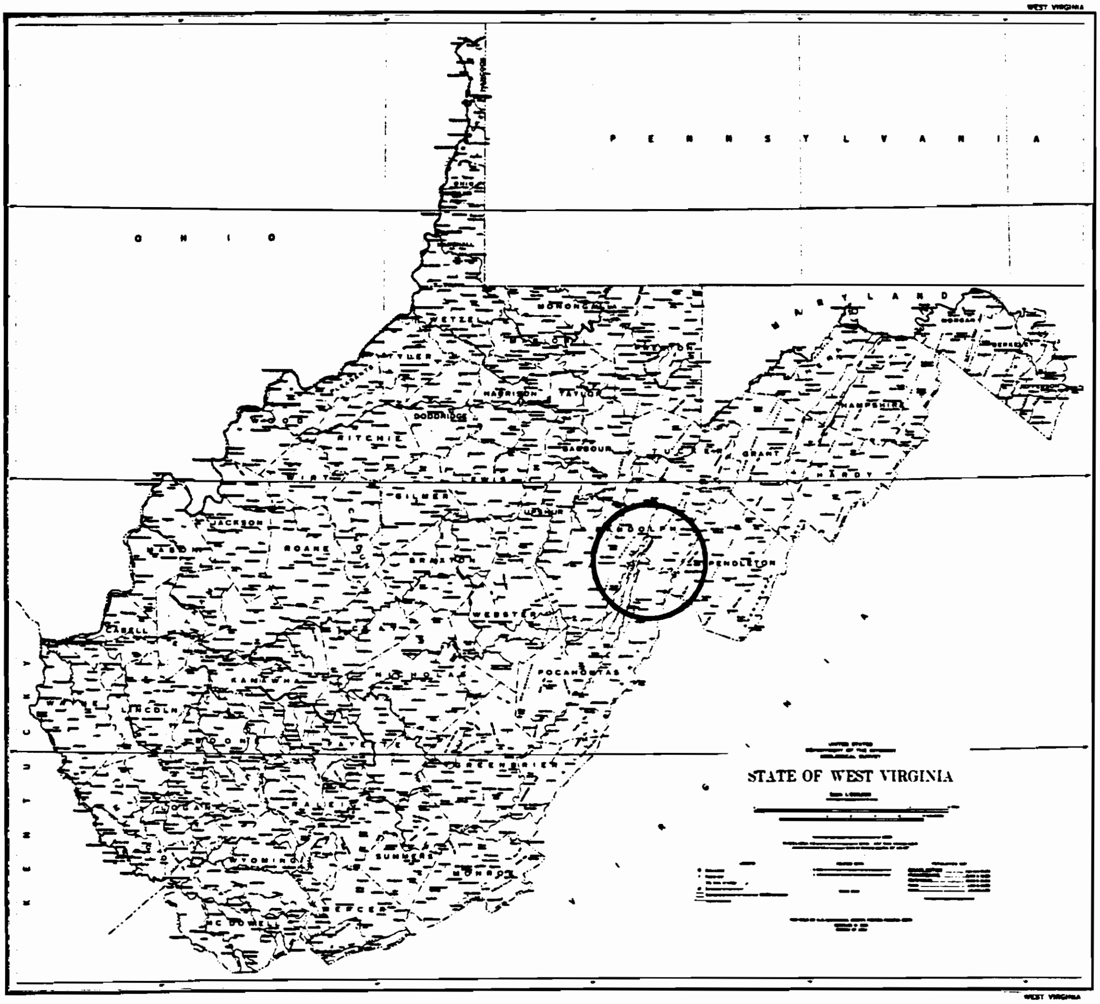

Figure 5
The Spruce Mountain Area

Definition Of Need

The people of this region want to improve their quality of life. They determine the quality of life by considering conditions in four sectors: economic, social, political, and environmental.

The economic sector produces the goods and services that the region needs. The people want to allocate the human resources, natural resources, and capital as efficiently as possible to create wealth at the lowest cost. The social sector should provide adequate health care, housing, education, recreation and leisure opportunities, safety and security. In the political sector the people want honest representative government that provides the basic services. The people want to feel that the government is open and responsive to them and guarantees their rights. The environmental sector considers clean water, air, land, and a healthy habitat for the many species which inhabit the region. The people live close to the land and care deeply about their environment. It is important to keep in mind that the quality of life is measured by far more than just economic standards.

In order to improve the quality of life the people seek to wisely develop the resources of the region. Drew and Hsieh define development as the process by which a society strives to move toward a greater control over its environment and the destiny of its people and to reduce its vulnerability to outside influences, both natural and manmade, through the more efficient use of resources achieved by a set of possible changes - economic, technological, social, and political. [5]

An important element of development is the electric power supply. A reliable, adequate, economical, and safe supply of electricity is necessary so that society can enjoy and prosper from the benefits of electricity such as light, heat, machinery and equipment, and electronics. Electricity has been shown to have a positive effect on rural agriculture, industry, commerce, education, and peoples perception of their quality of life. [4] A power system offers advantages such as economies of scale and reliability over the generation and utilization of electricity on an individual basis.

System Planning

Feasibility Study

Need Analysis

The first part of the feasibility study is to examine more closely the need for the system. The benefits to be derived from the system have been established and the projected power and energy demands must be determined. This is done by modeling the load. For this project the average hourly loads for Floyd, Virginia were used as a basis for the load. Floyd is a small rural mountain community for which hourly MW and MVAR loads were available for an entire year. The actual loads represented about 12,000 people, 4800 households, 200 commercial accounts, and 10 small industrial customers. These loads were divided by four to reflect the smaller assumed population of the study area. The average hourly loads for each season are shown in Figure 6. This load is winter peaking. The load has a strong inverse relationship to temperature. The cumulative probability distribution function was found from these loads for each season. The cumulative probability distribution function is also called the Load Duration Curve or LDC. The energy demand was found by integrating the load duration curve. These curves are shown in Figure 7. The peak loads and energy are listed in Table 3. The power and energy demands shown in Table 3 are for a society where electricity is fully integrated into their lifestyles. This load is the load that will develop in the Spruce Mountain region several years after people have converted over to electricity. Future growth in demand can be modeled by several methods such as an econometric, or time-trend model.

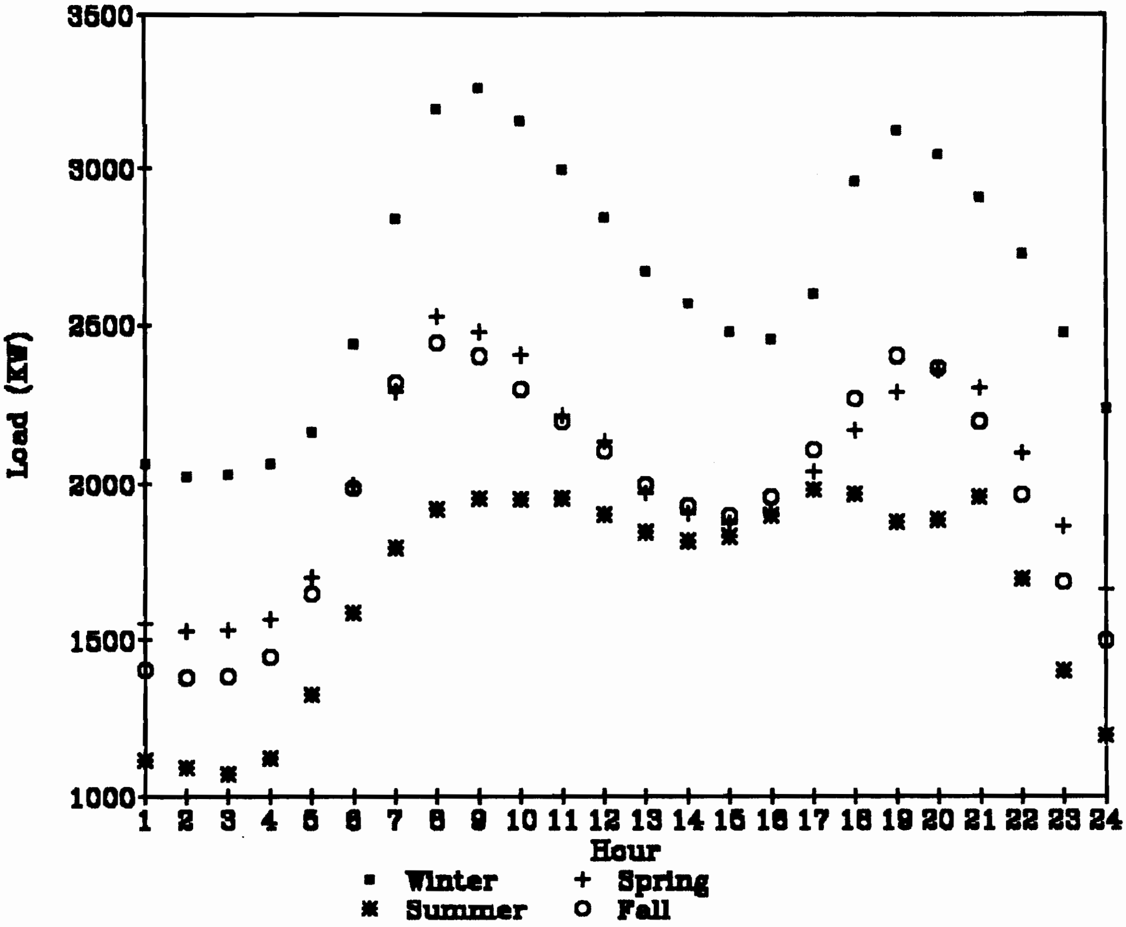

Figure 6
Average Hourly Loads

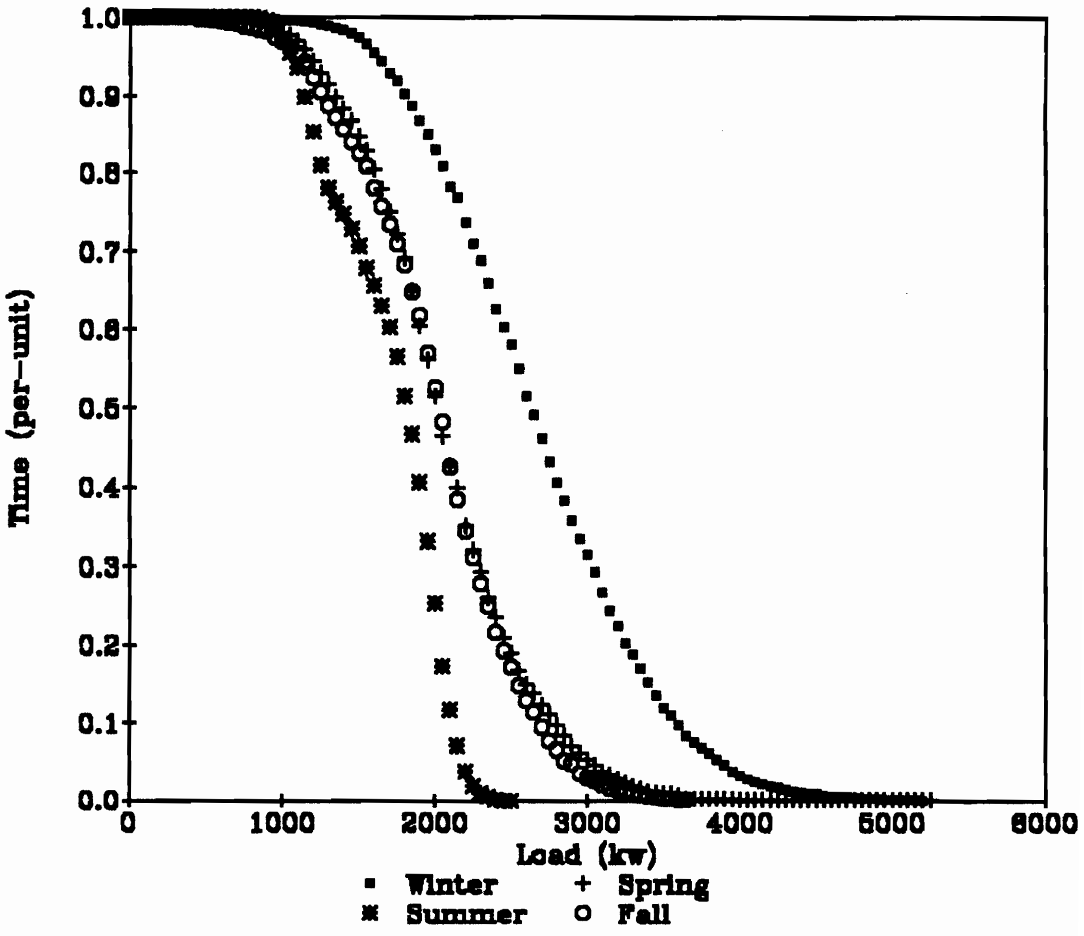

Figure 7
Load Duration Curves

TABLE 3
POWER AND ENERGY DEMAND

TIME	KW	KWH
WINTER	5,150	5,829,474
SPRING	5,250	4,581,201
SUMMER	2,400	3,826,282
FALL	3,650	4,433,581
YEAR	5,250	18,670,544

The next part of the feasibility study is to define the operational requirements and develop a maintenance concept for the Spruce Mountain Power System.

System Operational Requirements

Mission Definition: The electric power system is to provide adequate, reliable, economical, and quality electric power in a safe manner. It is to be administered as an independent agency of the local government.

Performance Parameters:

Frequency - 60 Hz

Distribution Voltages - 120/240v single phase
480 or 4160v three phase

Operational Deployment: The system will be deployed throughout the Spruce Mountain region. This includes roughly the areas of the watersheds of the forks of the Cheat River, the forks of the Greenbrier River, and Seneca Creek.The load centers are located at Bemis, Durbin, Whitmer, Cherry Grove, and Dry Fork.

Operational Life Cycle: 30 years

Utilization Requirements: 24 hours a day, 365 days a year

Effectiveness Factors:

Adequacy

- Power Capacity 6,000 kw
- Energy Capacity 20,000,000 kwh
- Loss-of-Load Probability <.0005

Reliability

- Availability > .997
- Customer Interruption Frequency Index < 1.5/year
- Customer Interruption Duration Index < 6 hours

Quality:

- Voltage Fluctuations Normal loading .975 - 1.050 p.u.
  Emergency loading .930 - 1.060 p.u.
- Frequency Fluctuations +/- .5 Hz

Economic:

- Annual Revenue Requirement < $2,500,000
- Cost per kilowatthour < 12.5¢

Manability:

- Personnel: 18 maximum
- Skill Levels: High..........3 people
  Intermediate..9 people
  Basic.........6 people

Operating Environment:

- Average Annual Rainfall: 30-50 inches

Average Annual Snowfall: 30-90 inches

Ice formation is common above 3200 feet during all the winter months. This is most often a thick glaze formed by freezing rain or snow.

Temperature (°F):

	Minimum	Average Low	Average High	Maximum
Winter	-37	12	38	-
Summer	-	53	78	104

Wind Speed: Median: 6 m/sec (13 mph)

Maximum: 21 m/sec (47 mph)

Topography: The topography is characterized by greatly dissected high altitude plateaus that form steep, rugged mountains separated by narrow valleys. The elevations range from Spruce Knob, which at 4860 feet is the highest point in West Virginia to 2300 feet at the lowest elevation. The drainage pattern is typically dendritic, consisting of numerous winding streams fed by many convoluted branches. The main streams in this area are the forks of the Cheat River-the Shaver's, Glady, Laurel, and Dry, the Greenbrier River and its East and West Forks, and Seneca Creek.

System Maintenance Concept

Six factors need to be considered to develop a system maintenance concept. These are what has to be maintained, what maintenance actions will be performed, where it is to be done, when it should be done, who is to do it, and what equipment will they need. Table 4 lists the elements of the system and their maintenance requirements.

Maintenance on the system will be performed out of a service center located at Bemis. Bemis is the largest community, it is centrally located to the load centers, and sits on a rail line. Personnel will be sent out as needed to the sites from this center. A storeroom will carry adequate spare parts and materials to perform routine and emergency maintenance.

The repair policy will emphasize repairing major components due to their size, weight, cost, and lead times. The repair-or-replace decision will be made by management on a case by case basis based on an assessment of the damage, the likelihood of success, and the cost of the repairs.

Table 4
Maintenance Requirements

		Crew Class	Location	Functions
Plants -	building and land improvements	D	1	1,5,6
	structures	C,D	1	1,5,6,7
	mechanical systems	A,B,C,D	1,2,3	1-7
	electrical systems	A,B,C,D	1,2,3	1-7
	control systems	A,B	1,2	1-7
Stations -	buildings and land improvements	D	1	1,5,6
	structures	C,D	1	1,5,6,7
	buswork	C,D	1	1,5,6,7
	transformers	B	1,2,3	1-7
	circuit breakers	B	1,2,3	1-7
	capacitors & reactors	B	1,2	1-7
	switches & fuses	C	1,2	1-7
	arresters	B,C	1	1,2,7
	relays & controls	A,B	1,2	1-7
	metering equipment	A,B,C	1,2	1-7
	communication	A,B,C	1,2	1-7
Transmission Lines	right of ways	D	1	1,5
	structures	D	1	1,5,6,7
	insulators	C,D	1	1,5,7
	conductors	C,D	1	1,6,7
Distribution Lines	right of ways	D	1	1,5
	structures	D	1	1,5,6,7
	insulators	C,D	1	1,5,7
	conductors	C,D	1	1,6,7
	switches	C	1,2	1-7
	reclosers	B,C	1,2	1-7
	transformers	C	1,2	1-7
	regulators	B,C	1,2	1-7
	arresters	C	1	1,2,7
	meters	A,B,C	1,2	1-7

Crew Classes
A - Engineer(s) with meters, tests sets, and hand tools in a car.
B - Technician(s) with meters, test sets, and hand tools in a car.
C - Linemen with hand and power tools in bucket and equipment trucks.
D - Unskilled laborers with hand and power tools in an equipment truck.

Location
1 - Site maintenance is performed at the equipments installed location.
2 - Shop maintenance is performed by removing the equipment (or a part of it) to the nearest system facility.
3 - Factory maintenance is performed by shipping the equipment (or a part of it) to the factory for repairs.

Maintenance Functions
1 - Inspection
2 - Testing
3 - Calibration
4 - Operation
5 - Cleaning
6 - Repair
7 - Replacement

System Alternatives

Two alternative schemes exist. The first is to build transmission lines into the region, tie them into a subtransmission and distribution system and supply the power from a central grid. The second is to generate the power locally and to feed a subtransmission and distribution system. Possible technologies include fossil fuels, hydro, biomass, wind, or solar. Either alternative is technically feasible, both employ mature technologies. The difference between the alternatives is their cost-effectiveness. The approach this project takes is to develop the second alternative and then find what distance from the central grid would make this the preferred alternative to transmission lines. This completes the feasibility study.

System Specifications

These system specifications will be used to guide the engineering phase. Detailed specifications will be written at the completion of engineering to guide the design phase.

1. General Description

The Spruce Mountain Power System is to supply electric power to all customers in the region that apply for service. It is to be an agency of the local government. It is to generate, transmit, and distribute electric power independent of a interconnected network.

2. Operational Requirements
  - 2.1 The system will operate continuously, 24 hours per day, 365 days per year.
  - 2.2 The system is to operate over a 30 year life span.
  - 2.3 The system will operate through out the Spruce Mountain region. Its boundaries will roughly be the watersheds of the Shavers Fork, Glady Fork, Laurel Fork, Dry Fork, Seneca Creek, and the East and West Forks of the Greenbrier River.
  - 2.4 The system will operate satisfactorily under all weather conditions.

3. Maintenance Concept
  - 3.1 Maintenance will be done out of a central facility located at Bemis.
  - 3.2 An onsite repair policy will be emphasized.

4. Performance Characteristics
  - 4.1 The system will operate at a frequency of 60 Hz.
  - 4.2 Distribution voltages available to consumers will be 120/240v single phase and 480 or 4160v three phase.

5. Effectiveness Characteristics
  - 5.1 Adequacy Characteristics
    - 5.1.1 Installed capacity will be at least 6,000 kw.
    - 5.1.2 Annual energy production capability will be at least 20,000,000 kwh.
  - 5.2 Reliability
    - 5.2.1 System availability will be greater than .997.
    - 5.2.2 Customer interruption frequency index will be less than 1.5 per year.
    - 5.2.3 Customer interruption duration index will be less than 6 hours.

5.3 Quality Characteristics

5.3.1 Voltage fluctuations will be between .975 and 1.050 per unit for normal operating conditions and between .930 and 1.060 per unit for emergency conditions.

5.3.2 Frequency fluctuations will be held to +/- .5 Hz.

5.4 Economic

5.4.1 The annual revenue requirement will be less than $2,500,000.

5.4.2 The average cost per kilowatt-hour will be less than 12.5¢.

5.5 Manability

5.5.1 The system will function with no more than 18 people in operation, maintenance, logistic support and administrative roles.

5.5.2 The breakdown of personnel by skill levels will be as follows: basic, 6; intermediate, 9; high, 3.

6. Design Characteristics

6.1 Maintainability

6.1.1 The system will be designed so that the available personnel and equipment can perform all routine maintenance.

6.1.2 The system will be designed so that the mean corrective maintenance times (MCT) are less than:
generation..... 96 hours
transmission... 48 hours
distribution.... 8 hours

6.1.3 The system will be designed so that the mean preventative maintenance times (MPT) are less than: generation..... 120 hours
transmission.... 60 hours
distribution... 12 hours

6.1.4 The system will be designed so that the mean time between maintenance (MTBM) for any part of the following subsystems is greater than:
generation.....1 year
transmission...2 years
distribution...3 years

6.2 Manability

6.2.1 The system will be designed so that the generation and distribution stations do not require continual operator supervision.

6.2.2 The system will be designed so that control of the system requires usually only 2 people with an intermediate skill level.

6.3 Transportability

6.3.1 All equipment shall be capable of arriving at Bemis by rail.

6.3.2 Major equipment shall be capable of being transported by truck over 16' wide unpaved roads

from Bemis to its installed location.
6.3.3 All line locations shall be accessible by tracked vehicles.
6.3.4 All equipment shall be capable of being handled by a 50 ton crane.
6.4 Interchangeability: Equipment shall be selected to maintain interchangeability among the elements of the system as much as possible.
6.5 Safety: All local, state, and national safety regulations will apply.
6.6 Expandability: The system will be designed to accommodate future growth.

7. Construction Specifications
7.1 Construction materials will be locally available materials wherever possible.
7.2 Construction equipment necessary will either be locally available or able to be shipped in by rail.
7.3 Industry standard practices are to be used.
8. Support Specifications
8.1 A central office will be built in Bemis and will house the administrative, operation and controls, communications, logistic support, and maintenance functions.
8.2 Adequate spare parts will be kept in stock to meet the following mean logistic delay times.

	corrective actions	preventative actions
generation	2 hours	60 days
transmission	1 hour	6 days
distribution	.5 hours	4 days

9. Documentation: Documentation will include the following:
9.1 One line diagrams with operating notes.
9.2 Location plans.
9.3 Automatic generation control software specs
9.4 Operating procedures
9.5 Equipment specifications

This concludes the feasibility study and the system planning phase. The specifications can now be used to guide the system engineering phase.

System Engineering

A functional analysis of the Spruce Mountain Power System is performed next. The first step is to describe the operational and support functions that are required for the system to meet the requirements. These functions are listed below.

Top Level Functions
- 1.0 Define the system requirements
- 2.0 Design the power system
- 3.0 Design the support system
- 4.0 Construct the power system
- 5.0 Construct the operation and control facilities
- 6.0 Construct the maintenance and logistic facilities
- 7.0 Construct the administrative facilities
- 8.0 Operate the power system
- 9.0 Maintain the power system
- 10.0 Administer the power system

First Level Functions
- 1.0 Define the system requirements
  - 1.1 Define the need for electric power
  - 1.2 Prepare the feasibility study
  - 1.3 Prepare the system specifications

- 2.0 Design the power system
  - 2.1 Engineer the power system
  - 2.2 Design the power system

- 3.0 Design the support system
  - 3.1 Engineer the support system
  - 3.2 Design the support system

- 4.0 Construct the power system
  - 4.1 Construct the generating plants
  - 4.2 Construct the transmission system
  - 4.3 Construct the distribution system

- 5.0 Construct the operation and control facilities
  - 5.1 Construct the operations control center
  - 5.2 Acquire and install the control and communication equipment

6.0 Construct the maintenance and logistic facilities
  6.1 Construct the maintenance shops
  6.2 Acquire and install equipment
  6.3 Acquire and place in stock the spare parts

7.0 Construct the administrative facilities
  7.1 Construct the administrative offices
  7.2 Acquire and install equipment

8.0 Operate the power system
  8.1 Monitor system conditions
  8.2 Automatically protect personnel and equipment from abnormal conditions
  8.3 Communicate data to and from the operations control center
  8.4 Control power flow
  8.5 Generate power
  8.6 Transmit power
  8.7 Distribute power

9.0 Maintain the power system
  9.1 Identify maintenance need
  9.2 Schedule maintenance
  9.3 Prepare the component for maintenance
  9.4 Perform maintenance action
  9.5 Verify that maintenance action was successful
  9.6 Return to service
  9.7 Complete maintenance report

10.0 Administer the power system
  10.1 Supervise the overall system operations
  10.2 Hire and train personnel
  10.3 Keep records
  10.4 Collect revenue from customers

Second Level Functions

8.1 Monitor system conditions
  8.1.1 Sense the system conditions (V,I,f,kw,kvar,etc.)
  8.1.2 Activate alarm signals

8.2 Automatically protect personnel and equipment from abnormal conditions
  8.2.1 Surge arresters operate
  8.2.2 Relays operate
  8.2.3 Fuses operate

8.3 Communicate data to and from the operations

control center
- 8.3.1 Send data, signals, voice, to the O&C center
- 8.3.2 Interpret information and decide on control action
- 8.3.3 Send instructions to operator

8.4 Control power flow
- 8.4.1 Operate control mechanism manually
- 8.4.2 Apply control signal
- 8.4.3 Control devices (switches/breakers) operate

8.5 Generate power
- 8.5.1 Generate real power
- 8.5.2 Generate reactive power

8.6 Transmit power
- 8.6.1 Transform voltage level from generator output to the transmission voltage
- 8.6.2 Transmit power

8.7 Distribute power
- 8.7.1 Transform voltage from transmission voltage to distribution voltage
- 8.7.2 Distribute the power
- 8.7.3 Regulate the voltage
- 8.7.4 Transform the voltage from the distribution voltage to the utilization voltage
- 8.7.5 Meter the power use

9.0 Maintain the power system

9.1 Identify maintenance need
- 9.1.1 Perform visual inspection
- 9.1.2 Receive alarm
- 9.1.3 Receive test results
- 9.1.4 Monitor system conditions
- 9.1.5 Follow Maintenance Schedule

9.2 Schedule maintenance
- 9.2.1 Assemble personnel, equipment, and materials
- 9.2.2 Schedule with O&C center

9.3 Prepare the component for maintenance
- 9.3.1 Install a spare component
- 9.3.2 Switch to a backup component
- 9.3.3 Leave in service
- 9.3.4 Isolate the component requiring maintenance

9.4 Perform maintenance action

9.5 Verify that maintenance action was successful

- 9.5.1 Perform visual inspection
- 9.5.2 Perform tests
- 9.5.3 Operate the equipment

9.6 Return to service
- 9.6.1 Remove spare
- 9.6.2 Remove the backup component
- 9.6.3 Return the component to service

9.7 Complete maintenance report
- 9.7.1 Submit a report of maintenance action
- 9.7.2 Compile the report into maintenance database

The top and first level functions are shown graphically in the functional flow diagrams of Figures 8a-c. From these functional flow diagrams it can be seen that the system has four basic functions: construction, operation, maintenance, and administration. The operation function has five subfunctions: generation, transmission, distribution, operation and control, and communication. To fulfill these functions the power system will be broken down into four subsystems based on the functional analysis. The operational subsystems are generation, transmission, distribution, and operation and control. This packaging scheme is shown in Figure 9. At this point it is not yet known how many generating plants, lines, substations, or circuits will be required. The packaging scheme basically consists of breaking the system down into subsystems with the understanding that it can be further subdivided as shown in Figure 9. The system requirements are now allocated among the subsystems. Table 5 lists the first attempt at allocating the requirements among the subsystems. These allocations are subject to change depending on the engineering analysis and design work to follow. They serve as a starting point for the evaluation of the alternatives.

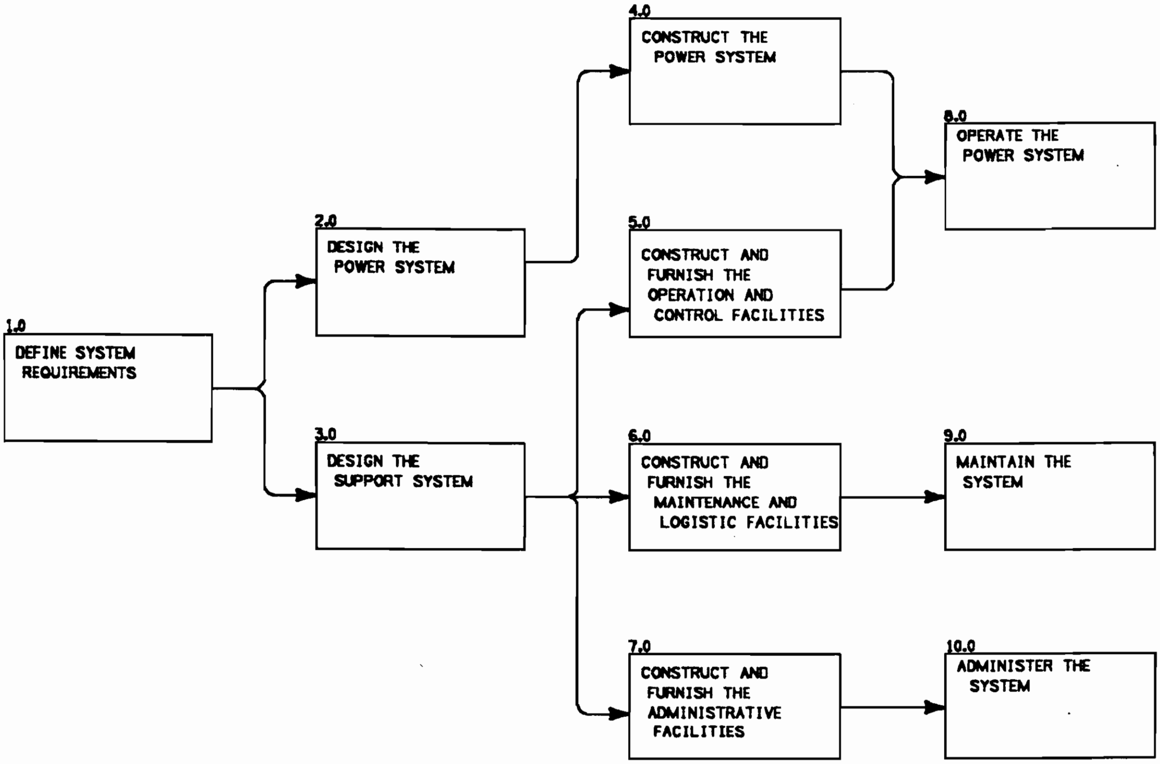

Figure 8a
Top Level Functional Flow Diagram

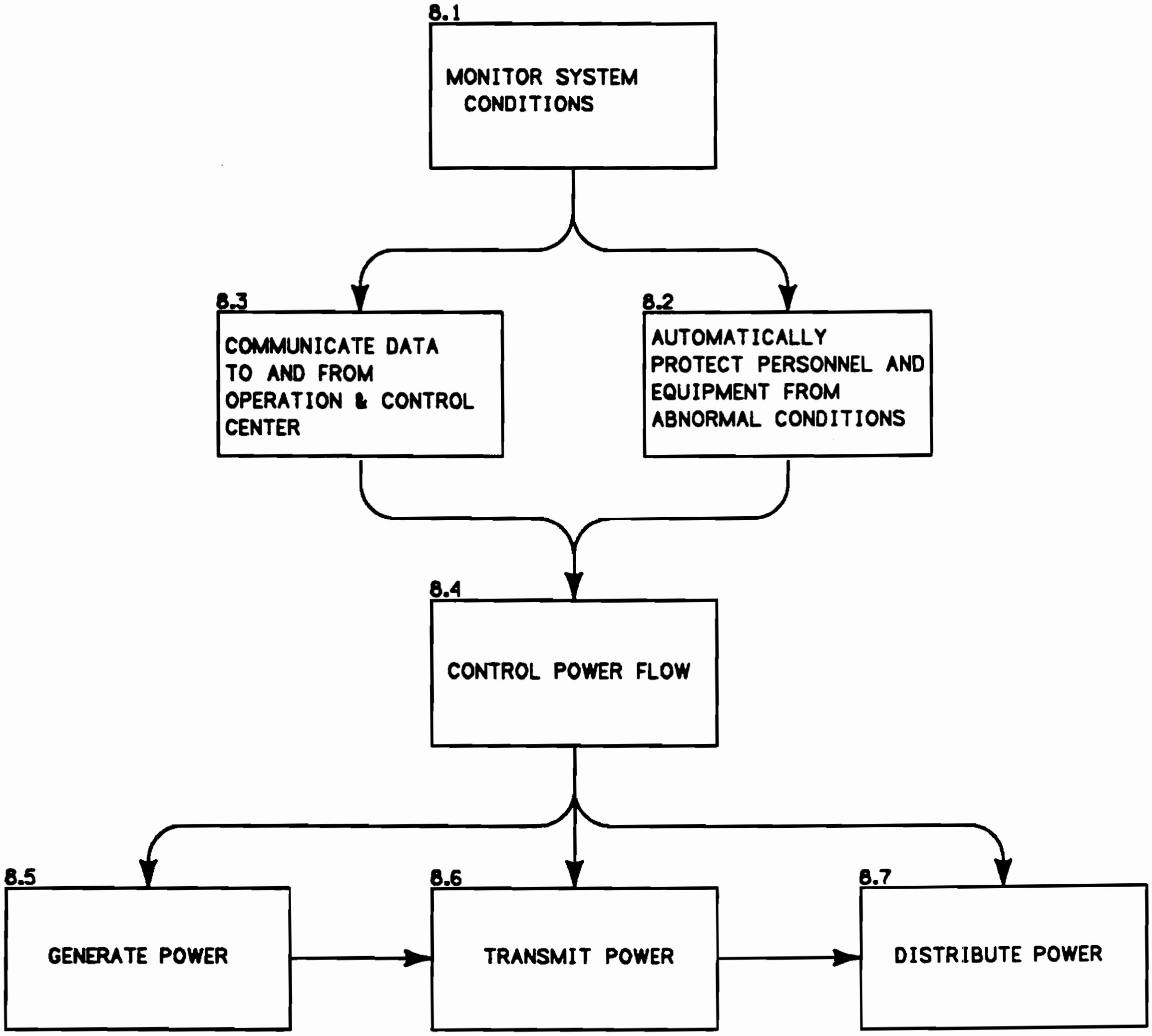

Figure 8b
First Level Operational Functional Flow Diagram

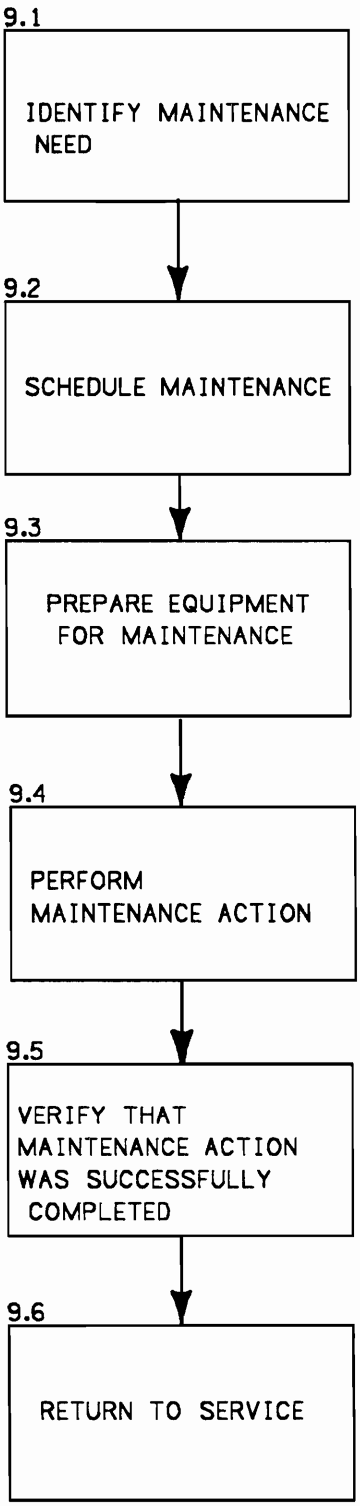

Figure 8c
FIRST LEVEL MAINTENANCE FUNCTIONAL FLOW DIAGRAM

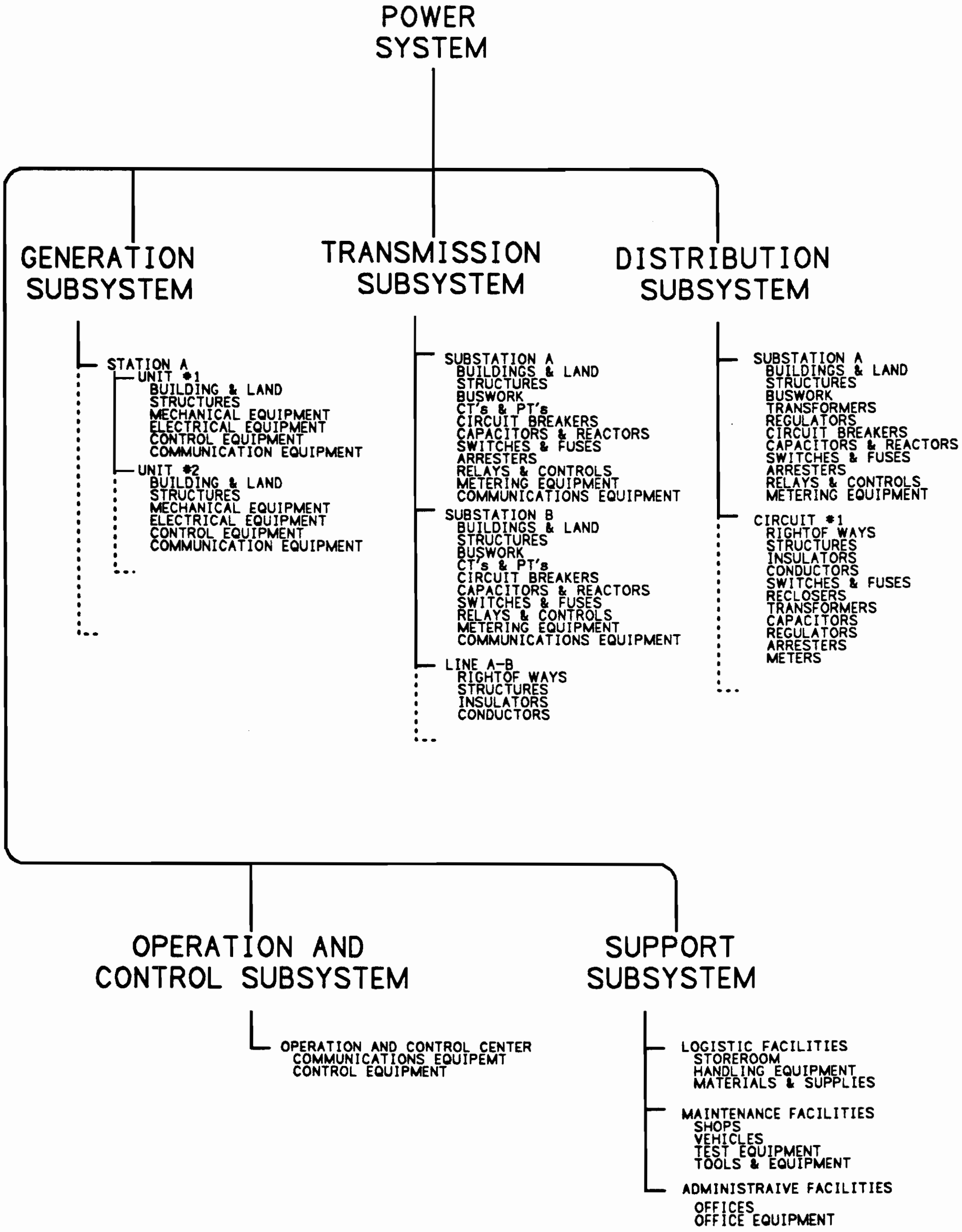

Figure 9

Functional Packaging Scheme

Table 5
Requirement Allocation Table

PACKAGE	RELIABILITY		COST		MANHOURS		
	REL.	AVAIL.	$/YEAR	$/KWH	BASIC	INTER.	HIGH
SYSTEM	.2132	.9979	2,500,000	.125	12,480	18,720	6,240
GENERATION SUBSYSTEM	.9642	.9995	1,125,000	.0563	800	4,000	1,040
TRANSMISSION SUBSYSTEM	.6065	.9991	500,000	.025	1,400	3,520	520
DISTRIBUTION SUBSYSTEM	.3679	.9993	625,000	.0313	4,040	6,000	520
OPERATIONS SUBSYSTEM			125,000	.0062	0	2,600	2,840
SUPPORT SUBSYSTEM			125,000	.0062	6,240	2,600	1,320

System Optimization

The system optimization process is an iterative process as described in the first part and shown in Figure 2. In this project only the generation and transmission subsystems will be considered. This same process can be used for the distribution, operation and control, and support subsystems.

Generation Subsystem

There are numerous ways to generate electricity each having inherent advantages and disadvantages. A partial list includes:

- Fossil fueled steam turbine (coal, oil, or gas)
- Nuclear steam turbines
- Gas combustion turbines
- Diesel, gasoline, or natural gas internal combustion engines
- Hydroelectric
- Thermal solar
- Photovoltaic
- Wind
- Geothermal
- Biomass\Biogas

These alternatives can be quickly screened by considering their cost, minimum size, energy availability, operating characteristics, and maintainability. Of these hydro, wind, and diesel are the most promising technologies and only these will be evaluated to determine if they are capable of meeting the requirements.

Energy Assessment Models

An energy assessment model is a tool that is used to determine the power and energy available from a particular resource. A different model is used for each resource.

Diesel

Diesel driven generators can furnish adequate power and energy if enough units are installed and fuel furnished. Diesel generating units are widely available in many sizes up to several thousand kilowatts. Diesel fuel has a heating value of approximately 135,000 BTU/gal. Diesel engine efficiency is about 36.5%. Based on these estimates diesel engines would require .0693 gal/kwh or 1,386,000 gallons of fuel per year to supply 20,000,000 kwh. It is assumed that adequate supplies of diesel fuel are available from outside the region and can be shipped in and stored. [16]

Hydropower

Hydropower potential for the three major rivers was evaluated. Topographic maps were used to determine that the terrain is suitable for developing the necessary head. All three river valleys have at various locations, narrow bottoms and steep sides. The average daily stream flows for a 6 to 14 year period in the 1970's and 80's were obtained. These were used to plot the stream flow duration curves shown in Figure 10a-c. These stream flows are dependent on rain and snow fall. The flow which is exceeded 25% of the time (Q_{25}) is used as the basis for computing the size of the turbines. The Q_{25} stream flows for each season for the three rivers are shown in Table 6. The hydraulic power model that is used is $P = Q*H*e/11.8$

where P is power in kw

Q is flow in cfs

H is net head in feet

e is the overall efficiency

11.8 is a conversion factor

In order to find the power and energy available certain assumptions must be made. Power will be calculated based on the maximum Q_{25}. Net head will be assumed to be 50 feet. The operating range will be 40-100% of Q_{25}. The overall efficiency will be assumed to be 85%. This model is used to develop power duration curves as shown in Figure 11a-c. This model is a simplified model and does not take into account the relationship between the net head and the flow. The flow will have an effect on the net head by producing changes in the headwater and tailwater elevations. Turbine efficiency also varies with the flow. This model gives a power output from the three rivers of 9150kw. The energy available is found by integrating under the power duration curves from 40-100% of Q_{25}. This yields 35,070,270 kwh annually which is more than required. However, due to the fact that stream flows are insufficient at times during every season due to drought or cold temperatures hydropower alone will not be adequate. [17,18,19,20]

TABLE 6

Q_{25} STREAM FLOWS (cfs)

	WINTER	SPRING	SUMMER	FALL
DRY FORK	1300	1440	500	700
SHAVERS FORK	540	560	320	340
GREENBRIER RIVER	480	540	160	220

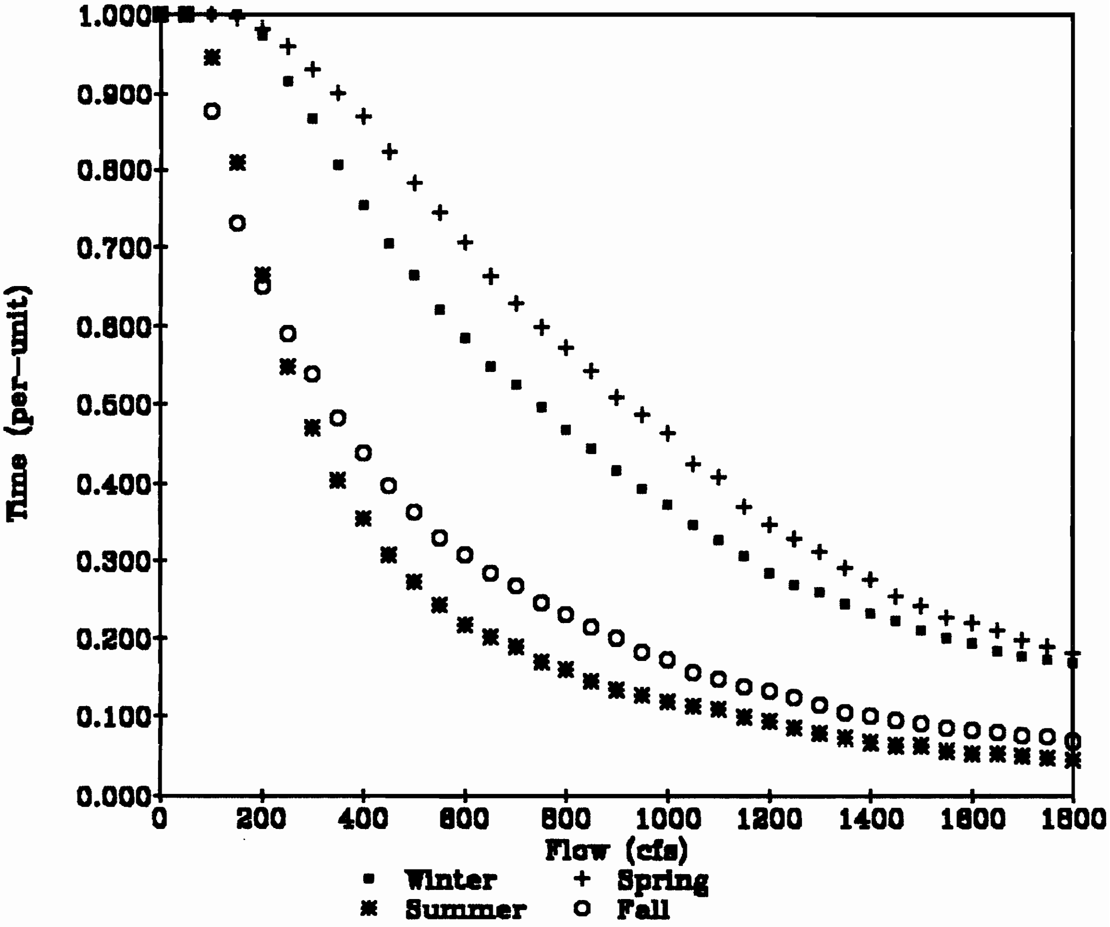

Figure 10a
Dry Fork Seasonal Flow Duration Curves

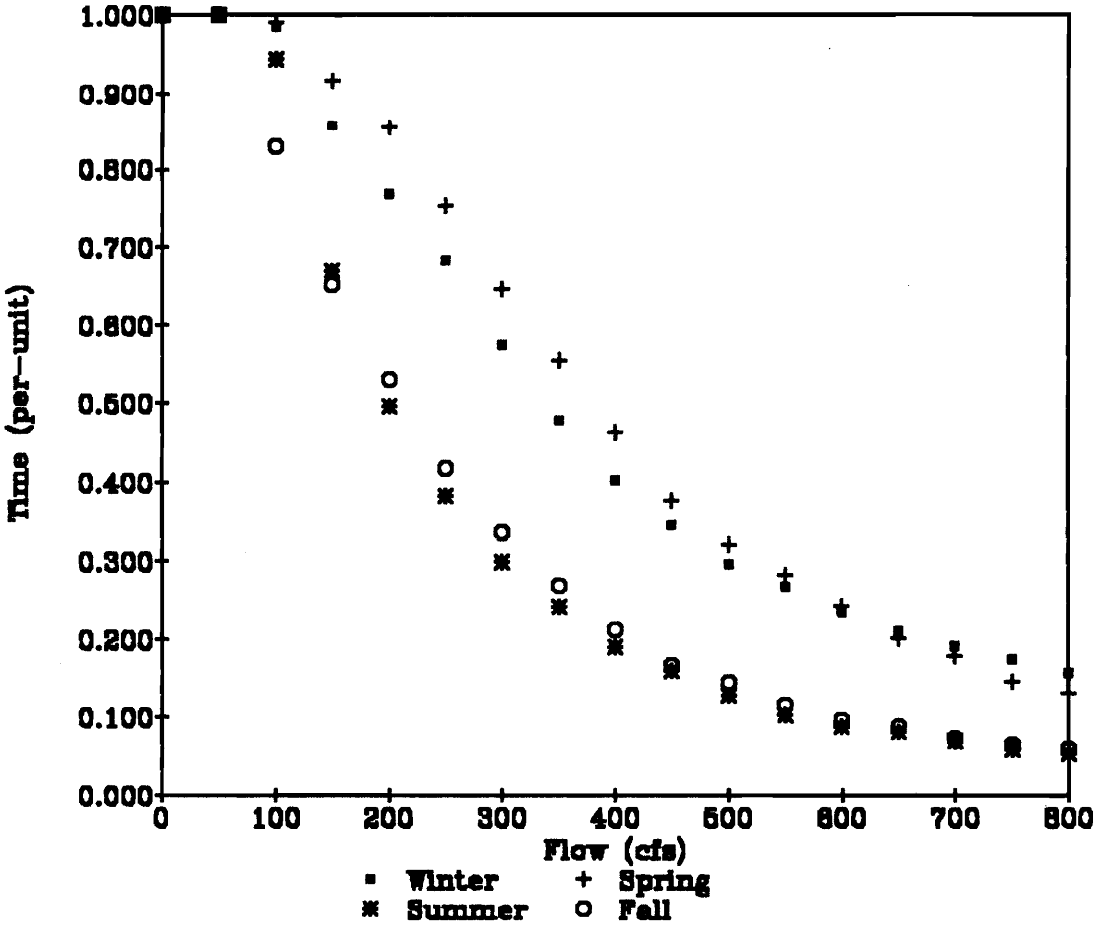

Figure 10b
Shavers Fork Seasonal Flow Duration Curves

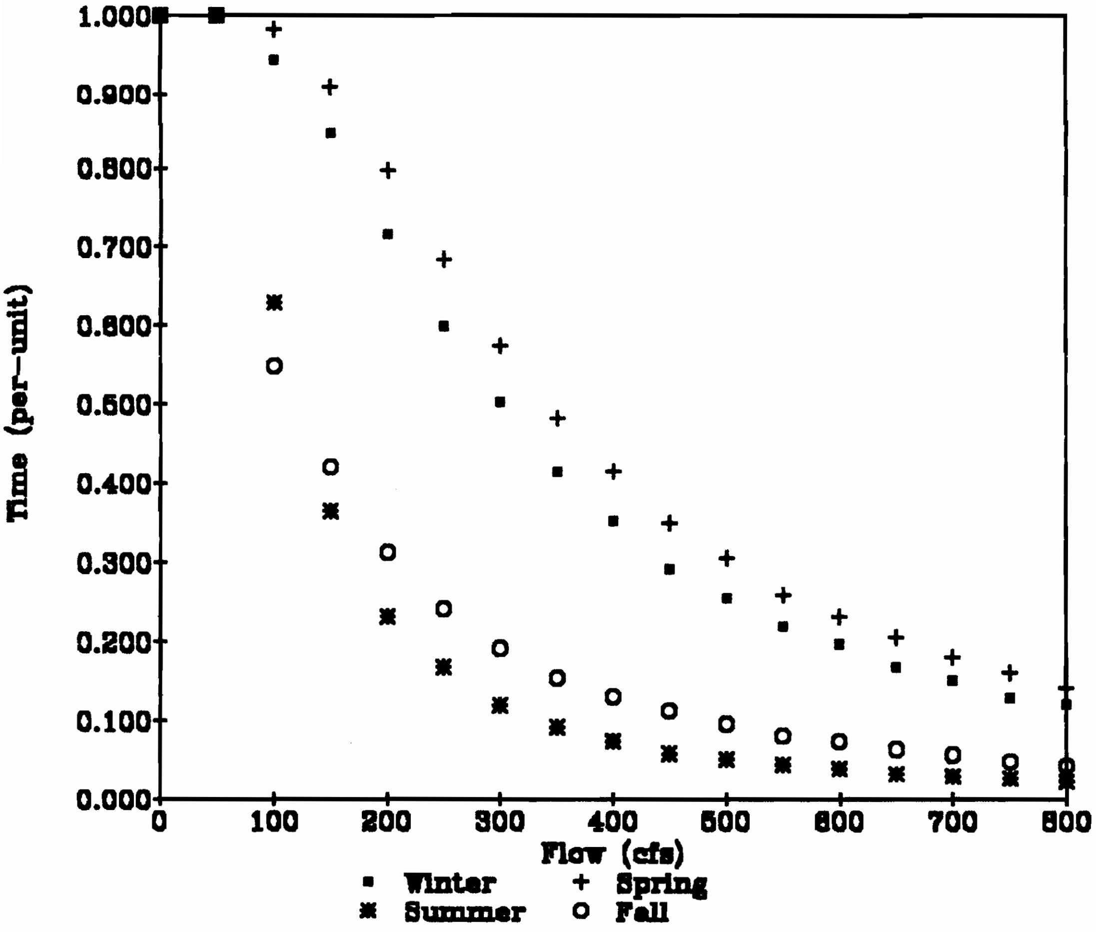

Figure 10c
Greenbrier River Seasonal Flow Duration Curves

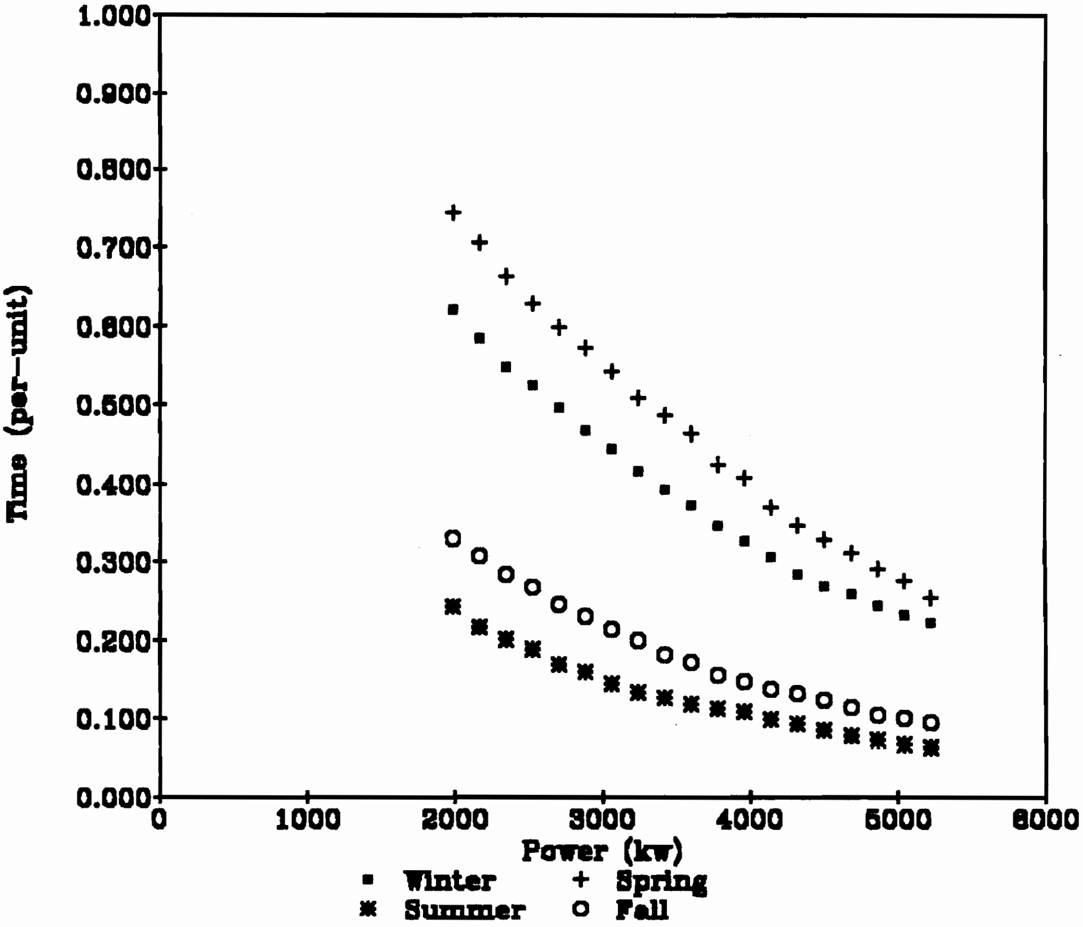

Figure 11a
Dry Fork Seasonal Power Duration Curves

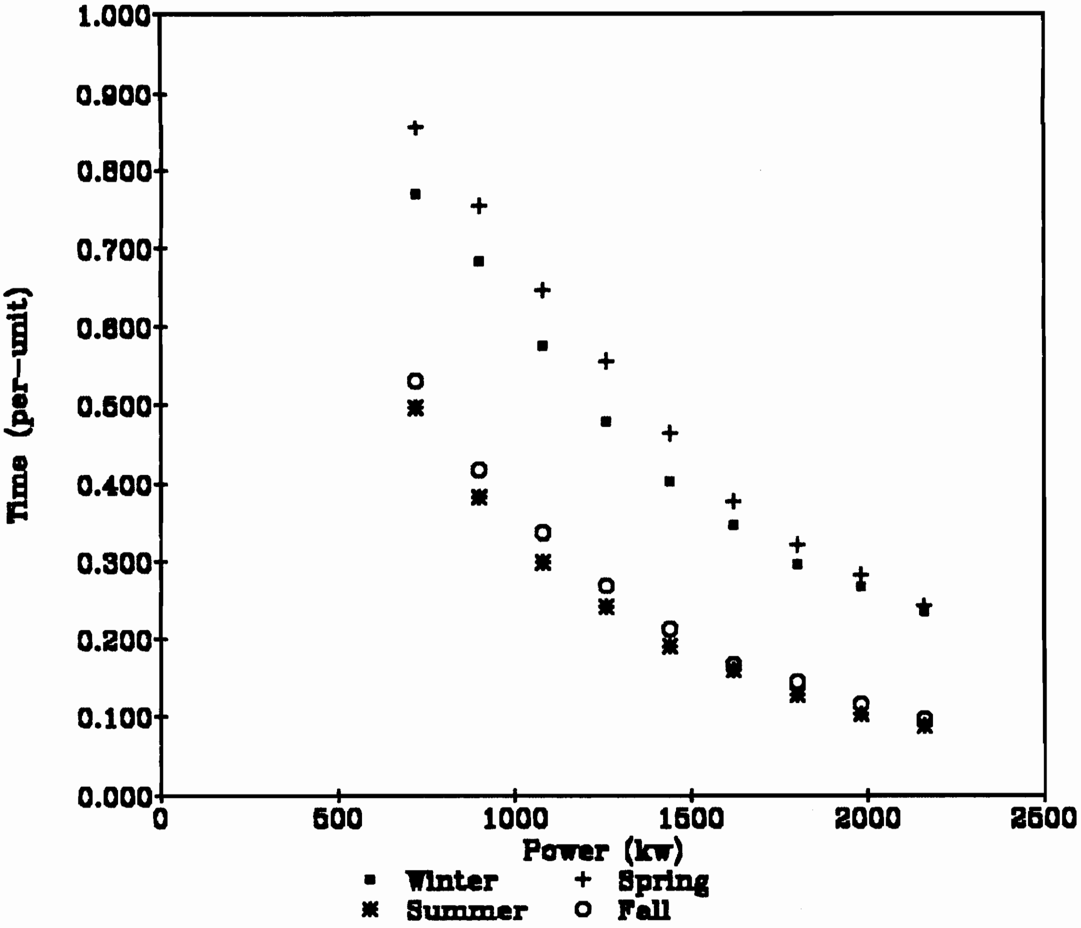

Figure 11b
Shavers Fork Seasonal Power Duration Curves

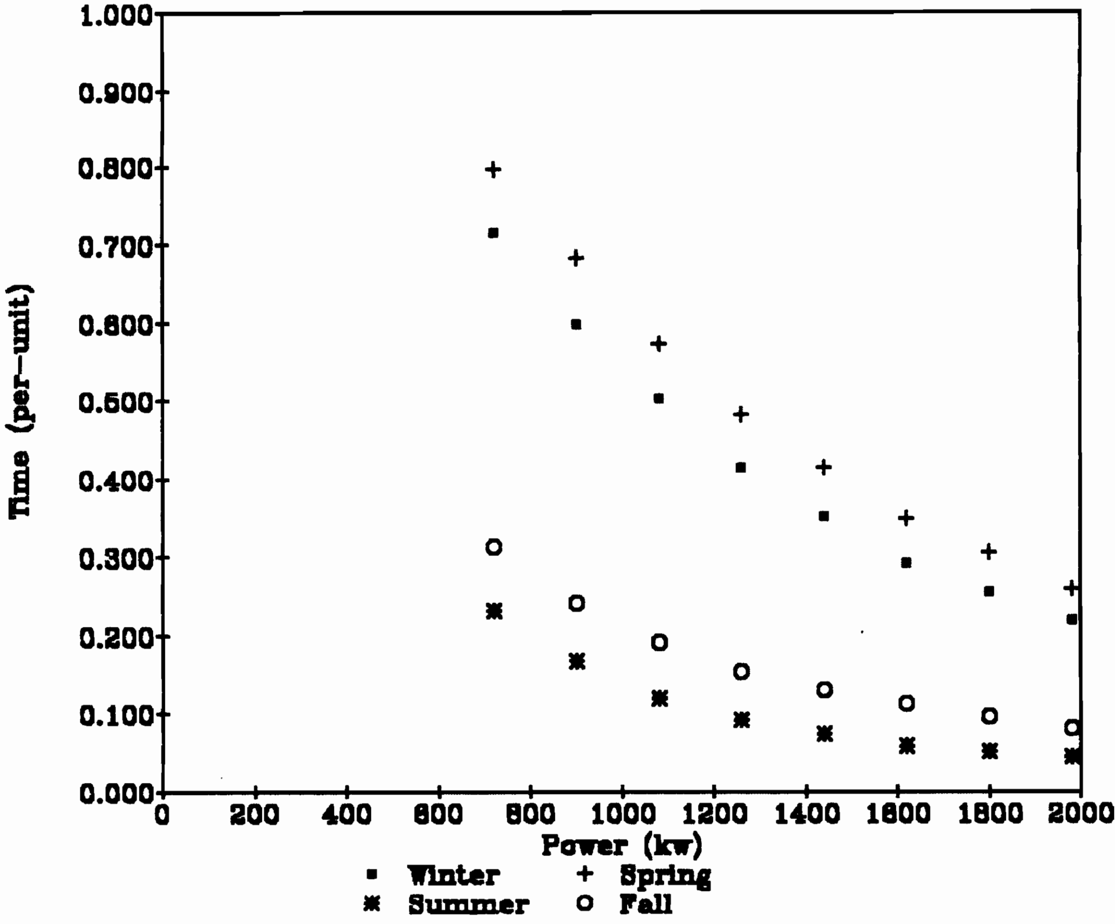

Figure 11c
Greenbrier River Seasonal Power Duration Curves

Windpower

Hourly wind speed data was obtained from a high elevation site in the Alleghenies about 100 miles from the Spruce Mountain area. These measurements were made at a height of 30 feet. The wind speed measured at 30' above ground was also extrapolated to the wind speed at the hub height of 83' by the 1/7 power law.

$$V_h = V * (H_{hub}/H_{anem})^{1/7}$$

where, V_h = wind speed at hub height

V = measured wind speed

H_{hub} = hub height

H_{anem} = anemometer height

Wind speed duration curves were produced using this data and are shown in Figure 12. The wind power model that is used is $P = \frac{1}{2}ceAdv^3$

where

P = power in watts

c = rotor coefficient of performance

e = efficiency

A = swept area of the blades in m^2

d = density of air in kg/m^3

v = wind speed in m/sec

U.S. Windpower, a manufacturer of wind turbines, sells 100kw rated machines with the following specifications:

Cut-in Wind Speed	5.4 m/s (12 mph)
Rated Wind Speed	12.7 m/s (29 mph)
Cut-out Wind Speed	19.7 m/s (44 mph)
Hub Height	83 feet
Swept Area	228.8 m^2

A constant rotor coefficient of performance * efficiency of .33 was assumed although it acually varies with the wind speed.

The density of air was assumed to be 1.3 kg/m^3.

The model was reduced to $P = 48.82 * V_{83}{}^3$ watts.

This model was used to develop the wind power duration curves for a five unit installation which are shown in Figure 13. The wind speed data was adjusted to usable wind speed by setting wind speed less than 5.4m/sec or greater than 19.7 m/sec to 0 and any wind speed greater than 12.7m/sec to 12.7. The rated power output is 500kw and the annual energy production is 1,139,354 kwh. Energy is found by summation of the average hourly wind power. Windpower is inadequate to supply all the load but can be used to supplement the other resources. [21,22,23,24]

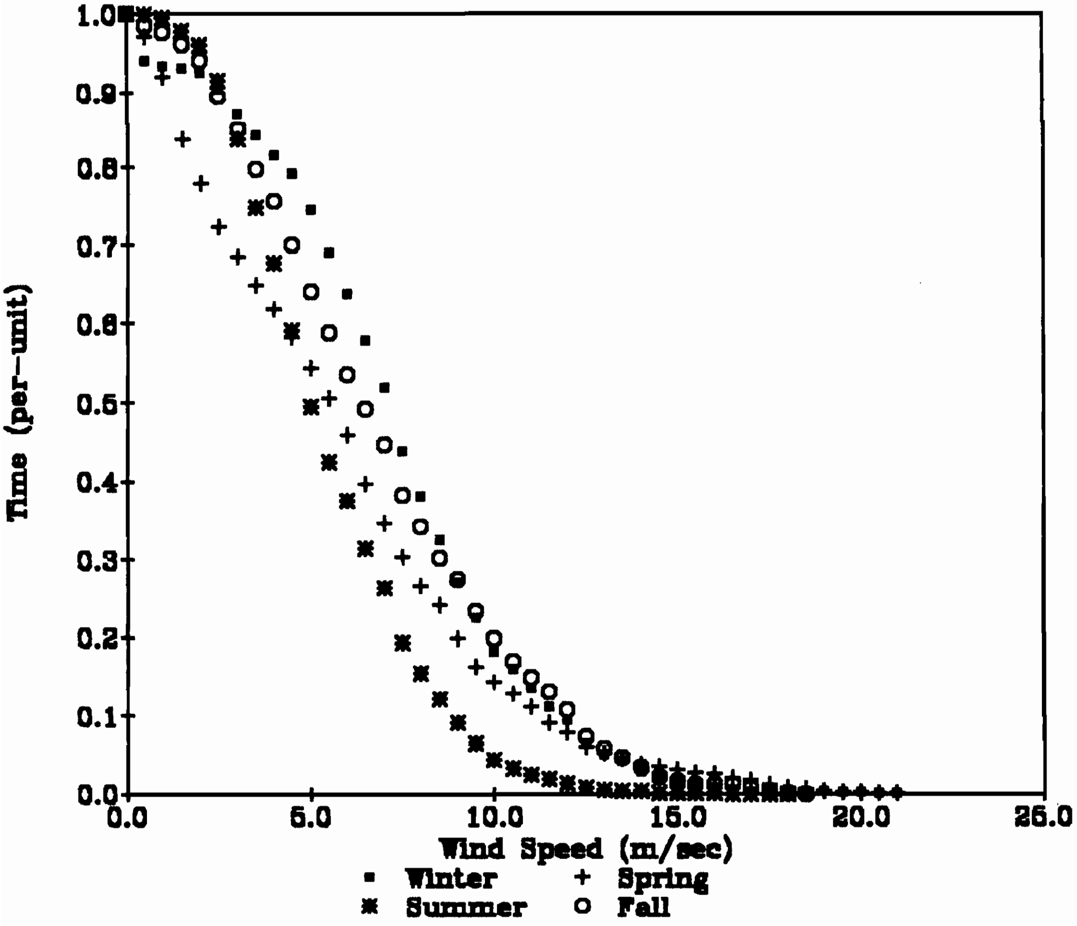

Figure 12
Wind Speed Duration Curves

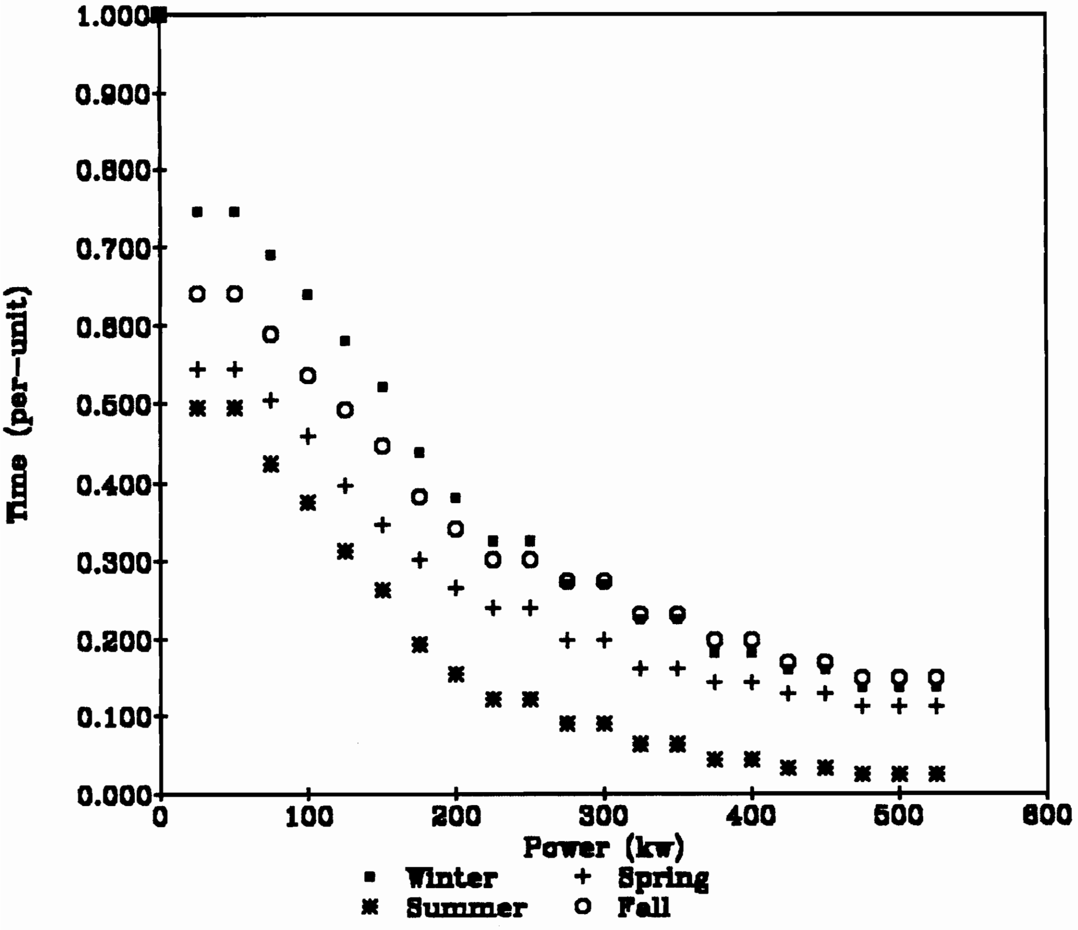

Figure 13
Wind Power Duration Curves

These three resources are capable of producing the power and energy to meet the system requirements. In order to fully evaluate their feasibility the impacts they have on the other aspects of the system life cycle and on society must be considered.

Diesel units require fuel to be shipped in and stored which has the potential for leaks and spills. They also cause air pollution. From an operational standpoint diesel units are very reliable and can be started up or shut down rapidly. They can follow the changes in load quickly. They are easy to operate and maintain. Retirement and disposal of diesel units and their associated facilities is relatively simple and straightforward. [16]

Hydroelectric facilities can have profound effects on the environment and society. These effects can be grouped together into three subsystems; physical, biological, and human. Examples of impacts to the physical subsystem include changes in the water quantity and quality, the land, the atmosphere, and the local climate. Dams and reservoirs will have impacts on both aquatic and terrestrial ecosystems. Plants and animals may be harmed or helped by the impoundment. The human impacts include the displacement of people, changes in transportation, recreation, hunting and fishing, and the flooding of archaeological sites. There is also the possibility of catastrophic dam failure which can cause disastrous flooding downstream. For the purposes of this project it is assumed that environmental impact studies to investigate the physical, biological, and human impacts of hydropower development on the streams in the Spruce Mountain region support the feasibility of hydropower as an energy source. Small hydroelectric units can be started or shut down rapidly and are capable of following the load quickly. They are easy to operate and maintain . Retirement and disposal of the dam should not present any problems since it is relatively small and can be done in low water conditions. [19,20,27]

Wind energy conversion systems also have impacts on the environment. Noise and visual intrusion are the greatest human impacts. The spinning blades of the wind turbines are a danger to birds. These units do not have an impact on operations because they are used as load modifiers and not as generating units. Maintenance poses no special problems and retirement and disposal is straightforward. [27]

These three resources can supply the power and energy and are capable of meeting the other specifications and needs. Alternatives can be developed that will employ these resources in various combinations.

The evaluation criteria for the alternatives will be the reliability as measured by the LOLP, life cycle cost measured by the annual revenue requirement and the cost per kwh, and the manability measured by the manhours required per year. Those alternatives which do not meet the requirements allocated to the generation subsystem will be discarded. The remaining alternatives will be evaluated using a weighted scoring system. [15] This scoring system is very simple and serves more as an example of the kind of alternative evaluation that can be done. Many other factors would have to be considered in addition to exercising sound judgement and common sense.

Three analytical models will be used to generate the data for the evaluation process. These models are an equivalent load duration curve, a production cost model, and an economic analysis model. Each alternative can be optimized through trade-off studies. Then the evaluation criteria can be applied to compare the alternatives and select a preferred approach. A sensitivity analysis can also be done to see how varying certain factors affect the result. Examples of sensitivity analysis that can be done are the annual revenue requirement versus interest rate or fuel cost.

The Equivalent Load Duration Curve Model

The load duration curve previously described is concerned only with the customers demand. An equivalent load duration curve is a modification of the LDC to incorporate the random nature of forced outages and maintenance. It treats units that are out of service as a demand on the system. The ELDC is derived by the recursive application of the following equation.

$$ELDC_n(x) = (1-FOR_n)*ELDC_{n-1}(x) + FOR*ELDC_{n-1}(x-C_n)$$

and if $x<0$, then $ELDC(x) = 1.0$

where

n = the unit under consideration

$ELDC_n$ = the equivalent load duration curve after unit n is added

FOR_n = the forced outage rate of unit n

$ELDC_{n-1}$ = the equivalent load duration curve before unit n is added

C_n = the capacity of unit n

Generating units generally have more than one possible operating state. That is a unit can be operated at less than full capacity. This is especially true of run-of-the-river hydro units whose available capacity depends on the stream flow. The above equation can be rewritten in a more general form to take into account these multiple states. The equation becomes:

$$ELDC_n(x) = \sum_{i=1}^{j} P_i * ELDC_{n-1}(x-C_i)$$

and if $x<0$, then $ELDC(x) = 1.0$

where

i = the state of the unit

P_i = the probability that the unit is in state i

C_i = the capacity out of service in state i

The Load Duration Curve is used for the ELDC in the first iteration. When the wind turbines are evaluated a wind integrated LDC is used. The hourly wind power generated is subtracted from the load and then an LDC is produced as before. This is done this way because the wind power is non-dispatchable, meaning it changes from minute-to-minute. These wind-integrated LDC's are shown in Figure 14. Integrating the wind with the load made a difference in the peak load by less than 100KW. This is due to the probability of hitting a peak demand coincident with peak wind speed. The LOLP is equal to the $ELDC_n(C)$ where C is the total installed capacity of the n units and $ELDC_n$ is the ELDC after the nth unit has been added. For this project a BASIC program was written to perform these calculations. A listing is included in the appendix. A step size of 50kw was chosen. Because the load and the hydropower varies a great deal from season to season the analysis was done for each season. [7,8,9,21]

The Production Cost Model

The equivalent load duration curve is also used to calculate the energy produced by each unit. The energy produced by each unit is given by:

$$E_n = P_n * T * \sum_{a_n}^{b_n} ELDC_{n-1}(x) * \delta x$$

where

E_n = the energy generated by unit n

T = the time period represented by the ELDC

P_n = the probability that unit n is available

a_n = the cumulative capacity of units 1 thru n-1

b_n = the cumulative capacity of units 1 thru n

δx = the step size

The cost per kilowatt-hour for each type of unit is assumed. These costs include fuel and operating costs. The energy produced by each unit times the cost per kwh gives the annual production cost of that unit. [7,8,9,21]

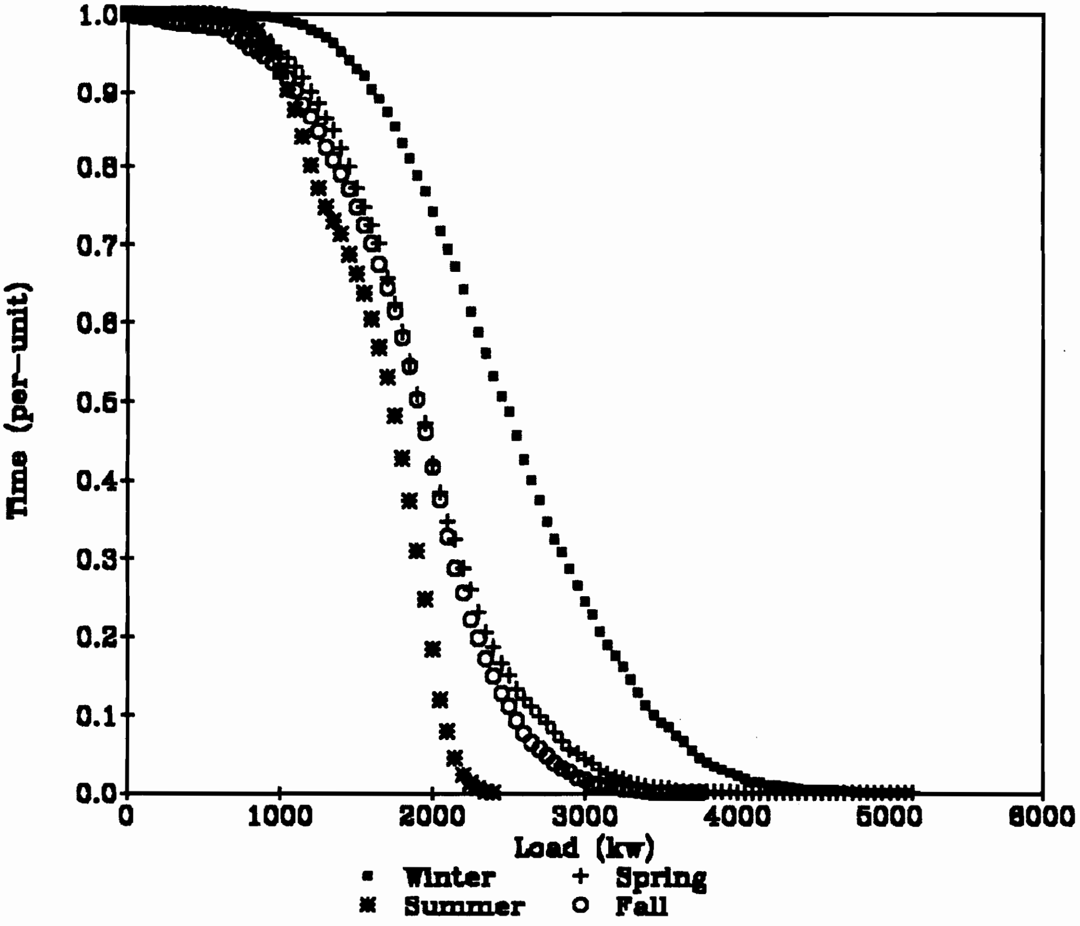

Figure 14
Wind Integrated Load Duration Curves

The Economic Analysis Model

A very simple economic analysis model was used to compute the annual revenue requirement. Five costs were assumed, the engineering and design costs (ED), the capital costs which cover the material and labor costs to build the facilities (C), the production costs (E), the maintenance costs (M), and the retirement and salvage and disposal costs (R). These costs are annualized using the following equation.

$$ARR = (A/P_{i,t})*(ED + C) + E + M + (A/F_{i,t})*R$$

where

ARR = the annual revenue requirement

$A/P_{i,t}$ = capital recovery factor

$A/F_{i,t}$ = sinking fund factor

i = interest rate

t = time period

It was assumed that 30 year 6% bonds would be used to finance the construction. It was also assumed that no other grants or funds would be available to reduce the initial investment cost. The cost per kilowatt-hour was found by dividing the annual revenue requirement by the total energy production. [14]

The three resources, diesel, hydro, and wind are, in various combinations, feasible methods of producing the power and energy required. Three alternative plans utilizing these resources were developed and evaluated.

Alternative #1

Install diesel engine driven units and their associated fuel handling and storage facilities. Areas for trade-offs in this alternative are the number and size of the units versus the cost and LOLP. For example two 600kw units will give a smaller LOLP than one 1200kw unit but it will have a higher cost per kw.

Assume the optimum arrangement is to install 6 1200kw units.
Assume each unit has a .95 availability.
Engineering and design costs are $54,000.
Capital costs are $180,000 per unit.
Production costs are $.08 per kwh.
Maintenance costs are $8000 per year.
Retirement and disposal costs are $5000 with a $1000 salvage value per unit.
Lifetime is 15 years

Power = 7200 kw

Worst Season LOLP = .00032 (winter)

Annual Energy Demand = 18,670,544 kwh

Annual Energy Production = 18,670,148 kwh

Annual Unserved Energy = 396 kwh

Annual Revenue Requirement = $1,619,403

Cost per kwh = 8.67 cents

Manhours Required = basic-300, intermediate-300, high-0

Alternative #2

Build dams and install hydroelectric units with diesel engine driven units as backup. Areas for trade-offs for the hydropower include the location and number of the stations and their operation, the number of units, the type and capacity of the turbines, and the height and construction of the dam. Pondage operation requires a larger dam but provides a means for energy storage and flood control. It also increases the environmental impacts. Run of the river stations rely solely on the available instream flows which can vary widely on a day to day basis. The stations can be built on any of the rivers or combination thereof. Multiple stations can be installed on each river in series with each other. The places on the rivers that the stations are built will determine the size of the dam and the penstocks and powerhouse structures. These will in turn determine the cost. The number of units at each station is related to the size of the turbines and the stream flows. Turbines can use between 30 and 100% of their rated capacity. If small capacity turbines are used then the smaller stream flows can be utilized but more units will be required for the power. Again having more units decreases the LOLP but increases the cost and there is a physical limit to how many units can be installed at any one station. There are three basic types of turbines - Pelton, Francis, and Kaplan. Each type has operating ranges for heads and flows that it will work for and advantages and disadvantages compared to the others. [25] Net head is related to the size of the dam or the steepness of the terrain and the length of the penstocks. The cost will increase as the head increases. The dam can be constructed of either concrete or earth. Earth construction is cheaper but requires a higher dam and spillway structures to prevent overtopping. These choices will have to be balanced against the power and energy demands, the cost, the LOLP, the environmental impacts, and the system operation.

Assume that the optimum arrangement is to install 7 run of the river hydro units at three stations as follows:

Dry Fork - 3 S-turbine units each operating at 50’ net head and 500 cfs capacity at 83% efficiency yielding 1760kw with .98 availability.

Shavers Fork - 2 S-turbine units each operating at 50’ net head and 300 cfs capacity at 83% efficiency yielding 1055kw with .98 availability.

Greenbrier River - 2 S-turbine units each operating at 50’ net head and 200 cfs capacity at 83% efficiency yielding 705kw with .98 availability.

It was decided to use low head (<50’) units to keep the costs down and to simplify construction. Stations are planned on all three rivers for diversity and the fact that three of the load centers are also on these rivers. The turbines were sized so that a single unit would match the summer/fall flow and additional units of the same size were added to match the winter/spring flows. S-turbines which are a type of Kaplan turbine were chosen because they operate over a range from 30-100% which produces a higher annual energy yield. In a horizontal configuration they make for a compact installation and can be delivered to the site in subassemblies. These type units are also limited to about 50’ of net head. The dam will be of concrete construction in order to use an uncontrolled crest as a spillway.

Engineering and design costs are $100,000.

Capital costs are $1,200/kw or $10,560,000.

Production costs are $.001/kwh.

Maintenance costs are $46,000/year.

Retirement and disposal costs are $ 32,000 with $2,000 salvage value per station.

Lifetime is 30 years

Also assume that the optimum arrangement for the diesel backup is to install 3 1200kw diesel units. There are times during the winter when stream flows are insufficient to generate any power. These units are sized to handle the largest non-interruptible load that can be expected. This load is considered to be residences, farms, and essential government and social services. This load is estimated at 3200kw.

Assume that each unit has a .99 availability.

Engineering and design costs are $27,000.

Capital costs are $180,000 per unit.

Production costs are $.08 per kwh.

Maintenance costs are $2000 per year.

Retirement and disposal costs are $5,000 with a $1,000 salvage value per unit.

Lifetime is 30 years

Power = 12,400 kw

Worst Season LOLP = .00083 (fall)

Annual Energy Demand = 18, 670,544 kwh.

Annual Energy Production = 18,669,700 kwh.

Hydro - 16,546,411 kwh

Diesel - 2,123,289 kwh

Annual Unserved Energy = 844 kwh

Annual Revenue Requirement = $1,041,329

Cost per kwh = 5.58 cents

Manhours Required = basic-600, intermediate-3600, high-840

Alternative #3

Install wind turbines in addition to the units in alternative #2. Trade-off areas for the wind turbines include the number, size, cut-in and rated wind speeds. As a rule-of-thumb the total capacity should be no more than 10% of the peak load. Wind turbines are available in many sizes. Reliability increases with the number of units as does the cost. The larger the units the higher the cut-in and rated wind speed. The higher cut-in speeds reduce the power output at low wind but higher rated speeds allow the units to generate more power at higher wind speeds.

Assume the optimum arrangement is to install 5 100kw wind turbines in addition to the units proposed in alternative

#2. It was decided that since the peak load is 5250kw, 500kw of wind generation could be utilized. Five 100kw units were used to reduce the overall size and cost of the installation as well as produce a high energy yield.

Assume that each turbine has a .98 availability.
Engineering and design costs are $20,000.
Capital Costs are $80,000 per turbine or $400,000.
Production costs are negligible
Maintenance costs are $1600/turbine/year or $8,000/year.
Retirement and disposal costs are $5,000 per unit with a $1,000 salvage value.
Lifetime is 30 years

Power = 12,900 kw (8800 hydro, 3600, diesel, 500 wind)
Worst Season LOLP = .00037 (Fall)
Annual Energy Demand = 18,670,544 kwh
Annual Energy Production = 18,670,138 kwh
    Wind - 1,139,354 kwh
    Hydro - 15,839,735 kwh
    Diesel - 1,691,049 kwh
Annual Unserved Energy = 406 kwh
Annual Revenue Requirement = $1,058,147
Cost per kwh = 5.67 cents
Manhours Required = basic-840, intermediate-4200, high-960

The results of each alternative for cost, reliability, and manability are compared in Tables 7, 8, and 9. Alternative #1 has the lowest initial cost but due to the price of fuel oil has the highest annual revenue requirement. The cost of fuel accounts for over 92% of the cost per kilowatthour. Alternatives #2 and #3 have high capital costs but low operating costs. It is interesting to note that Alternative #3 has a higher annual revenue requirement than Alternative #2. This is due to the fact that the higher capital cost of the wind turbines were not offset by lower operating costs. The wind turbines displaced mostly low cost hydropower and not as much of the more costly diesel power. The LOLP of Alternative #1 is highest during the winter when the load is at its peak. The LOLP's of Alternatives #2 and #3 are highest in the fall when loads are moderate but hydropower is greatly reduced due to low seasonal flows. This is in contrast to the winter season when loads are high but so are streamflows.

Table 7
Generation Subsystem Cost Comparison

COST ($)	ALTERNATIVE #		
	1	2	3
ENGINEERING AND DESIGN	54,000	127,000	163,000
CONSTRUCTION	1,080,000	11,100,000	11,500,000
PRODUCTION	1,493,612	186,410	151,124
MAINTENANCE	8,000	38,000	46,000
RETIREMENT & DISPOSAL	24,000	102,000	122,000
ANNUAL REVENUE REQUIREMENT	1,619,403	1,041,329	1,058,147
COST PER KWH (cents)	8.67	5.58	5.67

TABLE 8
LOSS-OF-LOAD PROBABILITIES

ALTERNATIVE #	WINTER	SPRING	SUMMER	FALL
1	.00032	.00003	.00000	.00002
2	.00049	.00017	.00053	.00083
3	.00026	.00001	.00003	.00037

TABLE 9
MANHOUR REQUIREMENTS

ALTERNATIVE #	BASIC	INTERM.	HIGH
1	500	300	180
2	600	3600	840
3	840	4200	960

The next step is to apply the evaluation criteria Alternative #1 can be eliminated because of its high cost. It does not even come close to meeting the cost requirement allocated to it and due to the fact that the cost is a function of the fuel cost it is insensitive to change in parameters such as interest rate or time period. Alternatives #2 and #3 both meet the allocated revenue requirements although only Alternative #2 satisfies the per kwh cost requirement. Alternative #3 is close enough to consider it as acceptable, reallocate the requirement, or recalculate the annual revenue requirement with a different bond rate. Alternative #2 does not meet the LOLP allocated to it during the summer and fall seasons, however it is close enough to either go back and reevaluate the requirement that the LOLP must be less than .0005 or to regard it as acceptable. Alternatives #2 and #3 can be evaluated using a weighted scoring system. The characteristics of interest are the cost in terms of the annual revenue requirement and the cost per kwh, the reliability, and the manhours required. The weights and the scoring system are subjective with the most emphasis on cost. Sixty percent of the weight is placed on the cost of electricity because if the cost is to high the people will not be able to use it and enjoy the benefits. Reliability, quality, and manability will not be very important if only a few customers can enjoy electricity

Attribute		Weight
Annual Revenue Requirement		.30
Cost per Kilowatthour		.30
Reliability		.20
Manhours Required -	Basic	.06
	Intermediate	.06
	High	.08

The scores assigned to each alternative for the cost components will be determined using the following two equations.

Annual Revenue Requirement

$Score = -.0000889*ARR + 180$

Cost Per Kilowatthour

$Score = -17.778*(¢/kwh) + 180$

The score assigned to each alternative for the reliability and the manhours required will be done using Tables 10 and 11. The weighted scores for the alternatives are shown in Table 12. The weighted scores for the alternatives are close enough to be considered equal. Based on the fact that Alternative #2 has the lowest initial cost and requires fewer manhours It will be the preferred alternative. Other factors such as social and environmental impacts, and operation and maintenance requirements also support this as the preferred alternative.

A sensitivity analysis comparing the bond rate's influence on the annual revenue requirement is shown in Figures 15. Alternative #2 requires less revenue than Alternative #3 at all interest rates. At interest rates greater than 6% both alternatives fail to meet the revenue requirement allocated to the generation subsystem. This may require that the original system cost requirements or the portion allocated to the generation subsystem be reevaluated and revised if necessary. It may also be desirable to develop new alternatives and repeat this trade-off and optimization process.

TABLE 10
RELIABILITY SCORING

LOLP	SCORE
$\leq .0005$	100
$\leq .0010$	90
$\leq .0015$	80
$\leq .0020$	70
$\leq .0025$	60

TABLE 11
MANABILITY SCORING

RANGE			SCORE
BASIC	INTERM.	HIGH	
<400	<3000	<800	100
400-800	3000-4000	800-1000	90
800-1200	4000-5000	1000-1200	80
1200-1600	5000-6000	1200-1400	60
>1600	>6000	>1400	40

Table 12
Generation Subsystem Alternative Analysis

ATTRIBUTE	WEIGHT	ALTERNATIVE #2			ALTERNATIVE #3		
		VALUE	SCORE	WEIGHTED SCORE	VALUE	SCORE	WEIGHTED SCORE
ANNUAL REVENUE REQUIREMENT	.30	1,041,329	87.45	26.24	1,058,147	85.95	25.79
$/KWH	.30	5.58	80.80	24.24	5.67	79.20	23.76
LOLP	.20	.00083	90.00	18.00	.00037	100.00	20.00
MH-B	.06	600	90.00	5.40	840	80.00	4.80
MH-I	.06	3600	90.00	5.40	4200	80.00	4.80
MH-H	.08	840	90.00	7.20	960	90.00	7.20
TOTAL	1.00			86.48			86.35

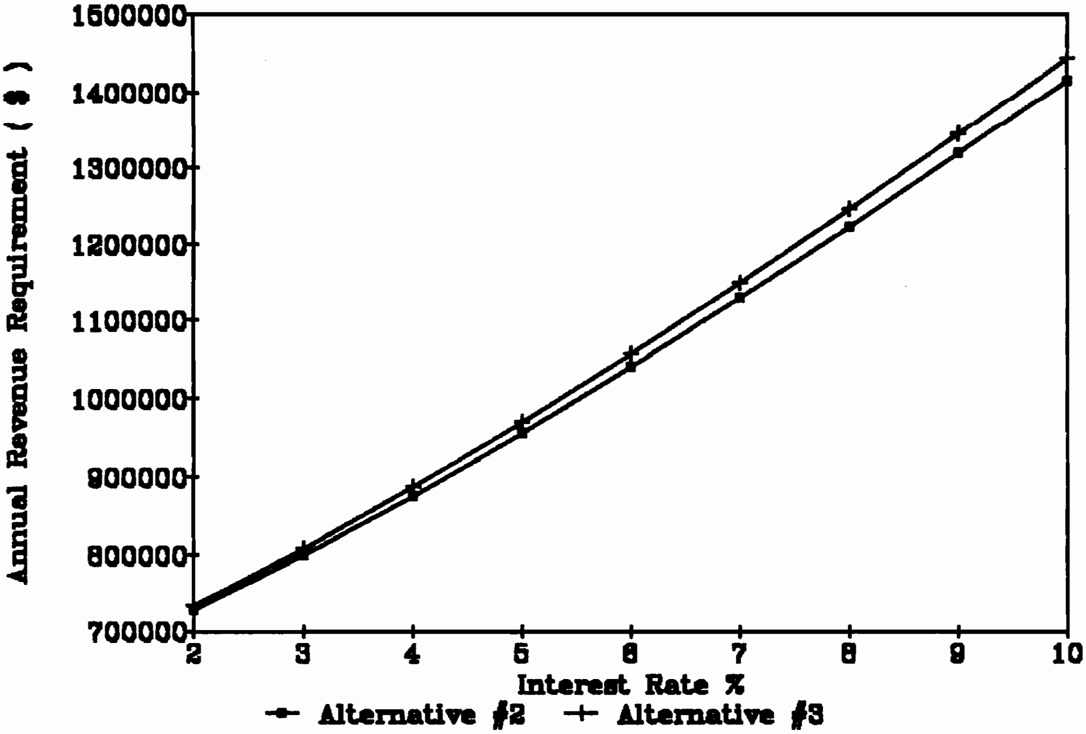

Figure 15
Sensitivity Of The Generation Subsystem Cost
To The Interest Rate

Transmission Subsystem

In developing alternatives for the transmission system the following guidelines were used:

1) each load center will be served from a substation
2) each substation will have at least two sources
3) each generating station will have at least two outlets.

Based on those guidelines there are numerous ways to layout the transmission system. Some of the factors that need to be considered are the terrain, the climate, and the environmental and human impacts. Two arrangements as shown in Figure 16a and b can be considered viable alternatives. The difference between them is the addition of a transmission line between Bemis and Whitmer.

The evaluation criteria for the alternatives will be the reliability as measured by the overall reliability from the swing bus at Bemis to any other station, the quality of power as measured by the voltage drop, the life cycle cost measured by the annual revenue requirement and the cost per kwh, and the manability measured by the manhours required per year. If an alternative does not meet the requirements allocated to the transmission subsystem it will be discarded. Weighted scores will be assigned to each alternative to form a basis of comparison. As in the evaulation of the generation alternatives this method serves more as an example and would have to to supplemented by other considerations.

A power flow program was used to evaluate the alternatives. This power flow program was written by J.Y. Ayoub for use with *Power System Analysis and Design*. [13] For the evaluation of alternatives it was done on the basis of peak load and adequate hydroelectric generation. The generation was divided up among the units according to the units share of the total capacity. The reactive power limits on the generators were assumed such that Q_{max} is 60% of P_{max} and Q_{min} is half of Q_{max}. This results in a simplified generator operating characteristic as shown in Figure 17. The load was divided up among the load centers to reflect the assumed residential, commercial, and industrial load at each. A power factor of .97 was assumed for each bus. Line data was calculated based on cable impedance data developed by the Aluminum Company of America. [26] Phase spacing depends on the voltage of the line. A spacing of 10 feet was assumed for 34.5kv. A nominal-π model was used for the transmission lines. The transformer impedances used were 1 and 6% for resistance and reactance respectively on the transformer base. The line, transformer, and bus input data are shown in Tables 13, 14, and 15. The data was entered on a 1 MVA base. The bus at Bemis was arbitrarily chosen as the swing bus. The program computes the voltage and phase angle at each bus and the real and reactive power generated at each bus. The power loss is found by subtracting the load from the generation and this is used to estimate the annual energy losses. The annual losses are the product of the power loss times 8760 times the transmission utilization factor. The transmission utilization factor is the integral of the load^2 over the year divided by the peak load^2. It was calculated to be .18 for this system. A cost of $.0558 per kwh was used for these losses.

Each alternative can be optimized through trade-off studies. Then the evaluation criteria can be applied to compare the alternatives. A sensitivity analysis can also be done to see how varying certain factors affect the result. An example of a sensitivity analysis that can be done is annual revenue requirement versus interest rate. Finally an alternative can be selected.

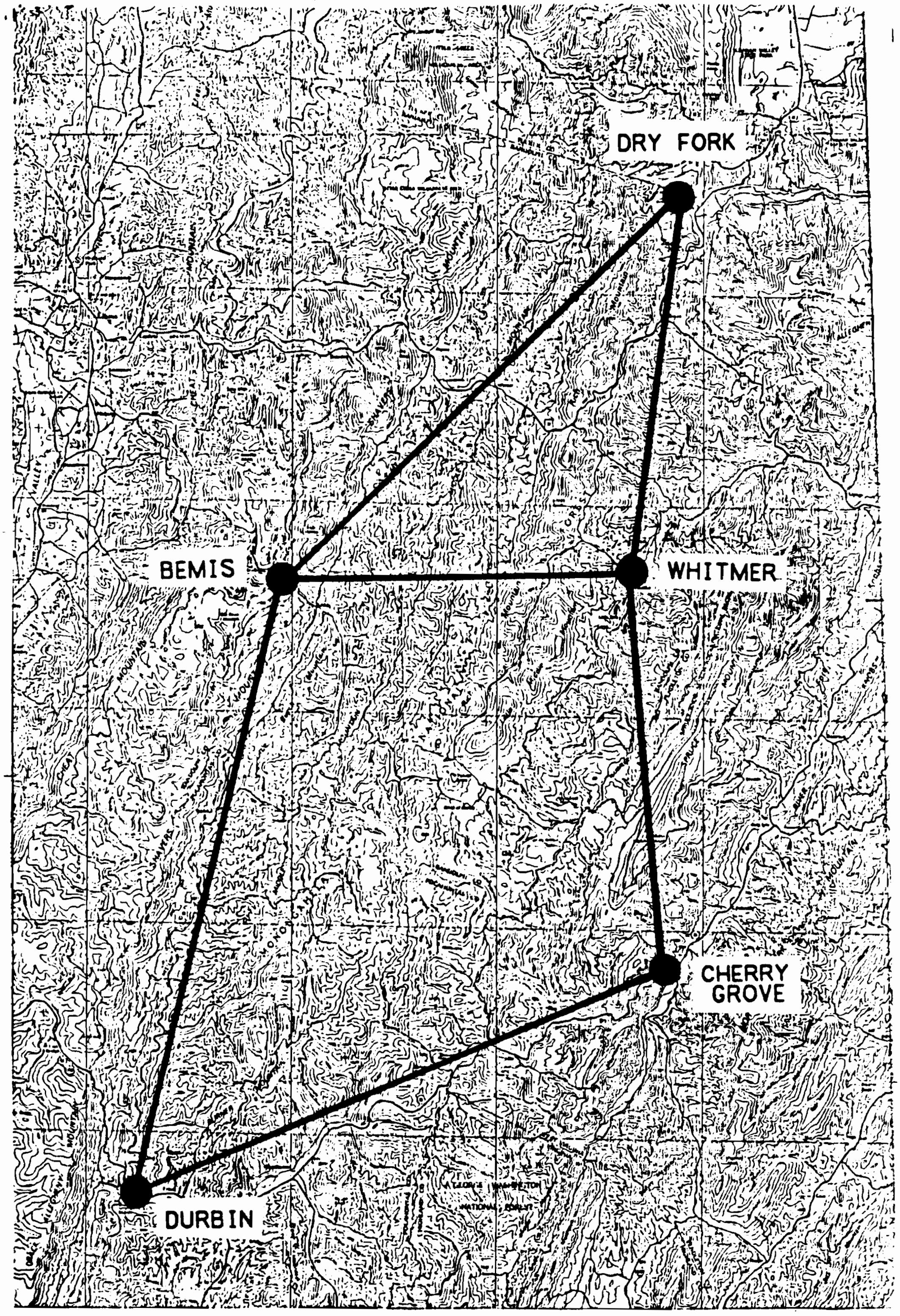

Figure 16a
Alternative #1

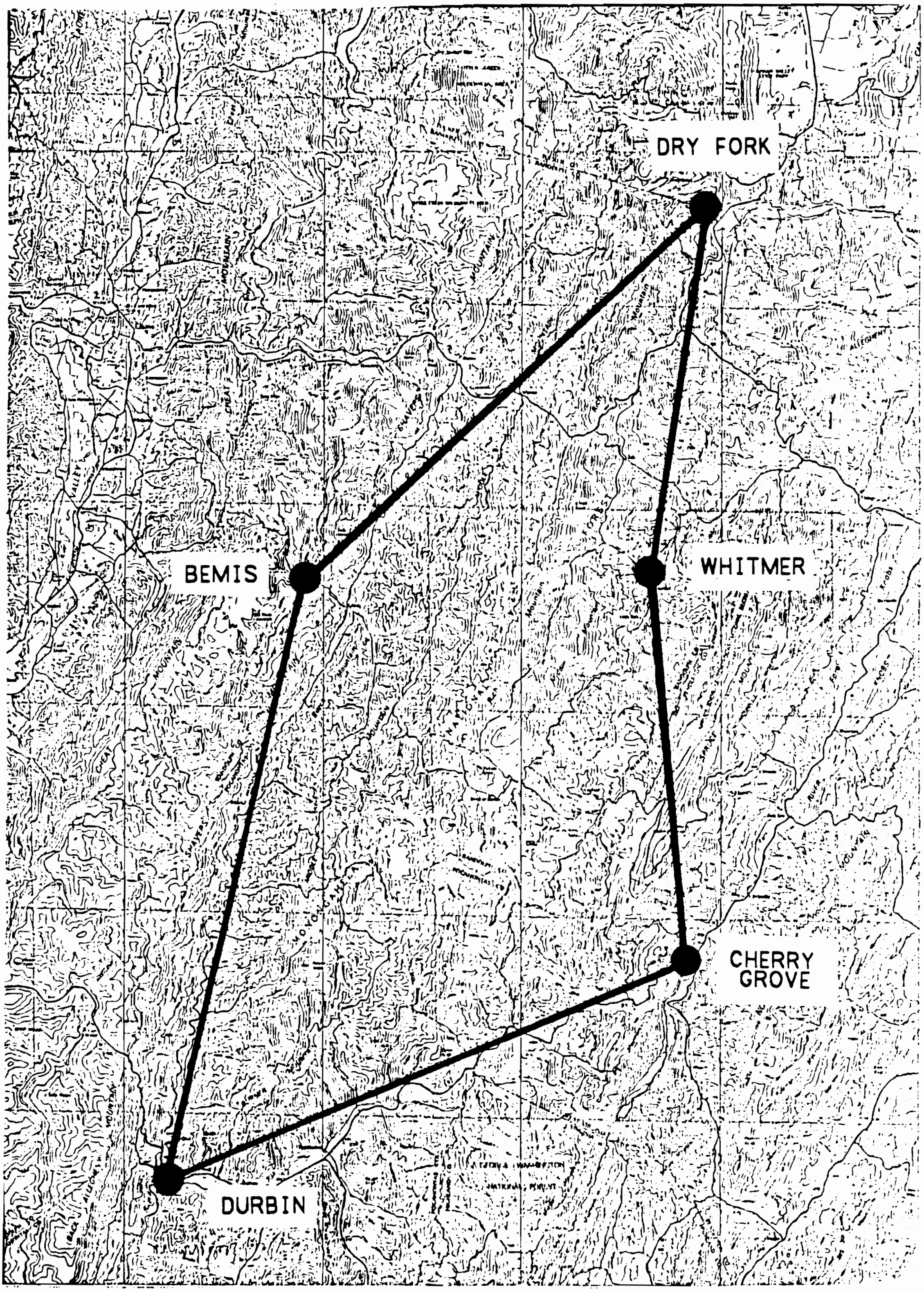

Figure 16b
Alternative #2

Table 13

LINE INPUT DATA

LINE#	BUS-TO-BUS		R	X	G	B	MAXMVA
			per unit	per unit	per unit	per unit	per unit
1	2	3	0.009	0.011	0.000	0.153	20.000
2	3	5	0.008	0.010	0.000	0.134	20.000
3	5	6	0.004	0.006	0.000	0.077	20.000
4	6	7	0.007	0.009	0.000	0.121	20.000
5	2	7	0.008	0.010	0.000	0.134	20.000
6	2	5	0.004	0.005	0.000	0.070	20.000

Table 14

TRANSFORMER INPUT DATA

TRAN.#	BUS-TO-BUS		R	X	G	B	MAXMVA	MAXTAP
			per unit	per unit	per unit	per unit	per unit	per unit
1	1	2	0.003	0.016	0.000	0.000	3.750	1.000
2	3	4	0.002	0.012	0.000	0.000	5.000	1.000
3	7	8	0.007	0.040	0.000	0.000	1.500	1.000

Table 15

BUS INPUT DATA

BUS#	TYPE	V	DELTA	PG	QG	PL	QL	QGMAX	QGMIN
		per unit	degrees	per unit	per unit	per unit	per unit	per unit	per unit
1	0	1.000	0.000	---	---	0.000	0.000	---	---
2	1	---	---	0.000	0.000	2.266	0.566	---	---
3	1	---	---	0.000	0.000	0.412	0.103	---	---
4	2	1.000	---	3.200	---	0.000	0.000	1.920	-0.960
5	1	---	---	0.000	0.000	0.824	0.206	---	---
6	1	---	---	0.000	0.000	0.206	0.051	---	---
7	1	---	---	0.000	0.000	1.442	0.360	---	---
8	2	1.000	---	0.900	---	0.000	0.000	0.540	-0.270

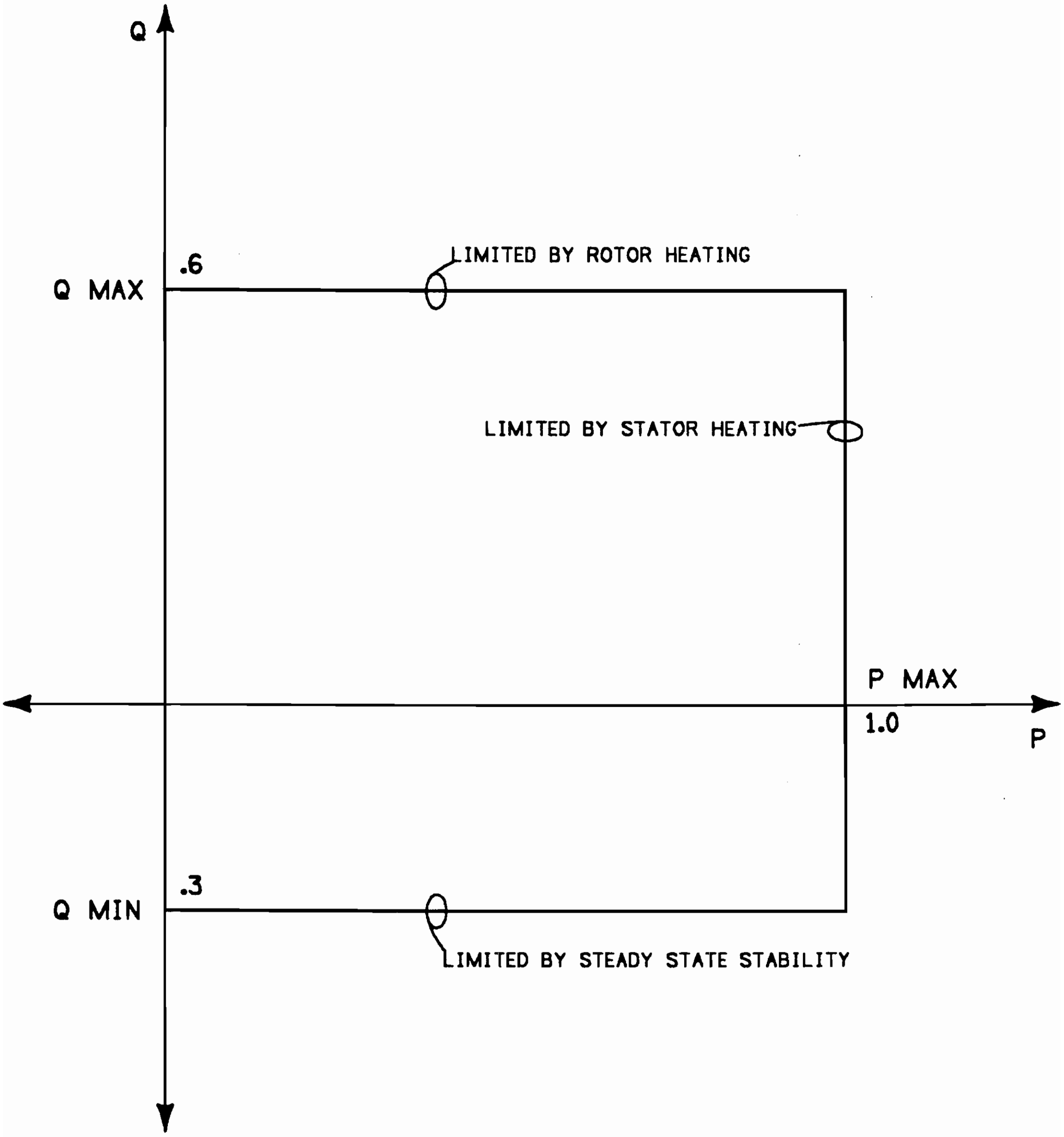

Figure 17
Typical Generating Unit Characteristics

Alternative #1

Utilize a transmission system as shown in Figure 16a . Areas for trade-offs include the operating voltage, the conductor size and type, and construction. Increasing the operating voltage will decrease the power losses but higher voltage lines cost more and require more right-of-way. Increasing conductor sizes will decrease the impedance which will reduce losses and voltage drop. The larger conductors also cost more. The types of conductors are copper, aluminum, and aluminum/steel or ACSR. Copper is very expensive but smaller sizes can be used for the same impedance and capacity as aluminum or ACSR. ACSR has excellent mechanical characteristics and is least expensive. Either wood pole or steel tower construction can be utilized.

Assume the optimum arrangement is to operate the system at 34.5kv using 4/0 ACSR and wood pole structures.
Total line miles = 108
Reliability transmission line: .020 failures/year/mile
terminal stations: 0.035 failures/year/station
Engineering and design costs = $60,000
Capital Costs = $4,320,000-line and $1,500,000-station
Operating Costs = $.0558/kwh
Maintenance Costs = $58,000-line and $6,000-station

Retirement Costs = $216,000/mile and $100,000-station

Life is 30 years

Analysis Results

Power flow program results are shown in Figures 18 and 19. The voltage profile is within specifications and no lines or transformers are overloaded.

Reliability = .776

Losses = 105,646 kwh

Annual Revenue Requirement = $500,962

Cost per kwh = 2.68 cents

Manhours required = basic-1200, intermediate-3600, high-480

Alternative #2

Utilize a transmission system as shown in Figure 16b. Areas for trade-offs are the same as for Alternative #1

Assume that the optimum arrangement is to operate the system at 34.5kv with 4/0 ACSR with wood pole structures.

Total line miles = 99

Reliability transmission line: .020 failures/year/mile

terminal stations: 0.035 failures/year/station

Engineering and design costs = $54,000

Capital Costs = $3,960,000-line and $1,400,000-station

Operating Costs = $.0558/kwh

Maintenance Costs = $51,300-line and $5,700-station

Retirement Costs = $198,000-line and $100,000-station

Life is 30 years

Analysis Results

Power flow program results are shown in Figures 20 and 21. The voltage profile is within specifications and no lines or transformers are overloaded.

Reliability = .570

Losses = 105,646 kwh

Annual Revenue Requirement = $459,880

Cost per kwh = 2.46 cents

Manhours required = basic-1080, intermediate-3240, high-400

```
   POWER FLOW BUS OUTPUT DATA FOR Alternative #1

     --------------------------------------
                                         GENERATION              LOAD
                                        -------------------------------------
     VOLTAGE     PHASE
    .MAGNITUDE   ANGLE        PG           QG           PL           QL .95>V>1.05
     ------------------------------------------------------------------------

      per                     per          per          per          per
BUS#  unit       degrees      unit         unit         unit         unit
---------------------------------------------------------------------------------

 1   1.000        0.000      1.117        0.707        0.000        0.000
 2   0.986       -0.927      0.000        0.000        2.266        0.566
 3   0.996        0.026      0.000        0.000        0.412        0.103
 4   1.000        2.253      3.200       -0.151        0.000        0.000
 5   0.986       -0.845      0.000        0.000        0.824        0.206
 6   0.984       -1.002      0.000        0.000        0.206        0.051
 7   0.983       -1.123      0.000        0.000        1.442        0.360
 8   1.000        0.863      0.900        0.288        0.000        0.000
                             -------------------------------------
                  TOTAL      5.217        0.845        5.150        1.286

MISMATCH =   9.67E-05
```

```
    POWER FLOW LINE OUTPUT DATA FOR Alternative #1

      --------------------------

 LINE #        BUS TO BUS        P           Q            S     RATING EXCEEDED
---------------------------------------------------------------------------------

   1            2     3        -1.320       0.085       1.322
                3     2         1.336      -0.214       1.353

   2            3     5         1.431      -0.163       1.441
                5     3        -1.415       0.051       1.416

   3            5     6         0.417      -0.102       0.429
                6     5        -0.416       0.028       0.417

   4            6     7         0.210      -0.079       0.225
                7     6        -0.210      -0.038       0.213

   5            2     7         0.339      -0.059       0.344
                7     2        -0.338      -0.070       0.345

   6            2     5        -0.174       0.088       0.194
                5     2         0.174      -0.156       0.233
```

```
      POWER FLOW TRANSFORMER OUTPUT DATA FOR Alternative #1

        ----------------------------------------

  TRAN.#          BUS TO BUS        P           Q            S          TAP    RATING
                                                                      SETTING EXCEEDED

  -------------------------------------------------------------------------------

   1               1     2        1.117       0.707        1.322      1.000
                   2     1       -1.112      -0.679        1.303

   2               3     4       -3.179       0.274        3.191      1.000
                   4     3        3.200      -0.151        3.204

   3               7     8       -0.894      -0.253        0.929      1.000
                   8     7        0.900       0.288        0.945
```

Figure 18

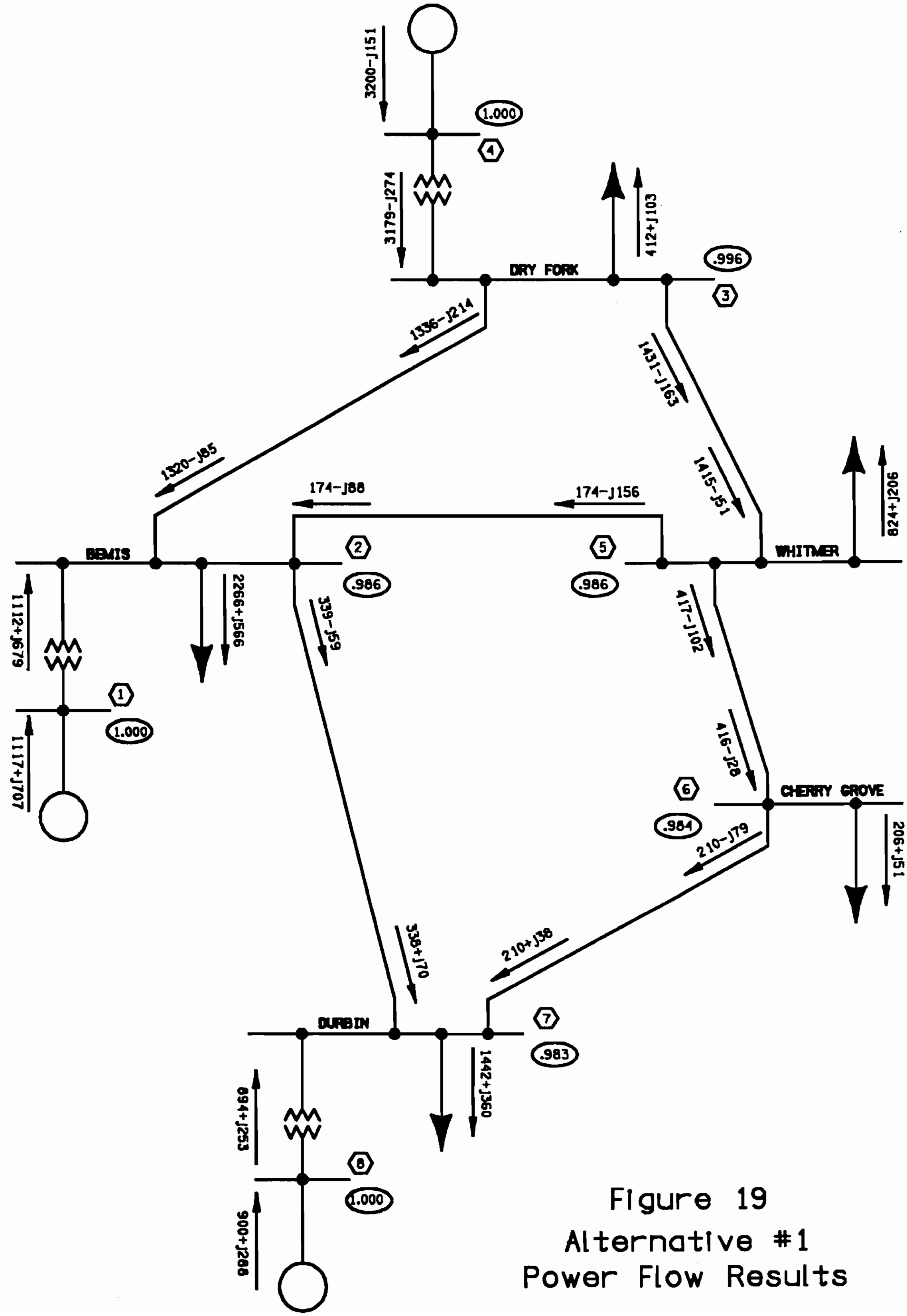

Figure 19
Alternative #1
Power Flow Results

```
        POWER FLOW BUS OUTPUT DATA FOR Alternative #2

         ---------------------------------------
                                          GENERATION                 LOAD
                                       ---------------------------------------
          VOLTAGE     PHASE
         .MAGNITUDE  ANGLE          PG            QG            PL            QL .95>V>1.05
         ---------------------------------------------------------------------------

           per                      per           per           per           per
    BUS#   unit        degrees      unit          unit          unit          unit
    ---------------------------------------------------------------------------------

     1    1.000        0.000        1.117         0.739         0.000         0.000
     2    0.985       -0.924        0.000         0.000         2.266         0.566
     3    0.996        0.125        0.000         0.000         0.412         0.103
     4    1.000        2.349        3.200        -0.123         0.000         0.000
     5    0.985       -0.652        0.000         0.000         0.824         0.206
     6    0.984       -0.854        0.000         0.000         0.206         0.051
     7    0.983       -1.046        0.000         0.000         1.442         0.360
     8    1.000        0.937        0.900         0.299         0.000         0.000
                                   ---------------------------------------
                       TOTAL        5.217         0.915         5.150         1.286

    MISMATCH =   8.71E-05
```

```
          POWER FLOW LINE OUTPUT DATA FOR Alternative #2

            ---------------------------

    LINE #            BUS TO BUS          P              Q              S     RATING EXCEEDED
    ---------------------------------------------------------------------------------

     1                 2     3          -1.412          0.147         1.420
                       3     2           1.431         -0.273         1.457

     2                 3     5           1.336         -0.075         1.338
                       5     3          -1.322         -0.038         1.322

     3                 5     6           0.498         -0.168         0.525
                       6     5          -0.497          0.095         0.506

     4                 6     7           0.291         -0.146         0.325
                       7     6          -0.290          0.029         0.291

     5                 2     7           0.259         -0.003         0.259
                       7     2          -0.258         -0.126         0.287
```

```
          POWER FLOW TRANSFORMER OUTPUT DATA FOR Alternative #2

            ---------------------------------------

    TRAN.#            BUS TO BUS          P              Q              S          TAP     RATING
                                                                                SETTING EXCEEDED

    ---------------------------------------------------------------------------------

     1                 1     2           1.117          0.739         1.339     1.000
                       2     1          -1.112         -0.710         1.320

     2                 3     4          -3.179          0.246         3.189     1.000
                       4     3           3.200         -0.123         3.202

     3                 7     8          -0.894         -0.263         0.932     1.000
                       8     7           0.900          0.299         0.948
```

Figure 20

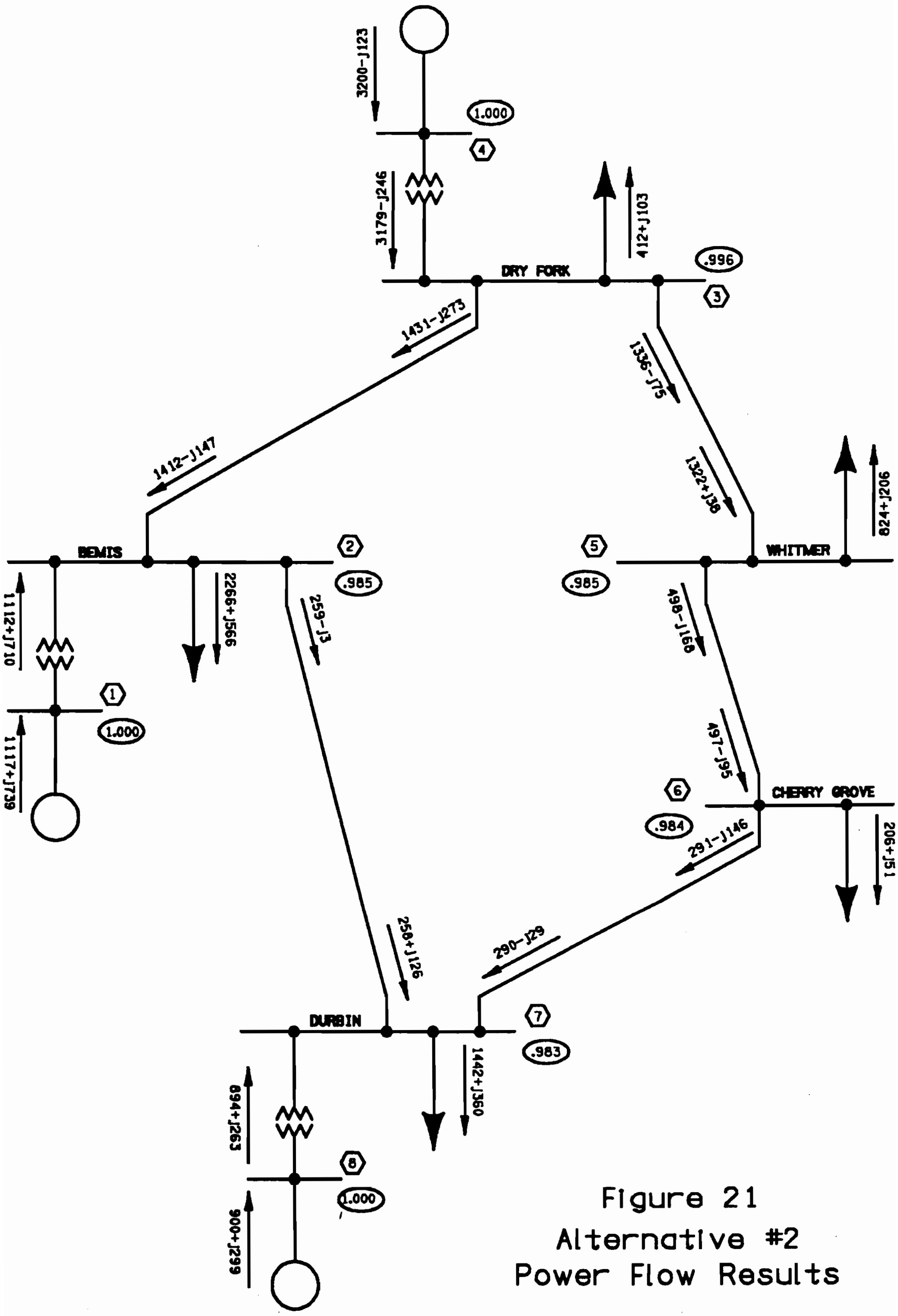

Figure 21
Alternative #2
Power Flow Results

The costs, reliability, and manability for each alternative are shown in Tables 16, 17, and 18. Both alternatives meet the reliability and the voltage quality requirements. Alternative #1 does not meet the cost requirements allocated to the transmission subsystem although it is close enough to consider it as acceptable, or reallocate the requirement, or recalculate the annual revenue requirement with a different bond rate. A weighted scoring system will again be used to evaluate between these two alternatives. The same weights and scoring system that were used for the generation alternatives will be used for the transmission system alternatives.

Attribute		Weight
Annual Revenue Requirement		.30
Cost per Kilowatthour		.30
Reliability		.20
Manhours Required -	Basic	.06
	Intermediate	.06
	High	.08

The score assigned to each alternative for the cost attributes will be determined by the following equations.

Annual Revenue Requirement

Score = -.0002 * ARR + 180

Cost Per Kilowatthour

Score = -40.0 * (¢/kwh) + 180

The score assigned to each alternative for the reliability and manhours required will be based on Tables 19 and 20. The weighted scores for each alternative are shown in Table 21. Alternative #2 has a higher weighted score and when other factors are considered is the preferred approach.

A sensitivity analysis showing the influence of interest rate on the annual revenue requirement is shown in Figure 22. Alternative #2 will meet the annual revenue requirement for interest rates under 7%.

Again it needs to be stressed that the requirements originally defined for the system and allocated to each subsystem are subject to reevaluation and revision during this process. It may also necessitate developing new alternatives and repeating the trade-off and optimization process.

This process can be repeated for the other subsystems until the optimum approach has been defined for each.

Table 16
Transmission Subsystem Cost Comparison

COST ($)	ALTERNATIVE #	
	1	2
ENGINEERING AND DESIGN	60,000	54,000
CONSTRUCTION	5,820,000	5,360,000
PRODUCTION	5,789	5,789
MAINTENANCE	64,000	57,000
RETIREMENT & DISPOSAL	316,000	298,000
ANNUAL REVENUE REQUIREMENT	501,068	459,986
COST PER KWH (cents)	2.68	2.46

Table 17
TRANSMISSION RELIABILITY

ALTERNATIVE #	RELIABILITY
1	.776
2	.570

Table 18
MANHOUR REQUIREMENTS

ALTERNATIVE #	BASIC	INTERM.	HIGH
1	1200	3600	480
2	1080	3240	400

TABLE 20
MANABILITY SCORING

RANGE			SCORE
BASIC	INTERM.	HIGH	
<1000	<2400	<300	100
1000-1200	2400-3000	300-450	90
1200-1400	3000-3600	450-600	80
1400-1600	3600-4200	600-750	60
>1600	>4200	>750	40

TABLE 19
RELIABILITY SCORING

RELIABILITY	SCORE
$\geq .800$	100
$\geq .700$	90
$\geq .600$	80
$\geq .500$	70
$\geq .400$	60

Table 21
Transmission Subsystem Alternative Analysis

ATTRIBUTE	WEIGHT	ALTERNATIVE #1			ALTERNATIVE #2		
		VALUE	SCORE	WEIGHTED SCORE	VALUE	SCORE	WEIGHTED SCORE
ANNUAL REVENUE REQUIREMENT	.30	500,534	79.89	23.97	459,452	88.11	26.43
$/KWH	.30	2.68	72.80	21.84	2.46	81.60	24.48
RELIABILITY	.20	.776	90.00	18.00	.570	70.00	14.00
MH-B	.06	1200	80.00	4.80	1080	90.00	5.40
MH-I	.06	3600	60.00	3.60	3240	80.00	4.80
MH-H	.08	480	80.00	4.80	400	90.00	7.20
TOTAL	1.00			77.01			82.31

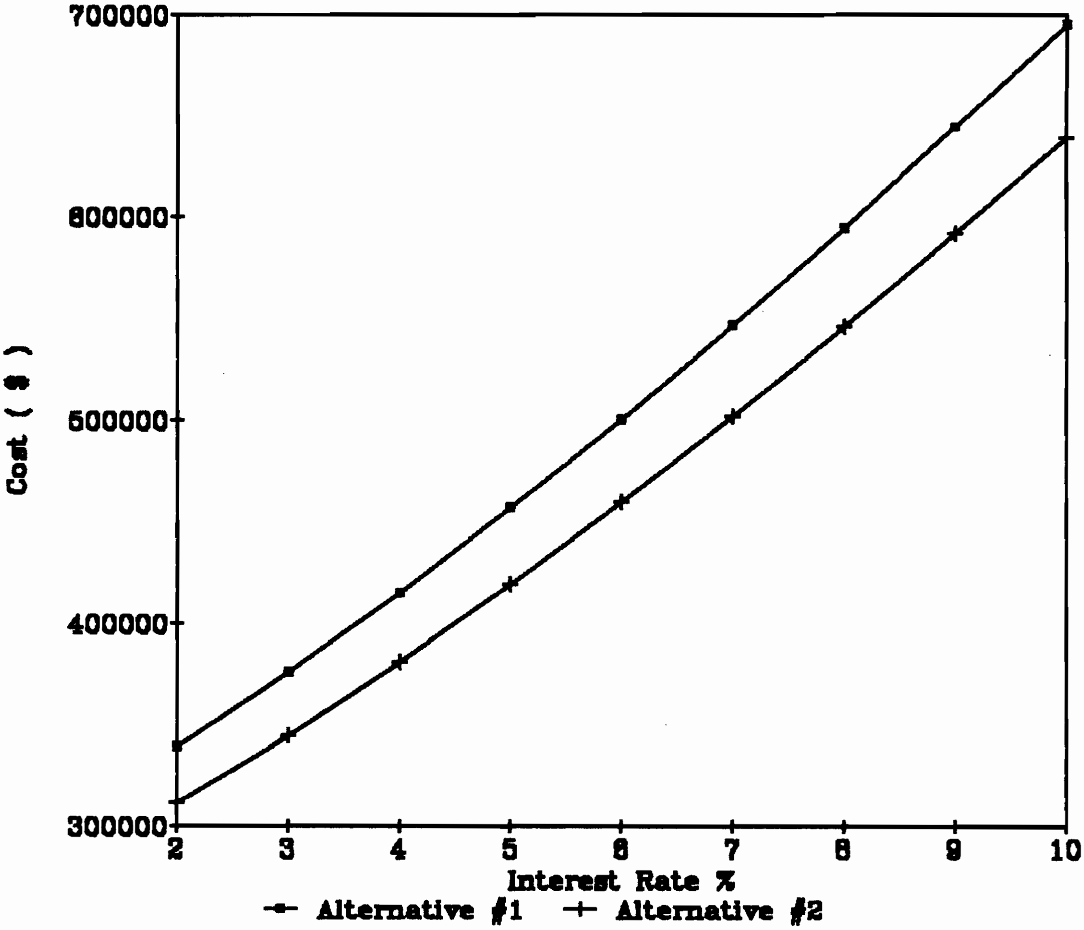

Figure 22
Sensitivity Of The Transmission Subsystem Cost
To The Interest Rate

System Synthesis

System synthesis is putting the pieces together and seeing how well they work as a system. For the generation and transmission system this can be done using the power flow program to test the system under a variety of loads or contingencies such as line outages, generator outages, or reduced generator outputs. A single outage contingency involving the loss of the Bemis-Dry Fork line under peak winter load conditions is modeled in Figures 23 and 24. In Figures 25 and 26 the situation of the peak summer load with no hydro generation is modeled. Under both these contingencies the system meets its operational requirements. Other studies can be done to see how the system responds to other situations such as faults or sudden losses of load or generation.

It was stated in the system planning step that this approach would be developed and compared to the alternative approach of building transmission lines into the region and serving the area from a central grid. At distances greater than approximately 100 miles from a central grid this approach is more cost effective.

At this stage it is also necessary to examine not only how well the system meets the requirements but also how well it meets the desire of society to improve its quality of life. In the definition of need it was stated that four areas were considered in peoples perception of the quality of life; economic, social, political, and environmental. This system will improve the economy of the region by increasing productivity and reducing costs and possibly encouraging new industries. It will improve the social well-being of the population by making hard and time consuming tasks easier and providing clean, bright light and power for radio and television. Environmentally this system relies mostly on renewable resources and while it does dam the rivers the flooded areas are small. The hydroelectric plants are also run-of-the-river plants so instream flows are preserved. The small impoundments will displace few people. Environmentally, this is a relatively benign system. In the political sense people will feel that the local government is responding to their wishes by implementing this system. This system satisfies the needs of society as well as its own requirements.

The last step in the system engineering phase is to write detail design specifications. These will consist of the engineering specifications modified as a result of the system engineering phase and detailed one lines and location plans, operating notes, and equipment specifications. These design specifications should tell the design team everything needed to produce detailed construction documents. Three elements of these specifications are the station one lines and location plans and the transmission line corridor maps. The one line diagram for Durbin Station is shown in Figure 27. It shows how the major components are electrically connected at this location. The location plan for this station is shown in Figure 28. This shows the physical location and arrangement of the structures and equipment. A portion of the transmission corridor map for the Bemis-Durbin 34.5kv line is shown in Figure 29. Within this corridor the designers will have to site the structures. These figures serve as examples of the engineering documentation required. Similar drawings would have to be done for the other stations and lines in addition to writing specifications for all the equipment.

Once the specifications are fully developed for all five subsystems the detailed design work can proceed. This will in turn be followed by construction of the system and its startup and operation.

```
     POWER FLOW BUS OUTPUT DATA FOR Contingency #1

      ---------------------------------------
                                           GENERATION              LOAD
                                        --------------------------------------
        VOLTAGE    PHASE
        MAGNITUDE  ANGLE         PG           QG           PL           QL .95>V>1.05
        ----------------------------------------------------------------------------

           per                   per          per          per          per
BUS#       unit      degrees     unit         unit         unit         unit
--------------------------------------------------------------------------------

 1      0.970       0.000       1.195        0.729        0.000        0.000
 2      0.955      -1.061       0.000        0.000        2.266        0.566
 3      0.995       3.281       0.000        0.000        0.412        0.103
 4      1.000       5.502       3.200       -0.081        0.000        0.000
 5      0.976       1.554       0.000        0.000        0.824        0.206
 6      0.970       0.790       0.000        0.000        0.206        0.051
 7      0.962      -0.303       0.000        0.000        1.442        0.360
 8      0.989       1.648       0.900        0.540        0.000        0.000
                                --------------------------------------
                     TOTAL      5.295        1.188        5.150        1.286

MISMATCH =  9.22E-05



      POWER FLOW LINE OUTPUT DATA FOR Contingency #1

        ---------------------------

LINE #          BUS TO BUS        P            Q            S     RATING EXCEEDED
---------------------------------------------------------------------------------

  2              3    5         2.767       -0.306        2.784
                 5    3        -2.706        0.253        2.718

  3              5    6         1.882       -0.459        1.937
                 6    5        -1.864        0.409        1.909

  4              6    7         1.658       -0.460        1.721
                 7    6        -1.636        0.375        1.679

  5              2    7        -1.076        0.129        1.084
                 7    2         1.087       -0.240        1.113



      POWER FLOW TRANSFORMER OUTPUT DATA FOR Contingency #1

        ----------------------------------------

 TRAN.#          BUS TO BUS       P            Q            S          TAP     RATING
                                                                     SETTING  EXCEEDED

 --------------------------------------------------------------------------------

  1              1    2         1.195        0.729        1.400      1.000
                 2    1        -1.190       -0.695        1.378

  2              3    4        -3.179        0.203        3.186      1.000
                 4    3         3.200       -0.080        3.201

  3              7    8        -0.892       -0.495        1.021      1.000
                 8    7         0.900        0.540        1.050
```

Figure 23

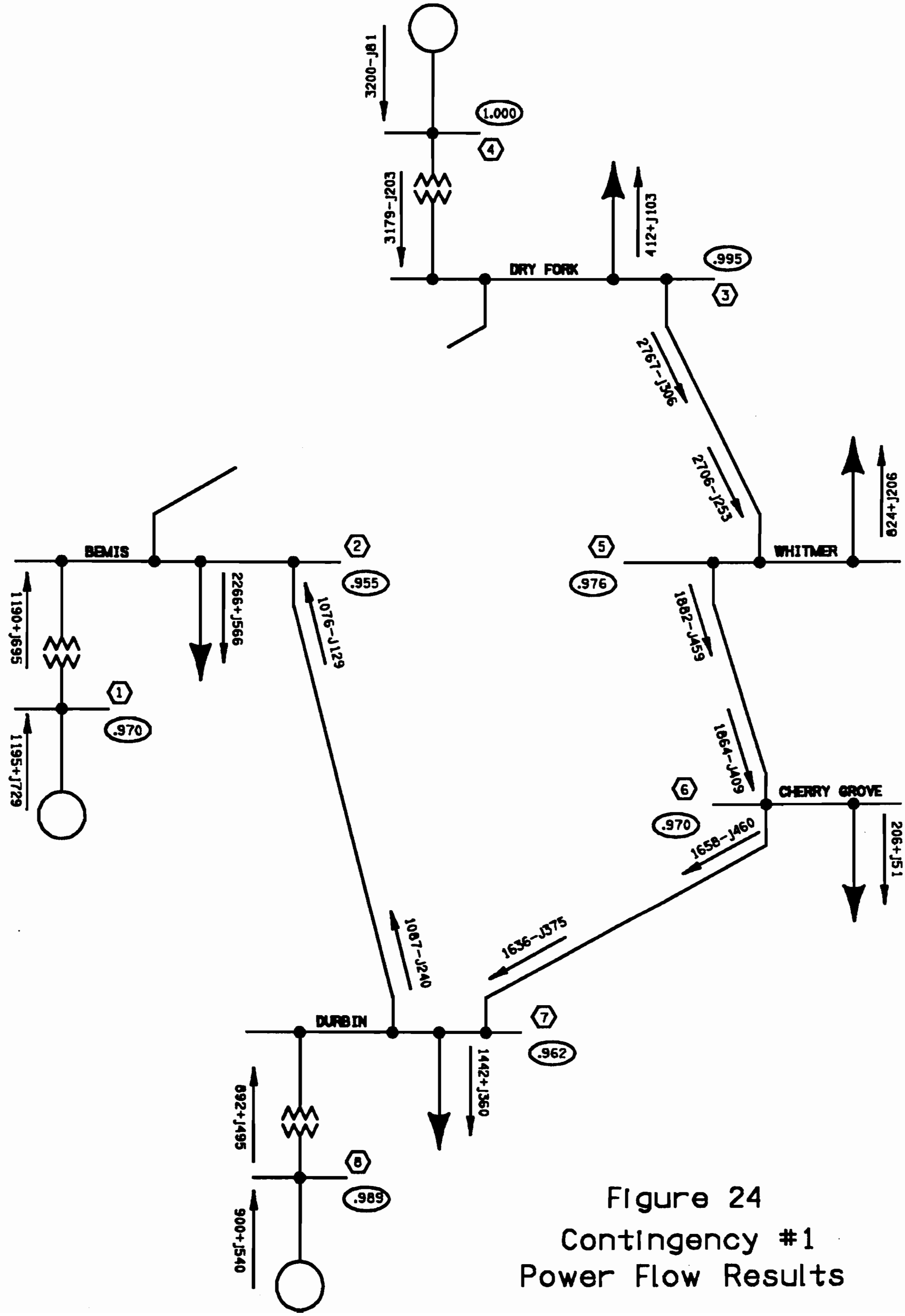

Figure 24
Contingency #1
Power Flow Results

```
        POWER FLOW BUS OUTPUT DATA FOR Contingency #2

         --------------------------------------
                                        GENERATION             LOAD
                                   -------------------------------------
          VOLTAGE    PHASE
          MAGNITUDE  ANGLE         PG          QG          PL          QL .95>V>1.05
          ----------------------------------------------------------------------

          per                      per         per         per         per
    BUS#  unit       degrees       unit        unit        unit        unit
    --------------------------------------------------------------------------------

     1    1.000      0.000         2.425       0.101       0.000       0.000
     2    0.993     -2.225         0.000       0.000       1.056       0.264
     3    0.989     -2.628         0.000       0.000       0.192       0.048
     4    0.989     -2.628         0.000       0.000       0.000       0.000
     5    0.986     -2.828         0.000       0.000       0.384       0.096
     6    0.986     -2.813         0.000       0.000       0.096       0.024
     7    0.986     -2.709         0.000       0.000       0.672       0.168
     8    0.986     -2.709         0.000       0.000       0.000       0.000
                                   -------------------------------------
                     TOTAL         2.425       0.101       2.400       0.600

    MISMATCH =   8.37E-05
```

```
         POWER FLOW LINE OUTPUT DATA FOR Contingency #2

          --------------------------

    LINE #        BUS TO BUS        P          Q           S      RATING EXCEEDED
    --------------------------------------------------------------------------------

     1             2     3        0.540     -0.165       0.564
                   3     2       -0.537      0.018       0.537

     2             3     5        0.345     -0.066       0.351
                   5     3       -0.344     -0.064       0.350

     3             5     6       -0.040     -0.032       0.051
                   6     5        0.040     -0.042       0.058

     4             6     7       -0.136      0.019       0.137
                   7     6        0.136     -0.136       0.193

     5             2     7        0.814     -0.093       0.819
                   7     2       -0.808     -0.032       0.809
```

```
          POWER FLOW TRANSFORMER OUTPUT DATA FOR Contingency #2

           ----------------------------------------

    TRAN.#        BUS TO BUS        P          Q           S         TAP     RATING
                                                                   SETTING  EXCEEDED

    --------------------------------------------------------------------------------

     1             1     2        2.425      0.101       2.427      1.000
                   2     1       -2.409     -0.007       2.409

     2             3     4        0.000     -0.000       0.000      1.000
                   4     3       -0.000      0.000       0.000

     3             7     8        0.000     -0.000       0.000      1.000
                   8     7       -0.000      0.000       0.000
```

Figure 25

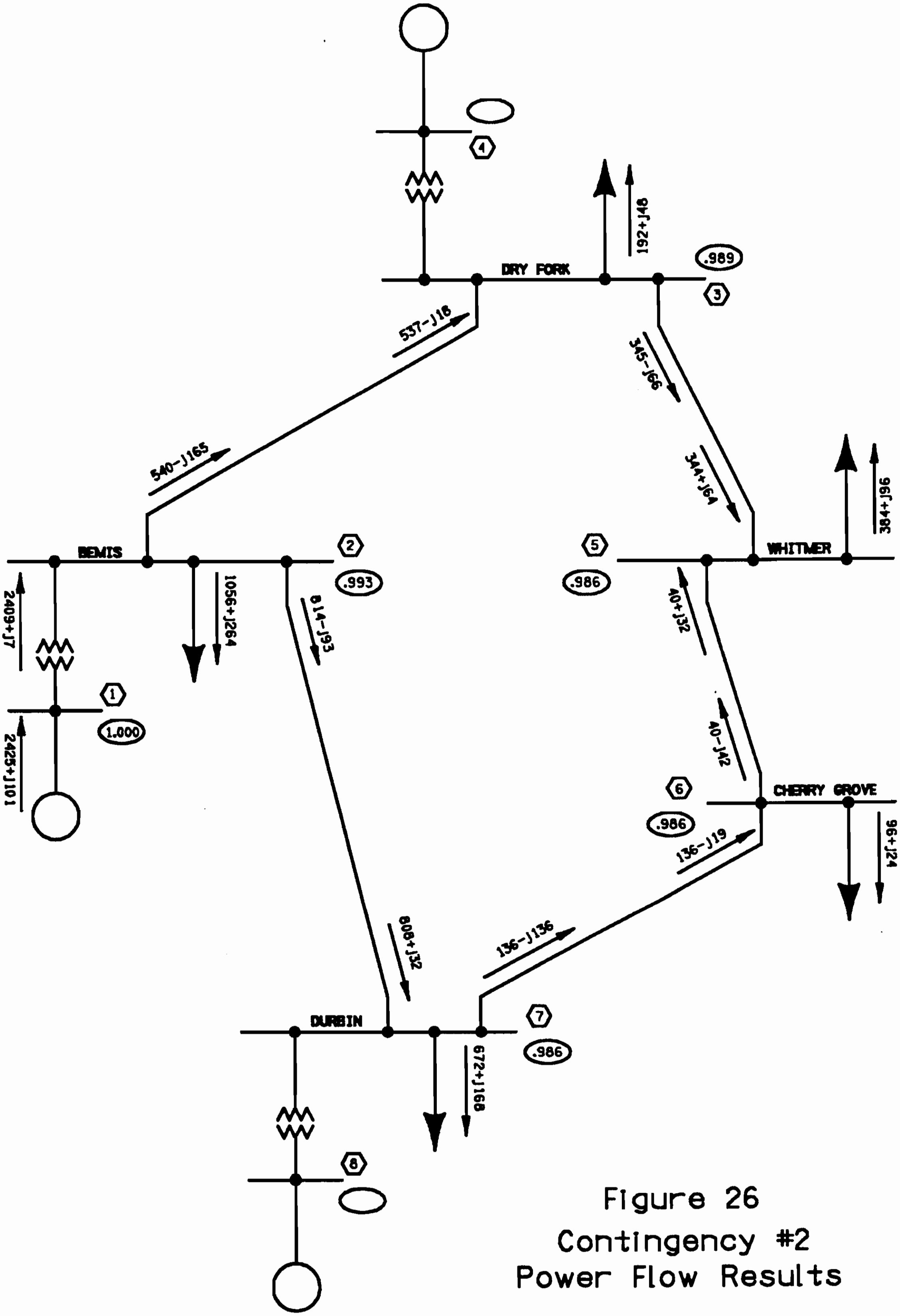

Figure 26
Contingency #2
Power Flow Results

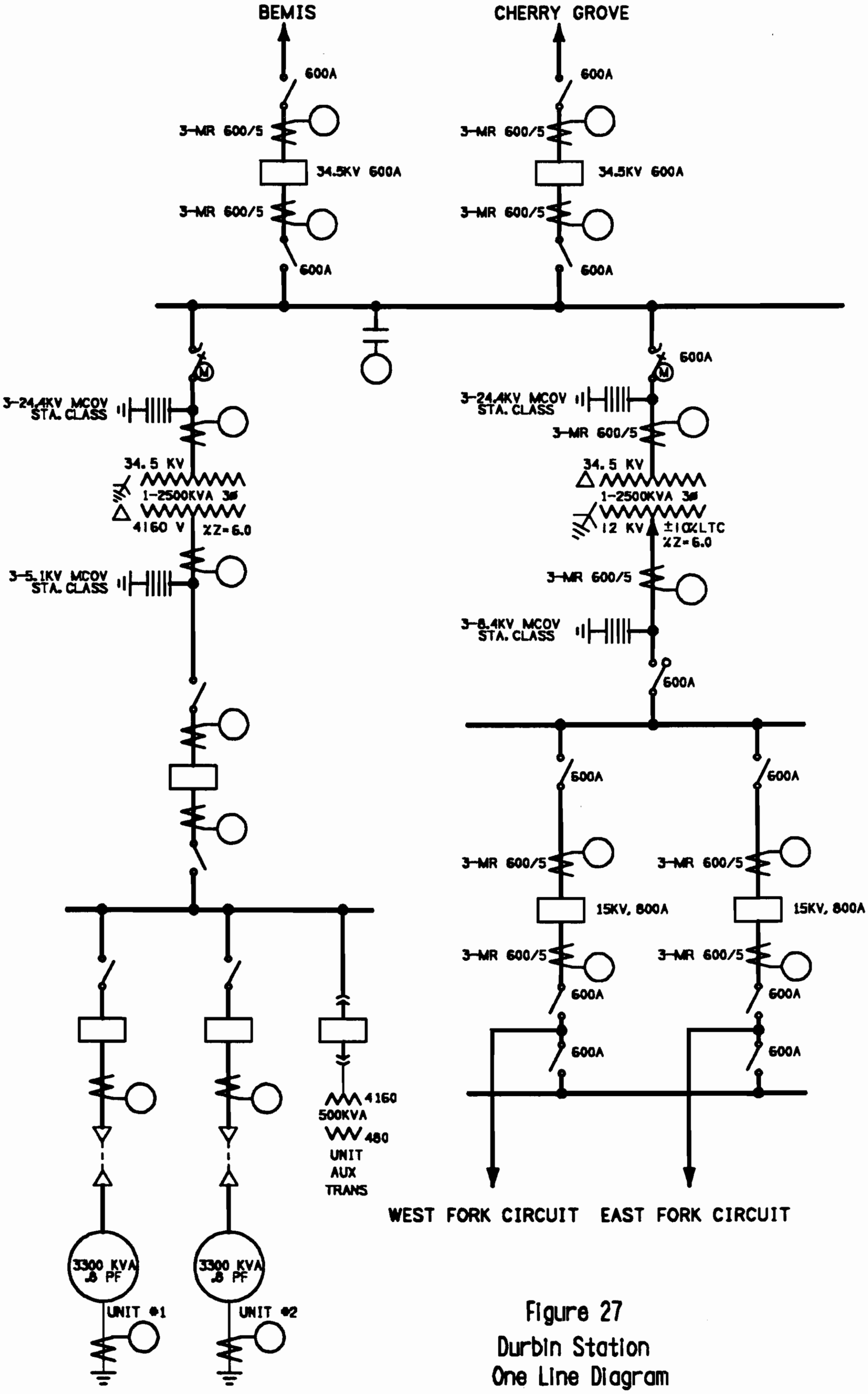

Figure 27
Durbin Station
One Line Diagram

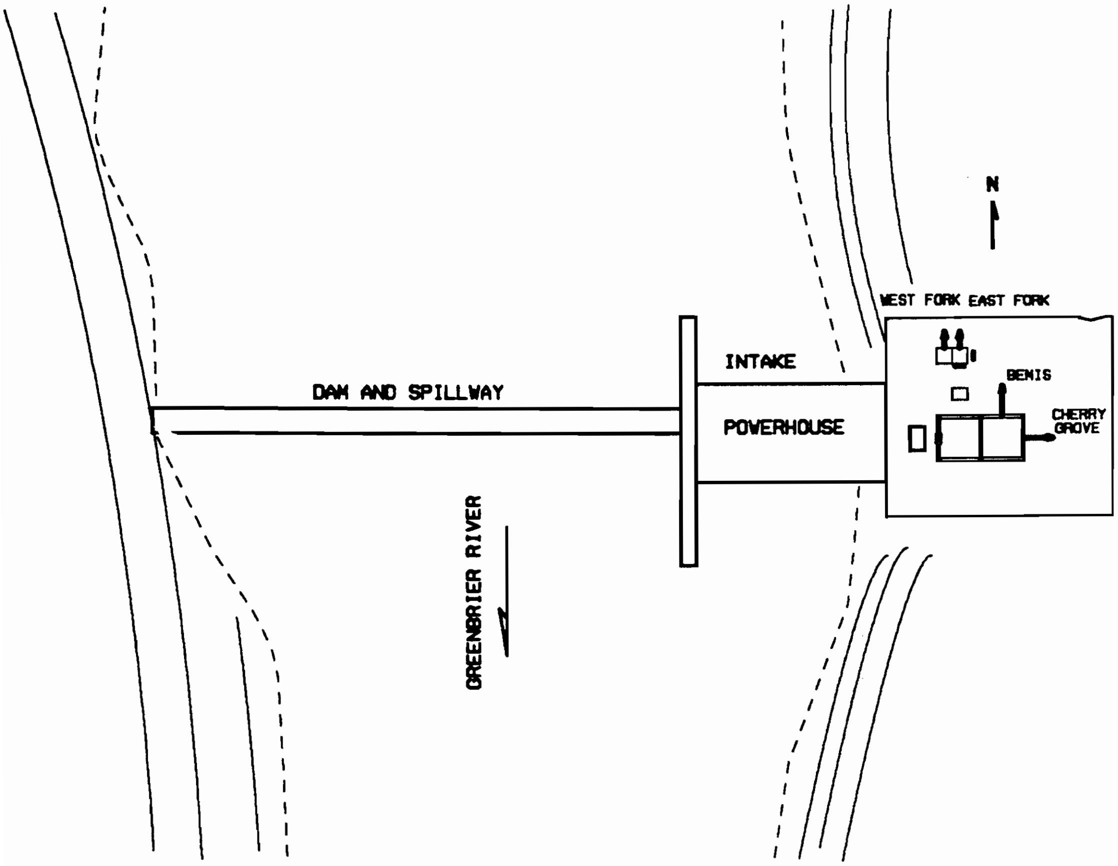

FIGURE 28

DURBIN STATION

GENERAL LOCATION PLAN

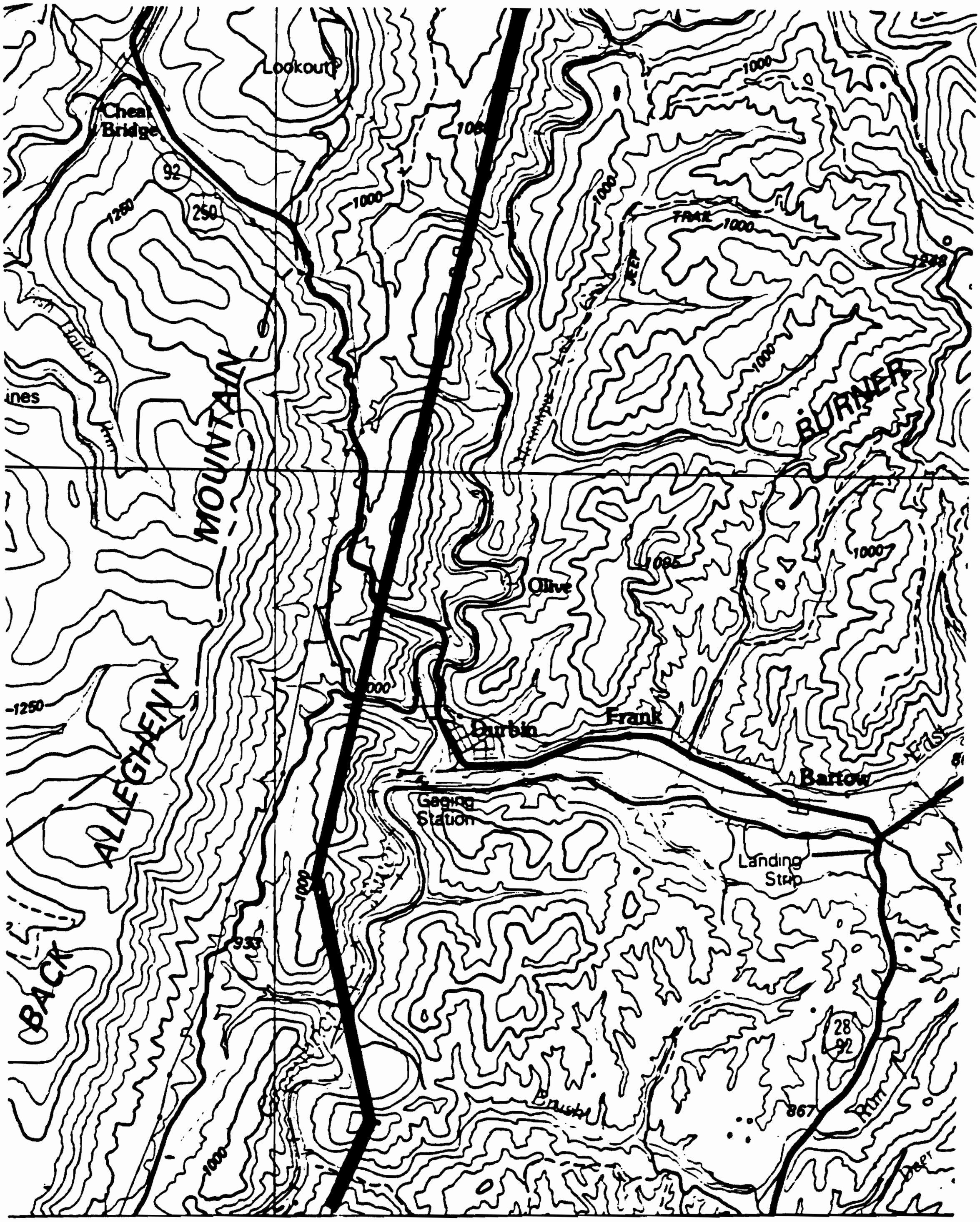

Figure 29

Partial Bemis-Durbin 34.5kv

Transmission Line Corridor

CONCLUSIONS

This project has demonstrated why a systems approach is appropriate to the problem of supplying electric power in remote areas and how it can be applied. It can easily be seen why the solution is a system. It requires many components working together for one goal: the delivery of electricity to the consumer. The systems design and operation will impact on the demand for electricity that the customer places on it. A poorly designed or operated system will be more expensive and less reliable and this will tend to reduce peoples use of electricity in favor of other energy sources.

A systems approach is appropriate because a power system will have far reaching impacts on many areas of society including it economy, its health and social welfare, and its environment. It requires the expertise of many different specialties. In this project principles from four branches of engineering were used: civil, mechanical, electrical, and industrial. Expertise in other areas such as finance, accounting, business administration, forestry, biology, chemistry, environmental engineering, and law would also have to be used in order to bring the system into being. It needs a top-down approach to be an effective system. The system could develop from the bottom up by each community developing its own system and then tying these systems together. This approach would lend itself to duplication of effort and inefficiencies. Finally the life cycle of the system especially operation and maintenance must be considered in order for the system to be effective. This is especially important in remote areas where personnel, equipment, and materials are not as readily available.

The system approach was demonstrated for a fictional but reasonable example. The first two steps of the systems engineering process were applied for the two major subsystems: generation and transmission. The methods, tools and techniques which were used in this example could be followed for a system in any part of the world with any type of generation.

This example considered the use of two renewable resources as energy sources. For power systems in remote areas minihydro facilities operating as run of the river units and wind energy conversion systems are both feasible means of generating a part of a regions needs. Their advantages are they are small, compact, and modular. They do not require a lot of operator attention or maintenance. Environmentally they can be relatively benign. Their biggest drawback is their lack of energy storage capability and unpredictable nature. Backup sources may be required to ensure an acceptable degree of reliability. These renewable resources can be cost effective methods of generation. Their low production costs can offset the high capital investment costs and deliver the power at a lower price per kilowatthour than conventional fossil fuel plants.

In summary power systems which are reliable and economical can be built, operated, and maintained in remote areas using renewable resources. These system can be used to bring the numerous benefits of electricity to these remote regions.

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APPENDIX

This BASIC program is used to find the equivalent load duration curve for this project.

```
10 DIM P(300), ELN(300), ELO(300)
15 INPUT "LIMIT IN KW"; LIM
17 LIM=LIM/50
20 FOR K=0 TO LIM
30 PRINT K*50
40 INPUT ELO(K)
50 NEXT K
60 PRINT "UNIT CAPACITY": INPUT MAX
62 MAX=MAX/50
65 FOR L=0 TO MAX
70 PRINT L*50: INPUT P(L)
80 NEXT L
85 FOR K=0 TO LIM
90 FOR L=0 TO MAX
110 J=K-(MAX-L)
120 IF J<=0 THEN J=0
122 ELO(0)=1
130 ELN(K)=P(L)*ELO(J)+ELN(K)
170 NEXT L
175 NEXT K
180 FOR N=0 TO LIM
190 ELO(N)=ELN(N):ELN(N)=0
200 NEXT N
201 INPUT "DO YOU WANT TO PRINT THESE RESULTS, Y OR N"; PQ$
202 IF PQ$="N" THEN GOTO 210
203 INPUT "PRINT LIMITS"; N1, N2
204 N1=N1/50: N2=N2/50
205 FOR I=N1 TO N2
206 LPRINT I*50, ELO(I)
207 NEXT I
210 INPUT "ANOTHER UNIT"; Q$
220 IF Q$="Y" THEN GOTO 60
230 FOR K=0 TO LIM
240 PRINT K*50, ELO(K)
250 NEXT K
260 STOP
270 END
```

VITA

Paul C. Turner received a Bachelor of Electrical Engineering degree from Cleveland State University in December 1983. During his undergraduate work there he was employed as an engineering co-op with the Standard Oil Company at the Lima Refinery and at the Central Engineering Unit in Cleveland.

Following graduation he joined the Appalachian Power Company, an operating company of American Electric Power. From March 1984 to September 1988 he was employed as a project engineer in the Station Construction and Maintenance Group in Bluefield, West Virginia. In this position he supervised construction and maintenance projects in transmission, distribution, and communication stations in West Virginia, Virginia, and Tennessee. In September 1988 he transferred to the Station Engineering and Design Group in Roanoke, Virginia where he presently is responsible for the engineering and design of distribution stations. In 1989 he was appointed to be the companys public liaison on the issue of health effects and electromagnetic fields.

He enrolled in the systems engineering program at Virginia Polytechnic Institute and State University in the spring of 1987. He has attended the AEP Power Systems Concepts Course, the AEP Concrete School, and the EEPA/Rutgers University Management Of Electromagnetic Energy Hazards Course.

He is a registered professional engineer in West Virginia and is a member of IEEE. His date of birth is August 24, 1960.

Signed Paul C. Turner