Q-GERTS SIMULATION OF HARDROCK UNDERSEA TUNNELING (Q-SHUT)

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Q-GERTS Simulation of Hardrock Undersea Tunneling (Q-SHUT)

by

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ABSTRACT

Q-GERTS Simulation of Hardrock Undersea Tunneling (Q-SHUT) is a computer program utilizing Q-GERTS as a routine to produce simulated undersea tunnel construction times in hardrock under various conditions, and arrive at associated costs.

The simulation is founded on a tunneling system consisting of seven operational units developed thru the systems approach and represented in Q-GERT network form. Via Q-GERTS this network is translated to computer input, portions of which, being relevant to geologic conditions, method of transport, method of support and lining, are inherently variable. Thru a system of files this variable input is updated and subjected to Q-GERTS. Output is filed to await association with cost factors and manipulation into user requested format.

Q-SHUT produces simulated construction times and hence simulated costs over any single desired fraction of tunnel length used as a standard length or it may accumulate results over some multiple of this chosen standard.

By running Q-SHUT subject to all filed variable information, cost comparisons relative to geology, transport type, method of support and lining can be made and the cost effectiveness under different construction conditions subsequently determined.

PREFACE

Project Management provides an excellent opportunity to examine undersea tunneling as it relates to Newfoundland, and develop a computer simulation program to help minimize tunneling costs as well as facilitate scheduling on tunneling projects.

This report summarizes development of the Q-GERTS Simulation of Hardrock Undersea Tunneling (Q-SHUT) computer simulation program, and is presented in three chapters as follows;

1. Introduction
2. Q-GERT Network
3. Q-SHUT

A detailed examination of the Q-SHUT program with discussion relative to functional logic, input data and procedure for use, including flowcharts and program listing, is covered in a larger backup report entitled, "Computer Program Documentation for Q-GERTS Simulation of Hardrock Undersea Tunneling."

The evolution of Q-SHUT to a workable level has been a long and sometimes agonizing process. Difficulties incurred in having Q-GERTS accommodate the network representation of a large tunneling system, insufficient documentation for the version of Q-GERTS employed and testing of data manipulation mechanisms, provided many anxious weeks, cutting heavily into department computer time allocations.

The many setbacks and frustrations were made bearable and overcome only thru the patience, encouragement and counsel of Professor H.N. Ahuja. For this I wish to express my deepest gratitude.

I wish also to acknowledge the advice and encouragement of fellow students, the Newfoundland and Labrador Computer Services Ltd. and Pritsker and Associates, Inc.

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CHAPTER 1

1. INTRODUCTION

A tunnel is an artificial subterranean passage and the science of constructing such a passage may be defined as tunneling.

Tunneling may be broadly classified as to whether the construction is in clay or hardrock. Clay tunneling is relatively fast as opposed to hardrock tunneling where advance rates may be very small. This classification can be improved by further stating whether the tunneling is beneath the sea or inland. Thus a tunnel might be classified as an undersea hardrock tunnel and its construction as an undersea hardrock tunneling project.

Present practice in tunneling utilizes either a cyclic or continuous excavation method depending on the type of material excavated and the tunnel configuration (28). The cyclic or conventional method is the oldest and currently provides the most versatile application. It consists of the repetitive cycle of drill, blast and muck. Continuous or semi-continuous excavation is performed by mechanical excavators, often referred to as mechanical moles.

Many novel approaches have been proposed in the area of automated tunneling. Some of the more promising techniques which are now in the research and development phase include flame jet rock disintegration, hydraulic jet shattering, laser and plasma jet disintegration (20,15,22).

1.1 HISTORY OF TUNNELING

The first tunneling projects undertaken by man reach back to prehistoric times. Primitive man seeking shelter against inclement weather found retreat in natural caves (47). As the population grew so grew the need for larger caves and hence tunneling. During the late stone age, tunnels were developed to retrieve mineral deposits such as iron and copper.

History records the first tunnel being built by the Babylonians circa 2160 B.C. This tunnel went beneath the Euphrates River and was 1 km. in length with a cross section of 3.6 m x 4.5 m. During its construction the river was diverted form its bed, a considerable project even by today's standards.

With the introduction of gunpowder, tunnels were constructed in hitherto impregnable rock. This boon to tunneling was first used in 1679. The next major improvement in tunnel construction occurred in the late nineteenth century when the mechanical percussion drill was developed. This was a device for tunneling in relatively soft material such as clay. It was jacked forward and offered ceiling support at the face until permanent support could be installed. Then came the ultimate in tunneling, the tunnel-boring machine. This device was used in an attempt to drive a tunnel under the English Channel (48). Today the use of such man-made moles is becoming more and more feasible as research and experience lead to better quality machines.

1.11 TUNNELING AT PRESENT

At present nearly every country on earth is involved in some aspect of tunneling, whether estimating the cost of a small sewer tunnel or studying the feasibility of storing crude oil in large underground caverns. Two tunneling projects which are ambitious extentions of man's tunneling knowledge are the Seikan Undersea Tunnel and the Channel Tunnel. These have been designated to serve as high-speed transportation links. Both are very large construction projects and the experience gained here will undoubtedly aid future tunnel builders to undertake even more daring feats.

In North America hardrock tunnels have been driven primarily for hydro-electric energy development and water resource projects. The tunnels at Churchill Falls (44), the Oahe Tunnel in South Dakota (50), the Navajo No. 1 Tunnel in New Mexico (19) and the Azotea Tunnel which crosses the Colorado-New Mexico border (25) are such examples.

1.12 TUNNELING IN NEWFOUNDLAND

For centuries the island of Newfoundland has coaxed a pleasant living from the turbulent waters of the Atlantic Ocean. Ironically though, these waters have been the bane of economic progress, for they have served to isolate Newfoundlanders from the other provinces of Canada as well as restrict the movement of goods both to and from the mainland. Such isolation is demonstrated by Figure 1.1.

To help overcome this isolation the government has considered two direct transportation links with the mainland, namely causeway and tunnel. As a result of tunneling experience gained at the Churchill Falls power project (44,7,11), ice conditions in the Strait of Belle Isle (43) and the tunneling success of other countries, notably Japan, such consideration has resulted in focusing entirely on tunnel construction. Although a vehicular transportation tunnel is a long way from being started, it has nevertheless, forced common man and government official alike, to think ever increasingly in terms of tunnels. This thinking has been reflected in various studies carried out by both industry (38,46) and university (37,26). The culmination of this tunneling research came with the recent start on construction of an energy transmission tunnel linking the island of Newfoundland with the abundant electrical energy of the Churchill Falls. Unfortunately however, the whole project will be delayed by perhaps three years due to the Provincial

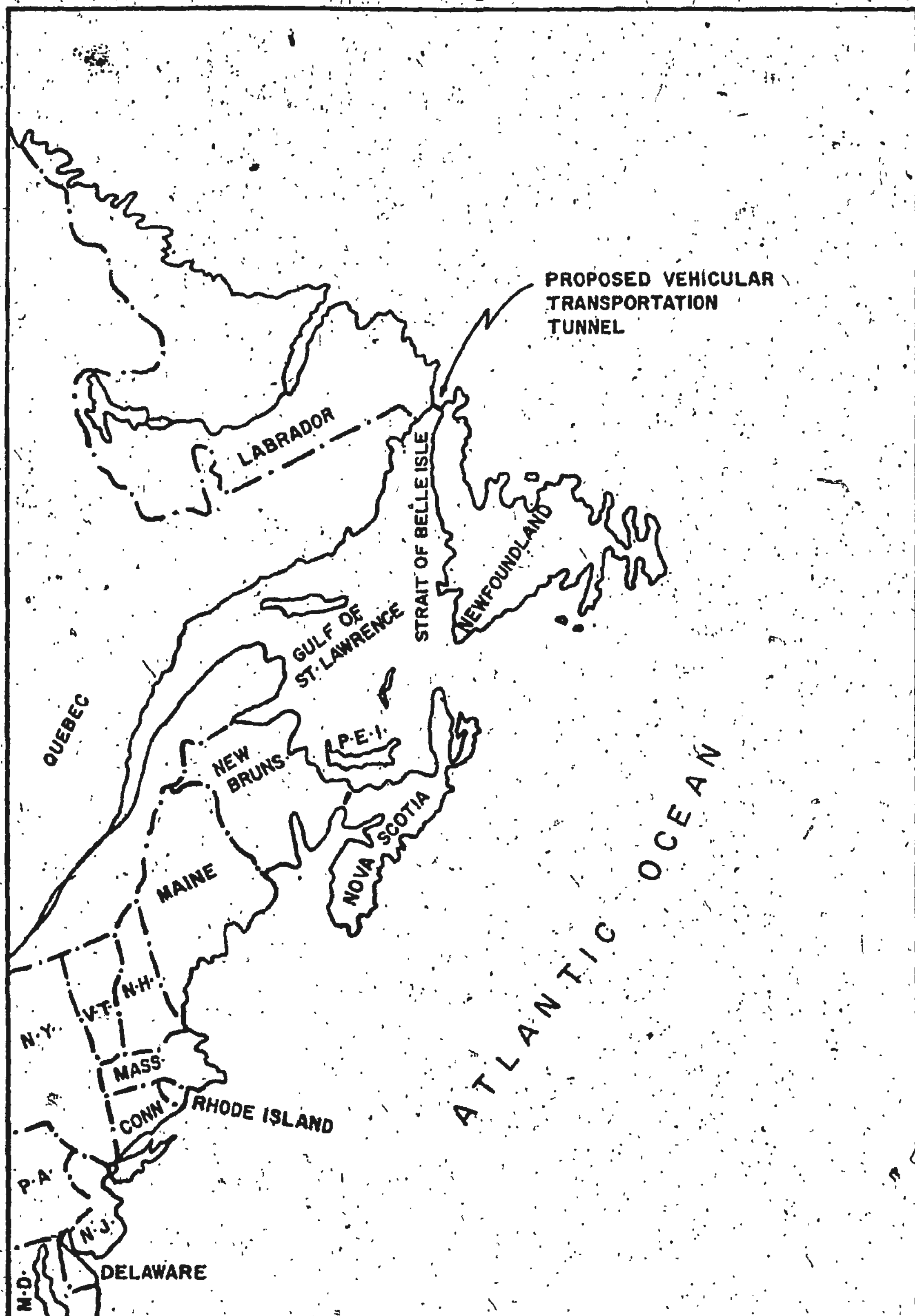

Figure 1.1. Map of Atlantic Provinces and Northeastern States

Government's austere financial cutbacks in keeping with the Federal anti-inflation policy.

Apart from this proposed vehicular transportation link and already started energy transmission tunnel, there is also the possibility of transporting oil via tunnel from possible oil fields off Newfoundland's southeast coast to refineries on the south coast.

Thus the economic future of Newfoundland may depend in part, on the construction of undersea tunnels. And anything which extends the tunneling state of art may in turn extend Newfoundland's prosperity.

To understand tunneling requires an ordered approach to the multitude of information presently available. Such scope can best be handled by applying an engineering systems approach.

1.2 SCOPE

The systems approach is a logical method of studying any overall tunneling system. The first publication discussing such an approach was authored by Howard (17) in 1967. The first detailed papers concerned with the systems approach were presented at the Second Symposium on Research and Development in Rapid Excavation at Sacramento State College in 1967. At this symposium ideas on the application of systems analysis to tunneling were presented by Bledsoe (6).

The approach developed here follows that outlined by Roe, Soulis and Handa (41).

The tunneling process consists of a number of interrelated activities taking place at various locations in the tunnel and on the surface. The major activities are (9);

1. Excavation, which consists of breaking or fragmentation and removal of in-situ rock or soil.
2. Ground support installation and maintenance to assure the safety of the tunnel.
3. Transport of muck or spoil from the excavation area to a disposal site on the surface.
4. Transport of construction materials from the surface to the point of installation or usage.
5. Transport on a shift cycle of personnel to and from the work sites within the tunnel complex.
6. Provision of an environment adequate for equipment and personnel to perform their functions.
7. Maintenance of operating equipment.
8. Above ground operations required to support underground activities.

1.21 ENVIRONMENT

These activities serve to relate hardrock tunneling to three basic environments;

1. Geological
2. Design
3. Construction

Considering tunneling beneath the sea, the tunneling process must naturally include some form of marine operations. Also, since the end result of tunneling is usually a tunnel for use in vehicular, material or energy transportation, and since undersea tunneling in Newfoundland directly involves politics, three more fundamental environments can be distinguished They are;

1. Marine
2. Use
3. Government

These six environments encompass all aspects of tunneling. The geologic environment for example may be characterized by selection of tunnel location, preliminary core sampling and analysis, geologic examination techniques and geologic updating procedures (28). Of course the extent to which this division may be carried is limited only by the knowledge and desire of the person involved with this environment. The same may be said for the other environments. Below is listed the six basic environments with some of their more salient characteristics.

Geological Environment:

1. Selection of tunnel location
2. Preliminary core sampling and analysis
3. Geologic examination techniques
4. Geologic updating procedures

Marine Environment:

1. Water depth
2. Ice movement
3. Undersea exploration

Design Environment:

1. Shape of tunnel
2. Shaft location
3. Method of ventilation and water removal
4. Lighting and power supply
5. Safety features

Government Environment:

1. Financing
2. Benefit studies
3. Politics

Construction Environment

1. Records of past tunnel construction
2. Knowledge of tunneling methods
3. Construction crew selection
4. Cost estimation
5. Equipment selection
6. Deposition of removed muck
7. Transportation of materials

8. Escalation
9. Strikes

Use Environment:

1. Rail transportation
2. Car and truck transportation
3. Storage purposes
4. Carrying cables, sewer lines, etc.
5. Pentstock, tailrace

All these environments are certainly complex and each one able to support studies in an effort at extending the tunneling art. However an environment that lends itself well to investigation from a construction project management view point is that of construction. Also, many factors comprising the construction environment are involved with actual construction wholly within Newfoundland and subject to Newfoundland working conditions.

1.211 PROBLEM AREA

A problem which arises in any tunnel construction project and which is encompassed by the construction environment, bears upon the proper selection of tunneling method and tunneling equipment so as to minimize construction time and cost. This is of particular importance in Newfoundland. A bad choice of equipment combination could spell an unecessary increase in construction cost, since a selection once made, will have to last a long time due to unbelievable shipping delays associated with importation of equipment comprising a new and supposedly more economical combination. Such delays are all too common. Hence a good combination at the outset will result in economy as construction proceeds.

To model a tunnel project and have it operate using various construction methods and equipment types would undoubtedly aid design engineers and contractors in making more reliable selections.

1.212 IMPORTANCE OF CONSTRUCTION ENVIRONMENT

Any of the factors which comprise the construction environment might undergo research leading to possible improvement. This is only logical since the whole aspect of tunneling - including factors associated with the other environments - has not evolved to the realm of perfection (1).

A report explaining materials handling for tunnels (9) suggests improvement in equipment selection. This is also reinforced by a report on the interrelationship of in-situ rock properties (18). In effect it states that the importance of a more logical approach to selection of tunneling method and equipment has been emphasized by the amount of research (dealing with selection of methods and equipment) to be initiated in the near future. The need for improvement in equipment selection has also been emphasized at the Advisory Conference on Tunneling held in Washington D.C. during June 1970 (1).

Directly related to equipment selection is another factor in the construction environment - knowledge of tunneling methods. Depending on the method of tunneling, various equipment selections are made in order to expedite construction.

The result of this direct relationship and the results of various reports, would seem to indicate a basic lack in the construction environment particularly in the area of selection of tunneling method and tunneling equipment. Since this environment is of definite concern to Newfoundland, research involving selection of method and equipment would appear beneficial.

1.22 CONSTRAINTS

The selection of tunneling method and equipment as it applies to the whole tunneling process (9) can be extremely complicated due to the many factors that need consideration. Not only must the tunneling process be examined as a system but various data concerning many types of equipment must be available. An idea of equipment types available and their specifications can be gleaned from a report by Patrick Harrison and Company Limited (46). This report together with examination of data relative to materials handling for tunneling (9), demonstrates the extent of present equipment information; a basic knowledge of the types and capacities of available equipment is a research project in itself. Thus any use of a methodology developed for equipment selection must be left to the ingenuity and preference of experienced tunnel contractors.

According to Mutmansky (27), for purposes of modeling, a tunneling system can be broken down into four unit operations designated as muck generation, tunnel support, environmental control and materials handling. Parker (28) has described a tunneling system as comprising of muck loading, tunnel support, pumping, grouting, lining and ventilation. Considering geologic prediction and excavation (muck generation) as an entire unit, then seven distinct operational units can be considered in relation to any tunneling system or process. And any choice of tunneling method and equipment must therefore be constrained by these units.

Because of the growing importance of the time element in commerce, industry and various defence commitments, there is at present widespread use of network analysis techniques (3). And tunneling is one area where such analysis can be easily applied and the benefits quickly seen. Most common among network analysis techniques are CPM and PERT (55). Representation of the tunneling process by a network, enables the contractor to see each operational unit in its proper context, to schedule completion of units relative to the whole system, to understand better the interactions between units and to predict a completion date for the entire project. Hence another constraint may be introduced. Any selection of method and equipment should relate to a network representation of the tunneling process.

Perhaps the most basic of constraints centers around geologic prediction and excavation (53,24,40). Whether the conventional method of tunneling is used on a project or a mole, certainly depends on the type of geology encountered. Likewise for equipment selection in the muck loading operation as well as tunnel support. As with the type of equipment available for tunneling, geologic prediction and excavation, as well as investigations related to this operation, rest mainly on the design engineer and the knowledge and experience of the contractor.

Thus an approach to developing a better methodology for selecting tunneling method and equipment will be subject to the following constraints;

Information Constraint:

1. Geologic prediction data should be selected mainly by the design engineer or contractor.
2. Equipment data selection be controlled mainly by the contractor.

Process Constatint: Selection of method and equipment must be relative to the following operational units;

1. Geologic prediction and excavation
2. Muck loading
3. Tunnel support
4. Pumping
5 Grouting
6. Lining
7. Ventilation

Network Constraint: Selection of method and equipment must relate to a network depicting all operational units.

Time-Cost Constraint: Any selection must be relative to the network and have final results expressed in terms of time and cost.

To aid in any approach at developing a selection method, a definition of a tunneling system must first be proposed.

1.23 SYSTEM DEFINITION

The tunneling system as used in this report is that aspect of tunneling involving the following seven units;

1. Geologic prediction and excavation
2. Muck removal (muck loading)
3. Tunnel support

4. Pumping
5. Grouting
6. Lining
7. Ventilation

Although this system is acted upon by all the environments mentioned earlier, only its functioning with regard to the construction environment and in particular equipment selection, will be considered.

1.231 SYSTEM INPUTS

Inputs to the system should be considered under the seven headings corresponding to the system units. These inputs include;

Geologic prediction and excavation:

1. Rock quality designation
2. Rock strength
3. Tunneling methods
4. Tunnel shape
5. Tunnel size
6. Groundwater inflow
7. Excavation times
8. Cost

Muck removal:

1. Type of muck haulage equipment
2. Type of loading equipment
3. Number of hauling and loading units
4. Data regarding loading and hauling times
5. Cost

Tunnel support, Pumping, Grouting, Lining, Ventilation :

1. Type of placing[1] system(s) available
2. Type of equipment used with each placing system
3. Data regarding loading, hauling and placing times
4. Cost

As can be seen, the basic input information is centered around method (placing system), equipment, time and cost.

1.232 SYSTEM OUTPUTS

The tunneling system operates to produce one all encompassing output, a tunnel. However this single end cannot usually be judged on a single merit, for if cost and/or construction time far exceeds all wildest estimates, then economic benefits from the physical tunnel could conceivably

[1]Placing system(s) refers to the method(s) used to install tunnel support, pumping, grout, etc.

be negated, even if construction is the epitome of advanced technology. Any judgement must revert to the fundamental. And apart from the technological aspect, nothing is more fundamental and universally accepted then time and cost. Thus output from the system should define an average completion time and average cost associated with each system component,[1] as well as a total completion time and total cost over all components collectively. Also, since equipment is part of system input, then system output should provide data on equipment utilization in any or all components as they interact.

A general schematic of the system showing its various components along with inputs and outputs is shown in Figure 1.2.

With a decided combination of method and equipment entering the system a unique set of completion times, costs and utilization information arises. Pass another combination to the system and a different output set is obtained. Hence the association of output with tunneling system is not only dependent upon system components but also the input combination serving the system. Carrying this further, completion times, costs and utilization information inevitably lead back to actual tunnel characteristics involving tunnel dimensions and encountered geology, hence output will also invariably depend on such variables.

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[1]System components, system sections, stages or units may be used interchangeably.

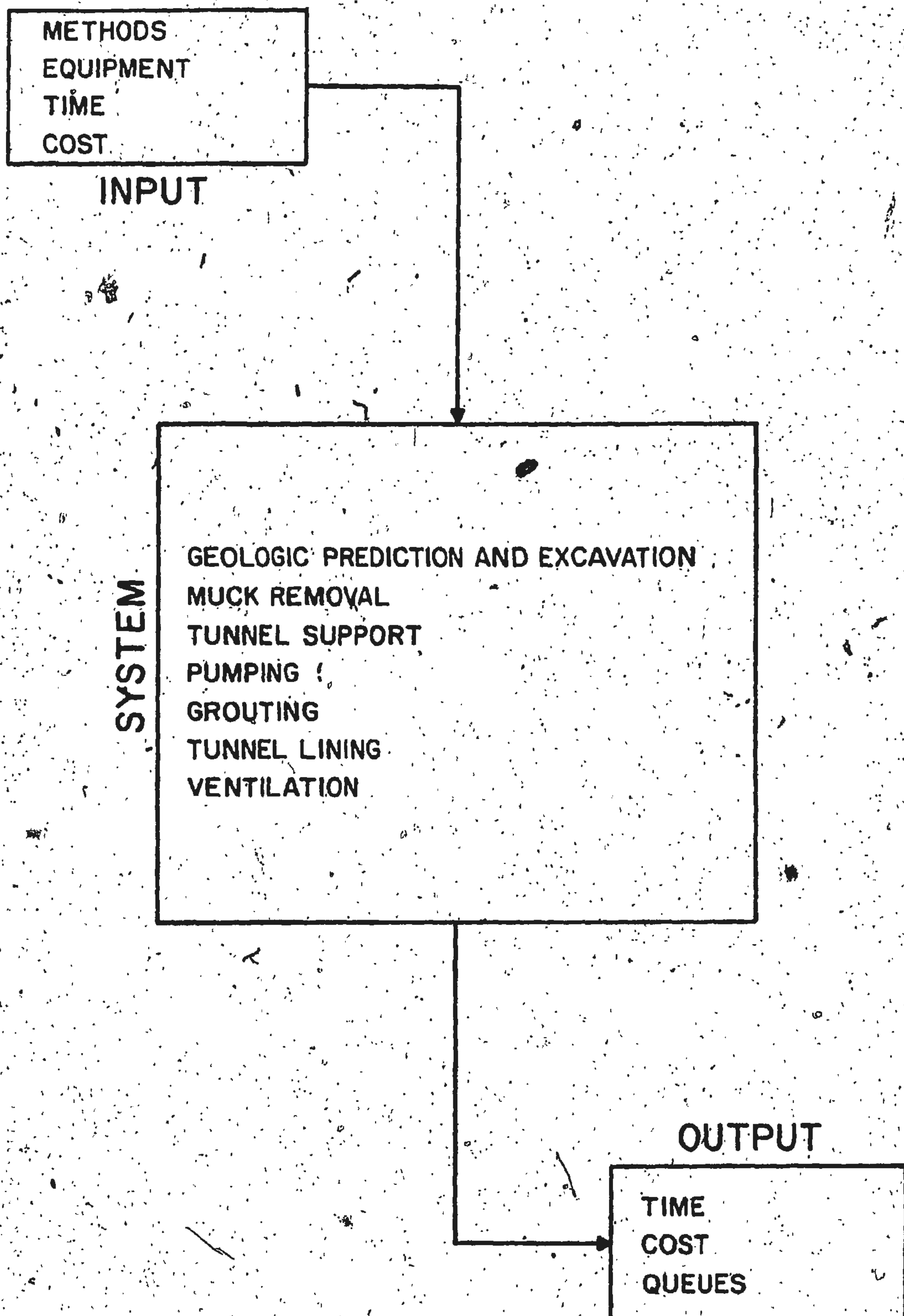

Figure 1.2. Input – System – Output.

The tunneling system by virtue of its definition depicts and encompasses basic tunnel construction in the real world. One may justifiably reason that as each stage of the system is executed in turn over the entire tunnel length, construction approaches completion. In actual fact, however, several stages may be performed simultaneously. Projecting this link between defined tunneling system and the physical tunnel, one may visualize construction reaching completion via total construction over specified lengths of tunnel each less than the total tunnel length, the sum of such lengths being equal to the total length. Thus if 1000 feet of tunnel is to be constructed, 100 feet may be entirely constructed - subjected to all aspects of the tunneling system - then another 100 feet until the whole 1000 feet is achieved. Such an interval view of construction closely approximates the real-life situation and at the same time provides a measure of convenience in producing system output.

In light of this interval approach aspect of tunnel building and from Figure 1.2, it may be generally concluded that output is influenced directly by the nature of system components and indirectly by input combination and tunnel characteristics in association with definite physical tunnel intervals. This may be illustrated by Figure 1.3.

The numerous interactions of system components with input, intervals and dimensions must be carefully modeled before output is acceptable for analysis. A way to do this is

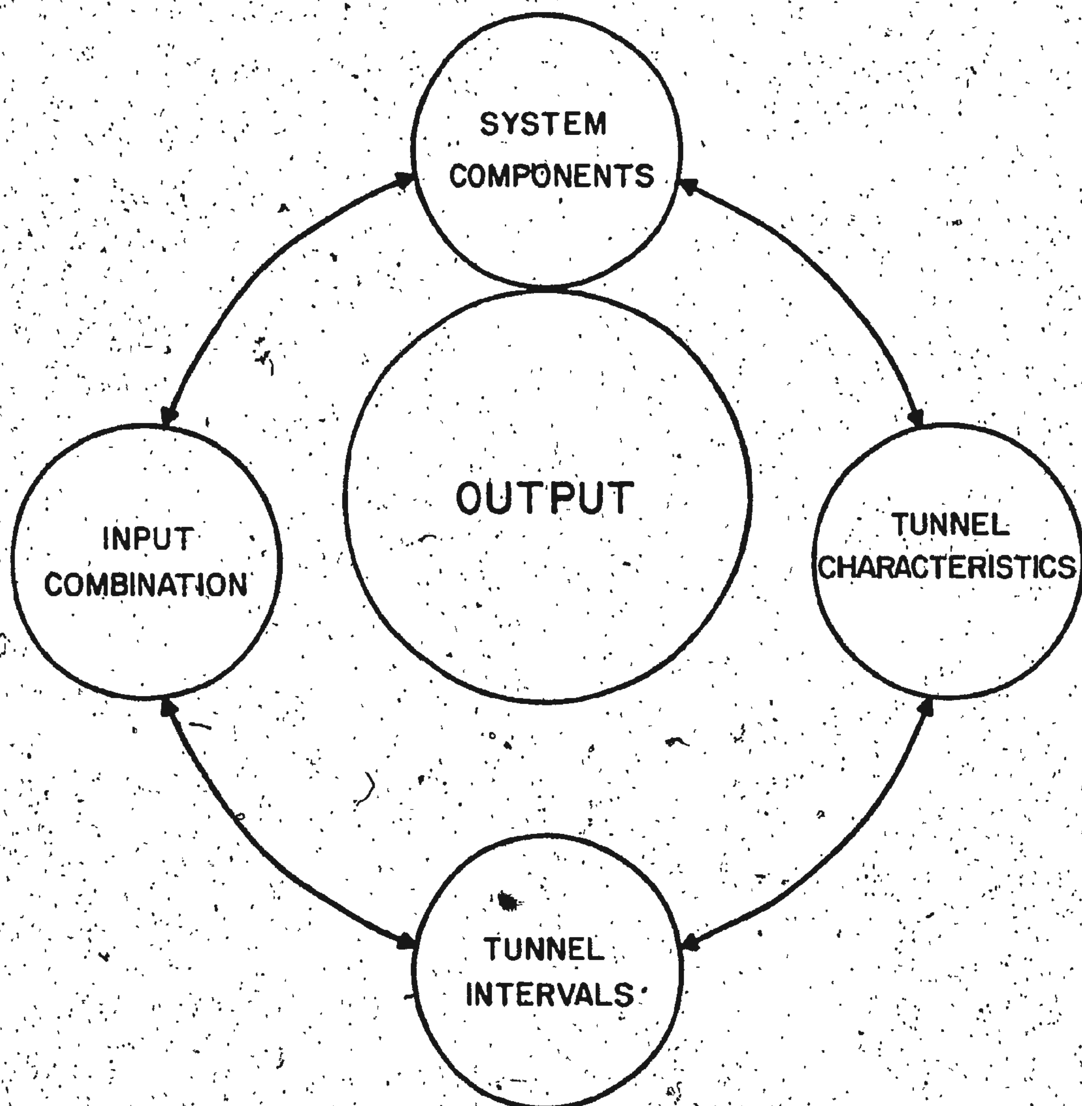

Figure 1.3. Major Influences Upon Output.

by simulating the entire tunneling system, and work being done at present would suggest the involvement of computers (16).

1.3 SIMULATION FOR SYSTEM ANALYSIS

Simulation is experimentation with a mathematical or logical model of an operation or system in order to predict what will occur in actual operation under any given set of assumptions (4). The usual reasons for using simulation are that the problem is either so complex that it cannot be solved analytically or that solution methods are too involved to be practical. The tunneling problen can certainly be solved analytically (28) but investigations to test the effect of different equipment types causes the problem to become difficult and very laborious to tackle. Only with a device capable of carrying out thousands of instructions, routines and tests per second has it become practical to attack such problems. While simulation has existed for centuries, the use of a mathematical simulation model to analyze and evaluate operations is largely a new technique. However its applications are fast becoming countless, as indicated by the number of journal articles and the amount of applications-oriented technical literature devoted to the subject (42).

To accomplish simulation of a physical system using a digital computer depends somewhat on the language employed in describing the system to the computer (45). Some simulation languages work only from differential equation descriptions of system behavior. Others use a block diagram description, while still others accept the system description as a number of interconnected transfer functions. Regardless of the language used however, it is necessary to express operations that must be performed, assign numerical values to constants and parameters, specify initial conditions and indicate the form of output. Some languages are; Continuous System Simulation Language (CSSL), General Purpose System Simulator (GPSS) and MIMIC.[1]

To develop a methodology for the selection of tunneling method and equipment, will by virtue of constraint, necessitate a network depicting all operational units of the tunneling system. These units as found in the tunneling system are acted upon by inputs consisting of method, equipment and time, such inputs involving rates, time distributions and probabilities. These probabilities would result from the necessity of selection between equipment operating levels capable of doing the same task, for the purpose of testing some equipment combination and producing an output. Hence any network depicting the tunneling system will be stochastic in nature. A simulation approach recently developed to analyze such a stochastic network is called Graphical

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[1]The name has no special meaning.

Evaluation and Review Technique Simulation (GERTS) (31). It is a computer program which simulates some operation or function that is represented in terms of a GERT (Graphical Evaluation and Review Technique) network. The fact that network simulation is involved makes this approach rather unique (29).

In addition to the 'AND' input and 'DETERMINISTIC' output characteristic of nodes in CPM and PERT networks, GERT embodies two additional logical relationships (8). The first is an 'OR' input, signifying that one, or some, but not all of the activities entering a node are necessary to realize the node.[1] The second additional logical feature is a 'PROBABILISTIC' output. These additional features provide a flexibility hard to find in any other network technique, especially CPM and PERT; CPM and PERT are project management information systems. Also, GERT does not use only beta distributions for activity durations as PERT. It permits a wide variety of probability distributions.

In addition to these features GERT has the capability of modifying its own network by the removal of designated branches relative to the occurrence of specific events. Such flexibility allows for accurate representations of real-life systems. An extension of the basic GERT concepts, Q-GERT,[1] allows for networks which contain nodes with storage capability. This in effect provides for queuing possibilities.

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[1]See description of GERT and Q-GERT in Appendix A.

Q-GERTS is the simulation approach to the analysis of a Q-GERT network.

1.31 PRESENT APPROACHES TO TUNNEL SIMULATION

Recent developments in simulation related to construction have revealed modularity as a significant feature of the simulation model (27). One interesting application of such an approach has been presented by Halpin and Happ (12). Here network elements are combined to build modules which frequently recur in the modeling of construction operations and processes.

The basic structure of computer simulation programs consists of (16);

1. A geology model to produce detailed and consistent representations of realistically complex geology.
2. A tunneling model to simulate any one of several excavation systems.

A simulation program employing the modular approach might have two modules corresponding to the above basic structure, or it may have several modules as the result of breaking down the fundamental structure. Also, the fundamental structure may be extended to include a cost estimating system. Hence the overall purpose of such a simulation model is to identify and provide a framework suitable for evaluating the cost and merits of various tunneling equipment systems. A computer program in present use, although not strictly a simulation program, has aided such evaluation. It is a program for estimating cost of hardrock tunneling (51).

1.32 LACK IN PRESENT APPROACHES TO TUNNEL SIMULATION

One very obvious lack in present approaches results from not having a problem oriented computer language for use in simulating a tunneling system. Such a lack requires the use of simulation languages not designed specifically for tunneling. GPSS is an example. Hence a tunneling contractor wishing to use simulation to evaluate a proposed tunneling system has to be familiar with simulation languages not wholly designed for his field of endeavour.

A second lack is that present approaches do not relate to any basic network representing tunneling operations. Most tunneling contractors are experienced in network representation as the result of work with CPM and PERT. Indeed most could very quickly prepare a network depicting a tunneling system far more easily than preparing a simulation program. Thus the ability to simulate a network representing a tunneling system would render a contractor capable of tunnel simulation.

A third lack comes from the inflexibility of some simulation models (16). All components and their individual elements are rigid in relation to the tunneling system. This does not allow adequate expression of the difficulty in undersea tunneling where geology connot be predicted with a reasonable measure of certainty. Consequently the prudent use of contractor experience in selecting equipment for tunnel construction is negated. To take full advantage of such information the simulation model should be less deterministic and employ a more probabilistic approach. Such an approach has been used by Halpin and Happ (12).

A fourth lack is in the area of cost planning (28). This is supposed to be perhaps the most important phase of any simulation - the actual calculation of cost. But again its whole relationship to the simulation is too deterministic. The final, delicate adjustment in costs, resulting from contractor experience, is lost due to program rigidity.

To produce a computer tunnel construction simulation program which eliminates all the basic deficiencies mentioned above would certainly be an accomplishment. Such a program would be well underway to becoming an effective tool in tunneling simulation. But this tool may be long in coming due to the immense task of combining the knowledge of experienced design engineers and contractors with endless research into selection of computers, computer languages, cost estimating systems and networking techniques. Thus an alternative approach is necessary; to look at not all the lacks in present approaches to tunneling simulation, but only some of them. To utilize contractor familiarity with networks and reflect uncertainty associated with tunnel construction, necessitates consideration of the second and third lacks above. These can partially be eliminated by using a simulation technique based wholly on networks and permitting the contractor to have more 'experience input' to the computer program. Such input would be possible by having a probabilistically oriented approach rather than a deterministic one. This combination of network representation and probabilistic approach is the basis of GERTS, a simulation technique mentioned earlier. Hence GERTS is a likely choice of method to simply represent the tunneling system and model its functioning. But since representation of tunneling operations will involve queues, then an even more likely choice of simulation technique will be Q-GERTS. For tunneling contractors already knowledgeable in the networking procedures of CPM and PERT, Q-GERTS provides familiarity as well as introducing new concepts which are the basis of wide ranging simulation possibilities.

1.4 STATEMENT OF PROBLEM

Having thus defined the system, presented inputs and outputs and discussed tunneling system simulation with its various lacks, it remains only to state the problem of selection of tunneling method and equipment in terms of the tunneling system as defined above. Hence the problem is to develop a Q-GERTS based computer model which simulates the tunneling system relative to previously mentioned constraints and records its functioning under various methods of tunneling using various pieces of tunneling equipment in an effort to improve selection of tunneling method and equipment.

1.41 OBJECTIVES

The objectives of the computer model should be,

1. To model the tunneling system using Q-GERT networking techniques and simulate it by Q-GERTS.
2. To have the simulation model fairly flexible so as to allow for different contractor inputs in the form of information files.
3. To have the simulation model obey the tunneling system constraints.

1.42 REQUIREMENTS

To meet the stated objectives requires a conceptual model of the tunneling system based on a Q-GERT network and a computer program utilizing Q-GERTS to simulate the system.

CHAPTER 2

2. Q-GERT NETWORK

Each section of the tunneling system may be represented by a Q-GERT network involving probabilities, activities, time distributions and other Q-GERT characteristics. To aid in understanding the functioning of each section, a modular approach has been adopted. Consequently each section is depicted in terms of small, compact clusters of Q-GERT networks called modules, categorizing the basic logic of the particular tunneling operation represented by that section. Also, since sections are linked to create an overall system network, three levels of networking may be recognized. These are;

1. The tunneling system network containing sections corresponding to system components.
2. Subnetworks representing the sections and containing modules.
3. The modular networks.

Figure 2.1 illustrates the tunneling system network.

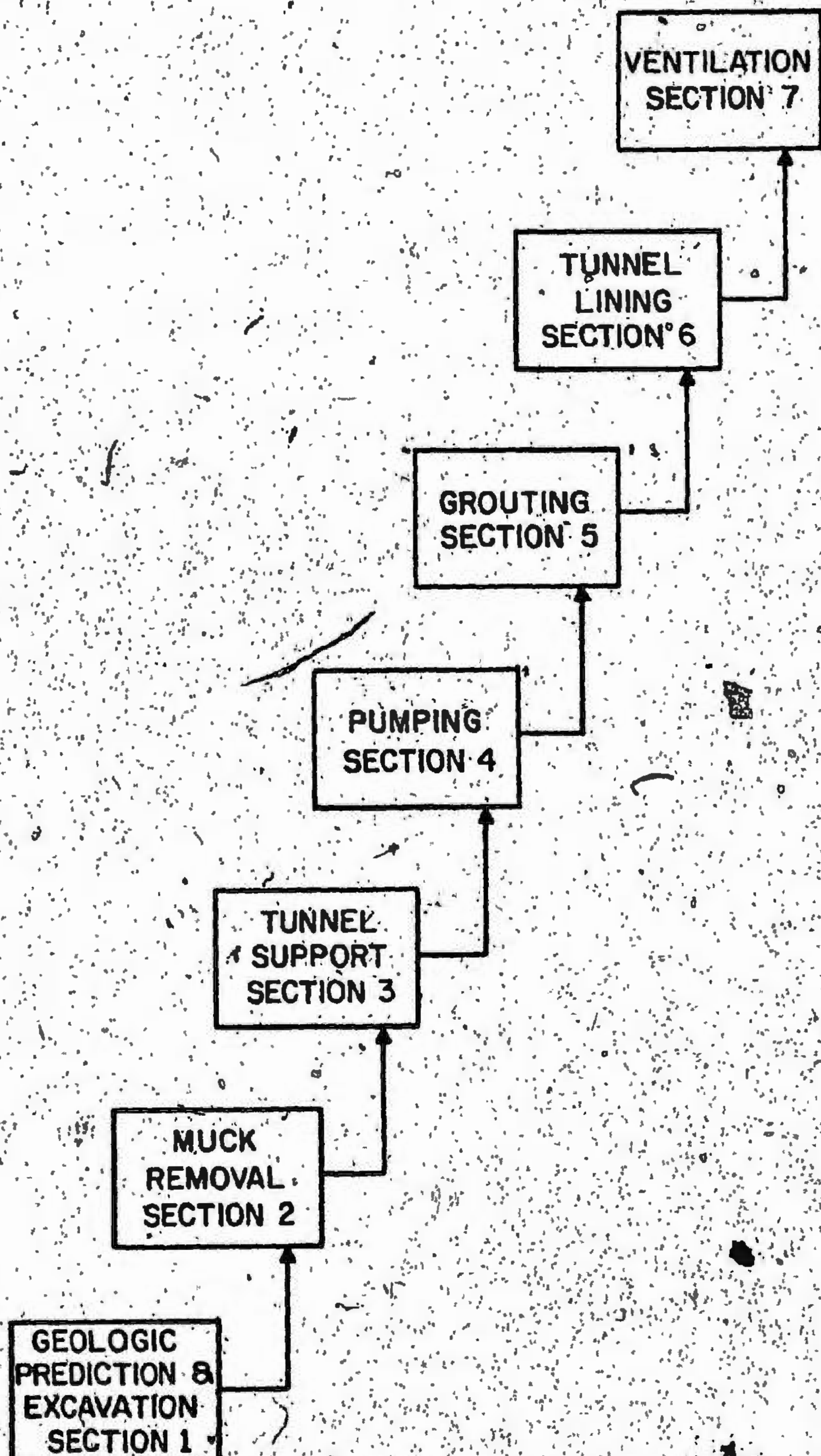

Figure 2.1. Tunneling System Network.

2.1 GEOLOGIC PREDICTION AND EXCAVATION (SECTION 1)

This section initializes representation of the Q-GERT tunneling system. Within it is determined the type of geology which may be encountered and the type of tunneling method to employ, relative of course to user knowledge and experience. Once determined the time to tunnel thru some specified distance can be arrived at and the remaining sections of the network dealt with.

Section 1 introduces the module concept and the numbering system employed to distinguish modules. This system utilizes two numbers and an uppercase M arranged as, number M number. The first number represents that of the section, the M indicates reference to module and the final number is that associated with the module. Thus 3M4 is the fourth module of section 3. Such numbering is employed to help locate various functions within the network.

The geologic prediction and excavation section also introduces the concept of working length.

2.11 WORKING LENGTH

The working length of tunnel[1] is a standard fixed length of tunnel used as the basis of various calculations.

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[1] Alluded to in Chapter 1 as tunnel interval.

In connection with geologic prediction and excavation it is the distance the tunnel face advances as the result of each Q-GERTS complete simulation run[1] of the tunneling system. Of course the time for this advance may vary with each complete simulation. Once it may take 2 hours to advance the working length while in another simulation run it might take 40 hours. In any event the working length - unit of tunnel progress per complete simulation - remains fixed. Moreover the working length is independent of the number of operations required to produce a portion of tunnel. If the conventional method is employed in construction for example, in one instance it might take 10 cycles of drill-blast-muck to go the working length, while in another it might take 50 cycles. Again the working length is fixed, the number of cycles vary.

The working length concept parallels real life in that it provides a length base allowing simulation (construction) to proceed in a step-like manner. It differs by having every step (for convenience) of the same length.

Consider a 5000 foot tunnel with a working length of 100 feet. Then each complete simulation run of the network representing the tunneling system will automatically advance the tunnel face 100 feet and arrive at a time for this

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[1]A complete simulation run is the net result of a definite number of simulations of the entire tunneling system. For example, a complete simulation run may consist of 10 simulations, the values for that run being a summary of values for the 10 runs. The definite number of simulations - 10 in this case - is referred to as the number of simulations per working length.

forward movement relative to the excavation method employed. Hence there will be 5000/100 or 50 complete simulation runs required to simulate the actual construction over 5000 feet. In this regard if it is wished to have 100 complete simulation runs then the working length must be 5000/100 or 50 feet. Now each complete simulation run will advance the tunnel 50 feet and consequently arrive at a time relative to this figure. In deciding upon a working length the user[1] must consider computing time and simulation accuracy. Generally speaking, the more complete simulations that are performed, the greater the accuracy of the overall simulation,[2] but with an attendant increase in computing time. Likewise for the number of simulations per working length. Thus a trade off between accuracy and computing time will result, involving statistics, the program user's individual tunneling experience and his knowledge of computers.

The principle of working length is applicable to all subsequent sections. However it does not vary from section to section ; it is fixed for the entire system. Thus if section 1 has a tunnel working length of 50 feet then so do all others. With regard to section 1 a time is produced which represents that required to advance the tunnel a

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[1]This is a person using the computer model (or program) proposed in Chapter 1 and discussed in Chapter 3, the basis of which (a Q-GERT network representation of a tunneling system) is described in this chapter.

[2]The number of simulations (sample size) for a desired accuracy may be found by statistics.

distance equal to the working length. As applied to section 7 a time is produced which represents that required to install ventilation equipment in a length of tunnel equal to the working length.

Illustrations in this report use 100 feet as a tunnel working length and is an arbitrary choice.

2.12 STRUCTURE

The structure of section 1 furnishes the basic logic for selection of an excavation time relative to geologic conditions, tunnel shape and size, and method of excavation. The time selected is that required to extend the tunnel face thru the working length using either the conventional or tunnel boring machine method. Fundamental geologic conditions considered are;

1. Rock Quality Designation (RQD)
2. Rock Strength (RS) in pounds per square inch (psi)
3. Groundwater Inflow (GI)

There are three ranges of RQD which may be utilized in a tunnel construction project; 75-100, 50-75 and 25-50 (51). These in turn employ two ranges of rock strength; 0-30,000 psi and 30,000-100,000 psi. Hence the logic of section 1 follows six paths resulting in six modules as shown in Figure 2.2.[1] In each module the rock strength range is related to either the conventional or tunnel boring machine method of excavation. A generalized module is illustrated by Figure 2.3. If the conventional method is used for tunnel construction then either a horseshoe, basket-handle or circular shape tunnel may result. For a tunnel boring machine the shape is circular. In any event the next portion of the module deals with tunnel size, followed by determination of groundwater inflow.

The Q-GERT network for section 1 when subjected to Q-GERTS yields an excavation time. The time distributions necessary to accomplish this are associated with the groundwater inflow branches of the network. Hence this section has 96 time distributions.[2]

Which branches are traversed during a simulation run thru the section depends on the probabilities attached to the branches.

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[1]Refer to reference 51. Graphs used to derive an advance rate have nearly all their curvature in the 0-30,000 psi range. Beyond 30,000 psi, curves approach straight lines parallel to the x-axis and have little effect in determining advance rate.

[2]There are 16 groundwater inflow branches in each module and there are 6 modules. Thus a total of 16 x 6 = 96 branches.

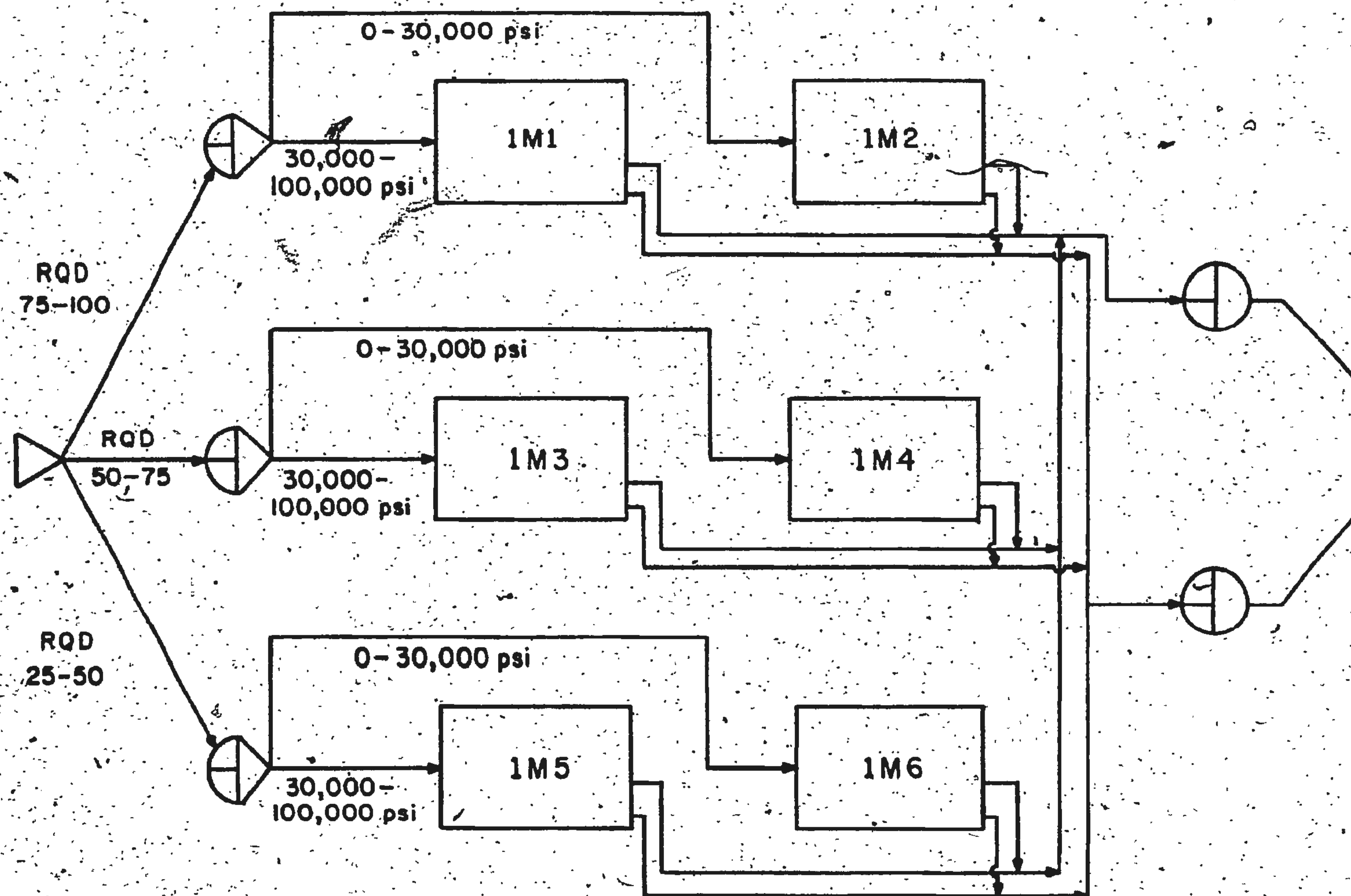

Figure 2.2. Section 1 Logic.

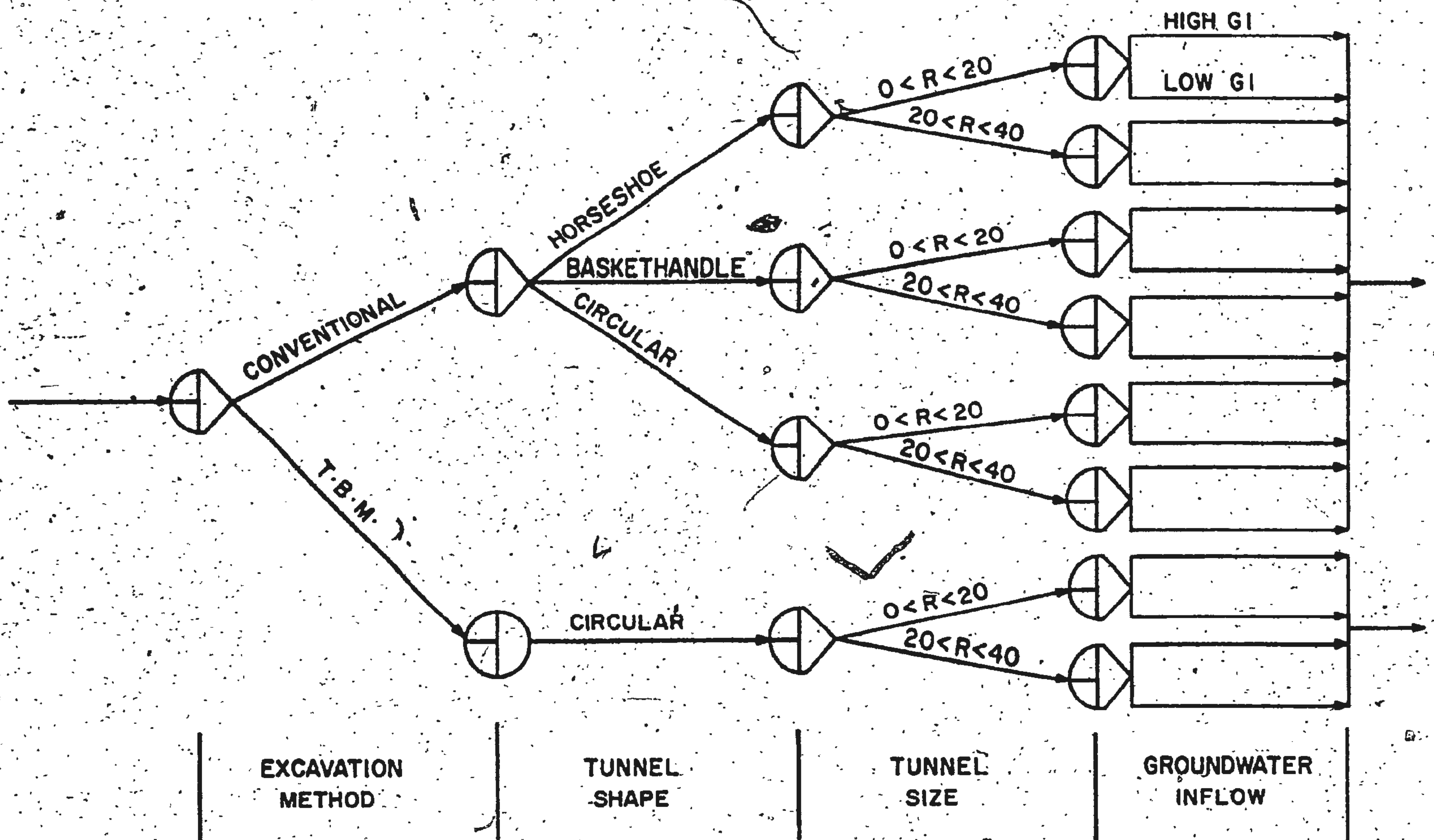

Figure 2.3. Generalized Module Section 1.

2.121 PROBABILITIES

The probabilities associated with the branches are entirely controlled by the network user. For example, should the user be absolutely certain that the RQD ranges between 75 and 100, and that the rock strength is definitely between 30,000 and 100,000 psi, then the 75-100 branch has an associated probability of 1.0. Likewise for the 30,000-100,000 psi branch. Other branches having RQDs and rock strengths have zero probability. If on the other hand, the user does not know the geology, or if he wishes to test the effect on time and cost estimates of different types of geology he expects to encounter, he may attach corresponding probabilities to the branches. For example, if geology is unknown then the 75-100 branch might have a probability of .33 and so would the 50-75 and 25-50 branches. The branches representing the possible rock strength might each have a probability of .50.

Within each module the same reasoning would apply. For example, a contractor might know for certain that the excavation method is conventional, the shape horseshoe, the size within the 0-20 foot range and the groundwater inflow high. Hence each of these branches will have a probability of 1.0.

2.122 TIME DISTRIBUTIONS

In section 1 the time distributions are associated with the groundwater inflow branches and are normal unless otherwise specified.[1] The choice of normal is based on the fact that this distribution is very common and where more accurate geologic information is not available, can be used without much regard for gross errors in a suitable advance rate.[2]

According to the Q-GERTS documentation a normal distribution type is described by four parameters. These are;

1. Mean value
2. Minimum value
3. Maximum value
4. Standard deviation

These values are related to excavation times in that the mean value is the mean excavation time while the minimum and maximum values are the minimum and maximum excavation times.

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[1] Association with the groundwater inflow branches comes about because these branches (not the activities they represent) are the result of all possible combinations of excavation method, tunnel shape and size and groundwater inflow.

[2] Although the computer procedure described in this report utilizes the normal distribution, if circumstances demand, other distributions may be used with a minimum of change.

Excavation times to satisfy distribution parameters are developed from mean tunnel advance rates.

2.1221 MEAN ADVANCE RATE

The mean advance rates are calculated using the National Technical Information Service publication entitled, A Computer Program For Estimating Costs of Hard Rock Tunneling (COHART).[1] Once obtained the rates are then converted to mean excavation times.[2] The mean advance rates and mean excavation times for 1M1 are illustrated in Appendix B.

2.1222 MINIMUM AND MAXIMUM EXCAVATION TIMES

The minimum and maximum excavation times are considered to lie equidistant from the mean.[3] Thus assuming the minimum to approach zero as a lower limit, the maximum must

[1] See reference 51.

[2] Pertinent graphs and formulas as well as illustrative calculations with resultant mean advance rates and conversion to mean excavation times are contained in the backup report entitled, "Computer Program Documentation for Q-GERTS Simulation of Hardrock Undersea Tunneling."

[3] This is in keeping with the symmetry of the normal distribution. Change may be effected with a minimum of Q-GERTS data alteration.

approach a value equal to twice the mean for an upper limit. As a result, time distributions in section 1 have zero and 2 x mean for minimum and maximum excavation times respectively.

2.1223 STANDARD DEVIATION

A large standard deviation produces a low, wide normal distribution which indicates a great variation of excavation times associated with a groundwater inflow branch in either module of section 1. A small standard deviation produces a high, narrow normal distribution indicating very little variation of excavation times from the mean excavation time.

For the purposes of the Q-GERT network developed here, a standard deviation will be used which is equal to that of the standard normal distribution. Unless a contractor has, from experience or estimates, developed his own set of standard deviations for each groundwater inflow, it will be assumed that all these branches each have a standard deviation of 1 hour. This is effected merely for convenience and does not reflect any statistical analysis.[1]

[1] An alternate method to get a standard deviation may be employed as desired.

2.123 STATISTICS NODES AND RELEASES

There are no statistics nodes in section 1. The number of releases and the number of releases to repeat is one for all nodes.

Module 1M1 with complete Q-GERT notation is contained in Appendix C.[1]

2.2 MUCK REMOVAL (SECTION 2)

The fundamental operations of section 2 are the production of muck and its subsequent loading and removal (transportation). The fundamental operations of sections 3 to 7 involve the transportation and placing of tunnel support, pumping equipment, grout, tunnel lining and ventilation equipment. Thus all aspects of tunneling reduce to transportation and material loading (section 2) or material and equipment placing.

Because of the number and types of devices used in transportation and placing (placing system) in each section, no one selection is incorporated into the Q-GERT network. Instead flexibility is maintained to allow greater user influence. This is partly reflected thru the concept of

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[1]Modules 1M2, 1M3, 1M4, 1M5 and 1M6 are found in the backup report, "Computer Program Documentation for Q-GERTS Simulation of Hardrock Undersea Tunneling." These modules are identical in structure and perform a similar function.

levels introduced in section 2.

Muck removal involves eight transportation levels and six system levels. These apply to a type of transportation and a type of loading system as selected for simulation by the program user.

2.21 TRANSPORTATION LEVEL

The first aspect of transportation level involves capacity and may be introduced by considering an example. Suppose a tunneling contractor has decided to use trucks with a 10 cubic yard capacity as a type of transportation in the removal of muck.[1] Each time a truck is loaded the amount of muck it contains will not consistently be 10 cubic yards. Load size will vary, perhaps due to the loading method used, the experience of the loader operator or the type of muck being removed or some combination of these factors. Variation in load size might also occur due to transportation conditions inside the tunnel. If the traveling surface is smooth and level offering a low rolling and gradient resistance, the truck may be loaded to its rated capacity. On the other hand if the traveling surface is not level and has protruding rocks that make it difficult to drive over, then the capacity of a truck may in effect be

[1]Type of transportation and transport type are used interchangeably.

reduced in order that driving conditions be negotiated. This is equivalent to using a smaller capacity truck. Such a restriction would not necessarily be in force for the entire tunnel length and it will not be applicable over the total duration - if it were selection of a different means of transport would be in order - but only for certain portions.

These changes in the truck's capacity produce several transport capacity levels or TC levels. The levels and associated occurrence probabilities are decided by the program user. Possible TC levels for a truck may be as follows;

Level	Capacity (cu. yds.)	Probability
1	8	.02
2	9	.01
3	10(rated capacity)	.90
4	11	.06
5	12	.01
		1.00

The idea of TC level applies only to sections 2,4 and 7. Section 2 allows for five TC levels since it is felt that at the muck loading stage in undersea tunnel construction, loading and transportation problems could conceivably produce more capacity variation in any transport type than at the installation of pumping (section 4) and ventilation (section 7) equipment stages since pieces of equipment can be easily counted, providing some degree of precision in loading a transport device to its rated capacity, and since by the time ventilation equipment is to be installed, the traveling surface is usually in better condition than at muck removal. Sections 4 and 7 have three TC levels.

It should be noted that TC levels apply not only to truck but also train and conveyor[1] transportation.

The second aspect of transportation level concerns area and is applied to sections 3, 5 and 6. Again an example may prove helpful. Condider section 3 - tunnel support. If trucks are being used to carry rock bolts to the bolt placing machines and job and management conditions are good, then a truck may carry enough rock bolts to service a 900 sq. ft. area of tunnel. If geology changes and/or job and management conditions alter, then a range of transport service areas or TA levels develop. The levels and associated probabilities are chosen by the program user. Possible TA levels for truck transportation might be as follows;

Level	Area Serviced(sq. ft.)	Probability
1	200	.05
2	500	.05
3	900	.80
4	1200	.09

[1]For conveyor the TC level is based on a length of conveyor equal to the tunnel working length.

Level	Area Service(sq. ft.)	Probability
5	1800	.01
		1.00

All methods of support in section 3 have five levels. Sections 5 and 6 have three TA levels with each method of section 6 exhibiting the three levels. TA levels also apply to train transportation.

The third aspect of transportation level rests with the number of transportation units involved in any haulage within the tunneling system. Perhaps inside tunnel operating conditions at one point allow four trucks to participate in materials transportation whereas at another point ten trucks may be utilized. Consequently a variation in the number of transportation units results, a variation which may be categorized via levels, in this case transportation unit levels or TU levels. Sections 2 to 7 of the tunneling system have three TU levels applicable not only to truck but also train and conveyor.

The fourth and final aspect of transportation level concerns the time at which the information inherent in the levels is entered into actual tunnel construction simulation and whether or not this information is updated as simulation proceeds the length of the tunnel.

Firstly, all transportation levels for a single transportation type and a single method of support and lining are entered and used in simulation at the very outset.[1]

Secondly, as simulation is carried down the length of tunnel only the TC levels for truck and train associated with sections 4 and 7 can be altered by having new values for carrying capacities entered. The only way any amount of control can be extended over the TA levels is indirectly by varying the fraction of tunnel circumference requiring support, grout and lining as the simulation proceeds. TU levels do not change either directly or indirectly from the values entered at the start of simulation; likewise for occurrence probabilities.

Thirdly, the only definite way apart from the TC level, to pass geological, transporting surface condition and loading variations as they affect transportation levels to the actual simulation, is immediately at its start and by a judicious choice of level values and probabilities.

Any user wishing to negate this multilevel structure may do so by selecting one TC, TA and TU level and associating with it a probabiltiy of 1.0.

[1]All transportation levels for all transportation types in all sections is originally prepared and stored. One transport type and one method is selected only.

2.22 SYSTEM LEVEL

Suppose a tunnel contractor is using a muck loading system composed of five front-end loaders. If space limitations within the tunnel permit, then all five loaders may be in operation simultaneously. Should proper space not be available or mechanical difficulties arise, the number of active loaders will decrease. Also a change in TC level may produce a corresponding change in loaders needed to fulfil the loading task. Hence there is inherent in loading a variation with respect to the number of loaders. Such variation results in possible system levels or S levels.

The loading system may not only be composed of a single loading device but several. For example the system may contain two front-end loaders and one conveyor loader. If such were the case the total number of loaders at any level would result from x front-end loaders and y conveyors. Thus the particular structure of S levels is left entirely to the person using the program.[1] But whatever the structure the simulation user must keep it in mind when time and probability values for system levels are actually prepared for input to the tunneling simulation; likewise for trans-

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[1]No effort has been made to define different capacity levels for loading devices since the ultimate effect (introduction of a measure of real-life variation) is adequately achieved (for purposes of tunneling simulation herein described) thru the capacity levels of transport devices and loading system levels.

portation levels.

Section 2 has six S levels whereas the subsequent sections have only three. Also, these subsequent sections have their S levels referring to placing devices[1] and not loading devices as in section 2. The number of levels have been decided relative to system complexity associated with each aspect of the tunneling process.

System levels are entered and used in simulation at the outset and cannot change either directly or indirectly as tunnel construction is simulated. Likewise for occurrence probabilities. As with the TU level, loading and placing variations are passed to the simulation routine only by a wise choice of S level values and occurrence probabilities.

This multilevel structure as with transport type may be negated by using one S level and giving it a probability of 1.0.

2.23 STRUCTURE

The Q-GERT network for section 2 consists of five modules representing the logic involved in combining muck, transport type and loading system. It is shown in Figure 2.4.

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[1] A placing device may be a machine, several machines, a work crew or several work crews used in the installation of tunnel support, tunnel lining, pumping equipment, grout and ventilation equipment.

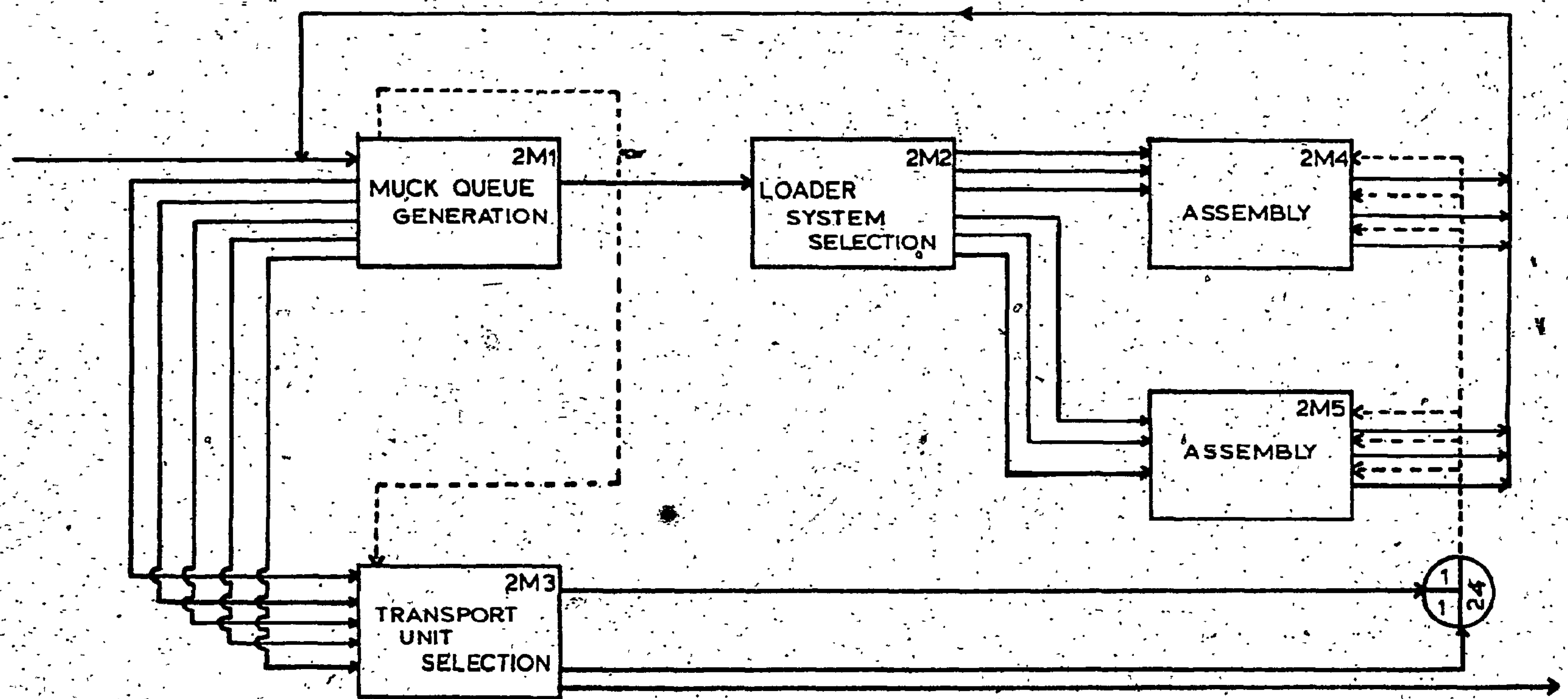

Figure 2.4. Q-GERT Network for Section 2.

2.231 MODULE 2M1

This module has the mechanism to select a transport capacity level for association with a transport type in order that muck be removed from the tunnel face, and also the mechanism to generate a definite muck queue. Figure 2.5 illustrates the Q-GERT network for module 2M1.

The muck queue is defined as the number of whole loads of muck contained in a length of tunnel equal to the working length. Thus the queue is subject to working length, transport type, transport capacity level, tunnel size and tunnel shape. These factors are combined outside the Q-GERT network to establish a definite queue. In doing so no allowance is made for probable tunnel collapse[1] which would produce instantaneous queues not resulting from any excavation via section 1. The procedure for obtaining a queue relative to the above factors is found in Appendix D. It is repeated for different factor values and the results filed for use when the Q-GERT network is simulated. Selection of values from the file is achieved outside the network and then plugged into module 2M1 at the appropriate locations during network simulation. Each simulation of the module may produce different muck queue values, but in any event, the Q-GERT network is fixed; values attached to nodes and

[1]Tunnel collapse is considered the exception rather than the rule in undersea hardrock tunneling.

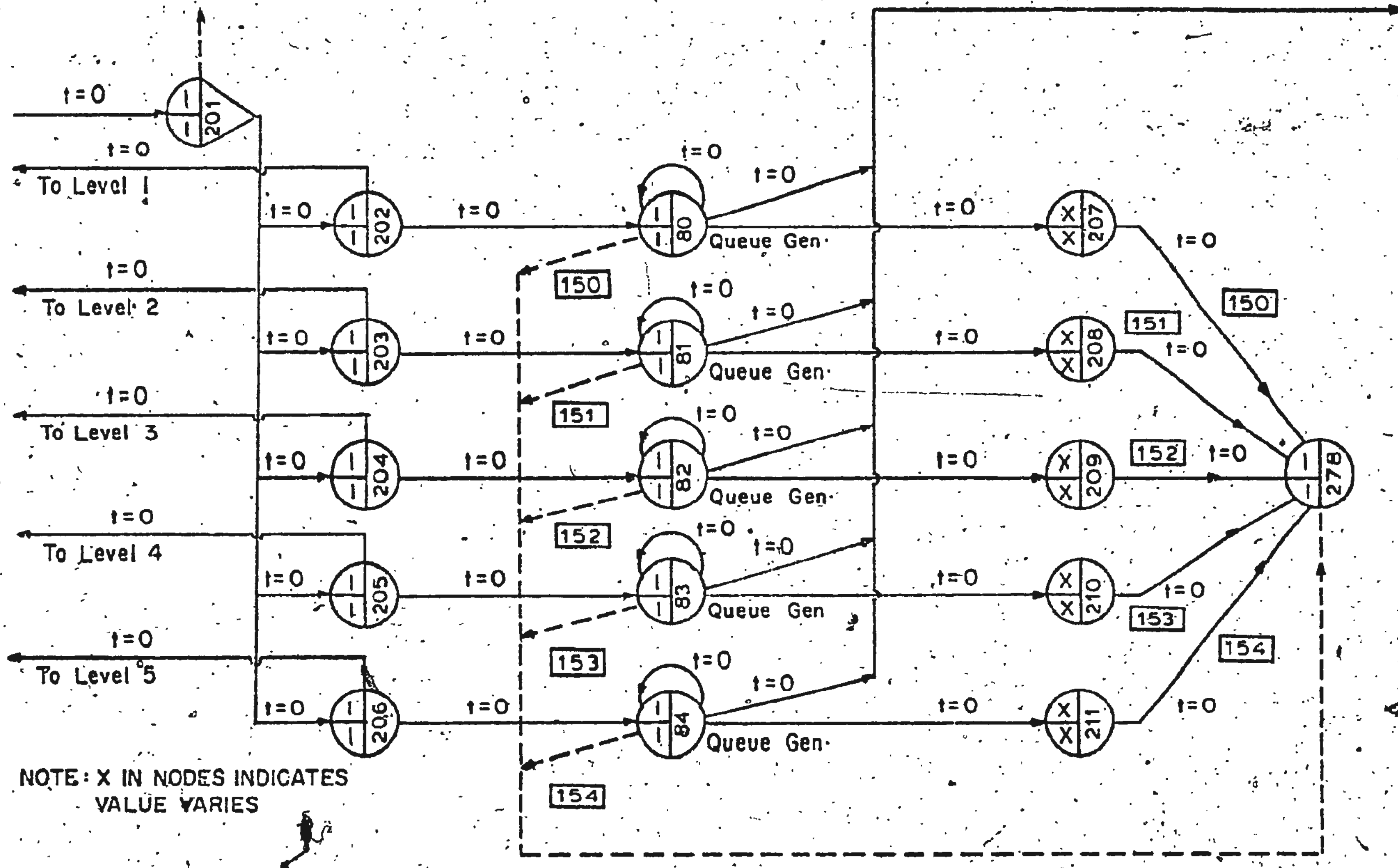

Figure 2.5. Q-GERT Network for Module 2M1.

branches change.

In Figure 2.5 node 201 is probabilistic and therefore the logic may follow one of five branches. Assume for illustration's sake that the branch from node 201 to node 202 is chosen. Node 202 is deterministic and hence both output branches are taken. One branch determines transport capacity level 1 and the other leads to node 80 which generates the muck queue subject to the queue size as contained in node 207 (x in position for number of releases and number of releases to repeat). The generated loads of the queue pass to module 2M2. Once the queue size has been reached, (activity 80-207 has been released x times) network logic causes node 278 to be realized which initiates the removal of the queue generator (node 80) and subsequent replacement[1] by node 278. Such replacement curtails the production of muck. Simulated removal is accomplished via the other modules of section 2.[2] The reasoning is similar had some other branch from node 201 been chosen. All branches have zero time.

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[1]This replacement modifies the network logic. Modules having such modification are modification modules.

[2]The muck removed by simulation is equivalent to physical removal in the real-life situation.

2.232 MODULE 2M2

The first run thru this module (first load of muck from muck queue generator in 2M1) causes selection of a loader system level from the six available. See Figure 2.6 and Figure 2.4. This initiates the replacement mechanism so that the chosen system level is held for all subsequent runs. Activities 12 to 17 lead to the various levels as represented in modules 2M4 and 2M5. The branches in this module have zero time.

2.233 MODULE 2M3

This module has two basic functions. They are;

1. To determine the number of transport units (TU level) to enter into the muck loading operation.
2. To determine the hauling, dumping and return times associated with each transport unit at the selected transport capacity level.

The Q-GERT network for module 2M3 is shown in Figure 2.7.

Following from module 2M1, assume transport level 1 has been selected. This brings the module logic to node 282. At this point both branches emanating from node 282 are traversed. The branch or activity 282-287 determines hauling

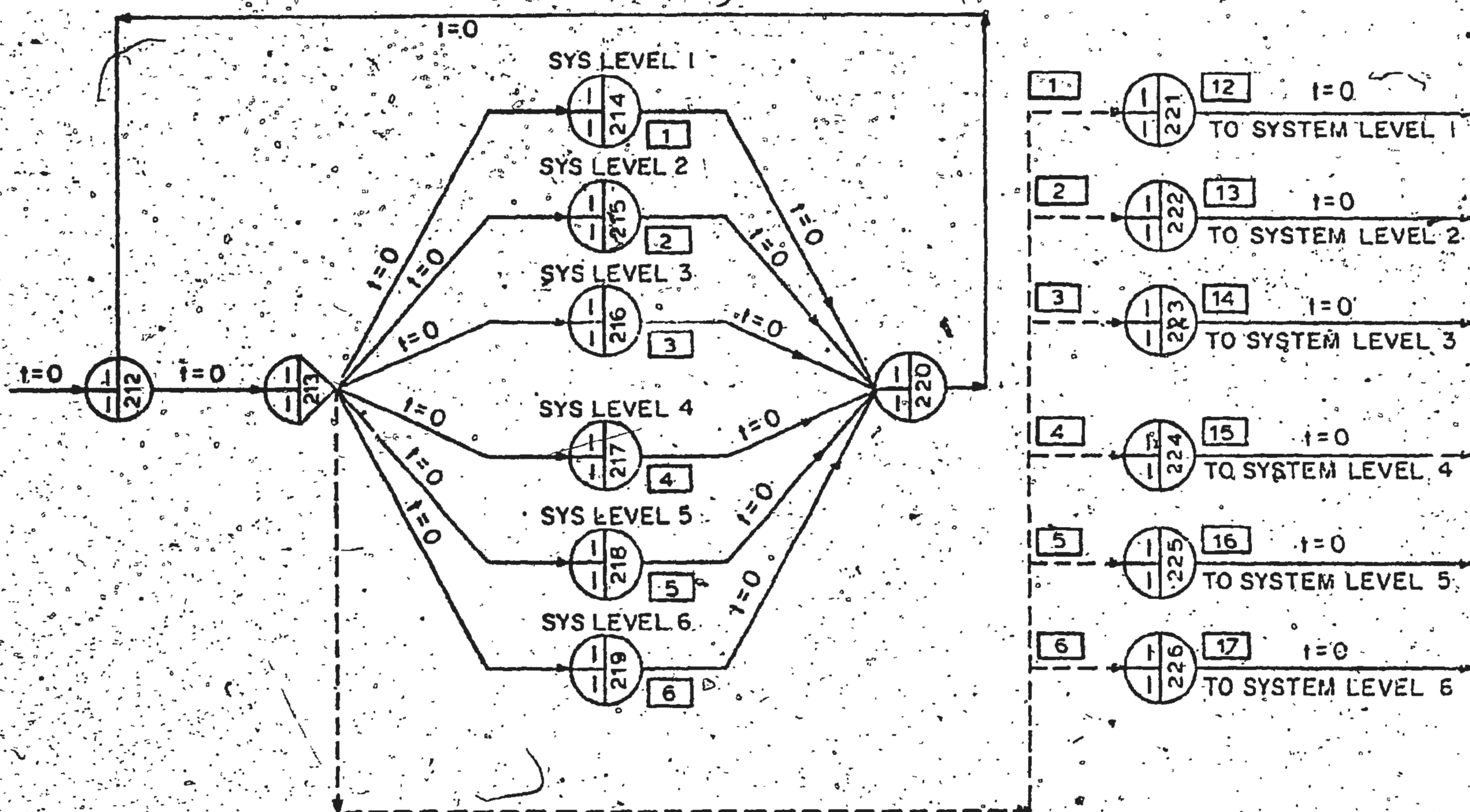

Figure 2.6. Q–GERT Network for Module 2M2.

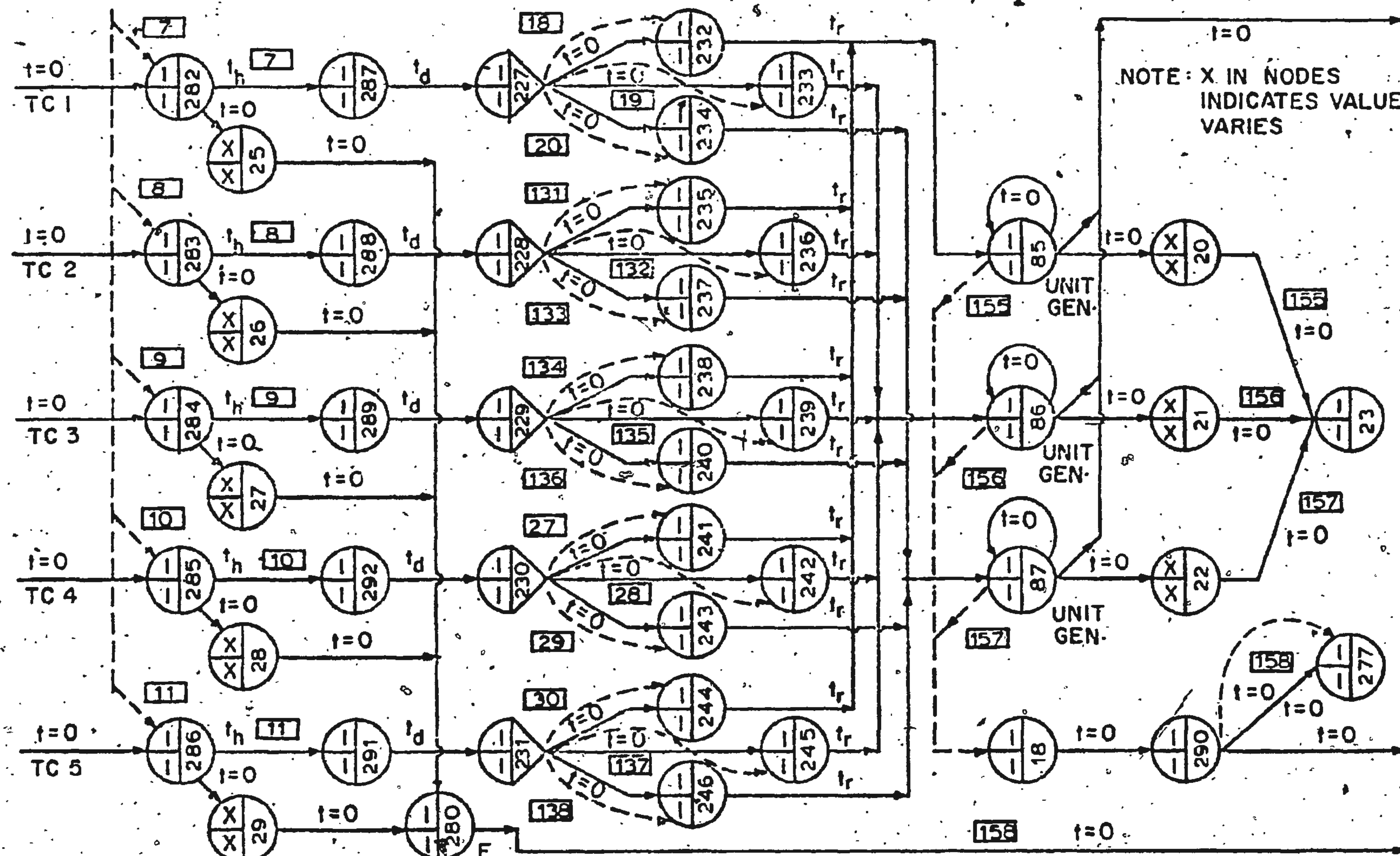

Figure 2.7. Q-GERT Network for Module 2M3.

time at level 1 while branch 282-25 has zero time. Once 282-287 has been released and node 287 realized, the logic of module 2M1 is altered by a replacement of node 201 with node 282. This assures that subsequent looping from modules 2M4 and 2M5 is brought thru module 2M3, preventing another selection of transport level before another simulation of section 2 is initiated. Realization of node 25 is achieved only after x releases of 282-25. The value x corresponds with x in node 207 of module 2M1 and assures that node 25 will only be realized (and consequently simulation logic carried to section 3 via 25-280 and activity 158) after all loads in the muck queue have been hauled away and dumped.

With the realization of node 287 the dumping time at transport level 1 may be determined and node 227 realized. At this point one of three branches representing transport unit levels is selected and the number of transport units at that level are entered into the simulation via the unit generator at node 85, 86 or 87. Assume TU level depicted by activity 227-232 is chosen. When this activity is released once, node 232 is realized and activity 232-85 is traversed with the transport unit return time being determined. Of course with the realization of node 232, modification is brought to bear and any further looping thru module 2M3 during a simulation run will always follow the TU level just selected. The mechanics of the unit generator is similar to that of the queue generator dealt with earlier. The units generated arrive at one of the system levels in modules 2M4 or 2M5 via network modification as illustrated in Figure 2.4. After generation is finished, network logic moves to node 290 then back to module 2M4 or 2M5.

With the realization of node 280 (statistics collected on the time of first realization) and the release of activity 158, logic proceeds to the next section and and node 290 is replaced by node 277 to terminate simulation of section 2.

The reasoning presented here may apply to any TU level in any transport level.

Activities in module 2M3 having associated time distributions are indicated in Figure 2.7 by t_h, t_d and t_r.

2.234 MODULES 2M4 AND 2M5

Modules 2M4 and 2M5 contain six levels of a muck loading system associated with section 2. They each have muck queues (determined in module 2M1), transportation type queues (determined in module 2M3) and loader queues (determined outside the network). The function of both modules is to assemble loads of muck, transport unit and loader system to simulate the muck loading operation. The networks for these modules are illustrated in Figures 2.8 and 2.9. The temporary resting time of the loader system after completion of a loading operation is represented by t_{lag}, the

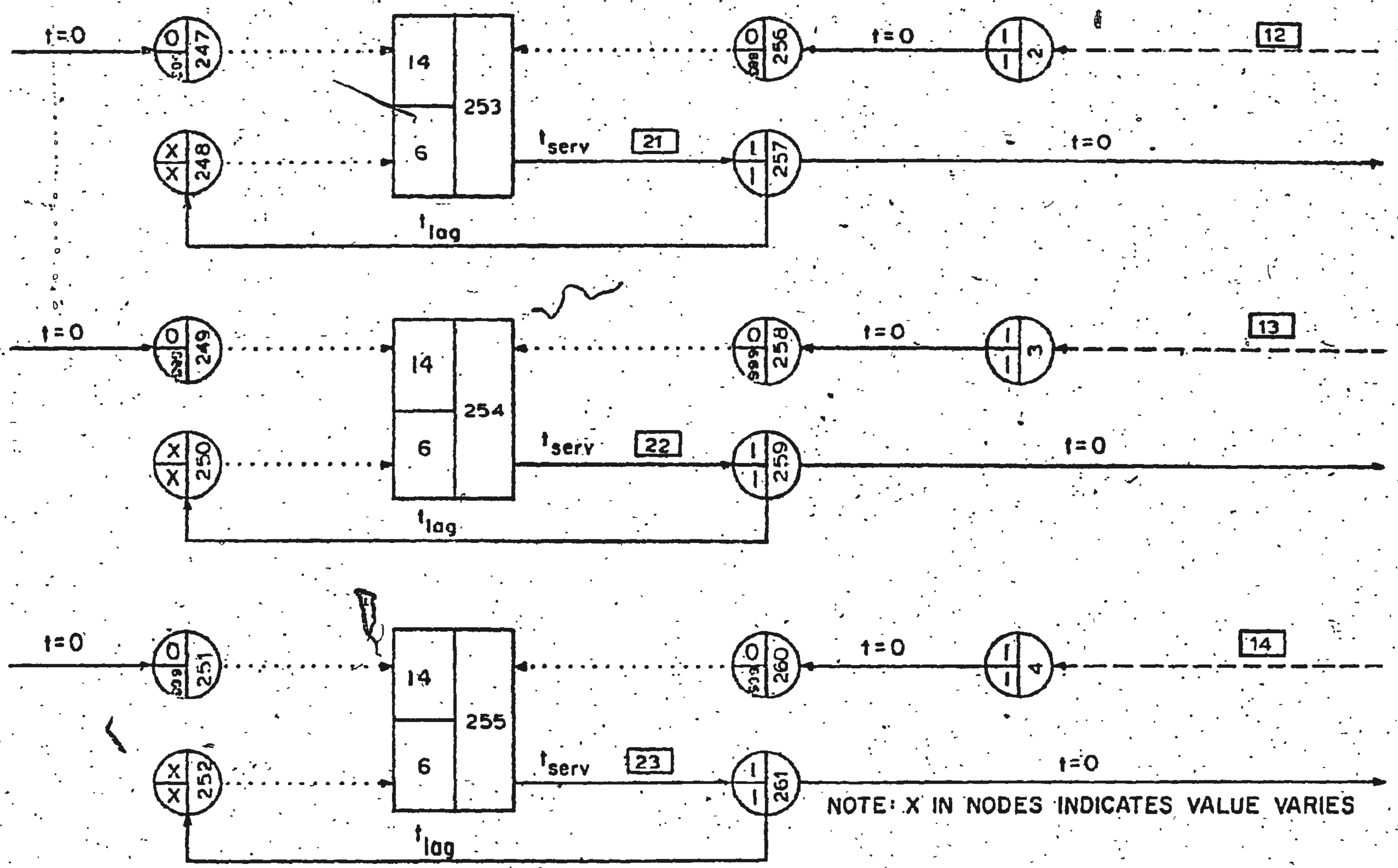

Figure 2.8. Q-GERT Network for Module 2M4.

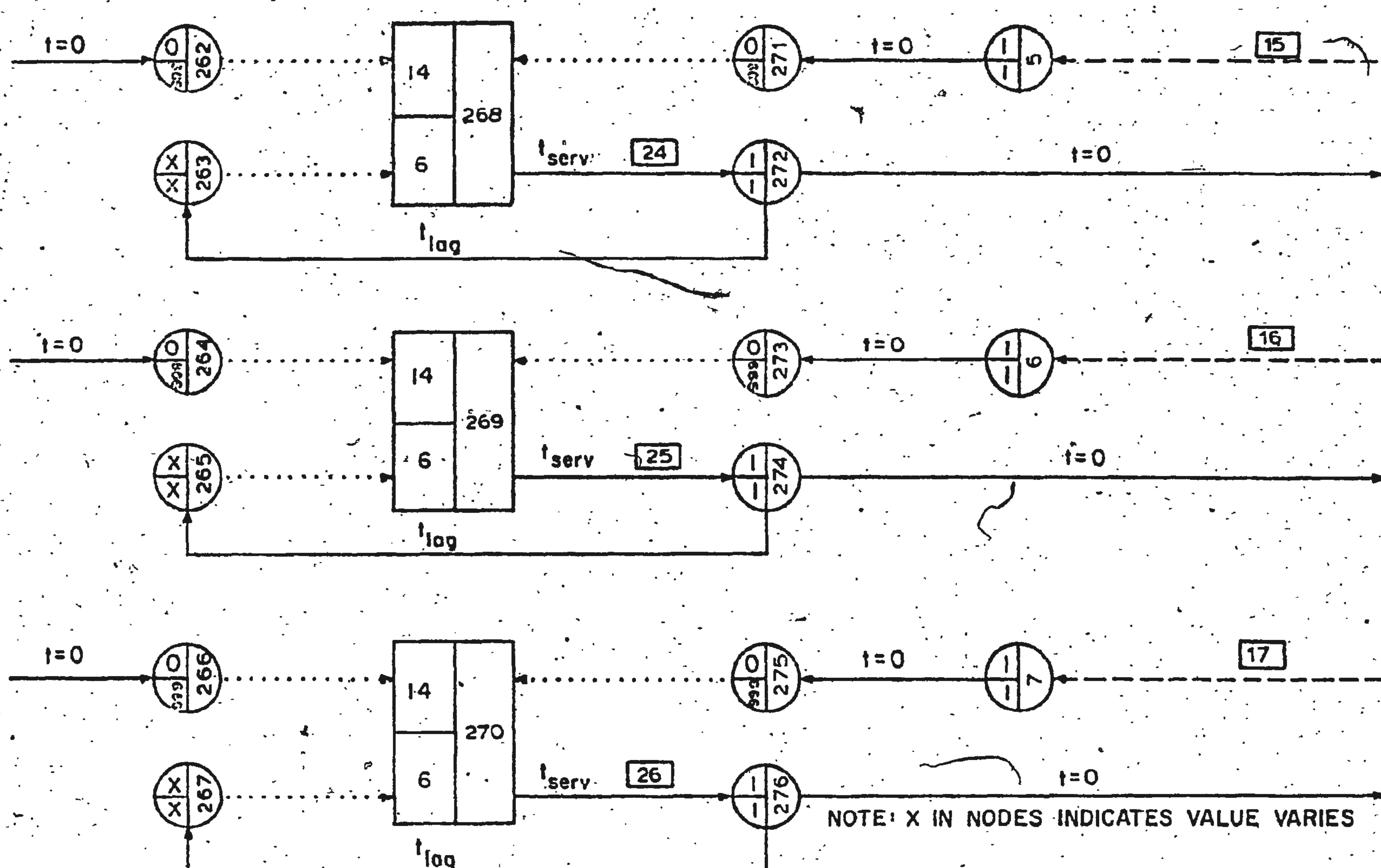

Figure 2.9. Q-GERT Network for Module 2M5.

service time by t_{serv}.

To understand the logic of modules 2M4 and 2M5, assume system level 1 has been selected, there are 10 loads of muck to be removed (0 in node 247 has been replaced by 10), there are 2 loaders in level 1 (x replaced by 2 in node 248), and there are 3 transport units (0 in node 256 replaced by 3). Node 253 then combines via the functions of Q-GERTS, 1 load of muck, 1 loader and 1 transport unit. Hence each queue in system level 1 is reduced by 1. If no loader or transport unit is available, the loading system remains idle. When the muck queue is empty, combination via the S-node ceases and simulation halts.

2.235 SUBSTITUTION

Suppose the operation of section 2 were simulated using trucks as the type of transport. Then all Q-GERTS data related to transport type would involve trucks. To accommodate a change to some other transport type, either train or conveyor, would necessitate different Q-GERTS data involving muck queues (the levels for train and conveyor will represent different capacities for muck), branch probabilities, TU levels, distribution parameters and perhaps distribution type. No network alteration would be required. Hence a simulation program capable of channeling the necessary network values into Q-GERTS, at user command, should expand modeling capabilities. Thus section 2 might represent truck loading, train loading or conveyor loading, depending on contractor wishes.

As a result of this data selection or substitution, files are maintained which store all relevant information pertaining to the use of section 2 for either truck, train or conveyor loading. These can be updated by a contractor at will and are used when the tunneling system is simulated. Further information regarding files is found in Chpater 3.

2.24 TIME DISTRIBUTIONS

Time distributions in section 2, as with distributions in section 1 are considered normal. This has been assumed since for tunnel construction simulation purposes, loading, hauling, service, lag, return, dump and exit times can be regarded as normally distributed, and not greatly affect the simulation results. However other distributions may be employed if conditions warrant it.

Distribution parameters are decided by the simulation user in accordance with knowledge and experience.

2.3 TUNNEL SUPPORT (SECTION 3)

This section of the tunneling system is represented by a Q-GERT network showing selection of a transport capacity level, TU level and system level to supply and install proper tunnel support. Three types of support are associated with this section. They are;

1. Rock bolts
2. Blocking and lagging
3. Steel sets

In general, all that has been previously said about probabilities, time distributions, statistics nodes, number of releases and number in queue as applied to section 2, also applies to section 3 and all remaining sections. Numbers may change but the basic idea remains the same.

2.31 STRUCTURE

Section 3 utilizes four modules to depict basic support operations. The Q-GERT network for section 3 is illustrated by Figure 2.10.

2.311 MODULE 3M1

This module selects a transport capacity level for association with a transport type to provide transportation

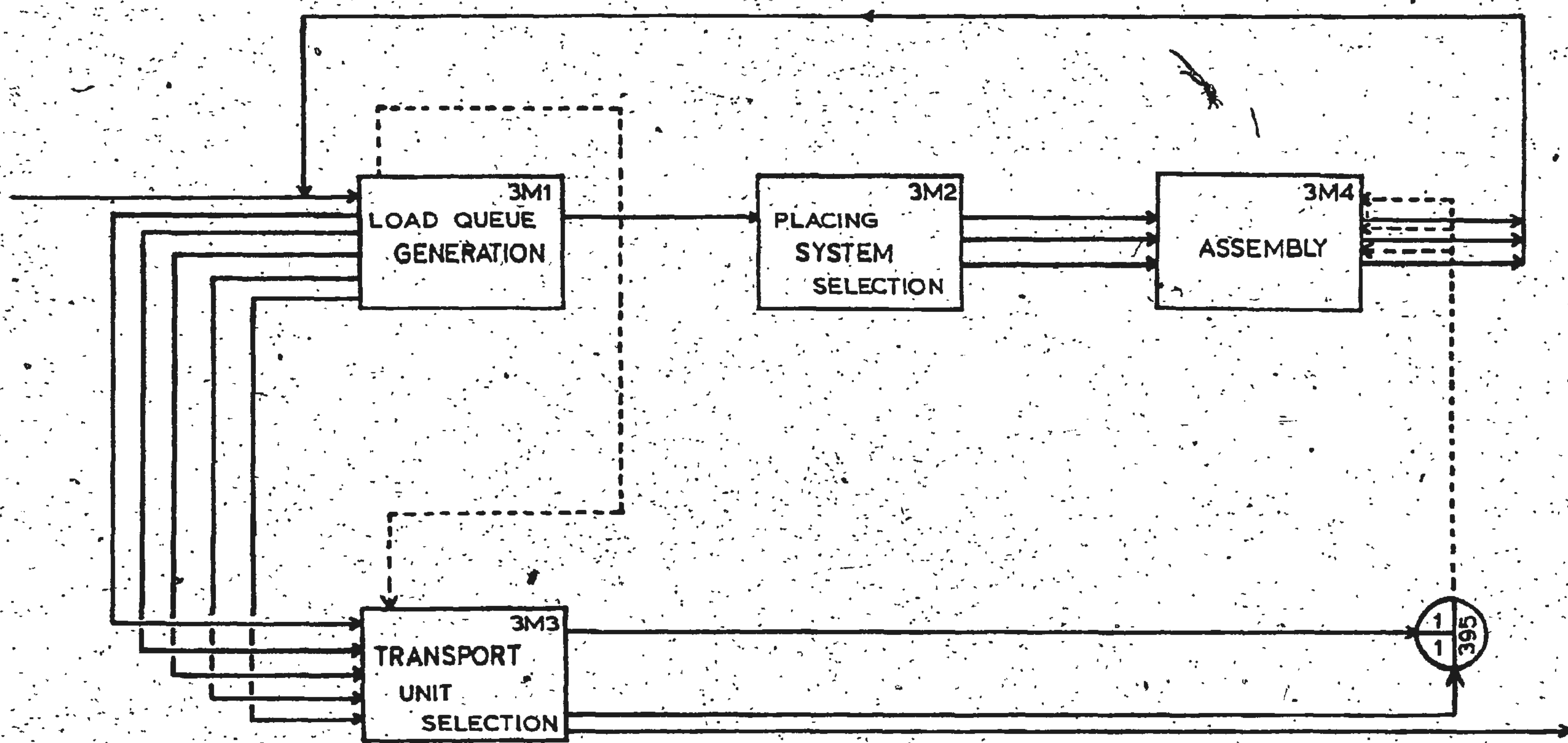

Figure 2.10. Q-GERT Network for Section 3.

of tunnel support materials to the tunnel face. It also generates a queue of loads. The module is illustrated by Figure 2.11.

2.3111 LOAD QUEUE

The load queue in section 3 is defined as the number of whole loads of support material (devices) required over the working length of tunnel. It is not only dependent on transport capacity level but also area of tunnel requiring support, that area being contained within the working length. Arriving at an area might be similar to the following calculation;

Example:

Tunnel shape = circular

Tunnel size = 20 feet diameter (characteristic dimension)

Working length = 100 feet

Fraction of tunnel circumference requiring rock bolts[1] = .5

Area to be rock bolted:

= .5 x circumference x working length

[1]For illustration, the method of support is considered to be rock bolts, and the fraction = .5.

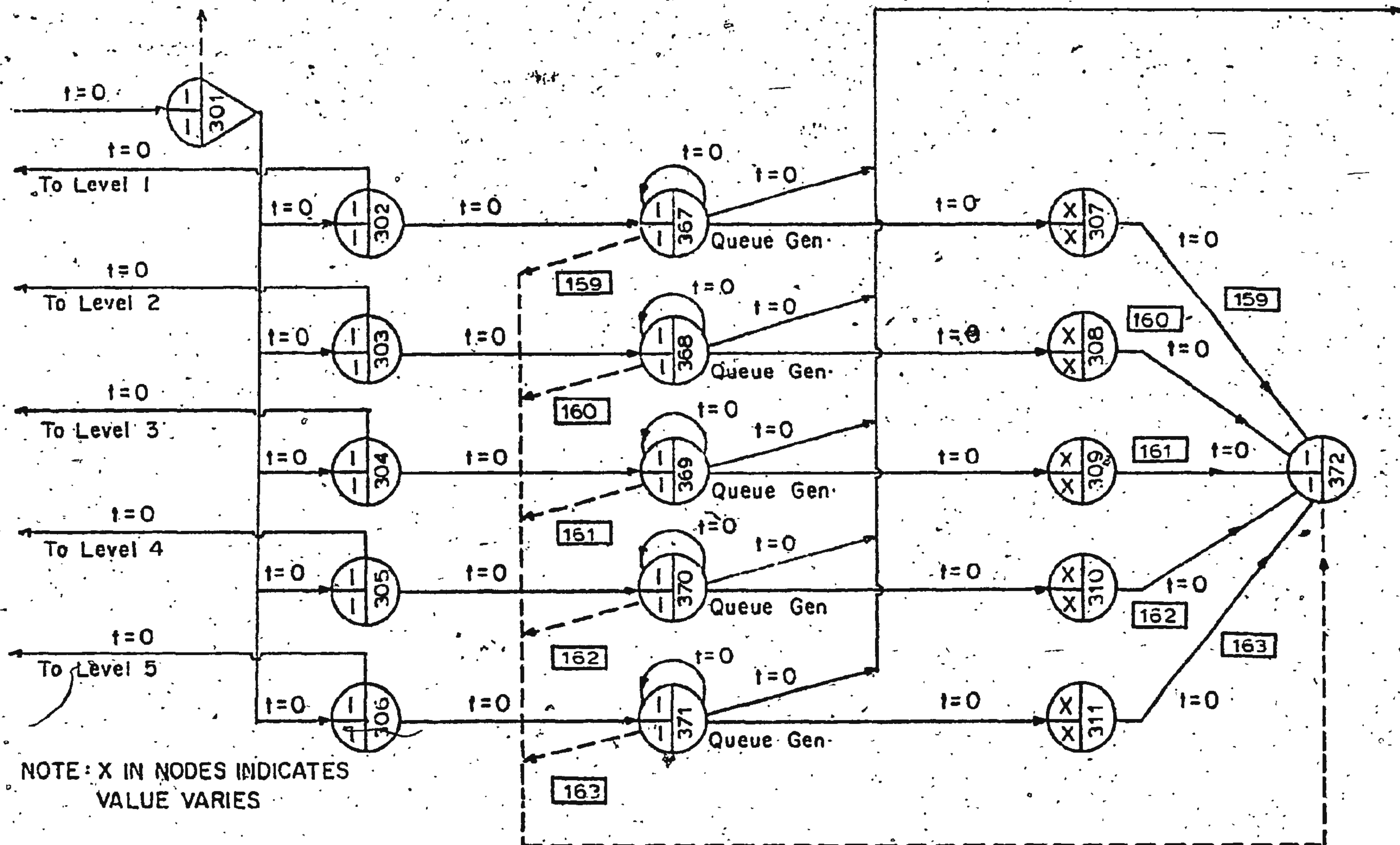

Figure 2.11. Q-GERT Network for Module 3M1.

$$= .5 \times 20 \times 3.1416 \times 100$$

$$= 3141.6 \text{ sq.ft.}$$

Having thus found an area, and assuming that the transport type[1] is operating at a level giving it a capacity of 1 ton, and that 1 ton of rock bolts services an area of 100 sq. ft. (in effect area serviced by the transport type), then a load queue can be calculated as follows;[2]

Example:

$$\text{Load queue} = \frac{\text{Area to be rock bolted}}{\text{Area serviced by transport type}}$$

$$= \frac{3141.6}{100}$$

$$= 30 \text{ loads}$$

This implies that 3141.6 sq. ft. of tunnel is waiting for 30 loads of rock bolts relative to the TC level of transport type. This queue of loads is different from the muck queue in section 2. The muck queue represents a queue of loads to be removed from the tunnel; the load queue represents a queue of loads to be brought into the tunnel. The queuing concept however is the same.

The above calculations are performed separate from

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[1]Transport type may be truck or train.

[2]These figures are used to illustrate the concept of load queue. Actual values would have to be supplied by a program user relative to competency of the rock.

the Q-GERT network for various values of the factors involved and the results filed. Before the Q-GERT network is simulated, a selection of load queue values from the file for the five transport levels, relative to specific data, is accomplished outside the network. This is similar to the muck queue selection of section 2. The retrieved values are then substituted into section 3 at the correct locations. This substitution process is extended to probabilities, TU levels, and distribution parameters similar to that described in section 2.

2.312 MODULE 3M2

The first run thru module 3M2 selects a placing system from the three available. See Figure 2.10 and Figure 2.12. The first run initiates the replacement mechanism so that the chosen system level is held for all subsequent runs.

2.313 MODULE 3M3

This module has two basic functions. They are;

1. To determine the number of transport units (TU level) to enter into the tunnel support operation.

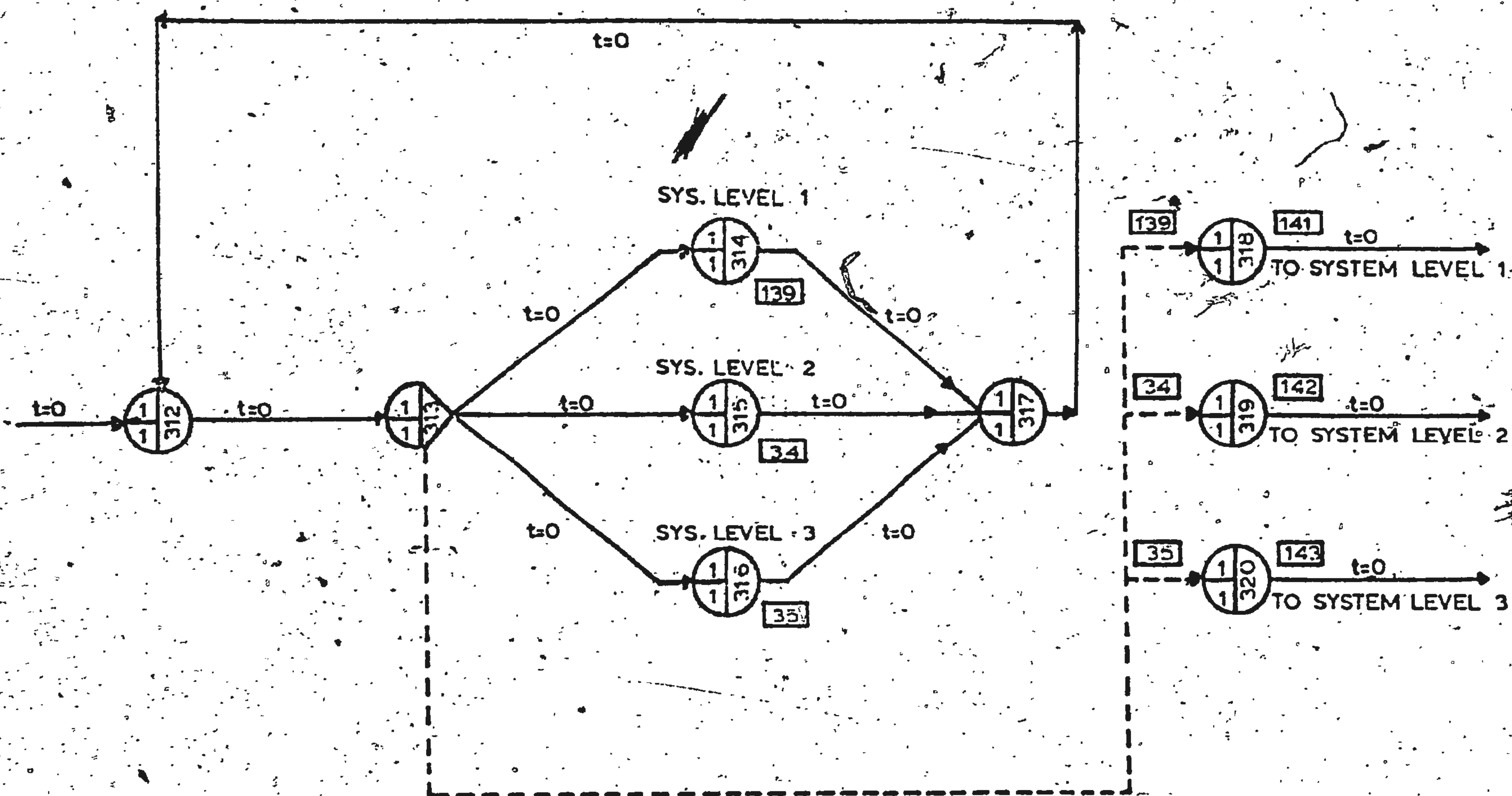


Figure 2.12. Q-GERT Network for Module 3M2.

2. To determine the exit, load and return times associated with each transport unit at the selected transport capacity level.

The Q-GERT network for module 3M3 is shown by Figure 2.13.

The functional logic of module 3M3 is similar to that described for module 2M3 in section 2, with hauling and dumping times replaced by exit and load times respectively.

2.314 MODULE 3M4

Module 3M4 contains three levels of a support placing system (for rock bolts, blocking and lagging or steel sets) associated with section 3. It has a load queue (determined by module 3Ml), a transportation type queue (determined in module 3M3) and placing system queues (determined outside the network). The function of the module is to assemble loads of support material, transport unit and placing system to simulate the tunnel support operation. The network for this module is illustrated by Figure 2.14.

2.4 PUMPING (SECTION 4)

This section presents the network logic for supplying the tunneling system with water pumping equipment and a

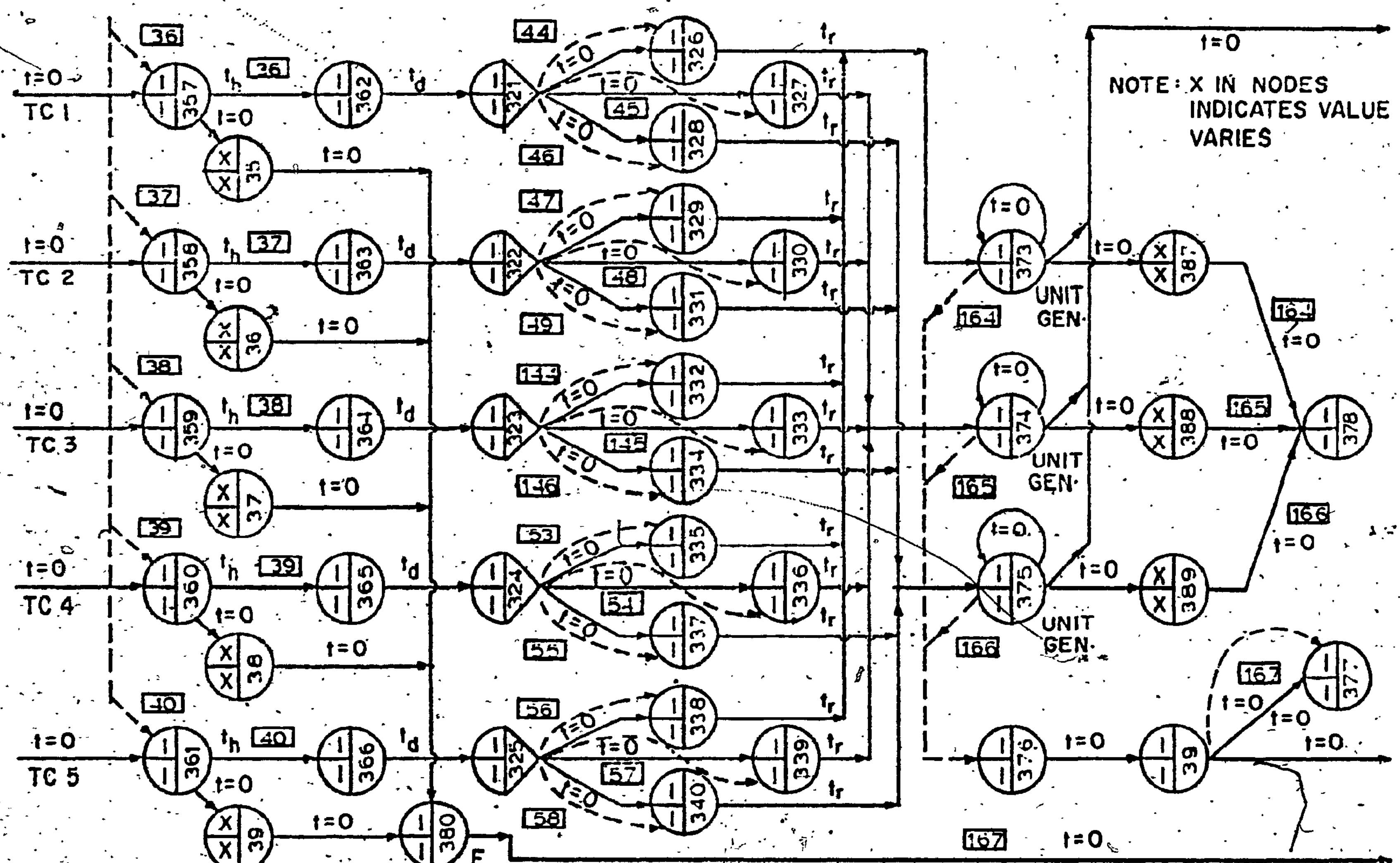


Figure 2.13. Q-GERT Network for Module 3M3.

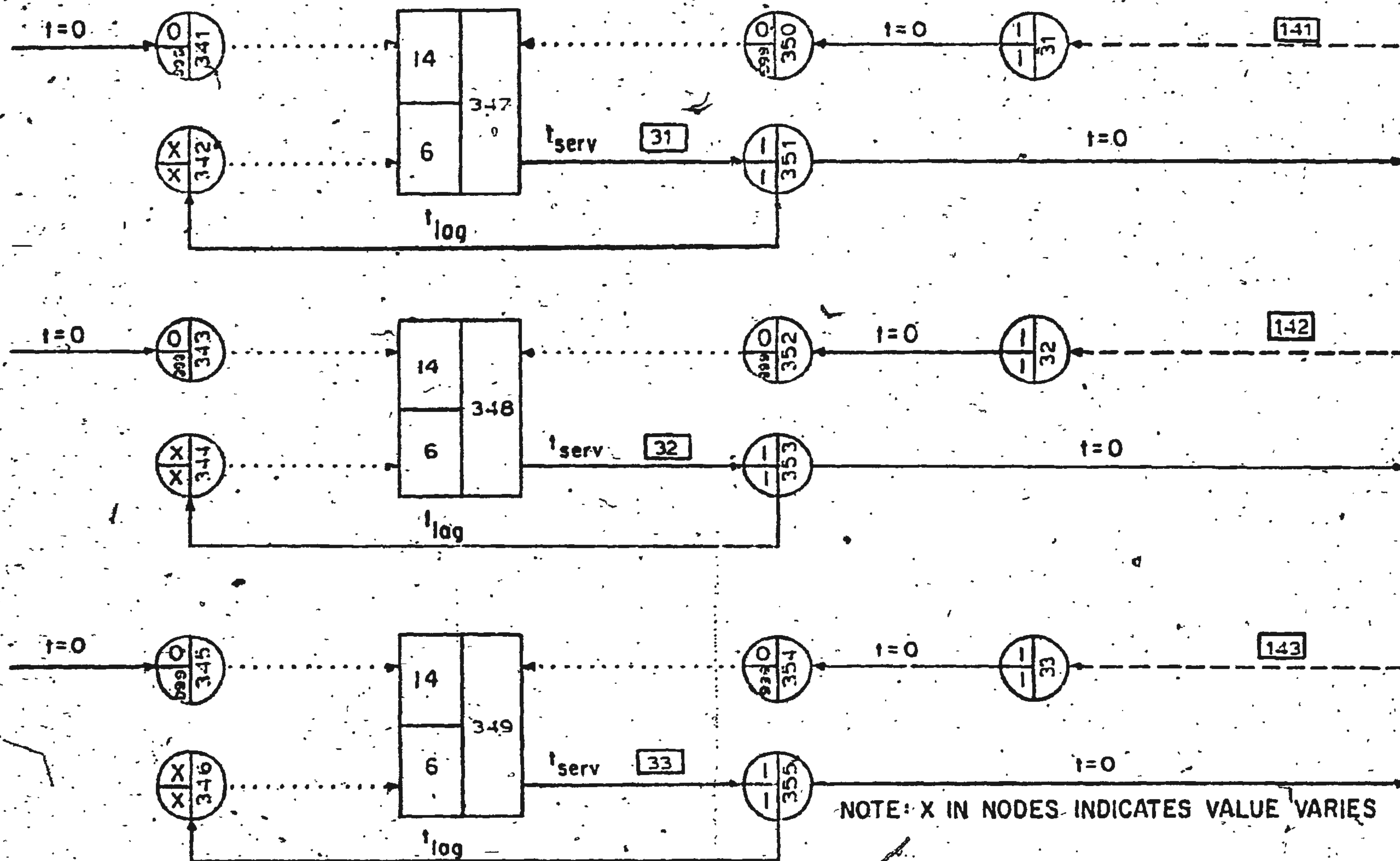


Figure 2.14. Q-GERT Network for Module 3M4.

device to install the equipment.[1] The transport types are truck and train only.

2.41 STRUCTURE

Section 4 utilizes four modules to describe the basic operations of pumping. The Q-GERT network for section 4 is illustrated in Figure 2.15. Modules 4M1, 4M2, 4M3 and 4M4 are illustrated by Figures 2.16, 2.17, 2.18 and 2.19 respectively.

The functional logic and network mechanism for these modules is similar to that described by section 2 structure, the only differences being in the number of system levels (3 levels), and the replacement of hauling and dumping times (section 2) by exit and loading times respectively.

2.411 LOAD QUEUE

The load queue is the number of whole loads of pumping equipment required in the working length of tunnel, and is dependent not only on transport capacity level but also on tunnel shape, size and groundwater inflow. The queue at each level is arrived at apart from the Q-GERT

[1] Pumping equipment includes pumps, pipes, valves and anything else vital to water control.

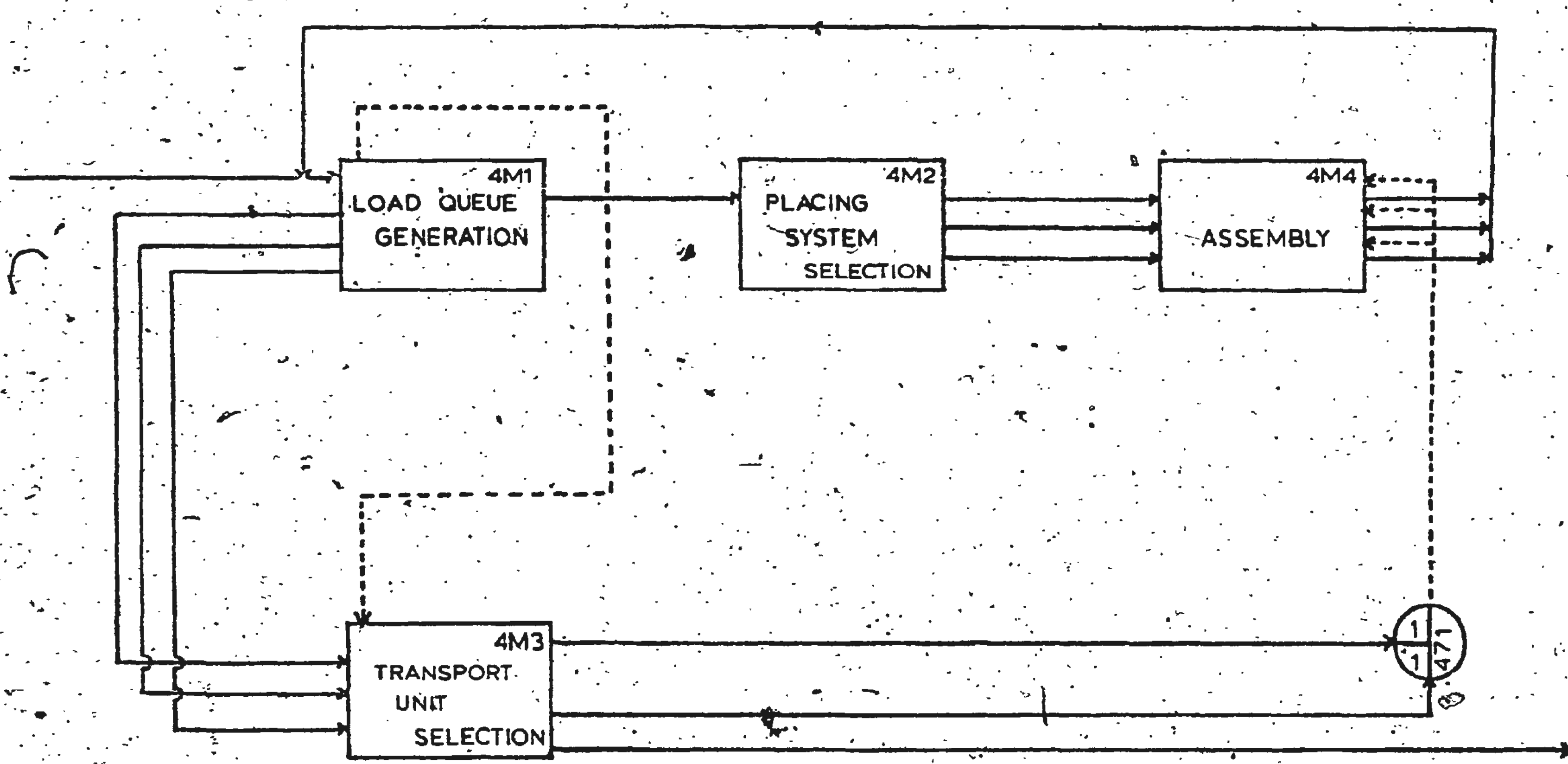
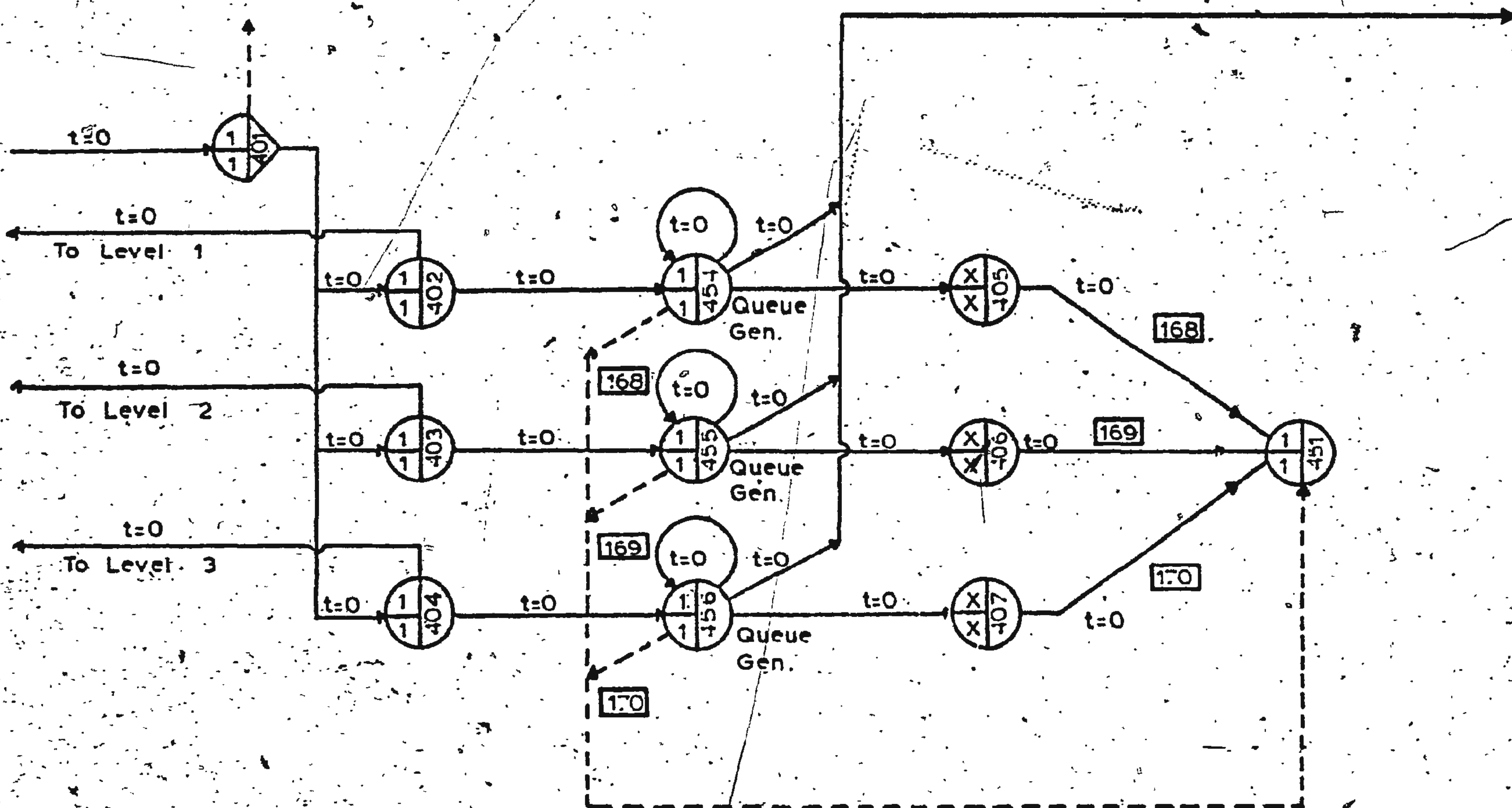


Figure 2.15. Q-GERT Network for Section 4.



NOTE: X IN NODES INDICATES VALUE VARIES

Figure 2.16. Q-GERT Network for Module 4M1.

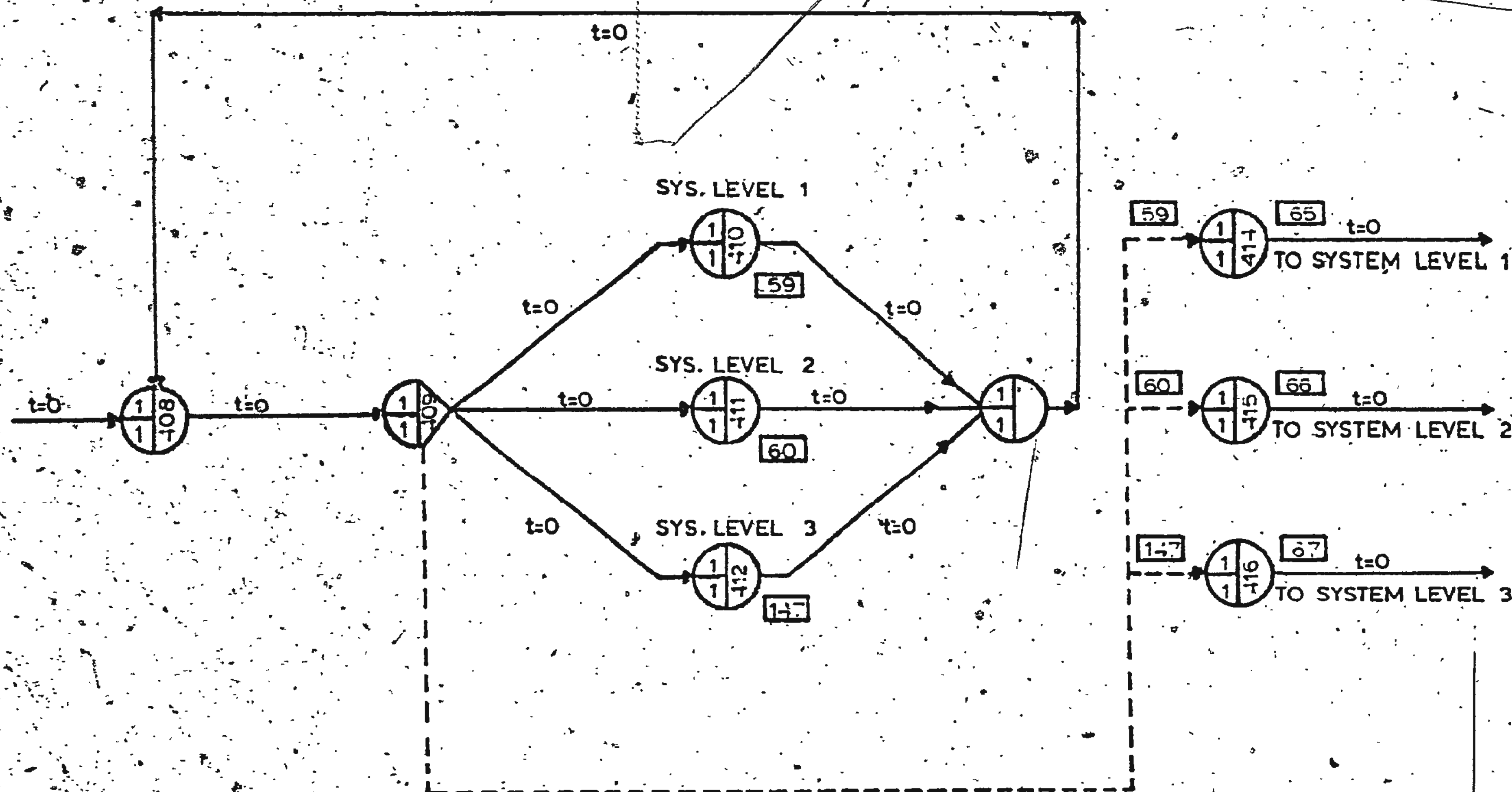


Figure 2.17. Q-GERT Network for Module 4M2.

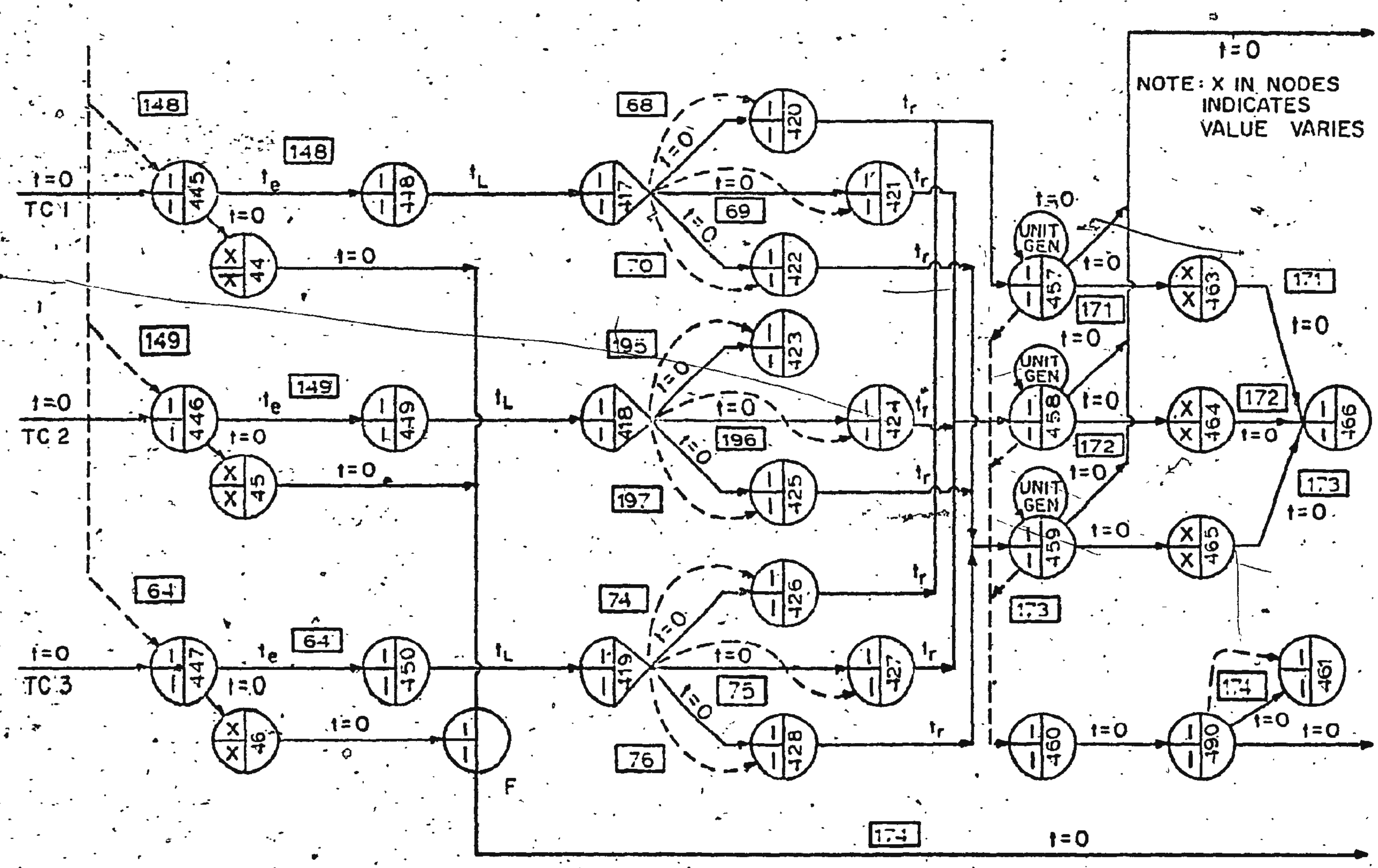


Figure 2.18. Q-GERT Network for Module 4M3.

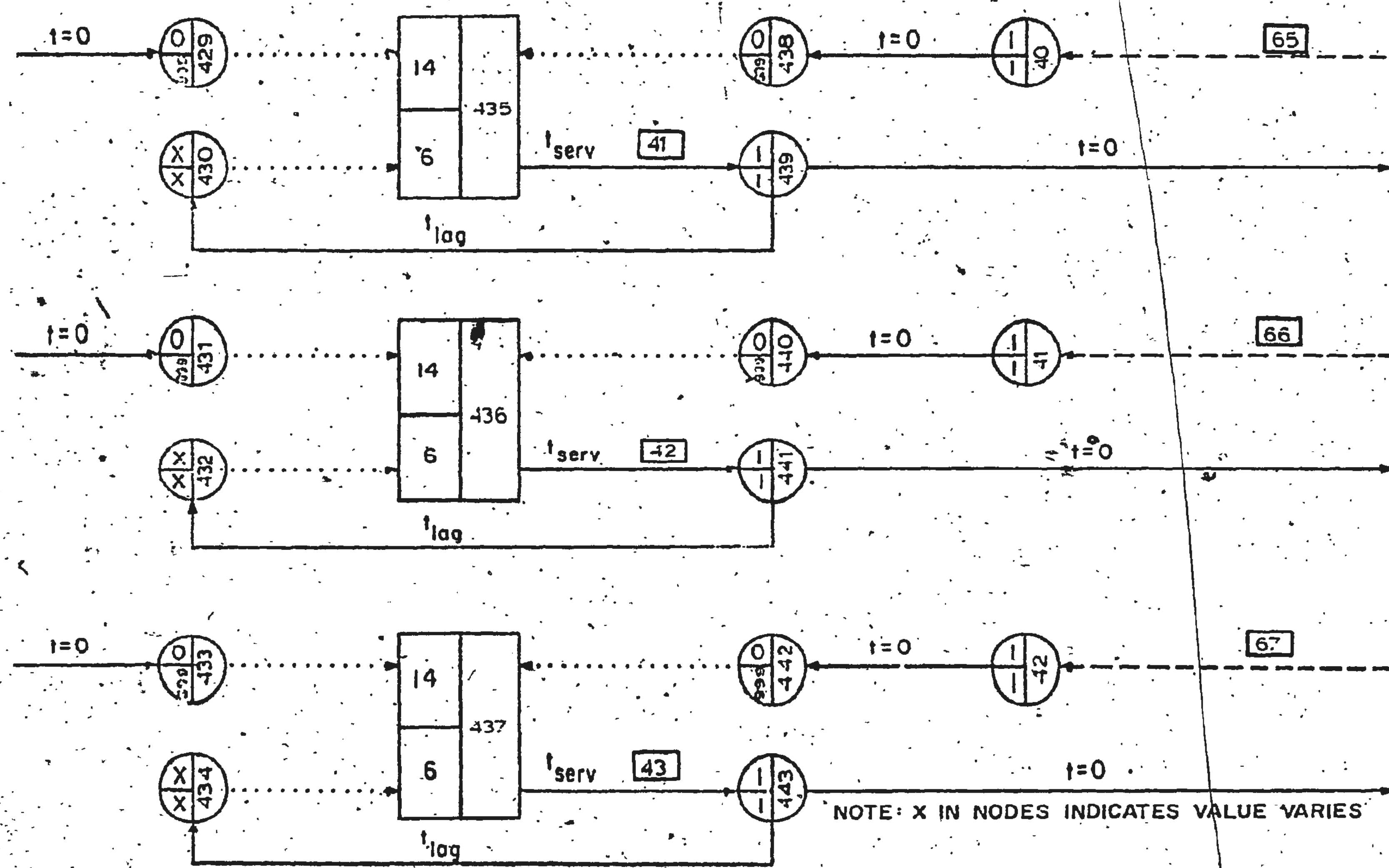


Figure 2.19. Q-GERT Network for Module 4M4.

network and comes about thru an application of the user's experience and judgement relative to tunnel characteristics.

2.5 REMAINING SYSTEM SECTIONS (GROUTING, LINING, VENTILATION)

The Q-GERT network for the remaining sections including all modules, is identical in structure, functional logic and network mechanism to the Q-GERT network for section 4 and its modules. Illustrations of the remaining sections and respective modules are contained in Appendix C.

Section 6 (lining) is somewhat similar to section 3 (support) in that whereas section 3 has a choice of three methods of support, section 6 has a choice of four methods of lining. These methods are;

1. Concrete
2. Prefab. Concrete
3. Prefab. Metal
4. Shotcrete

Sections 2,4,5 and 7 have no choice of any methods to execute the functions they represent.

CHAPTER 3

3. Q-SHUT

An examination of the tunneling system sections, bearing in mind the data preparation for Q-GERTS operation required before the sections can be simulated, leads to the idea of a separate non-Q-GERTS computer program to aid in such preparation. This idea has been adopted and indeed carried one step further. The end result is that the computer program (computer model) developed to simulate the tunneling system as described herein, is largely a data manipulation program, having as one subroutine the Q-GERTS program. Since Q-GERTS is fundamental to such simulation, this program utilizing Q-GERTS will hereafter be referred to as Q-GERTS Simulation of Hardrock Undersea Tunneling, or Q-SHUT.

All variation in Q-GERTS input centers around Data Types 1, 2, 3 and 4, General information, node, parameter value and activity description respectively.[1] A study of such variation and its locations reveal that not the entirety of Data Types 2, 3 and 4 are subject to changing either at the will of a tunnel contractor or as a result of the natural progression of tunnel construction. The fact is that portions of the Q-GERTS data contained in these data types are

[1]See description of Q-GERTS in Appendix A.

inalterably and forever fixed as long as the present network depiction of a tunneling process remains. Likewise it can be said that definite portions of the input data will be open to change and that change will relate to all sections of the tunneling system.

Depending on the tunneling experience of the program user and the advance of construction, there will always exist the need to constantly keep the Q-GERTS input data in an up-to-date condition. This is accomplished thru manipulation of the variable parts. Thus variation leads inevitably to updating.

3.1 UPDATING

There are three classifications of updating which apply to simulation of the tunneling system. They are;

1. Single update at start of simulation lasting for entire simulation of system.
2. Possible update at every working length (definitely at several)
3. Definite update at every tunnel working length.

An example of the first classification may be probabilities associated with different transport types in sections 2 to 7. These cannot change during the entire simulation of a particular tunneling system. The second classification applies to probabilities related to geologic characteristics of the tunnel. These values may change a dozen times, depending on geologic change, but certainly no more than the number of tunnel working lengths contained in the whole tunnel length, provided the tunnel working length is not so large that it approaches this whole length. The third classification relates to parameter values connected with return time, hauling time, and exiting time distributions. These parameter values change every tunnel working length.

The Q-GERTS input data is updated relative to the updating classification by information contained on punched cards or as the result of information produced by subroutines. Original punched card information which goes immediately to update Q-GERTS input is referred to as card update. Such information is used only to update per entire simulation and to provide possible update per working length. Information resulting from subroutines and subsequently used to update Q-GERTS input is called subroutine update. There can be subroutine update per entire simulation, possible subroutine update per working length and definite subroutine update per working length.

The mechanics of the updating process in tunneling simulation is illustrated in Figure 3.1.

The information necessary to create subroutine update is fed to Q-SHUT via cards. Thus in the final analysis all

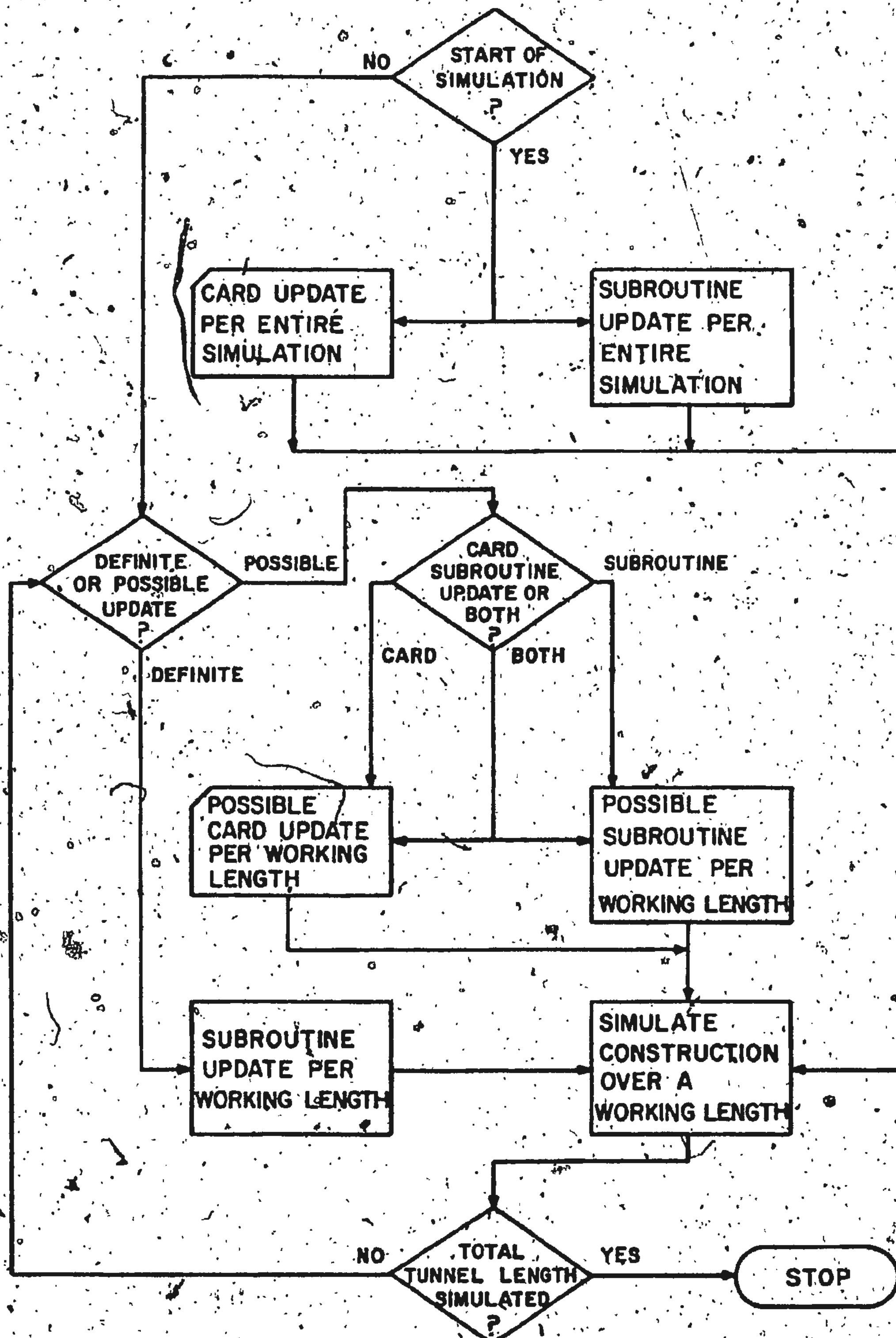


Figure 3.1. Mechanics of Updating Process.

updating, one way or another, originates at the input deck.

3.12 INPUT DECK

Input to the subroutines may be required only once during an entire simulation or it may be required many times. Therefore, since input is attempted via card deck, the deck will have data for use per entire simulation or possible use per working length. Since this division corresponds to card update classifications, then card update and subroutine input can occupy the same deck, and each card of the deck may contain information belonging to either Q-GERTS input or subroutines or both. If data for possible use per working length is considered in a class apart from data for use per entire simulation, then the input data deck may be said to have two divisions; data associated with changes per working length (either card update or subroutine input) and data associated with changes per simulation (either card update or subroutine input). Figure 3.2 shows this basic division.

3.2 PROCESSING

It has been shown that Q-GERTS input constantly requires updating to agree with progressing tunnel construction characteristics. The information to accomplish such

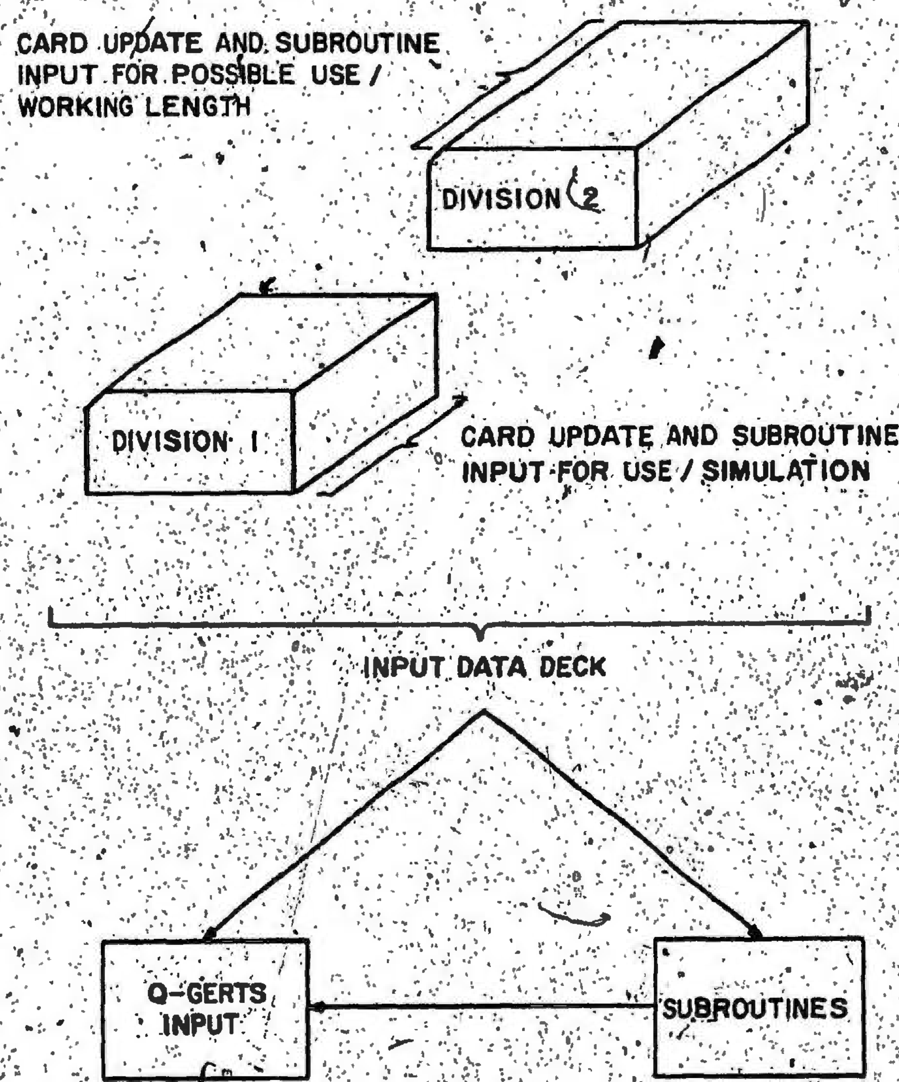


Figure 3-2 Input Data Deck Division.

update is provided by way of card deck, portions of which hold data to be utilized by several updating subroutines. It remains therefore to store and sort the input data, select input to Q-GERTS when needed and properly locate the selections within Q-GERTS input. In general to process the input so that the Q-GERTS simulation routine will receive updated data per tunnel working length. To achieve this processing necessitates the creation of a system of input files.

3.3 INPUT FILES

All the data to update (correct) the Q-GERTS input is stored on disk in two correction files. These store data on all transport types at all levels and in the case of the tunnel support and tunnel lining section of the tunneling system, data related to all methods of support and lining. Hence these files may be considered the banks or foundations of the substitution process dealt with earlier. From these files Q-SHUT, under programmer (tunneling contractor) control, selects relevant records and substitutes them into Q-GERTS input.

3.4 OUTPUT FILES

The result of using Q-GERTS is the production of various simulated times for the construction of one working length of tunnel relative to the Q-GERT model of the tunneling system. These times go immediately into temporary storage after which they may be printed and then combined with simulation results from other working lengths or they may go directly from temporary storage to combination. The combined times of several working lengths are stored permanently, that is until the construction of the tunnel is completely simulated. This permanent file may also have its contents printed at any working length. The instructions regarding printing of simulation results for a particular working length or for a series of working lengths, are coded in division 2 input data thru a simulation results indicator.

It may be seen from the above description that associated with Q-GERTS simulation output are two storage areas, temporary and permanent. In actual fact these storage areas manifest themselves via a secondary output accumulator file (SOAF) and a primary output accumulator file (POAF) respectively.

3.5 SIMULATION CONTROL MODULE (SCM)

The simulation control module integrates all subroutines into a comprehensive simulation package. The only remaining touch is the creation of a small main program to define the appropriate files as well as all file numbers and unit numbers for computer input-output hardware, and pass such numbers to SCM.

It was discussed previously that all data pertinent to the simulation of tunnel construction was fed to Q-SHUT via cards consisting of divisions 1 and 2. The construction of several tunnels may be simulated sequentially by stacking the different data sets, likewise each set consisting of divisions 1 and 2. Also, each tunnel may have its construct-tion simulated under varied combinations of method, transport type and groundwater inflow. SCM as well as controlling the calling of subroutines provides the logic for dealing with stacked data sets and combinations.

The functioning of Q-SHUT as determined by SCM is depicted in Figure 3.3.

3.6 USING Q-SHUT

Discussion thus far has centered on the fundamentals of tunneling simulation as embodied in Q-SHUT, namely tunneling system definition, Q-GERT representation of system, data preparation and manipulation of data via files prior to actual use by Q-GERTS. The next step is to utilize Q-SHUT to give simulation results.

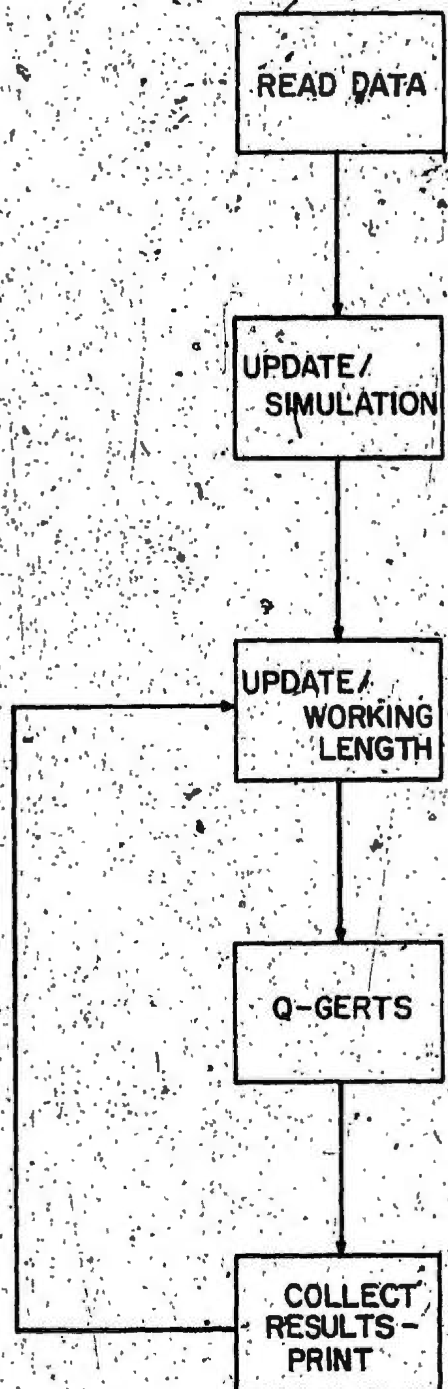


Figure 3.3 Functioning of Q-SHUT as Determined by SCM

3.61 COLLECTION OF DATA

Prior to using Q-SHUT certain basic information must be collected. This may be categorized as follows;

1. Initial simulation data
2. Combination data
3. Divisions 1 and 2 data

Collection of all data, to provide a structured and panoramic view of a simulation data set, is achieved thru use of several collection sheets.

3.62 Q-SHUT OUTPUT

Q-SHUT output provides the user with selected basic Q-SHUT input information, simulated times and costs, and data regarding server utilization. The selected input concerns reference and combination data and serves to relate simulated values to a specific simulation. Thus every Q-SHUT run produces a three part output as follows;

1. Reference data
2. Combination data
3. Simulation results

3.621 REFERENCE DATA

This portion of output is illustrated in Figure 3.4. It shows the Q-SHUT user a selection of pertinent facts surrounding the simulated construction of a specific tunnel. Facts such as shape, characteristic dimension, total tunnel length and length of working day depict the physical tunnel and real world. Facts such as number of simulations, scale factor and length of working length are concepts which help to model the real world.

Tunnel shape may be circular, horseshoe or basket-handle. Characteristic dimension[1] is limited to a maximum of 80 feet.

The information presented as reference data is selected from the Q-SHUT input data.

3.622 COMBINATION DATA

Figure 3.5 illustrates the combination data. Information is presented in tabular form with respect to the seven tunneling system sections, followed by a comprehensive legend.

The table shows the combinations of method (method of support - section 3, method of lining - section 4),

[1] See Appendix E.

```
O-SHUTS SIMULATION
     TUNNEL A

NUMBER OF SIMULATIONS OF WORKING LENGTH =   10
SCALE FACTOR FOR DISTRIBUTION TYPE 10 =     1.0000
LENGTH OF TUNNEL WORKING LENGTH (FEET) =  100
TOTAL LENGTH OF TUNNEL =       2500
LENGTH OF WORKING DAY (HOURS) =   8.

TUNNEL SHAPE = CIRCULAR

CHARACTERISTIC DIMENSION IN FEET = 25.
```

Figure 3.4. Reference Data

COMBINATION DATA

	Section 1			Section 2			Section 3			Section 4			Section 5			Section 6			Section 7		
CN	M	T	EDC	M	T	EDC	M	T	EDC	M	T	EDC	M	T	EDC	M	T	EDC	M	T	EDC
1	0	0	2	0	1	4	1	1	3	0	1	1	0	1	3	4	1	6	0	1	1
2	0	0	2	0	2	5	2	2	4	0	2	2	0	2	4	5	2	7	0	2	2
3	0	0	2	0	1	4	3	1	3	0	1	1	0	1	3	7	1	6	0	1	1

LEGEND

METHOD

SECTION 3

CODE	MEANING
0	NOT APPLICABLE
1	ROCK BOLTS
2	BLOCKING & LAGGING
3	STEEL SETS

SECTION 6

CODE	MEANING
4	CONCRETE
5	PREFAB.CONCRETE
6	PREFAB.METAL
7	SHOTCRETE

TRANSPORT TYPE

CODE	MEANING
0	NOT APPLICABLE
1	TRUCK
2	TRAIN
3	CONVEYOR

NOTE: CODE 1,2,3 = SECTION 2
CODE 1,2 = SECTIONS 3 - 7
CN = COMBINATION NUMBER
M = METHOD
T = TRANSPORT TYPE
EDC = ESTIMATED DAILY COST (HUNDREDS OF DOLLARS)

Figure 3.5. Combination Data

transport type and estimated daily cost, coded M, T and EDC respectively, under which the tunneling system will be simulated. For example, under combination number (coded CN) 1, section 6 of the system will be simulated subject to concrete type of support (M=4), truck transportation (T=1) and an estimated daily cost of $600.00. Under the same combination number, section 1, geologic prediction and excavation, will be simulated with respect to an estimated daily cost of $200.00. No method (M=0) or transportation type (T=0) is applicable.

The combination data portion of Q-SHUT output is a duplicate of the combination information as supplied via the data collection sheets. It is provided as output to aid in analyzing simulation results.

3.623 SIMULATION RESULTS

Simulation results are not strictly Q-GERTS or Q-GERTS formated results. Rather the Q-GERTS output has been altered somewhat.

Simulation results may be retrieved at any selected multiple of tunnel working length as decided by the Q-SHUT user. Two types of results are available. They are;

1. Simulation results for a single working length starting at selected multiple.

2. Simulation results for cumulative working lengths up to selected multiple.

The format for any one type of result consists of two parts. They are;

1. Final results
2. Average server utilization

3.6231 FINAL RESULTS

This part consists of a main heading with appropriate reference data for results displayed, two basic categories of results and associated headings (per-section and cumulative sections) and a brief legend at the bottom. See Figure 3.6.

The per-section category shows the simulated total mean time for the operation of each section of the tunneling system, relative to the type of simulation results. If the results are for a single working length, as in Figure 3.6, then the total mean time is that over the working length. Thus section 7 (ventilation - indicated by node 780) takes 4.8 hours to complete over a single working length. Had the results been for cumulative working lengths, then the total mean time would have been over the cumulated lengths. Simulation results for cumulative working lengths are

Q-SHUT SIMULATION PROJECT , 1
TUNNEL A
DATE 10/ 3/1975

COMBINATION NUMBER 1
DISTANCE SIMULATED THUS FAR 600 FEET
TIME UNIT = HOURS
COST UNIT = HUNDREDS OF DOLLARS

FINAL RESULTS FOR 10 SIMULATIONS OF WORKING LENGTH STARTING AT 500 FEET

NODE	(PER SECTION) TOTAL MEAN TIME	(CUMMULATIVE SECTIONS) MEAN TIME	STD.DEV.	STD.DEV. OF MEAN	COEFF. VAR.	NO OF OBS.	MIN. TIME	MAX. TIME	STAT TYPE
700	4.8	149.6	146.4	46.4	1.0	10.	52.8	424.8	F
COST/SECTION...	0.6								
600	6.4	144.8	147.2	46.4	1.0	10.	48.0	421.6	F
COST/SECTION...	4.8								
500	3.2	138.4	147.2	46.4	1.1	10.	42.4	419.0	F
COST/SECTION...	1.2								
400	4.0	135.2	147.2	46.4	1.1	10.	38.4	412.0	F
COST/SECTION...	0.5								
300	2.4	131.2	146.4	46.4	1.1	10.	34.4	405.6	F
COST/SECTION...	0.9								
200	3.2	128.0	146.4	46.4	1.1	10.	32.0	403.2	F
COST/SECTION...	1.6								
10	125.6	125.6	146.4	46.4	1.2	10.	27.2	403.0	F
COST/SECTION...	31.4								
TOTAL TIME	149.6								
TOTAL COST	41.0								

Figure 3.6. Simulation Results for Single Working Length.

FOR FINAL RESULTS

NODE 700 REFERS TO SECTION 7(VENTILATION)
NODE 600 REFERS TO SECTION 6(LINING)
NODE 500 REFERS TO SECTION 5(GROUTING)
NODE 400 REFERS TO SECTION 4(PUMPING)
NODE 300 REFERS TO SECTION 3(SUPPORT)
NODE 200 REFERS TO SECTION 2(MUCK LOADING)
NODE 10 REFERS TO SECTION 1(GEOLOGIC PREDICTION AND EXCAVATION)

F INDICATES TYPE OF STATISTICS COLLECTED AT NODE, REFER TO Q-GERTS TERMINOLOGY.

illustrated in Figure 3.7.

Below each total mean time in the final results, there is a cost. Thus each section has a cost based on the mean time. At the bottom of the per-section category, the times and costs for the sections are summed.

The cumulative sections category shows the mean time, standard deviation, standard deviation of the mean, coefficient of variation, number of observations, minimum time, and maximum time over any number of sections all relative of course to the type of simulation results.[1] For example, if the results are for a single working length as in Figure 3.6, section 1 (geologic prediction and excavation -indicated by node 10) takes a mean time to complete of 125.6 hours, which agrees with the total mean time in the per-section category. Section 2 (muck loading -indicated by node 280) on the other hand has a mean time of 128.8 hours, that is a cumulated mean time of 128.8 hours. It is the time taken to complete section 1 and section 2 (125.6 + 3.2 from the per-section category). Thus the mean time for section 7 is the time required to complete all sections including 7, or 149.6. This agrees with the sum of total mean times in the per-section category.

The cumulative sections category for the final results does not display costs. Sufficient cost information

---

[1]Mean time, standard deviation etc., is regular Q-GERTS output.

Q-SHUT SIMULATION PROJECT 1
TUNNEL A
DATE 10/ 3/1975

COMBINATION NUMBER 1
DISTANCE SIMULATED THUS FAR 1500 FEET
TIME UNIT = DAYS
COST UNIT = HUNDREDS OF DOLLARS

FINAL RESULTS FOR 10 SIMULATIONS OF EACH WORKING LENGTH UP TO 1400 FEET

NODE	(PER SECTION) TOTAL MEAN TIME	(CUMMULATIVE SECTIONS) MEAN TIME	STD.DEV.	STD.DEV. OF MEAN	COEFF. VAR.	NO OF OBS.	MIN. TIME	MAX. TIME	STAT TYPE
700	9.5	217.6	145.1	45.8	0.7	10.	94.5	520.1	F
COST/SECTION...	9.5								
600	13.2	208.1	145.3	46.0	0.7	10.	85.0	519.0	F
COST/SECTION...	132.0								
500	7.4	194.9	145.3	46.0	0.7	10.	72.1	505.1	F
COST/SECTION...	51.8								
400	7.6	187.5	145.3	46.0	0.8	10.	65.0	497.0	F
COST/SECTION...	38.0								
300	3.9	179.9	145.5	46.0	0.8	10.	57.2	489.0	F
COST/SECTION...	19.5								
200	7.1	176.0	145.5	46.0	0.8	10.	53.2	480.0	F
COST/SECTION...	71.0								
10	168.9	168.9	145.8	46.2	0.9	10.	46.7	480.0	F
COST/SECTION...	1013.4								
TOTAL TIME	217.6								
TOTAL COST	1335.2								

Figure 3.7 Simulation Results for Cumulative Working Lengths.

FOR FINAL RESULTS

NODE 700 REFERS TO SECTION 7(VENTILATION)
NODE 600 REFERS TO SECTION 6(LINING)
NODE 500 REFERS TO SECTION 5(GROUTING)
NODE 400 REFERS TO SECTION 4(PUMPING)
NODE 300 REFERS TO SECTION 3(SUPPORT)
NODE 200 REFERS TO SECTION 2(MUCK LOADING)
NODE 10 REFERS TO SECTION 1(GEOLOGIC PREDICTION AND EXCAVATION)

F INDICATES TYPE OF STATISTICS COLLECTED AT NODE, REFER TO Q-GERTS TERMINOLOGY.

is contained in the per-section category. For example, if the cost over three consecutive sections is desired, then the individual section costs are just added.

Had results been for several working lengths (cumulative working lengths) as illustrated in Figure 3.7 rather than a single working length, then the mean time as well as being based on several section times, would also be based on several working lengths, that is all previous working lengths.

The statistics type column in the final results serves to indicate the type of Q-GERTS statistics collected per section.

3.6232 AVERAGE SERVER UTILIZATION

The format for this simulation result consists of a main heading with appropriate reference data and two categories of results with associated headings - average server utilization and time periods of server. See Figures 3.8 and 3.9.

The average server utilization category shows the simulated mean time that each server level in each tunneling system section is in use relative to the type of simulation results. If results are for a single working length, as in Figure 3.8, then the utilization of each level is based on use over a working length of tunnel. If the results had been

Q-SHUT SIMULATION PROJECT 1
TUNNEL A
DATE 10/ 3/1975

COMBINATION NUMBER 1
DISTANCE SIMULATED THUS FAR 600 FEET
TIME UNIT = HOURS

AVERAGE SERVER UTILIZATION BASED ON WORKING LENGTH — TIME PERIODS OF SERVER

SERVER NO.	MEAN TIME	STD. DEV.	NO. OF OBS.	MIN. TIME	MAX. TIME	LONGEST PERIOD IDLE	LONGEST PERIOD BUSY

Figure 3.8. Format - Server Utilization: Single Working Length.

Q-SHUT SIMULATION PROJECT 1
TUNNEL A
DATE 10/ 3/1975

COMBINATION NUMBER 1
DISTANCE SIMULATED THUS FAR 1500 FEET
TIME UNIT = DAYS

AVERAGE SERVER UTILIZATION , CUMMULATIVE LENGTHS — TIME PERIODS OF SERVER

SERVER NO.	MEAN TIME	STD. DEV.	NO. OF OBS.	MIN. TIME	MAX. TIME	LONGEST PERIOD IDLE	LONGEST PERIOD BUSY

Figure 3.9. Format - Server Utilization: Cumulative Working Lengths.

for cumulative working lengths, then utilization is the sum of utilizations over all working lengths. See Figure 3.9.

The time periods of server gives the longest period idle and busy for each server level in each section. Once again this is relative to the type of simulation result.

It should be noted in both final results and average server utilization, that results are for particular points along the length of the tunnel whose construction is being simulated. The desire to have simulation results so displayed may stem from geologic changes or updates occurring at those points, and the user's wish to analyze that change or update.

3.63 THE OBJECTIVE OF Q-SHUT

The objective of Q-SHUT is to aid in selecting an optimum tunneling method and equipment combination for use on a particular tunneling project. No definite procedure can be outlined to achieve such an aid as all approaches to Q-SHUT are subject to the wishes and experience of the program user relative to program flexibility. As user experience in actual program operation and capabilities is gained, a standard approach to Q-SHUT analysis may arise. Until this point of development is reached, only suggestions regarding the analysis of a tunneling project via Q-SHUT, can be proposed.

3.631 SELECTION OF TUNNELING METHOD

One way to select a method of tunneling by Q-SHUT might be to simulate tunnel construction using the conventional method of excavation, then simulate construction using TBM, (all other variables unchanged) comparing resultant times and costs. However, this assumes using one method for the entire tunnel construction. Perhaps only a portion of the tunnel length can be excavated by TBM. Thus Q-SHUT may be utilized to simulate construction of a tunnel equal in length to this portion, first with respect to TBM and then with respect to conventional excavation. Results for TBM may be compared with conventional and thus aid in any final selection of method. The remaining portion of tunnel (part not subject to TBM excavation) may have its construction simulated by again assuming construction of a tunnel equal in length to that portion, subject to conventional excavation. This approach (simulating construction in portions) is necessary because Q-SHUT does not have the capability to update tunneling method at any point (corresponding to a multiple of the tunnel working length) during simulation. Tunnel geology such as RQD, rock strength and groundwater inflow may be updated at any point, but not the actual excavation method.

Perhaps another way to select method might involve the use of Q-SHUT over portions of the tunnel which may be excavated by either of the two methods considered, and by using a more quantitative approach over portions where only one method can apply

As can be seen, how Q-SHUT is utilized as an aid in selecting excavation method is indeed varied, depending on user ingenuity. However, whether the entire tunnel construct-tion is simulated or only portions, selection may eventually come down to a comparison of simualtion results for convent-ional and TBM excavation, provided all other simulation variables (not immediately connected with excavation method) have remained constant.

3.632 SELECTION OF EQUIPMENT COMBINATION

Selecting a good equipment combination, in terms of time, cost and server[1] utilization, might be achieved by simulating tunnel construction with respect to several combinations of tunnel support and lining, and transportation type (and associated costs), then comparing results. If time and costs for one combination is lower than others, with a high server utilization, then this combination is a likely choice to use in real construction. Of course any final choice must be tempered by user knowledge, perhaps involving trade-offs between time, cost and server utilization, or even facts external to any Q-SHUT simulation. Q-SHUT is an

[1]Server may be loading or placing system.

aid only, selection is at the program user's discretion. If selection of equipment is based on such comparison, other simulation variables must be constant during simulation of the tunneling system for each combination.

Equipment selection might also be accomplished by assuming only one combination (referring to combination data), varying selected information contained in other collection sheets (subject to user discretion) with each simulation of entire tunnel construction, and comparing results.

Still another approach to selection might involve maintaining only one combination (referring to combination data) and original information contained on other collection sheets, and introducing variability via the updating capability of Q-SHUT. Thus one working length of tunnel may be simulated subject to one set of facts, while the next working length may be simulated subject to another set of facts. Comparisons can then be made between simulation results over portions of tunnel equal in length to the working length rather than between simulations based on the entire tunnel length.

As with selection of excavation method, the utilization of Q-SHUT to aid in determining equipment combination, rests with the needs and experience of the program user. Also, any selection based wholly on Q-SHUT will result from comparisons of values comprising the simulation results.

3.64 FUTURE DEVELOPMENT OF Q-SHUT

All computer programs in the early development stage have room for improvement; growing pains are all too frequent. And Q-SHUT is no exception. In its present state the program is fundamental and quite unadorned. Basic concepts are sound but need to be utilized more efficiently. Experience gained in actual Q-SHUT operation together with continued research and development should eventually lead to a more mature simulation program.

Perhaps the major condemning fault of Q-SHUT is its high CPU time. To simulate construction of a tunnel with twenty-five working lengths, a minimum of updating and results collection at only five points along the length, presently requires approximately 20 minutes of CPU time. The time may be reduced by increasing the size of a working length so there are fewer per total tunnel length, decreasing the amount of updating or collecting fewer simulation results. But doing so defeats the whole purpose of Q-SHUT, -- to select tunneling and equipment combination based on comparisons of simulation results.

The inefficient CPU time results from the system of filing and updating employed by Q-SHUT. This system served to develop Q-SHUT into a successful program, but with high CPU times resulting, it was intended to streamline the system, making it more efficient CPU-wise once Q-SHUT reached a somewhat more workable level. However inflation decreed otherwise. Budgeted CPU time was drastically reduced from the allotment of previous years, and continued Q-SHUT research had to be curtailed.

Any future development of Q-SHUT must first deal with a better system of filing and retrieving simulation variables as well as creating a smoother procedure for updating.

The second fault of Q-SHUT rests with the utilization of simulation results. At present a Q-SHUT user must compare simulation results by hand to determine adequate excavation methods and equipment combination. Such procedure may be stifling when copious results are necessary for a complete analysis. A more logical approach would be to have Q-SHUT collect and analyze simulation output and present the result, in report form, to the program user. This added capability, as well as making Q-SHUT more flexible and comprehensive, would permit more simulations of a tunneling system (and consequently greater accuracy in simulated times, costs and server utilization) and more detailed simulation results. Thus future development of Q-SHUT must examine how to better utilize simulation results.

One other fault of Q-SHUT is its inability to simulate single sections of the tunneling system. For example, in trying to determine an excavation method by simulation, only the geologic prediction and excavation section need be simulated with respect to the two methods considered by Q-SHUT. It is not necessary to carry simulation to all other sections. However, Q-SHUT in its present state delivers simulated times for all sections, thereby wasting valuable CPU time. Future development of Q-SHUT might give it the capability of barring certain sections from simulation, at the wish of the program user.

Future development of Q-SHUT should also extend its updating capabilities to include changes in distribution parameters.[1] This extension could allow Q-SHUT to account for possible tunnel collapse and machine downtime,[2] without any alteration in the present Q-GERTS network representation of the tunneling system. An extension of updating capabilities could also allow variation in excavation method at any point along a tunnel's length equal to a multiple of the tunnel working length. Such extensions would render to Q-SHUT an improved ability to model a real tunneling project.

Other future developments might include altering the Q-SHUT output format making it easier to interpret, permitting the Q-GERTS routine in Q-SHUT to produce results (to be included in Q-SHUT output) describing queues which arise during simulation, and perhaps even linking Q-SHUT with a user established computer library, housing all Q-SHUT pertinent facts gleaned from the user's tunneling experience.

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[1] Distribution parameters provide Q-GERTS with information necessary to produce simulated times for the various activities of the tunneling system.

[2] The Q-SHUT program was not originally designed to accommodate directly possible tunnel collapse and machine downtime.

All these suggestions for future improvement are concerned with Q-SHUT input, output and the efficient manipulation of both. They all encircle the whole foundation of Q-SHUT - a Q-GERTS representation and simulation of a carefully defined tunneling system. It is felt that this foundation is adequate and sound, giving Q-SHUT good simulation potential, a potential which undoubtedly warrants its future development.

3.7 CONCLUSIONS

Conclusions may be summed up as follows;

1. Q-SHUT is based on a Q-GERT network of a tunneling system and utilizes Q-GERTS.
2. The program simulates tunnel construction in intervals and permits specific Q-GERTS data to be updated at any interval.
3. Data updating and manipulation is handled by a filing system permitting access to a wealth of variable tunneling information.
4. Data collection for input to Q-SHUT is executed via a series of collection sheets.
5. Several tunneling systems may be simulated in one Q-SHUT run.
6. Each tunneling system may be simulated with

respect to a specific method of excavation.

7. Each tunneling system may be simulated with respect to a specific combination of support method, lining method, transportation type and estimated costs.
8. Selection of excavation method and equipment combination is based on comparisons of simulation results tempered by user experience and discretion.
9. Simulation results may be retrieved from Q-SHUT at any point in the simulation which represents a distance along a physical tunnel equal to the working length.
10. Results may pertain to the simulation of tunnel construction over a length of tunnel equal to the working length, or the sum of working lengths starting with the first.
11. Q-SHUT simulation output consists of simulated times, costs and utilization of loading and placing systems in all sections.
12. Q-SHUT warrants future development, especially in the area of file manipulation.

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APPENDICES

APPENDIX A

GERT

GERT networks consist of nodes and directed branches. The nodes may be considered as deterministic or probabilistic and are described by shape, number of releases, number of releases to repeat and node number. Nodes are illustrated in Figure A1.

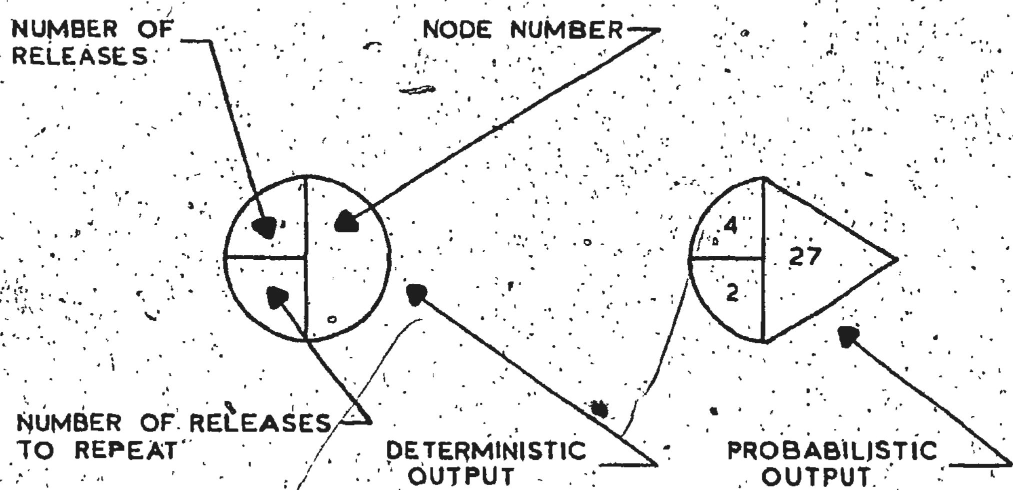


Figure A1. Node System for GERT Networks.

The number of releases specifies the number of times activities incident of the node must be realized before the node can be realized. It is possible to specify the number of releases to be less than or greater than the number of activincident to the node. The number of releases to repeat specifies the number of times activities incident to the node must be realized before the node can be realized again.

Nodes may also be characterized as to whether they are;

1. A source node
2. A sink node
3. A statistics node
4. A mark node

Activities originating from a source node are begun at time zero. A sink node indicates that the network may be realized when it is realized. A statistics node is one on which statistics are collected. A mark node is mearly a reference node which allows the calculation of the time it requires to go between two nodes of the network.

Associated with statistics nodes are five types of time statistics. They are;

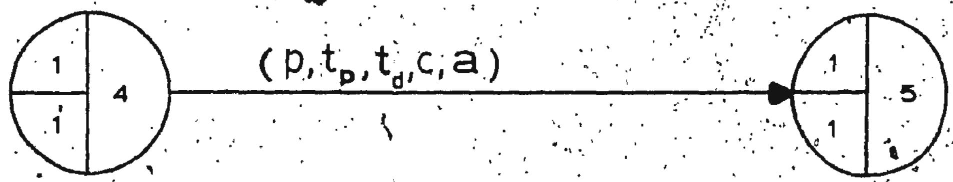
1. The time of first realization of a node. Code F.
2. The time of all realizations of a node. Code A.
3. The time between realizations of a node. Code B.
4. The time interval required to go between two nodes in the network. Code I.
5. The time delay from first activity completion on the node until the node is realized. Code D.

The branches (activities) of a GERT network have associated with them a probability that the branch will be realized, provided its start node is realized, and a time to perform the activity, provided that the activity is realized. The time variation is specified by one of nine distribution types. They are;

1. Constant
2. Normal
3. Uniform
4. Erlang
5. Lognormal
6. Poisson
7. Beta
8. Gamma
9. Beta fitted to three parameters as in PERT.

The time variation is also specified by a parameter set number. This number refers to a particular group of parameters which may be used to describe one or several of the distribution types.

The activities of a GERT network also have associated with them a counter type which specifies some counter to be increased by 1 when a certain activity is realized. Each activity also has an activity number. An activity and the variables that describe it are represented in Figure A2.



Legend

p = Probability of realization
t_p = Parameter set for time
t_d = Distribution type
c = Counter type
a = Activity number

Figure A2. Illustration of Activity Description.

Q-GERT

Quite often in simulating various systems there arises the need for a form of storage capability. This need is met by introducing into GERT a Q-node having queuing potential. This node is illustrated in Figure A3. As can be seen, the concept of number of releases is not applicable to a Q-node. The activity following a Q-node is a service activity.

With intricate networks of queues it is necessary to provide some form of transition between regular nodes and Q-nodes, between Q-nodes and service activities and between service activities and Q-nodes of successor activities. Such transition is accomplished by a selector node, also known as

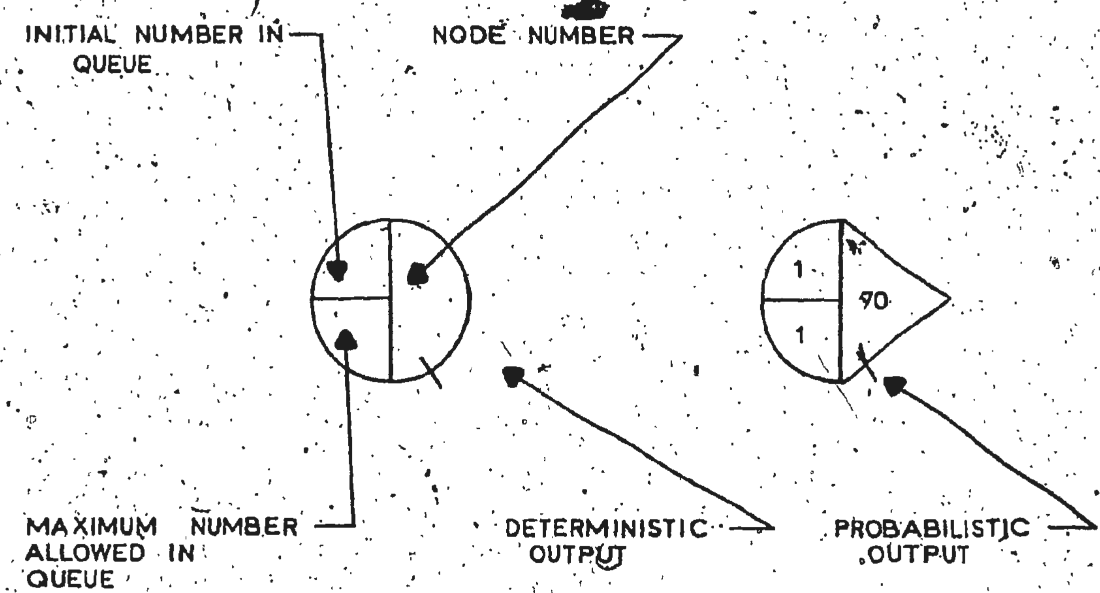


Figure A3. Q-nodes.

an S-node. This node performs one or more of the following functions;

1. Selects a Q-node for any item demanding service.
2. Selects a server from those available.
3. And/or selects a queue which may be served when service becomes available.

The following list of priority rules can be associated with S-nodes for selecting from a set of parallel queues;

1. Priority given in a preferred order.
2. Cyclic Priority - transfer to first available

Q-node starting from the last Q-node that was selected.

3. Random Priority-assign an equal probability to each Q-node that is available.
4. Priority given to the Q-node which has had the largest average number in it to date.
5. Priority is given to the Q-node which has had the smallest average number in it to date.
6. Priority is given to the Q-node for which the waiting time of its first customer is the longest.
7. Priority is given to the Q-node for which the waiting time of its first customer is the shortest.
8. Priority is given to the Q-node which has the current largest number of items in it.
9. Priority is given to the Q-node which has the current largest number of items in it.
10. Priority is given to the Q-node which has had the largest number of balkers from it to date.
11. Priority is given to the Q-node which has the smallest number of balkers from it to date.
12. Priority is given to the Q-node which has the largest remaining unused capacity.
13. Priority is given to the Q-node which has the smallest remaining unused capacity.
14. An Assembly Operation - a selection will not be made until all Q-nodes preceding the selector

have at least 1 unit in them. An item from each queue will then be taken and operated on by the service activity.

The following list of priority rules can be associated with S-nodes to select from a set of parallel service activities;

1. Select from free servers in a preferred order.
2. Select servers in a cyclic manner.
3. Select servers by a random selection of free servers.
4. Select the server that has had the largest amount of usage to date.
5. Select the server which has the smallest amount of usage to date.
6. Select the server who has been idle the longest.
7. Select the server who has been idle for the shortest period of time.

The S-node is illustrated in Figure A4.

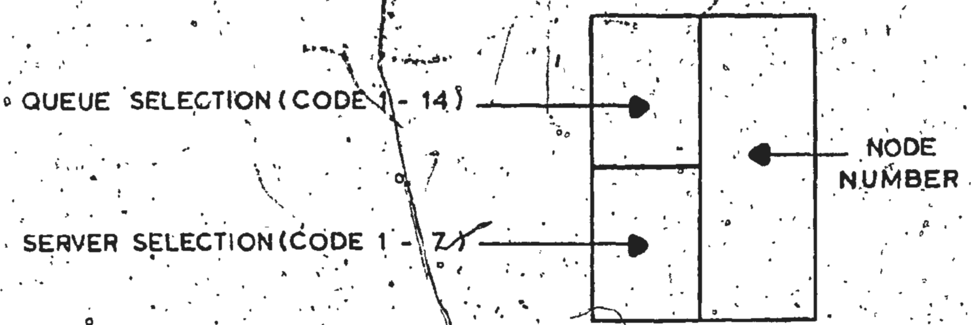


Figure A4. S-node.

Q-GERTS

Q-GERTS is the computer program which simulates the functioning represented by a Q-GERT network. Input to the program consists of five categories of data called Data Types. They are;

Data Type 1: General Information

Data Type 2: Description of Nodes

Data Type 3: Parameter Values for Sampling from Time Distributions

Data Type 4: Activity Descriptions

Data Type 5: Node Modification

Basic Q-GERTS output can be categorized as follows;

1. Echo check of input.

2. Final results for x number of simulations.
3. Average number in Q-node.
4. Average server utilization.
5. Histograms.

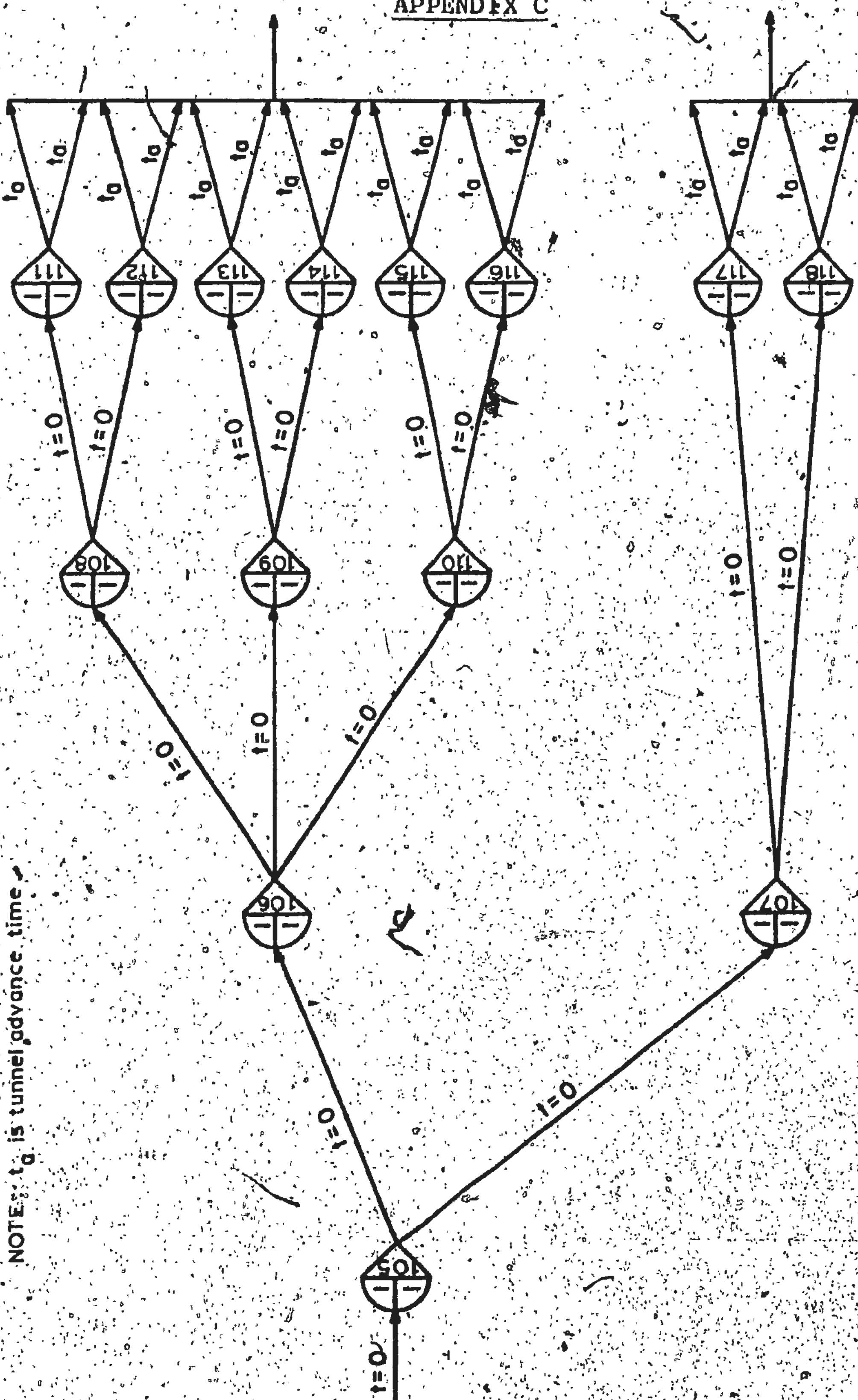
APPENDIX B

Table A1. Summary of Mean Advance Rates and Mean Excavation Times for 1M1.

Excavation Method	Tunnel Shape	Tunnel Size	Groundwater Inflow	Mean Advance Rate (ft./day)	Mean Excavation Rate (hours)
Conventional	Horseshoe	0 R 20	High	18.5	133
			Low	39.6	60
		20 R 40	High	11.7	205
			Low	25.0	96
	Baskethandle	0 R 20	High	17.8	135
			Low	38.2	63
		20 R 40	High	11.3	210
			Low	24.2	99
	Circular	0 R 20	High	21.0	114
			Low	45.0	53
		20 R 40	High	13.3	180
			Low	28.5	84
T.B.M.	Circular	0 R 20	High	9.0	265
			Low	20.2	119
		20 R 40	High	3.6	670
			Low	8.1	300

Note: Values are based on a rock strength of 30,000 - 100,000 psi. and a working length of 100 feet.

APPENDIX C



NOTE: t_a is tunnel advance time

Figure C1. Module 1M1.

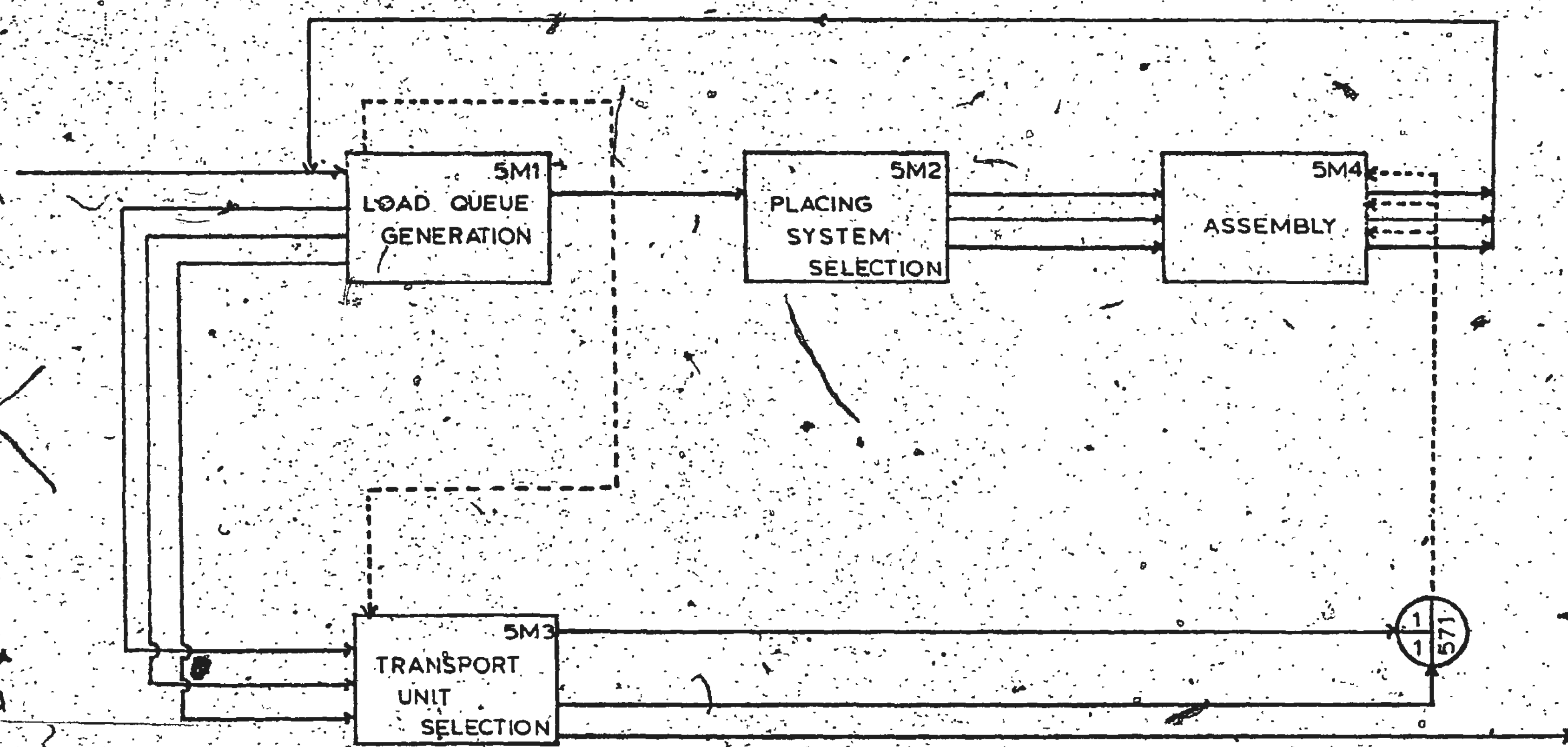
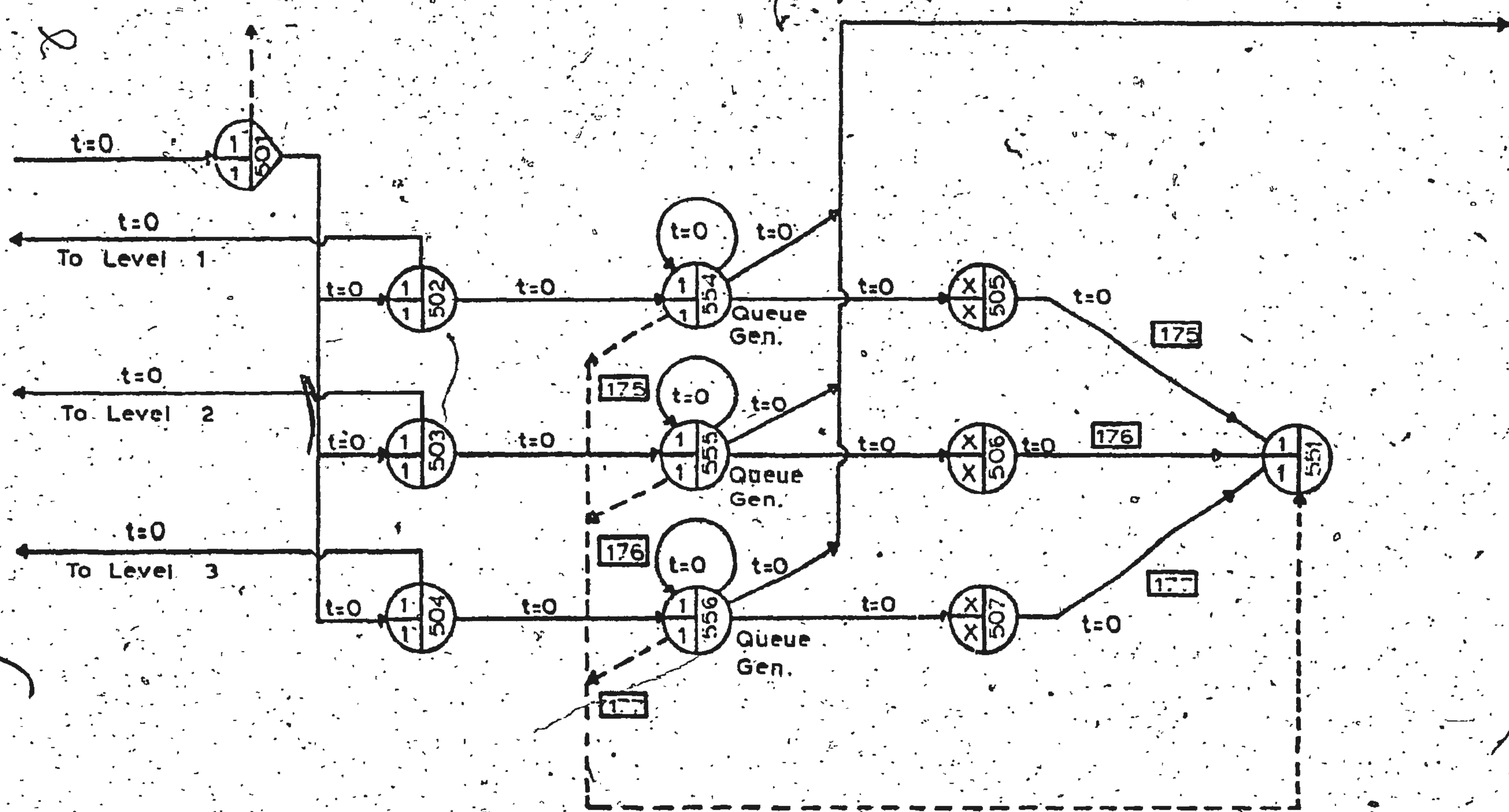


Figure C2. Q-GERT Network for Section 5.



NOTE: X IN NODES INDICATES VALUE VARIES.

Figure C3. Q-GERT Network for Module 5M1.

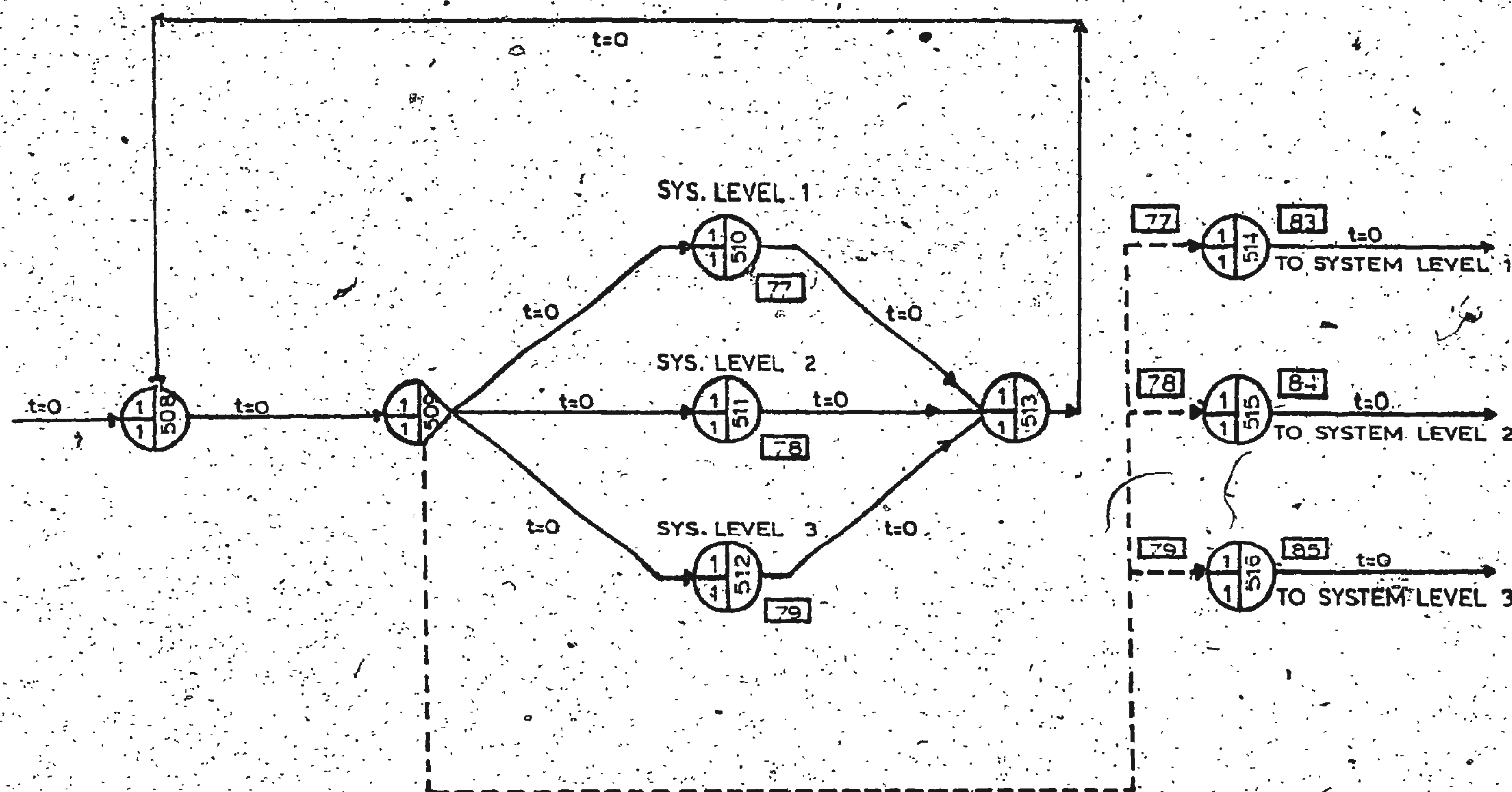


Figure C4. Q-GERT Network for Module 5M2.

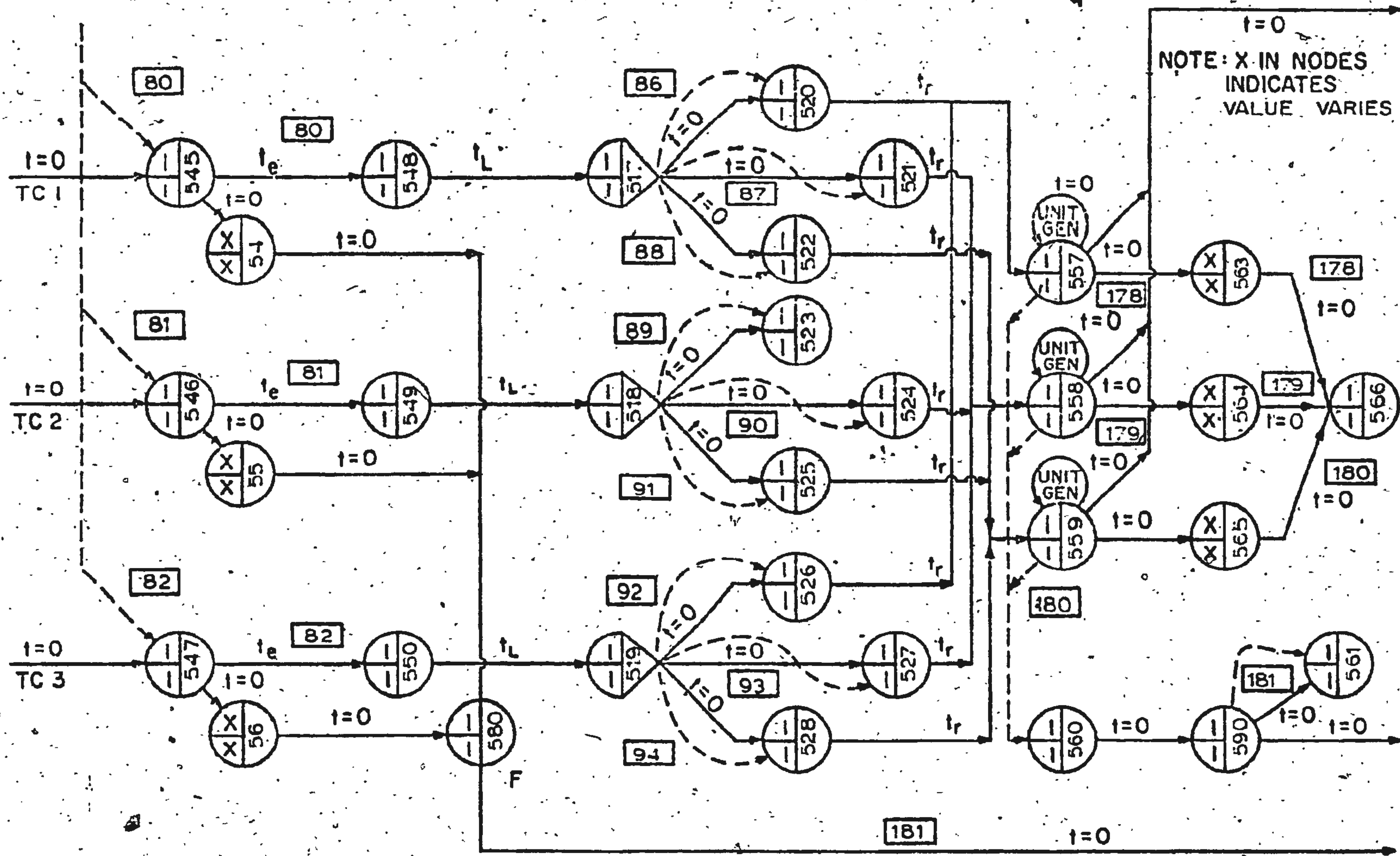


Figure C5. Q-GERT Network for Module 5M3.

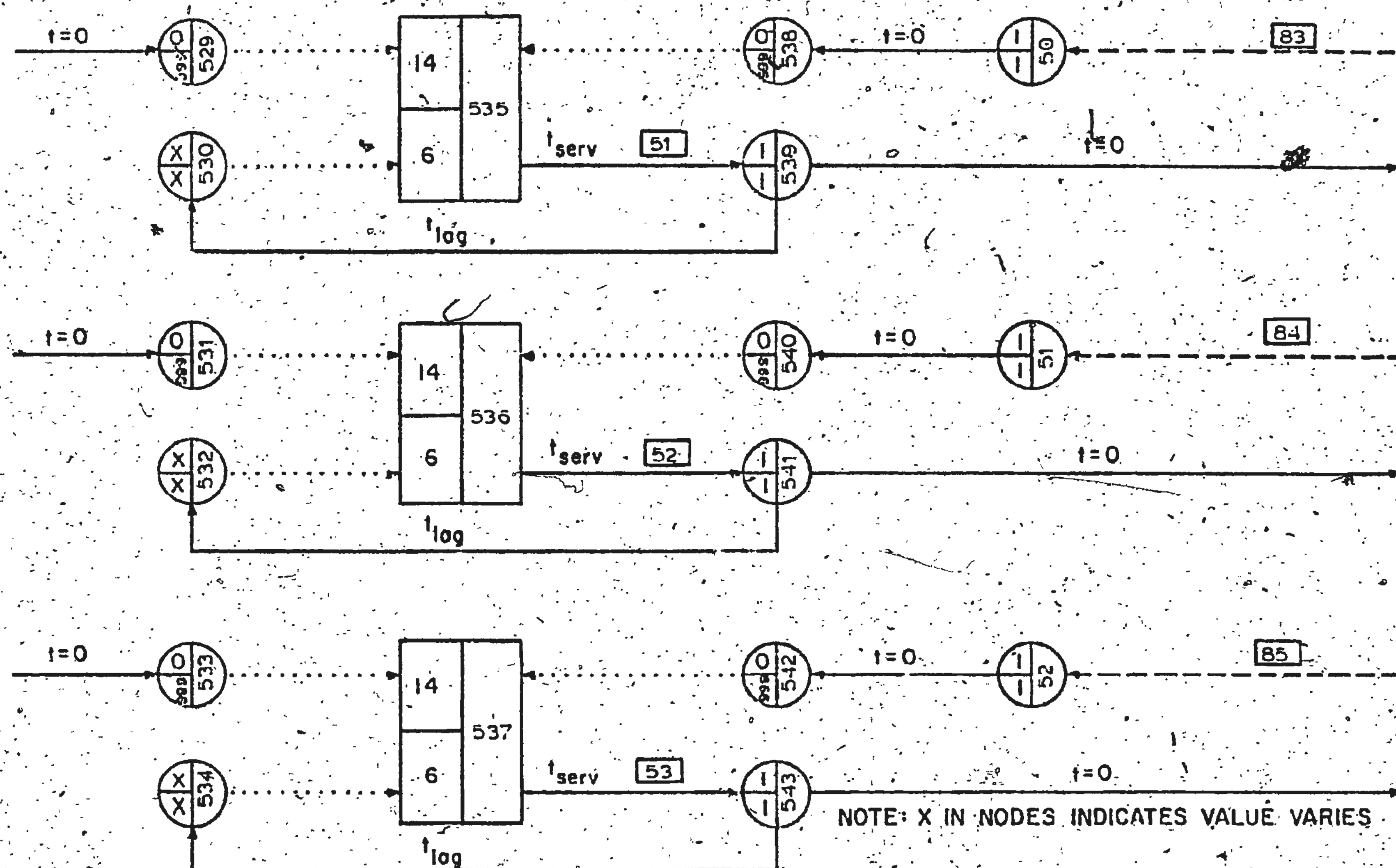


Figure C6. Q-GERT Network for Module 5M4

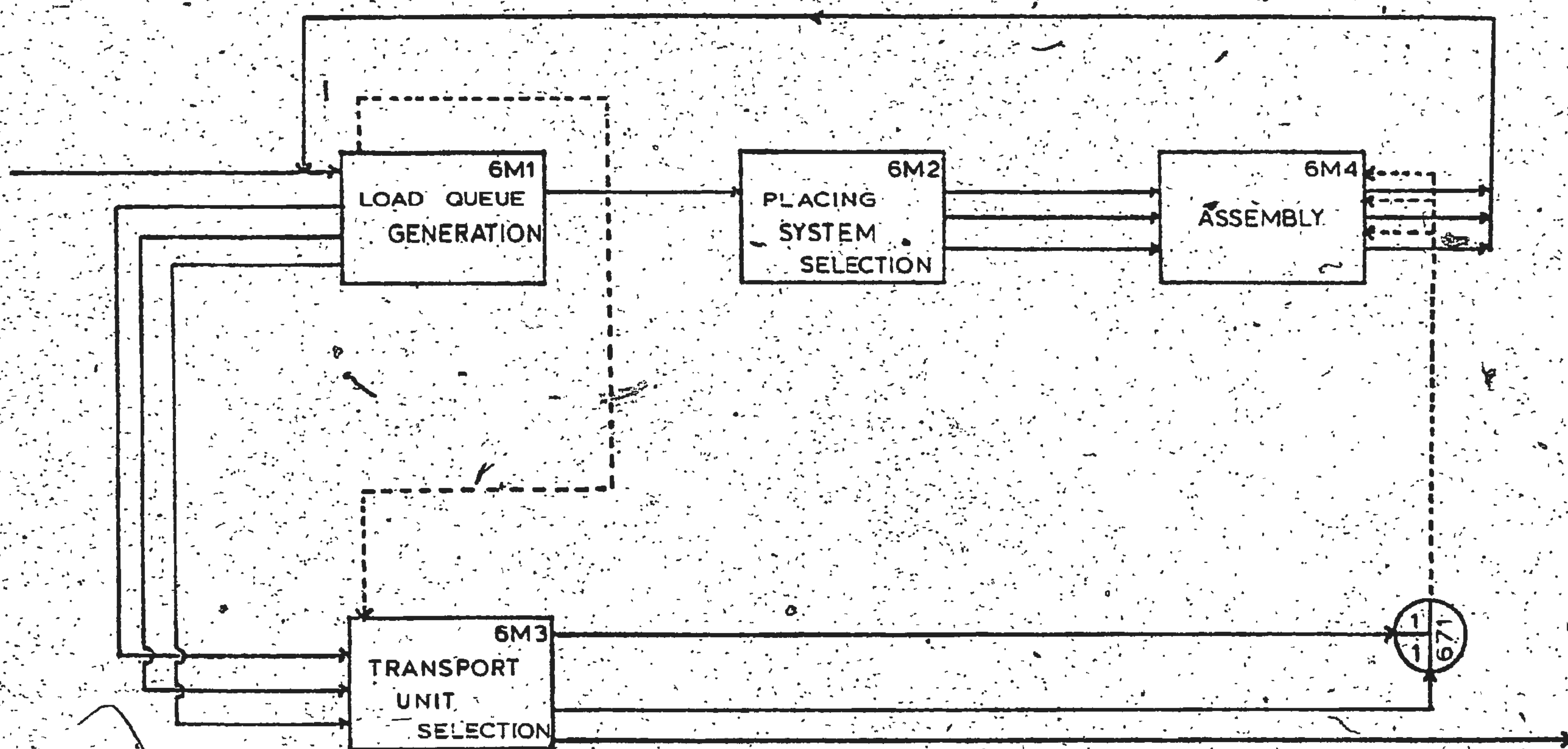
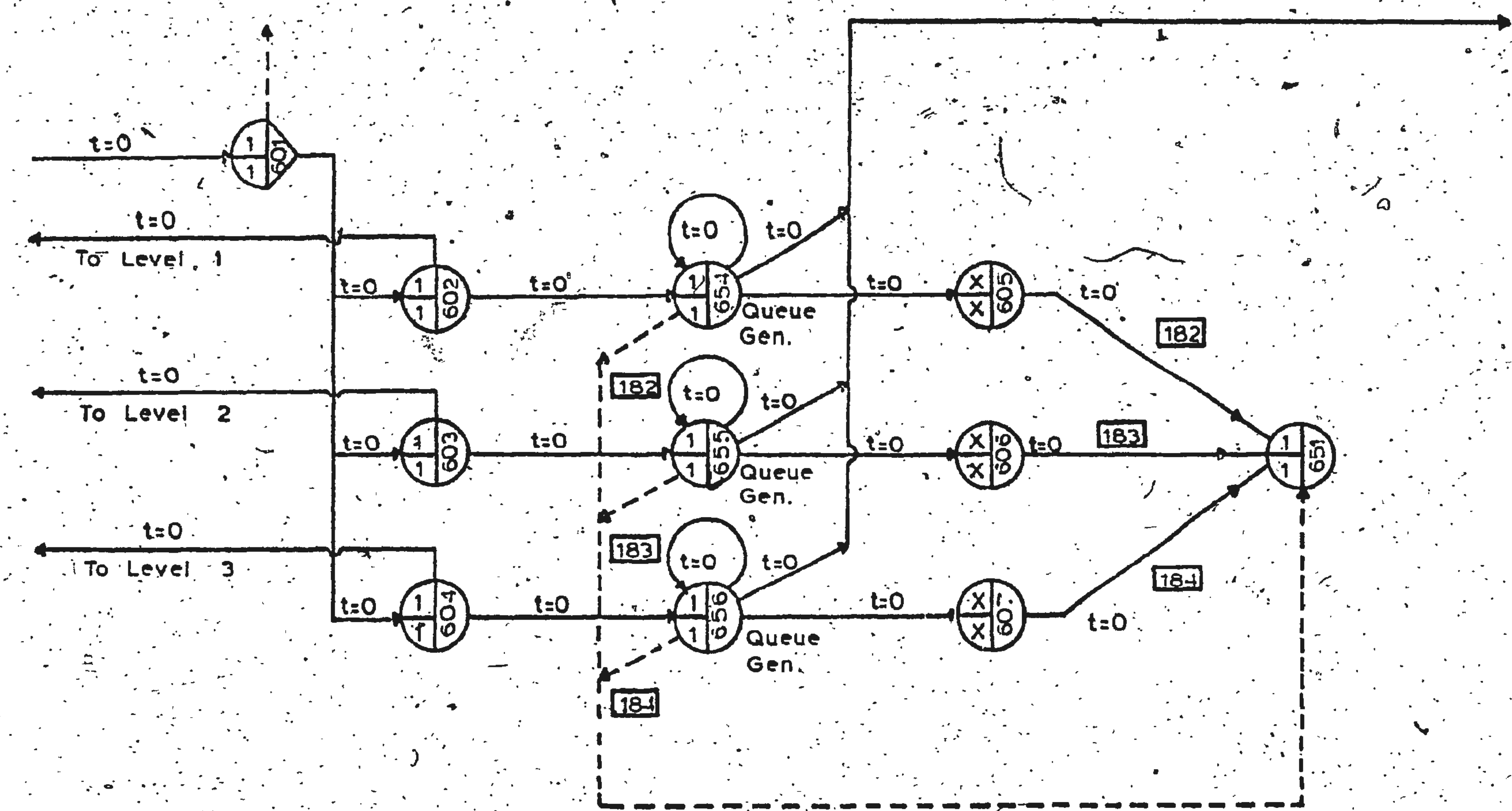


Figure C7. Q-GERT Network for Section 6.



NOTE: X IN NODES INDICATES VALUE VARIES

Figure C8.Q-GERT Network for Module 6M1.

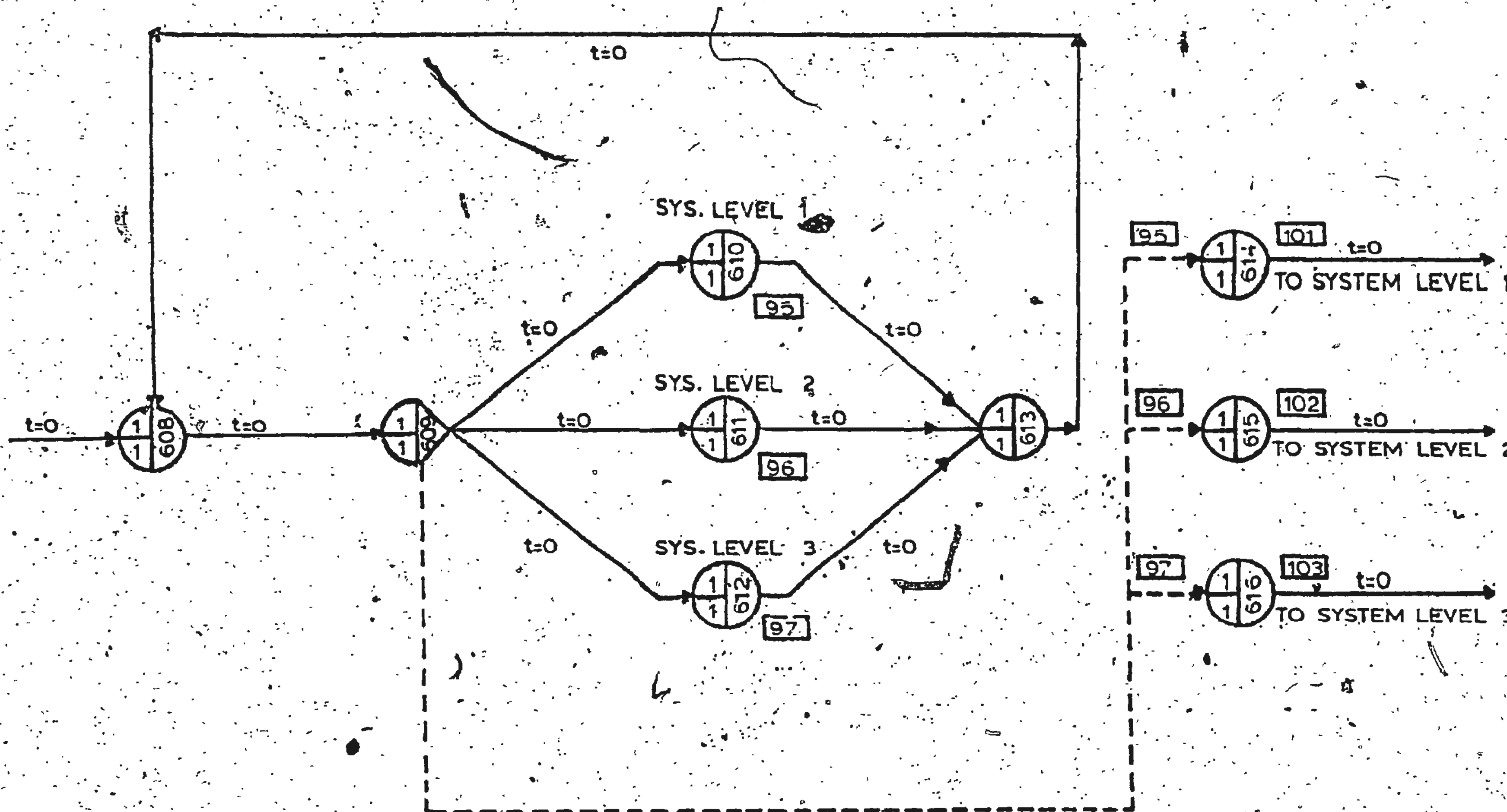


Figure C9. Q-GERT Network for Module 6M2.

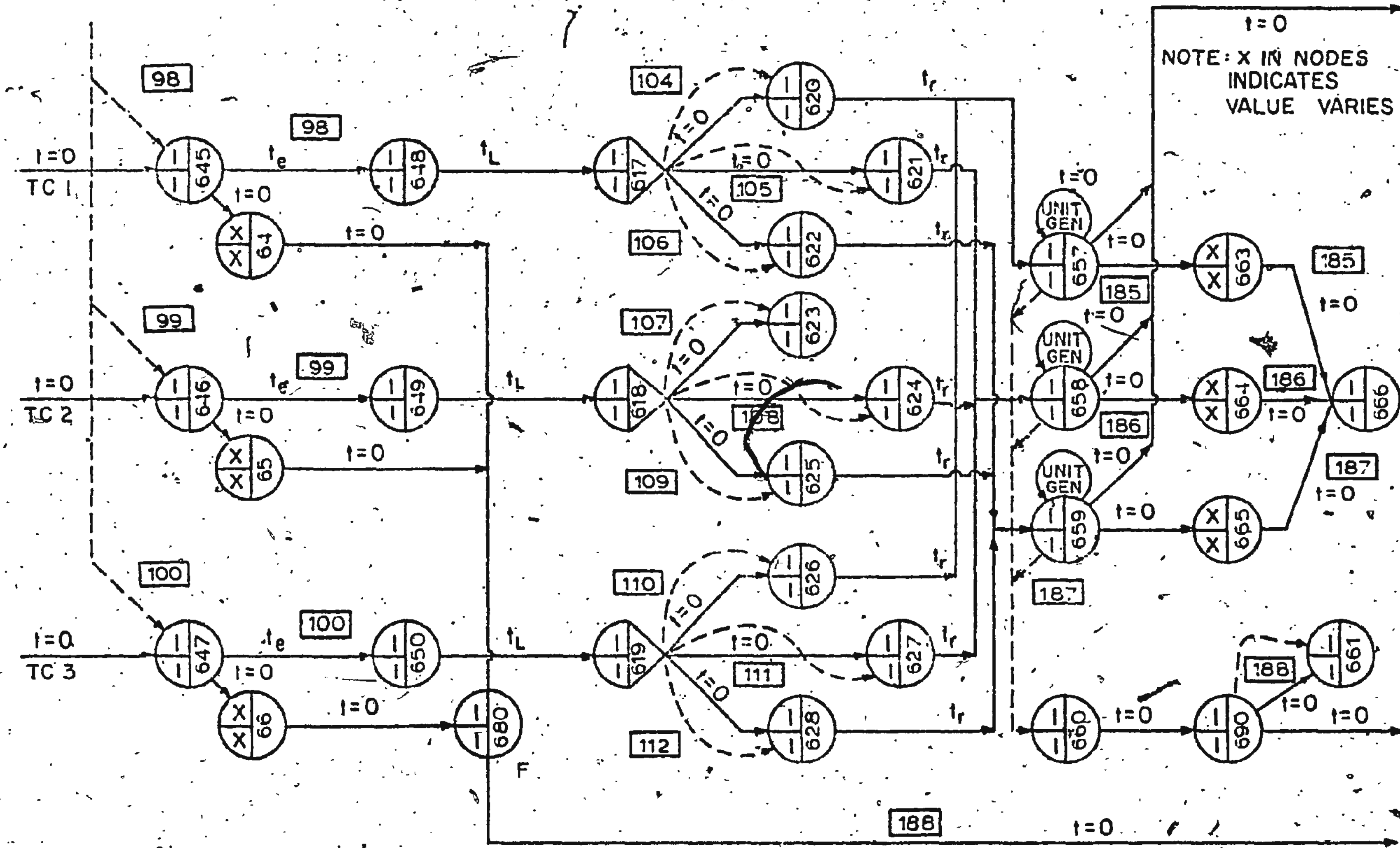


Figure C10. Q-GERT Network for Module 6M3.

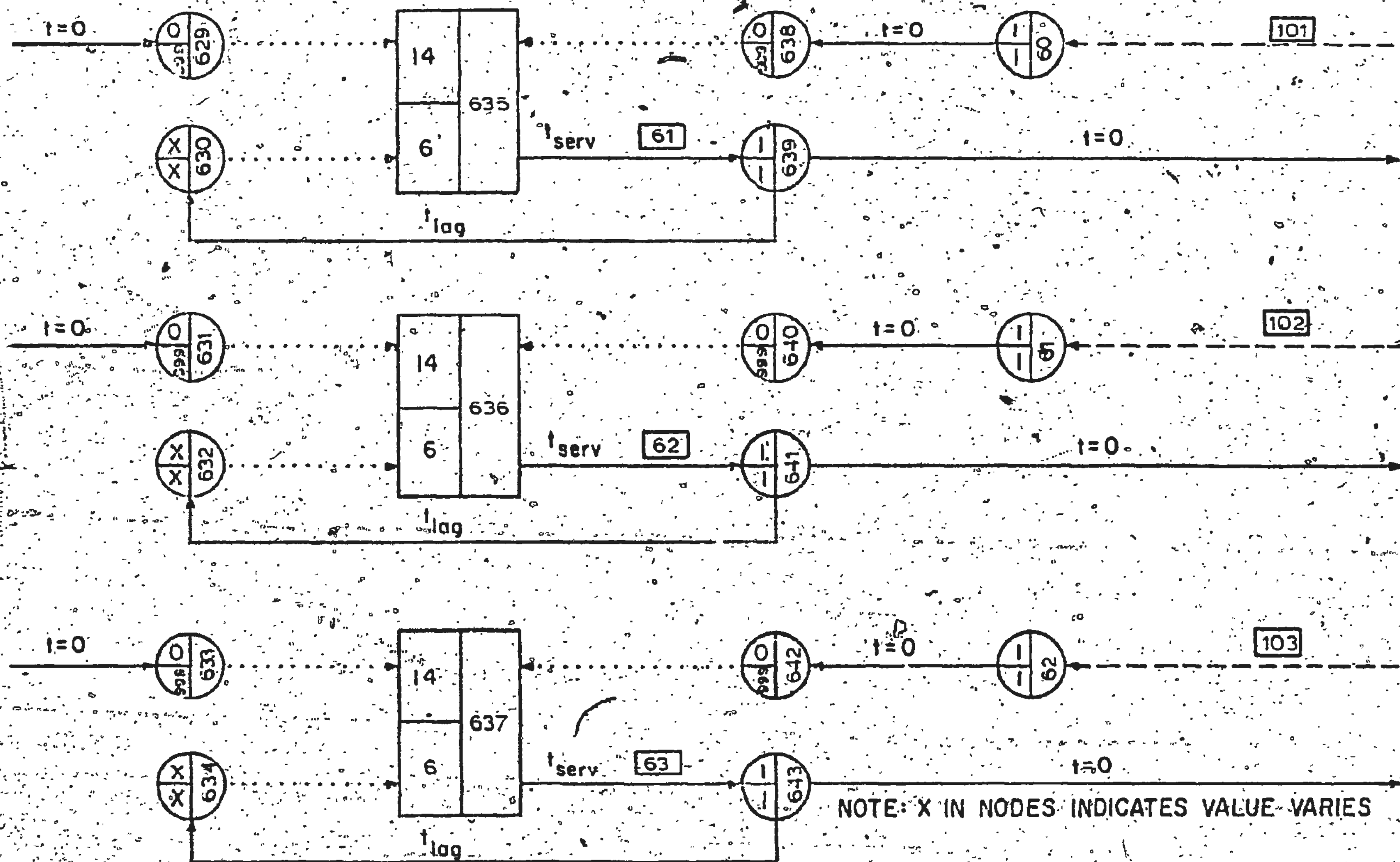


Figure C11. Q-GERT Network for Module 6M4.

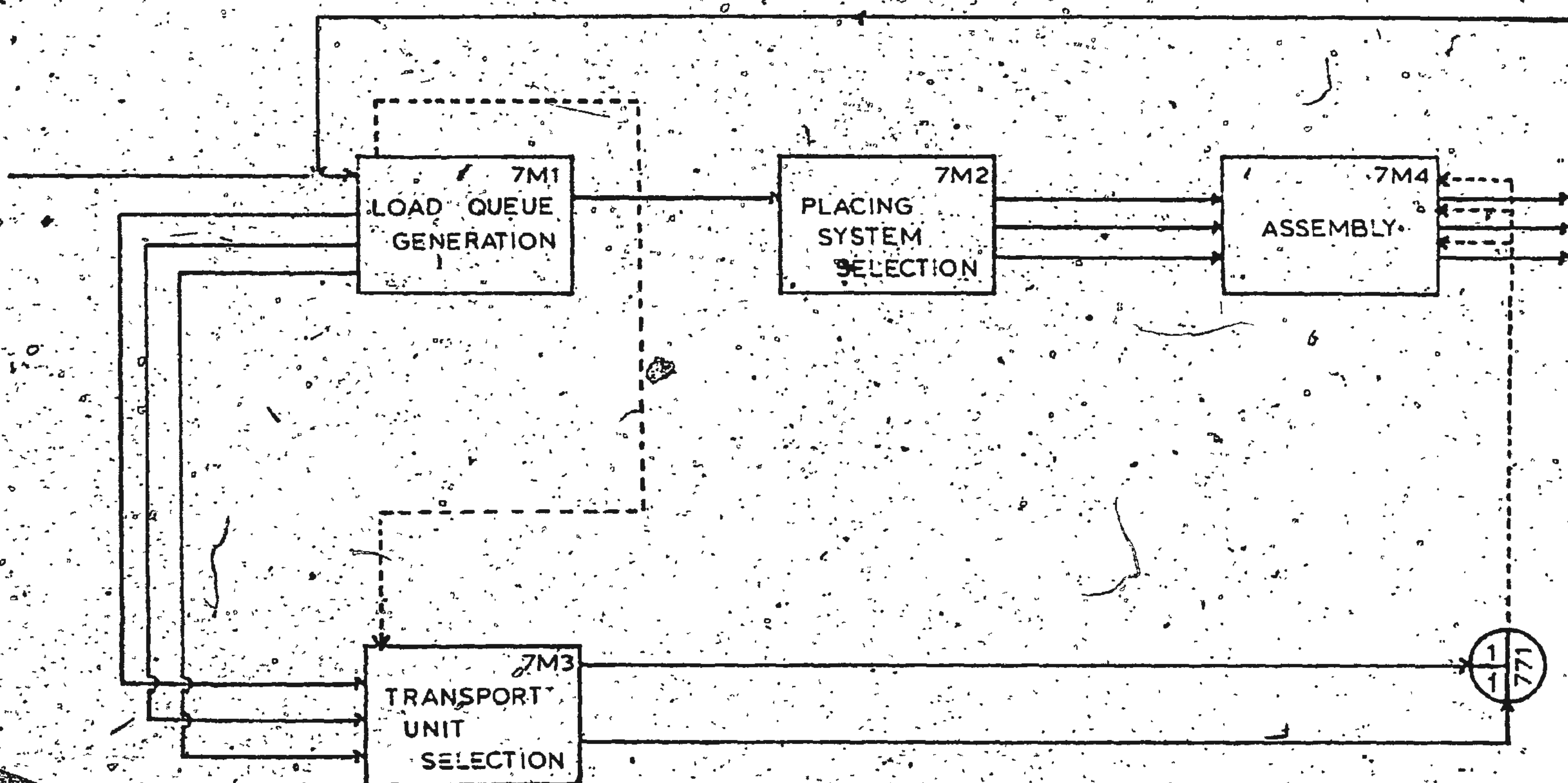
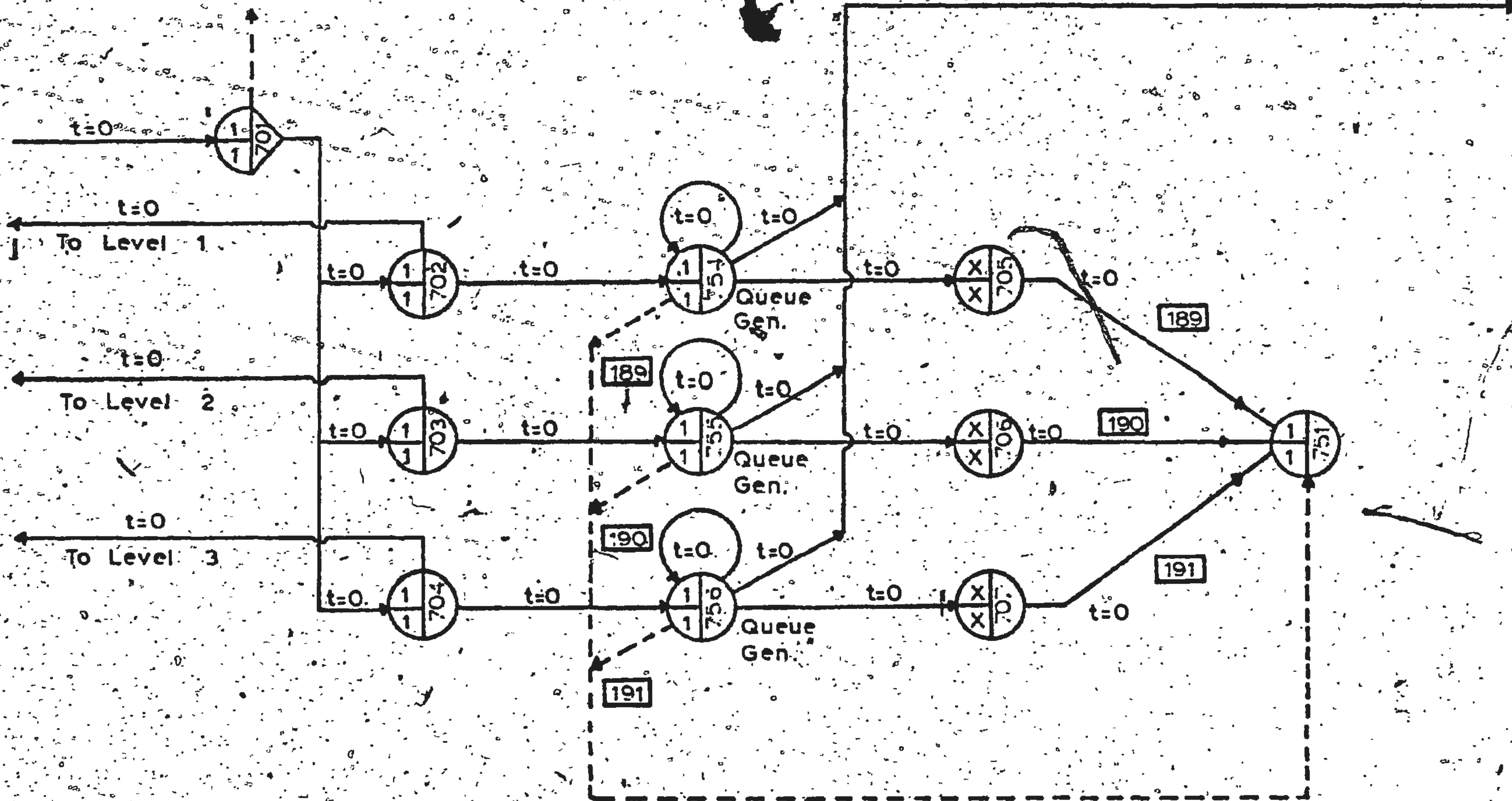


Figure C12. Q-GERT Network for Section 7.



NOTE: X IN NODES INDICATES VALUE VARIES

Figure C13.Q-GERT Network for Module 7M1.

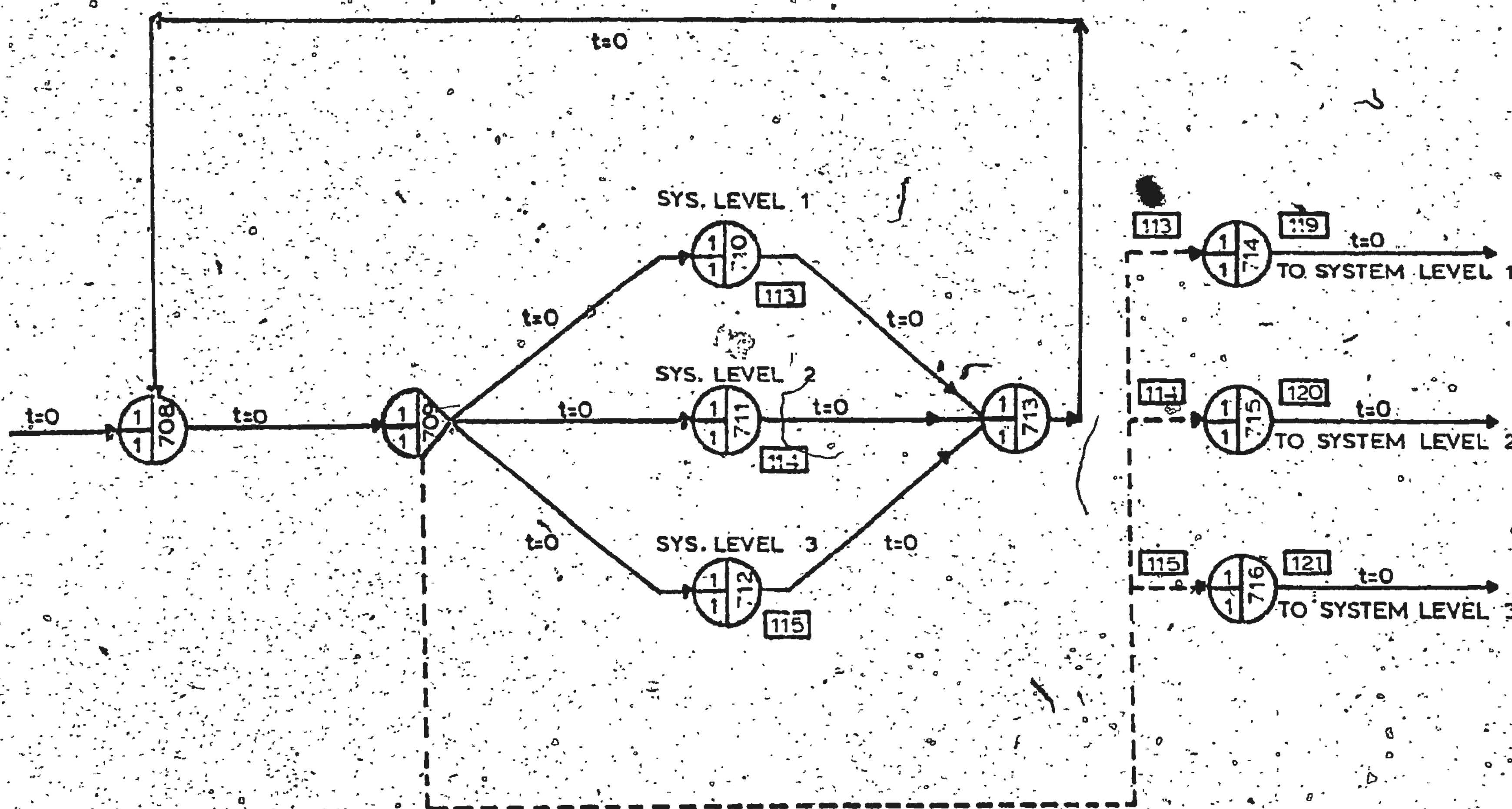


Figure C14. Q-GERT Network for Module 7M2

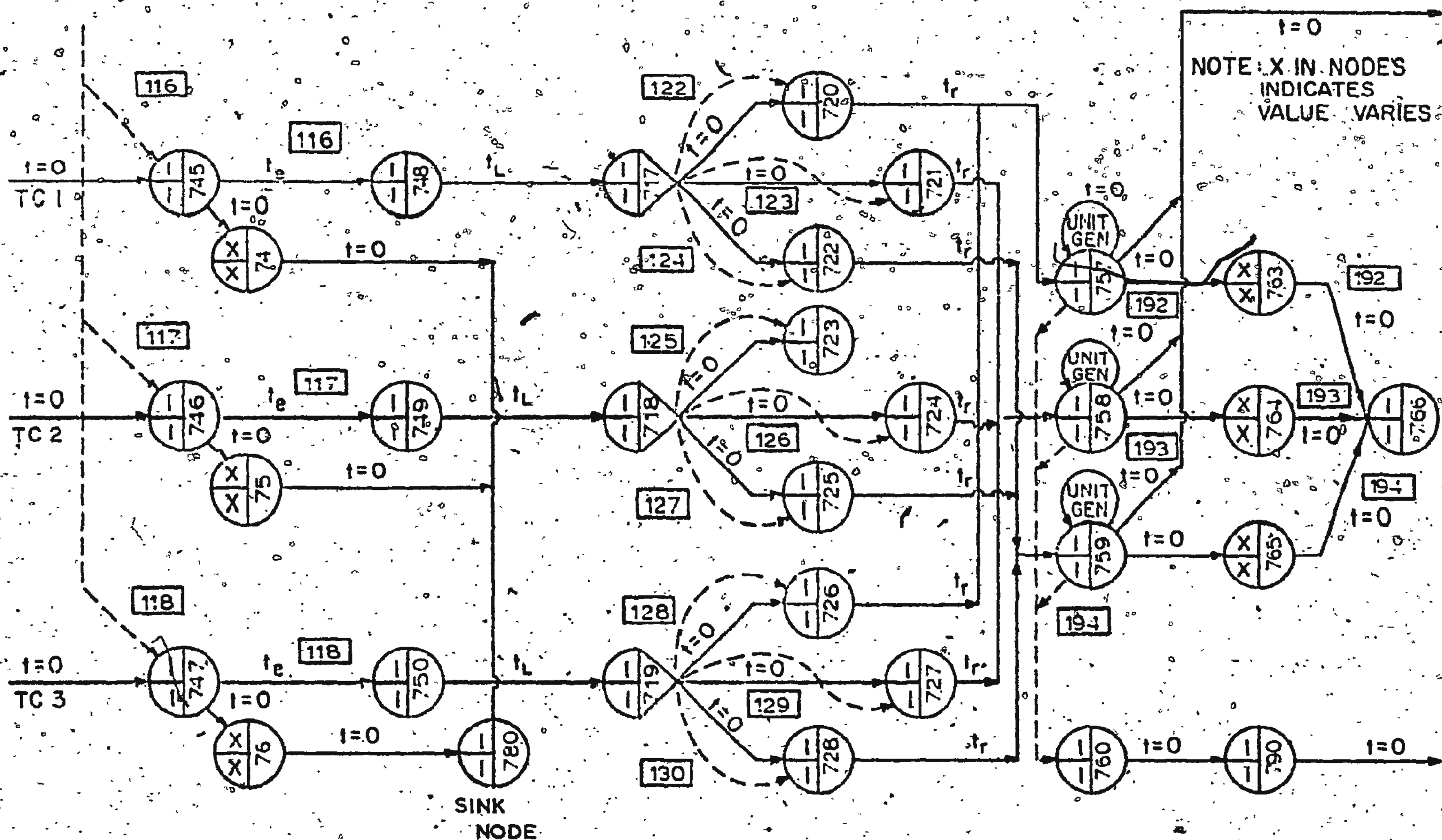


Figure C15. Q—GERT Network for Module 7M3.

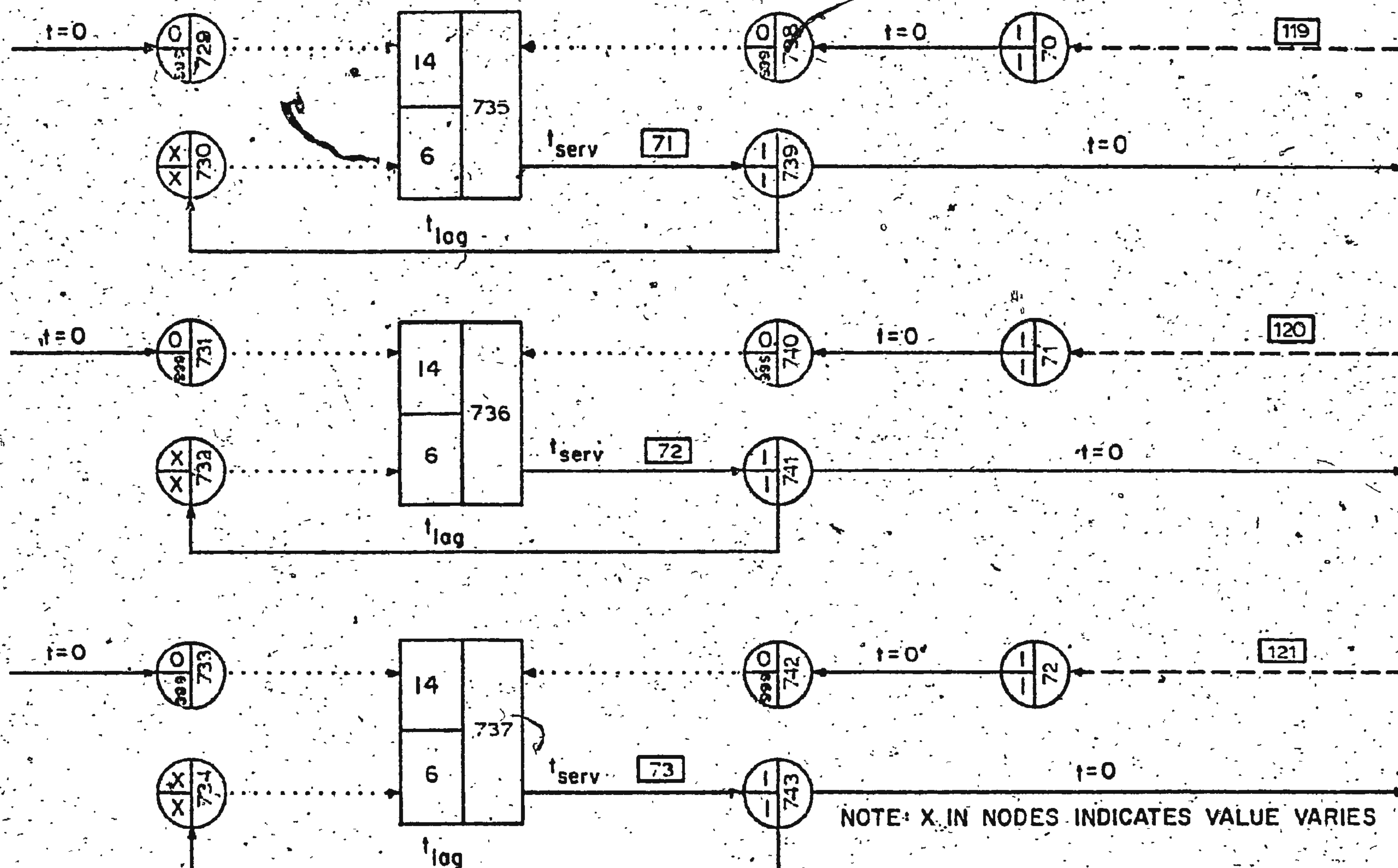


Figure C16. Q-GERT Network for Module ZM4.

APPENDIX D

Example:[1]

Working length = 100 feet

Transport type = Truck, Chev. dump. Capacity 8 cu. yds. at transport level.

Tunnel size = 20 feet diameter (characteristic dimension)

Tunnel shape = Circular

Volume of muck in 100 feet of tunnel

$$= .7854 \times (20)^2 \times 100 = 31400 \text{ cu. ft.}$$

$$\text{Muck queue} = \frac{\text{Volume of muck in 100 ft. (cu.yds.)}}{\text{Level 1 capacity (cu.yds.)}}$$

$$= \frac{31400 \times .03703}{8}$$

$$= 150 \text{ loads}^{2}$$

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[1] Calculations for train and conveyor are similar to this example.

[2] This value would replace x in nodes 207, 208, 209, 210 and 211 of module 2M1. Therefore it cannot be less than 1.

APPENDIX E

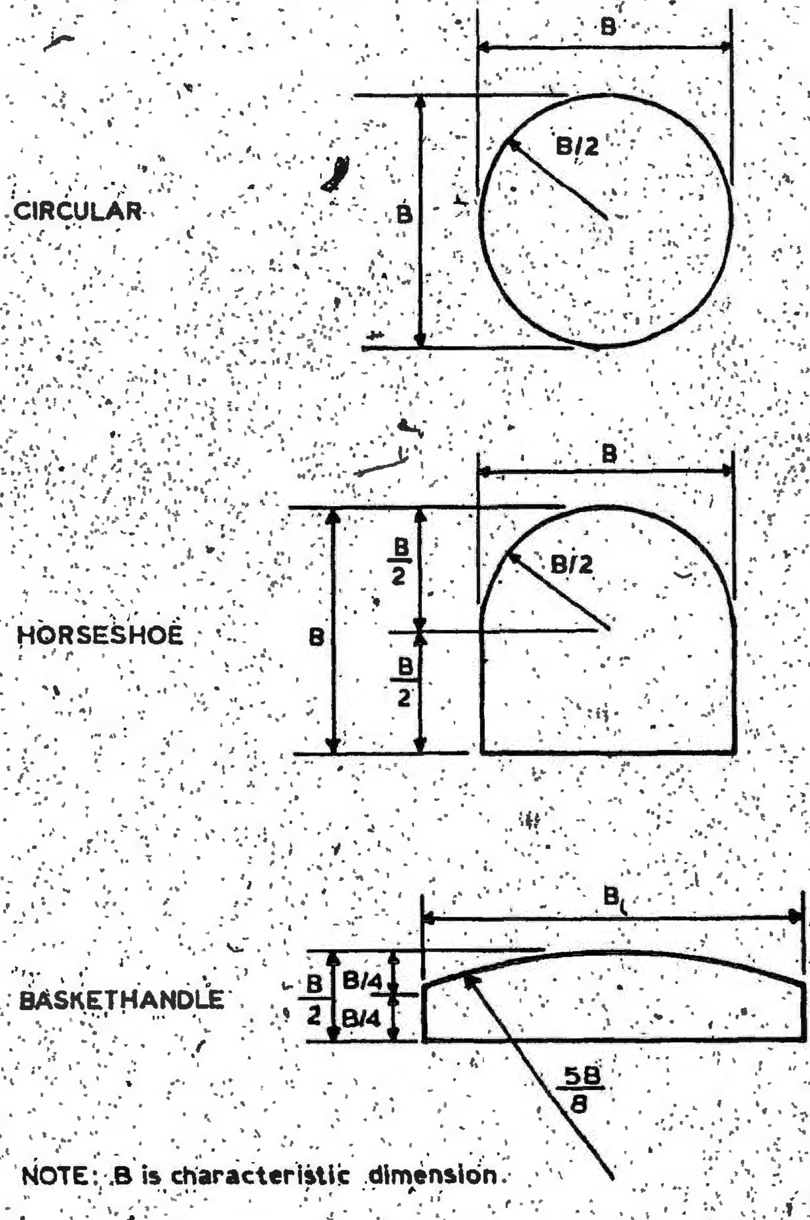

Figure E1. Tunnel Shape.