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# A Closed Network Queue Model of Underground Coal Mining Production, Failure, and Repair

G. M. Lohman

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# ABSTRACT

Underground coal mining systems production, failure, and repair cycles were mathematically modeled as a closed network of two queues in series, in order to understand better the technological constraints on availability of current underground mining systems and to develop guidelines for estimating the availability of advanced mining systems and their associated needs for spares as well as production and maintenance personnel.

## SUMMARY

Over the last eight years, underground coal mining productivity has dropped by almost 50%, resulting in a parallel increase in the price of that coal. Whatever the root causes of the productivity decline, it is an empirical fact that the availability (fraction of time producing) of equipment at the working face is generally less than 75%. Thus, the work presented in this report was undertaken with two objectives in mind:

- To understand better the technological constraints on the availability of current underground mining systems, and

- To develop guidelines for estimating the availability of advanced mining systems, and their associated needs for spares, as well as production and maintenance personnel.

The delays impacting availability can be classified as occurring either predictably or randomly. Predictable delays may be accounted for using functional flow diagrams, but previous studies of random delays have been limited to statistical analyses of historical data or large simulations of specific mining technologies, rather than the development of analytical models with predictive capability.

This report presents the construction and analysis of such a model. An underground mine is mathematically represented here as a collection of work stations (sections) that alternately require servicing by one production crew and one repair crew, each drawn from a respective pool of homogeneous crews. This interaction is modeled as a closed network of two queues in series, and is solved as a classical finite-state birth-and-death process. As such, the model is applicable to any cluster of processes that operate and fail independently, but which share pools of production and repair crews.

Sensitivity analysis of the model produces four major conclusions:

- The mean availability of a section has a theoretical limit of $\rho/(1+\rho)$, where $\rho$ is defined to be the "maintainability ratio" of Mean Time Between Failures (MTBF) to Mean Time to Repair (MTTR). Moreover, this theoretical limit will be achieved only when there are so many production and repair crews that sections never need to wait for either.

- Given a value for the maintainability ratio representative of current operating experience, section availability exhibits steep improvement in response to small improvements in the maintainability ratio. Hence big payoffs can be expected from concentrating efforts upon developing ways to increase the time between failures and/or decrease the time to repair failures.

- The number of production crews should be 0.85 to 1.00 times the number of sections, and the number of repair crews should exceed the quotient of the number of production crews divided by the maintainability ratio, $\rho$.

- The sensitivity of production at the mine mouth to the availability of any link in the haulage system is exactly equal to the quantity of coal that that link is expected to receive from all sections and haulage links feeding into it, times the availability of all haulage links between it and the mine mouth.

Key Words: Modeling, Energy, Coal, Underground Mining, Reliability, Production, Failure, MTBF, Equipment Utilization, Repair, MTTR, Network, Queue, Markov Process, Sensitivity Analysis.

## ACKNOWLEDGMENTS

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A CLOSED NETWORK QUEUE MODEL OF

UNDERGROUND COAL MINING PRODUCTION, FAILURE, AND REPAIR

## A. MOTIVATION

Coal is generally recognized to be the leading short-term energy alternative to oil for the United States. Nearly two-thirds of the recoverable U.S. coal reserves lie at depths too great to be extracted economically by surface mining techniques. Underground minable reserves of bituminous coal alone amount to 114.8 billion tons [Ketron]. By comparison, in one year (1974) coal production from underground mining was only 282 million tons, or about 48% of that year's total coal production in the U.S., of which almost half was used for producing electricity [Hittman].

Over the last eight years, underground coal mining productivity has decreased by almost 50%, from a national average of 15.6 tons per man-day in 1969 to 8.5 tons per man-day in 1976, resulting in a parallel increase in cost. Various reasons for the observed decline have been suggested, including

- Lost production time due to implementation of the 1969 Mine Health and Safety Act;
- Additional men required on a section of the mine due to changes in the union contract;
- More lost time due to worsening geologic conditions as mining has progressed to more difficult seams;
- Changes in the composition of the work force, notably the retirement of older, more skilled labor, and their replacement with younger miners who are initially less skilled and motivated [MEI].

Whatever the root causes of the productivity drop, it is an empirical fact that mine availability (fraction of time producing) is generally poor, indicating levels of utilization of both labor and capital that adversely impact coal costs [DOE LC]. For example, a study by Bendix Corporation of the monthly down times of 35 continuous miners found an average availability of this piece of equipment to be 73% of the face time (production shifts less travel time) [Bendix]. Since the equipment within a continuous mining section is essentially linked in series with the miner itself, system availability would be considerably less than 73%. During a time and motion analysis by Ketron, Inc., of conventional mining systems, monthly data from 9 different sections showed availabilities ranging from 55% to 100%, with an average of 68.2% [Ketron]. Statistics calculated by a previous Jet Propulsion Laboratory study, on data itemizing individual delays over 11 months, found the availability of one longwall section to be 76%, and of one shortwall section to be 68% [JPL II, L&S]. These figures exclude time lost to travel, scheduled maintenance (sometimes an entire shift), setup and teardown, moving equipment (see page 4 below), etc. Hence availability as a percentage of hours in a day was often much less than 50%. It is interesting that longwall and shortwall equipment have about the same availability as conventional mining technology. In some cases, the sophistication and/or bulkiness of the machinery used by these newer methods may have caused longer repair times than for conventional mining equipment [JPL III]. The geological origin of many of these delays also suggests that availability will not improve in the future, as seams with worsening geological conditions are exploited [Bendix, JPL III].

This "down" time is a significant contributor to the overall cost of producing coal. Besides the obvious costs for repair personnel, spare parts, and premature machine replacement, there are more subtle impacts. Some labor is idled while repair or service takes place. To this cost may be added the opportunity cost of lost production whenever the system is not operating at full capacity, assuming sufficient market demand for additional production. These direct costs in turn have associated indirect costs. For example, the spare parts inventory requires storage space, handling, and investment, and the lost production from idled crews may justify the added overhead of having spare sections or crews (see Section D, below). For a more precise description of the relationship between availability and production cost see [DOE LC].

The work presented in this report was undertaken with two objectives in mind:

- To understand better the technological constraints on the availability of current underground mining systems; and

- To develop guidelines for characterizing the availability of advanced mining systems and their associated needs for spare equipment, spare sections, and maintenance personnel.

Previous studies of availability have been limited to statistical analyses of historical data on delays [Bendix; COMINEC; JPL II, L&S; JPL III; Ketron] or to large simulations of specific mining technologies [Battelle]. To predict availabilities of new systems or of existing systems with modifications, however, requires construction of a general model of the complex interaction of labor, machinery, random failures, and repairs. And this model should be an analytical model, so that the sensitivity of availability to variations in the system parameters can be thoroughly examined at low cost.

This report presents such a model, which projects availability and other productivity measures, given two equipment reliability parameters usually determinable from engineering studies — the mean time between failures (MTBF) and the mean time to repair (MTTR) — plus the number of sections, production crews, and repair crews employed in the mine. Sensitivity of productivity to variations in these parameters is also readily derivable from this model, suggesting appropriate areas for research and development, as well as the proper balance of labor and equipment, in advanced coal mining systems. Within the larger context of manufacturing technology, this model is applicable to any cluster of processes that operate and fail independently, but which share pools of production and repair crews.

The terminology used throughout this report is first defined in Section B, and various types of delays are characterized. Then Section C develops the mathematical model and its underlying assumptions. Mathematical analysis and discussion of the model's results follow in Section D. In Section E the availability of the haulage network is incorporated into the model, and its impact on overall availability is derived. The sensitivity of mine performance to personnel, sections, and equipment maintainability is discussed in detail in Section F. Finally, the conclusions obtained from this analysis are summarized in Section G, and suggested validation procedures are briefly presented in Section H.

## B. NOMENCLATURE

Before proceeding with development of the model, it is useful to define the terminology employed to describe mining operations and the operational status of equipment.

### Mine Terms

An underground mine is usually composed of several independent work units called sections, each with its own complement of mining components such as a miner, bolter(s), scoop(s), shuttle car(s), conveyor belt(s), etc. A section mines a portion of the coal seam called a panel, each composed of a series of cuts, the exact definition of which depends upon the method of mining. Sections share a pool of production crews and repair crews, although sometimes a production crew will perform minor repairs. Sections also often share a common haulage system that transports their coal from the face to the mine mouth. Links in the haulage system can be shuttle cars, conveyors, rail lines, slurry pipelines, etc.

### Classification of Down Time

Non-productive, or "down", time can and has been classified many different ways [Bendix; COMINEC; JPL II,L&S; Ketron]. For the purposes of predicting the occurrence and costs of all time lost, however, it is reasonable to classify delays by the predictability of their occurrence and the length of their duration. To a large degree, the predictability of a particular delay is determined by the nature of its cause. Hence the classification of delays shown in Table 1 is primarily by cause. Often delays such as preventive maintenance or safety meetings that can be scheduled, and which might otherwise absorb productive time, can be performed when another delay — such as failed equipment or waiting time — occurs unexpectedly. This makes unique classification of any one delay period somewhat subjective.

### Predictable Stoppages

A large percentage of delays are predictable, even for an unknown technology. Administrative delays encompass general inherent requirements of any mining system: travel time, lunch breaks, safety meetings, fire drills, etc. Lunch breaks almost always are 30 minutes, and travel time is a function of the distance from the portal to the face. Contractual delays are related to administrative, but, unlike administrative delays, they cannot be scheduled by management and occur much less frequently.

Table 1. Classification of Delays

| Type of Delay | Extent of Effect | Independent of Method? | Occurrence | Approximate Frequency | Approximate Length | Repair Required | Examples |
|---|---|---|---|---|---|---|---|
| 1. **Predictable Delays** | | | | | | | |
| Administrative | System | Yes | Scheduled | 2/shift to 1/week | 10-25 min. | None | Travel time, lunch, fire drill, safety meeting. |
| Contractual | System | Yes | Deterministic | 1/mo. to 1/many years | 1 shift to many weeks | None | Insufficient demand for coal, labor negotiations. |
| Major setup and teardown | Section | No | Deterministic | 1/panel | 15-50 days | Movers | Moving production equipment to a new panel, especially Longwall. |
| Minor setup and teardown | Section | No | Deterministic | 1/load to 1/cut | 1-40 min. | None | Tramming, advancing the line (Shortwall), cleanup. |
| Preventive maintenance and service | Section or System | No | Scheduled | 1/lift to 1/many cuts | Zero to one shift | Service | Changing oil, bits, or hoses; inspecting for loose or worn parts; charging scoop. |
| 2. **Unpredictable Delays** | | | | | | | |
| Personnel | Section | Yes | Random | Undetermined | 0-20 min. | None | Morale, operator misjudgments, spill. |
| Waiting time | Section | No | Random | 1/load to 1/cut | 0-15 min. | None | Congestion of components (especially shuttle cars), insufficient crews or crew members. |
| Geological | Section | No | Random | Many/shift to 1/week | 0-45 min. | Service | Faults, irregular floor, loose roof, lenses of rock. |
| Stalled Equipment | Section or System | No | Random | Many/shift to 1/week | 0-45 min. | Service | External belts or power system; face conveyor "hanging up" (Longwall). |
| Failed Equipment | Section or System | No | Random | 1/shift to 1/month | 30 min. to many shifts | Specialized Repair Personnel and/or Part | Essential equipment failure: mechanical breakage, electrical burnout, leaks, welding, broken belts or chains, etc. |

Major and minor setup/teardown delays cover the non-productive time needed to move equipment to the next panel and the next cut, respectively. The former move is less common but takes much longer — of the order of days rather than the minutes or hours required for minor setup and teardown. For example, longwall major setup/teardown occurred once during the 11 months observed but required 44 days [JPL II,L], whereas minor setup/teardowns for shortwall ("moving the line") occurred 460 times in a similar period, averaging 32 minutes per move [JPL II,S]. Still, like contractual delays, it can be determined when these delays will occur and approximately how long they will last.

Preventive maintenance and service time is generally scheduled by management, and may range from an entire shift dedicated to maintenance [JPL I and II], to degradation of production caused by one man inspecting equipment instead of performing his normal production duties. This category also includes time lost to service or part replacement forced by normal wear and tear, such as, charging batteries on scoops [JPL III] or changing machinery oil, bits, or hoses.

The amount of down time expected from predictable delays is derivable from functional flow diagrams of the mining process. An example of functional diagrams for a new technology may be found in Appendix C of reference [JPL B].

Unpredictable Delays

Unpredictable delays can be caused randomly by men, the (geological) environment, and/or machinery. In a strict sense, machinery failures — delays in which damage is sufficient to warrant a mechanic's attention and/or spare parts — are distinctly different from all other unpredictable delays. Failures typically occur much less frequently and usually last much longer because of their specialized labor and parts requirements. Non-failure delays frequently occur — often many per shift — and usually can be fixed on the spot by the production crew personnel in less than an hour.

Waiting time delays occur randomly, but wait time due to the congestion of mining components is somewhat predictable based upon the interactions of components necessary for any given method of mining. For example, in conventional mining, the loader must sometimes wait for the cutter [Ketron]. Continuous miners perform these two operations in parallel, eliminating that potential wait time. Another familiar example is shuttle cars waiting for each other, as contrasted with the relatively congestion-free conveyor belt systems. Waiting time due to insufficient crews is less predictable, and will be dealt with by the model developed in Section C below.

The amount of down time expected from unpredictable delays is derived by the model developed in Section C. It could be applied either to failures as strictly defined above, or more generally to all unpredictable delays, so long as the two input parameters mean time between failures (MTBF) and mean time to repair (MTTR) are consistently defined. Since the distinction between equipment failures and other unpredictable delays is seldom made in MTBF and MTTR data collection efforts, hereafter, the term "failure" will mean any unpredictable delay.

Availability Terms

Note that each of the following terms can apply to an entire mine, one section, or an individual machine (component), with potentially different meanings.

Clock Time is the scheduled work days, times 24 hours per day. It is composed of "up" or productive time and "down" or delay time.

Down (or Delay) Time is that portion of clock time during which coal is not flowing out of the mine/section/component. See page 3 above for a taxonomy of down time for a mine/section/component.

Up (or Productive) Time is that portion of clock time during which coal is flowing out of the mine/section/component. It is composed of time when the mine/section/component is operating either at full capacity or at a degraded rate.

Full Capacity is used to describe the time that the mine/section has all of its sections/components up at full capacity, i.e., at the maximum sustainable rate of production under ideal conditions (including well-trained crews, good roof and floor conditions, well-maintained equipment, etc.).

Degraded Operation is any up time for the mine/section when one or more of its sections/components is not up at full capacity, i.e., down or in degraded operation. For example, a mine with 6 of its 7 sections up is in degraded operation, as is a section with all components up but one shuttle car.

Face Time is clock time, less time for all predictable delays, except minor setup/teardown (i.e., less administrative, contractual, major setup/teardown, and preventive maintenance and service).

Non-Operational Time is that portion of face time a mine/section/component is awaiting or undergoing repair for an equipment failure that forced shutdown of that mine/section/component. Thus, non-operational time is repair time plus time awaiting repair.

Operational Time is face time minus non-operational time, i.e., that portion of face time during which the machinery is operational (not failed) but may or may not be up, cutting coal.

Repair Time is that portion of non-operational time when the mine/section/component that failed is actively undergoing one or more of the steps of repair: fault location, fault correction, and testing.

Productivity is the ratio of product quantity produced, divided by the number of men times clock time (e.g., tons per man-shift), for non-maintenance shifts only.

Reliability is the ratio of operational time to face time, i.e., the fraction of face time that the mine/section/component is not delayed by equipment failures.

Availability is the ratio of up time to face time, i.e., the fraction of face time that the mine/section/component is producing coal.

Utilization of a mine/section/component is the ratio of up time to clock time. Caution: this ratio is also sometimes referred to as availability.

Maintainability is the ratio of the mean time between failures to the mean time to repair, and indicates the mine's/section's/component's ability to keep operational and to get operational quickly when it fails.

## C. DEVELOPMENT OF THE MODEL FOR RANDOM FAILURES

The remainder of this report presents the derivation, analysis, and results of a mathematical model to project section and mine down times, due to random failures (unpredictable delays) of sections making up the mine. Actually, the model developed below has much wider applicability. It can be applied to any cluster of processes that operate and fail independently, while sharing pools of production and repair crews.

First consider any section within the mine during normal production. It is assumed that each section has a full complement of equipment necessary to mine coal. The major equipment for a single section is difficult to move and essentially configured in series. Hence, whenever one major component fails, the entire section fails and must be repaired [JPL II,L&S; JPL III], because the bulkiness of the components effectively prohibits replacing the failed equipment with spares from an equipment pool — or from another section. Instead, the production crew may be switched from the failed section to an operational section until a repair crew can get the equipment on the failed section operational again.* When the section is repaired, the repair crew moves on to the next section needing repair (if any), and a production crew, when available, will resume production on the repaired section.

It is assumed that each section fails independently of other sections, and only while in the process of production. Failures affecting all sections, such as a stoppage of a haulage system common to all sections, can be handled by treating the main haulage system as one component in a two-component series system, the second component being the aggregation of all sections feeding into that main haulage system (see Section E).

To further simplify the model, it is assumed that the equipment on each section of the mine has the same average performance, so that identical crews

*In practice, crews are moved only when the repair time is expected to be of sufficiently long duration, so the availability calculated below will not include the small amount of delay caused by the production crew waiting for completion of such small repairs. See also the discussion in Section H.

may operate on any section with equal effectiveness. Similarly, each production crew in the pool of production crews is assumed to have identical characteristics, and each repair crew in the pool of repair crews is assumed to have identical characteristics. That way each section has equal MTBF and MTTR.

The model visualizes each section as a customer, alternately requiring the "service" of one production crew until a failure occurs, and then one repair crew until repair is completed. If all available crews of the correct type are busy when a section requires production or repair "service", the section must "queue up" for that service. It is, perhaps, easiest to think of a section expediter standing in line to be assigned (first come, first served) a crew, first from a production crew dispatcher and then from a repair crew dispatcher each time the need for a service arises (i.e., getting in line prematurely, in anticipation of the need, is not allowed). The "time of service" by a production crew thus assigned is a random variable whose mean is MTBF $\equiv 1/\mu$; in other words, failures occur at an average rate $\mu$ per hour. Similarly, the "time of service" by a repair crew is another random variable whose mean is the MTTR $\equiv 1/\lambda$, indicating that a typical crew completes repairs at an average rate of $\lambda$ per hour.

It should also be noted that this model assumes negligible travel time between sections, whereas, in reality the time to move an entire crew to a new section and resume normal operation acts as a threshold discouraging the movement of a production crew awaiting completion of a minor repair. This hidden travel time can be accounted for by incorporating the travel times (between sections) of the production crew into the MTBF, and of the repair crew into the MTTR, respectively.

Given the above assumptions, production failure and repair in a mine may be modeled as a closed network of two multi-server queues, a P queue for production service by one of the $s_P$ production crews, and a serially-linked R queue for repair service by one of the $s_R$ repair crews. The "customers" of both services are the (identical) sections, and the service in each queue obeys a first in, first out (FIFO) priority rule. Note that the term "queue" is used here in the technical sense employed in the queueing theory literature, i.e., encompassing both the servers and the line of customers awaiting their service. The network is shown schematically in Figure 1.

Since a section is always either in the P queue or the R queue, and since the network is closed to entry or exit of sections, the location of all sections is described by the number of sections in the P queue. Hence, the states of the network system can be represented by a single variable: the number of sections in the P queue. For example, if the mine has m sections, and if i sections are in the P queue ($i = 0, 1, \ldots, m$), then $m-i$ sections are in the R queue. If i is less than $s_P$, $s_P-i$ production crews are idle and no sections are wanting for production crews; otherwise no production crews are idle and $i-s_P$ sections are idled by insufficient production crews. Similarly, if $m-i$ is less than $s_R$, then $s_R-(m-i)$ repair crews are idle and no sections are in the R line; otherwise no repair crews are idle and $(m-i)-s_R$ sections are in line for repair. Obviously, it makes little sense to have either $s_R > m$ or $s_P > m$, since the extra crews would never be used.

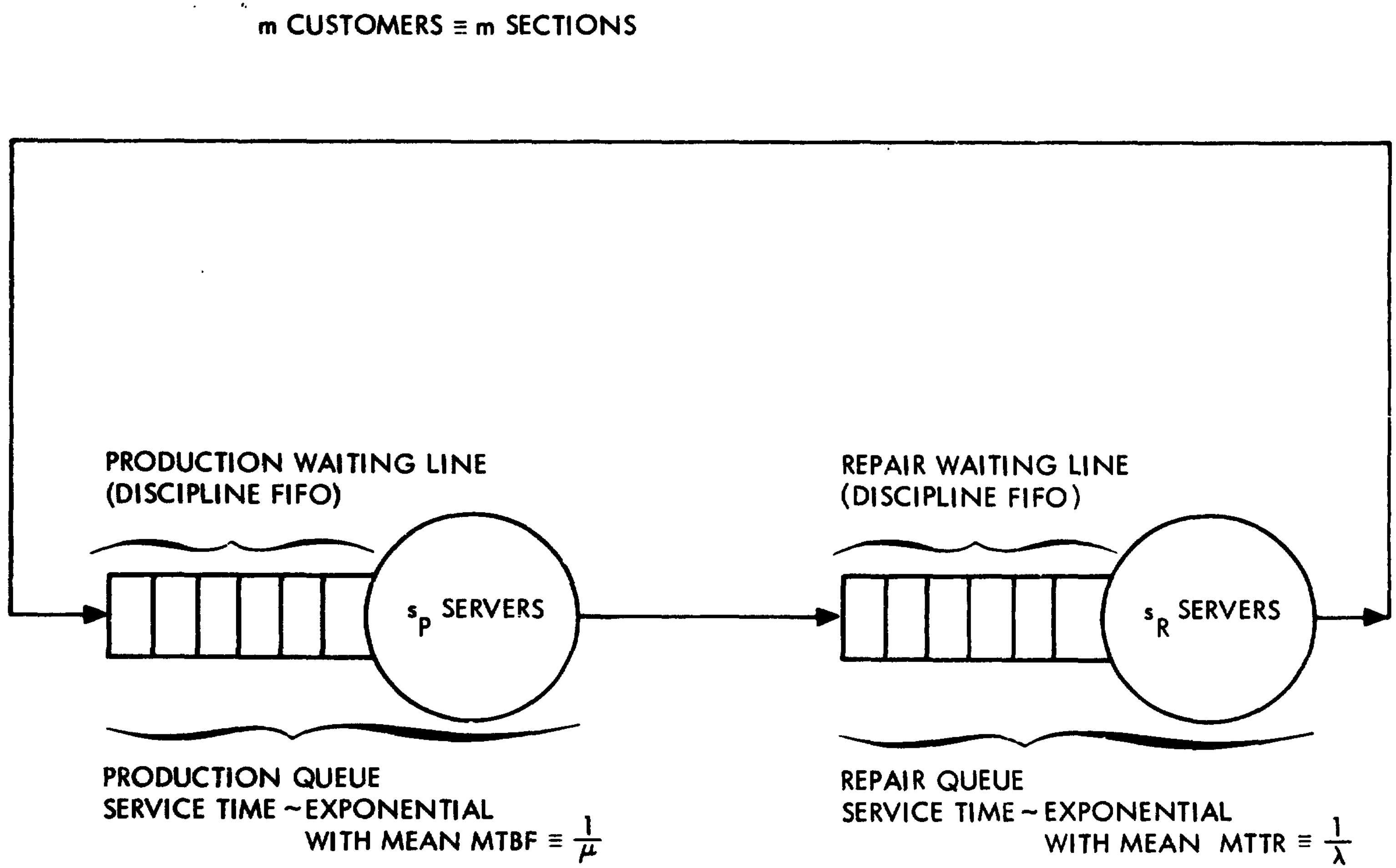



Figure 1. A Closed Network of Two Multi-Server Queues

If one makes an additional assumption that service times are distributed exponentially, then the state of the network can be described by a Markov process, for which many useful results are known. The assumption of exponentially distributed service times is quite common and has been verified for many different failure and repair processes under normal, steady-state operation.

As in any Markov process, the states to which the system can next move, and the rates at which it may go to those states, is a function only of the current state. The possible state transitions and their associated rates are best visualized schematically via an example. Suppose for illustrative purposes that $m=5$, $s_P=4$, and $s_R=2$. Then the system has six possible states: 0 up to 5 sections in the P queue. Each of these states is shown as a circle in Figure 2, with arrows showing the transitions, and the numbers along arrows being the instantaneous rates of transition for this example. Examination of Figure 2 indicates the system can go from state 3 to state 2 at rate $3\mu$, because only three of the four P crews are busy when there are three sections in the P queue, so only three P crews are suffering failures at rate $\mu$. And being in state 3 also implies that two sections are in the R queue, with both undergoing repair at rate $\lambda$; hence transition to state 4 (completion of the repair of one section and its return to the P queue) is occurring at rate $2\lambda$.

This process is a classical birth-and-death process, with state-dependent transition rates. In general, the rate of "birth" (arrivals from the R queue to the P queue) when in state i is denoted by $\lambda_i$ $(i=0,1,2,\ldots,m-1)$, and the rate of "death" (departures from the P queue to the R queue) when in state i is denoted by $\mu_i$ $(i=1,2,\ldots,m)$. Calculation of the transition rates in the manner described above yields the following general results:

$$\lambda_i = \begin{cases} s_R\lambda & 0 \le i \le m - s_R \quad \text{(repair crews all busy)} \\ (m - i)\lambda & m - s_R \le i \le m \quad \text{(some idle repair crews)} \\ 0 & i \ge m \quad \text{(impossible: only m sections)} \end{cases}$$

$$= \lambda \min\left\{s_R, m - i\right\}, \quad \text{for} \quad 0 \le i \le m - 1, \quad \text{and}$$

$$\mu_i = \begin{cases} i\mu & 1 \le i \le s_P \quad \text{(some production crews idle)} \\ s_P\mu & s_P \le i \le m \quad \text{(all production crews busy)} \\ 0 & i \ge m \quad \text{(impossible: only m sections)} \end{cases}$$

$$= \mu \min\left\{i, s_P\right\}, \quad \text{for} \quad 1 \le i \le m.$$

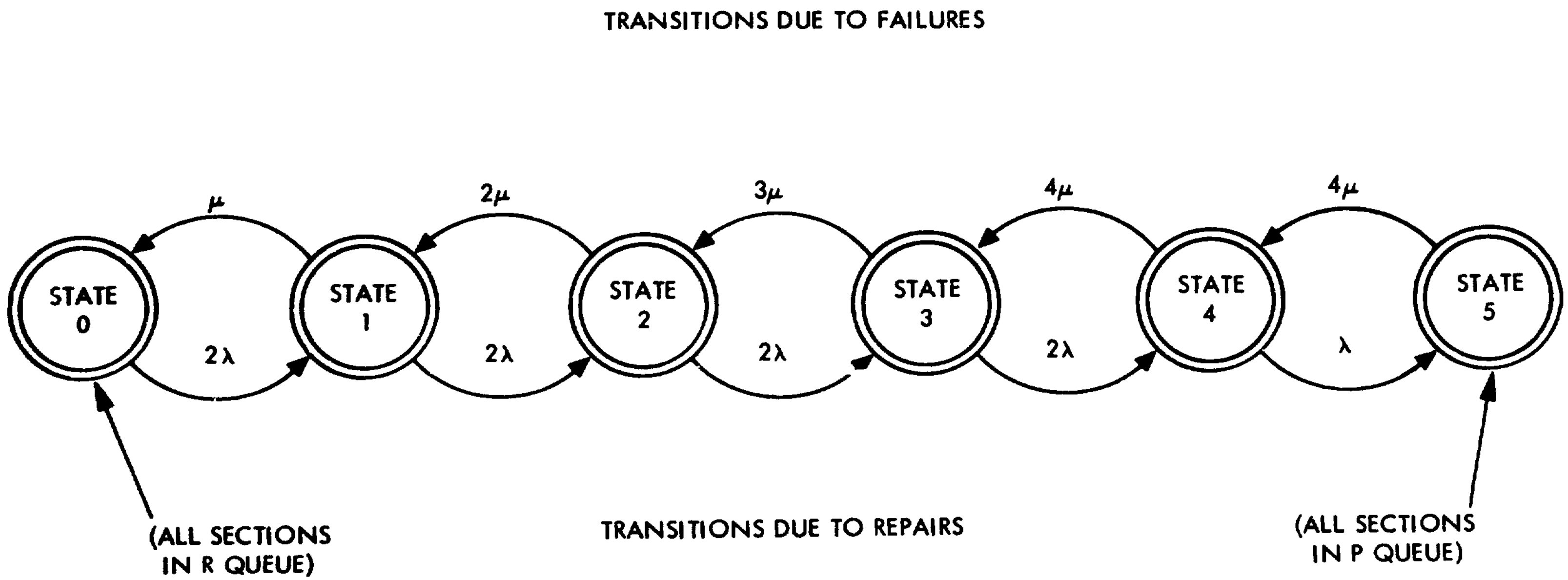



Figure 2. Possible States and Transitions (with rates) of the P Queue, for $m = 5$, $s_P = 4$, and $s_R = 2$

## D. ANALYSIS AND MODEL RESULTS

The above definitions permit immediate use of the known results for a birth-and-death process. Bhat [Bhat], among others, has shown for a birth-and-death process that the long-term (steady-state) probability, $\Pi_i$, of being in any particular state i, is

$$\Pi_0 = \left[ 1 + \sum_{j=1}^{\infty} \frac{\lambda_0 \lambda_1 \cdots \lambda_{j-1}}{\mu_1 \mu_2 \cdots \mu_j} \right]^{-1}$$

and

$$\Pi_i = \frac{\lambda_0 \lambda_1 \cdots \lambda_{i-1}}{\mu_1 \mu_2 \cdots \mu_i} \Pi_0 \qquad \text{for } i = 1,2,\ldots,$$

where the $\lambda_i$ and $\mu_i$ for this application are as given above.

Suppose for illustrative purposes that $s_R \le s_p$, i.e., that production crews exceed repair crews. Then the probabilities $\Pi_i$ can be simplified to the recursive equations:

$$\Pi_i = \frac{\min\{s_R, m-i+1\}}{\min\{i, s_p\}} \rho \Pi_{i-1} \equiv c_i \rho^i \Pi_0 \qquad \text{for } i = 1,2,\ldots,m$$

$$\Pi_0 = \left[ 1 + \sum_{j=1}^{m} c_j \rho^j \right]^{-1}$$

where

$$\rho \equiv \frac{\lambda}{\mu} = \frac{\text{MTBF}}{\text{MTTR}} \quad \text{and} \quad c_i \equiv \prod_{j=1}^{i} \frac{\min\{s_R, m-j+1\}}{\min\{j, s_p\}}$$

These results are identical to those obtained by Rau [Rau].

From the long-term probabilities $\Pi_i$ of being in any state i, a number of other performance measures can also be calculated, as described below:

Mine Availability ≡ the proportion of face time during which coal is flowing from the portal, i.e., the proportion of time one or more sections is producing coal;

$$= 1 - \Pi_0$$

ENIOS ≡ the expected number of idled but operational sections, i.e., extra sections waiting upon production crews, following repair by repair crews (This measures the shortages of production crews due to having too many sections.);

$$= \sum_{i=s_p}^{m} (i-s_p)\Pi_i$$

ENBPC ≡ the expected number of busy production crews, i.e., the expected number of crews producing coal on any section at any time, subject to availability of sections for them to work on;

$$= \sum_{i=0}^{s_p-1} i\Pi_i + \sum_{i=s_p}^{m} s_p\Pi_i$$

ENNOS ≡ the expected number of non-operational sections, i.e., those in the R queue, awaiting or undergoing repair;

$$= \sum_{i=0}^{m} (m-i)\Pi_i$$

$$= m - (\text{ENIOS} + \text{ENBPC})$$

UPC ≡ the utilization of production crews as a proportion of the number of production crews;

$$= \text{ENBPC}/s_p$$

$US \equiv$ the average proportion of sections utilized for production, or, equivalently, the availability of an average section in the mine;

$= ENBPC/m$

$ENBRC \equiv$ the expected number of busy repair crews;

$$= \sum_{i=0}^{m-s_R} s_R \Pi_i + \sum_{i=0}^{s_R-1} i\Pi_{m-i}$$

$URC \equiv$ the utilization of repair crews as a proportion of the number of repair crews;

$= ENBRC/s_R.$

As a check on the plausibility of the model, consider the special case of one section, one production crew, and one repair crew, i.e, no interaction with other sections. Application of the above formulae reveals that $\lambda_0 = \lambda$, $\mu_1 = \mu$, $\Pi_1 = \rho\Pi_0$ and $\Pi_0 + \Pi_1 = 1$, yielding a mine availability $= \Pi_1 = \rho/(1+\rho) =$ MTBF/(MTBF + MTTR) = section availability, as expected from the definitions of availability, MTBF, and MTTR. This result is true only because the single section has a captive production and repair crew, and so never has to wait for crews.

Note that all of the performance measures are simple functions of $\Pi_i$ and consequently, of the ratio of MTBF to MTTR! This is a result of considerable signficance, for it implies that performance of the mine would be equally affected by either a doubling of MTBF or a halving of MTTR.

## E. CONSIDERATION OF HAULAGE AVAILABILITY

Up to now, the haulage system from each section has not been considered in the model of mine availability, but it should be apparent that its impact can be significant. This impact is quantified below.

Suppose, for simplicity, that all sections have separate face haulage that feeds directly onto a main haulage system which serves all sections. This type of haulage configuration is, in fact, quite common. If the main haulage system has mean time between failures $MTBF_h$ and mean time to repair $MTTR_h$, its probability of being up at any time (or availability), $A_h$, is simply $MTBF_h/(MTBF_h + MTTR_h)$. Assuming these failures are independent of the section failures, which include face haulage failures, the probability that i sections are up is then a function of both the sections and the main haulage system being up simultaneously:

$$\Pr\left\{\text{i sections are delivering coal to the mine mouth}\right\}$$

$$= \Pr\left\{\text{i sections are producing } \underline{\text{and}} \text{ the main haulage system is operational}\right\}$$

$$= \Pr\left\{\text{i sections are producing}\right\} \times \Pr\left\{\text{the main haulage system is operational}\right\}$$

$$= \Pi_i A_h$$

Similarly, all of the mine performance measures should be multiplied by $A_h$ to allow for main haulage availability.

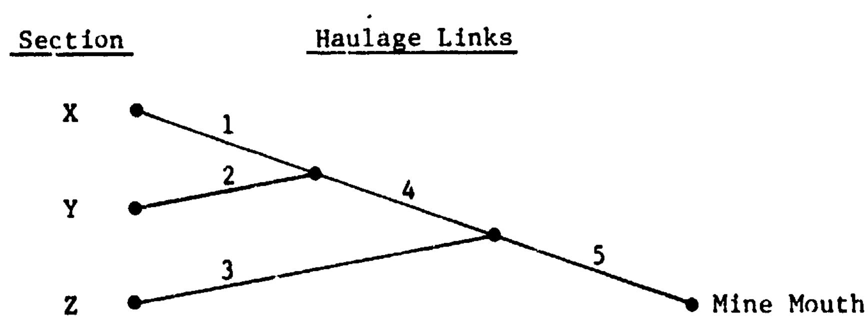
Mine mouth production can be calculated by using the revised expression for the expected number of busy production crews. If each section can produce T tons per minute, and each shift has F minutes of face time, the expected production of the mine per shift is

$$F \times T \times \left\{ \sum_{i=0}^{sp-1} i\Pi_i A_h + \sum_{i=s_p}^{m} s_p \Pi_i A_h \right\}$$

$$= F \times T \times A_h \times \text{ENBPC}$$

where ENBPC is the expected number of busy production crews, defined in the previous section.

In more complicated haulage systems having multiple links from section to mine mouth, mine mouth production can be calculated as follows. If, again, each section has F minutes of face time per shift and can produce at T tons per minute when it is up, then the expected tonnage per shift of each section is $F \times T \times US$, where US is the availability of a section that was derived from the $\Pi_i$ above. This section production is then multiplied by an availability factor for each link, $A_\ell$, and summed over all sections. Suppose, for example, that the mine's haulage is configured as follows:



Then expected mine mouth production per shift, assuming no surge bins, is simply

$$A_1A_4A_5(F \times T \times US) + A_2A_4A_5(F \times T \times US) + A_3A_5(F \times T \times US)$$

$$= F \times T \times US \left[A_5(A_4(A_1 + A_2) + A_3)\right],$$

where the second form of the equation emphasizes the parallel between the haulage configuration and expected production, and the importance this places upon availability of haulage links closer to the mine mouth. In fact, by taking partial derivatives with respect to each $A_i$, it can be shown that, in general, the sensitivity of mine mouth production to any link in the haulage system is exactly the volume of coal it can be expected to receive, times the availability of all links between it and the mine mouth.

## F. SENSITIVITY ANALYSIS USING THE MODEL

Due to the complexity of the equations for $\Pi_i$, sensitivity analysis by direct differential computation is not practical. Hence, a computer program was written to calculate and plot the performance measures for fixed values of $\rho$, $s_p$, $s_R$, and m. Model behavior was studied by systematically varying the four input parameters over a specified range.

Based upon historical data, four nominal cases were constructed to illustrate the effects of mine size and the balance between the number of production crews, repair crews, and sections. These cases are:

- A large mine, having average balance of crews and sections;
- A small mine, also having average balance;
- A poorly balanced mine; and
- An "optimized" mine, one with a better than average maintainability ratio and balance of crews and sections.

The relevant range of $\rho$ to be examined in these cases was derived from MTBF and MTTR data collected on a limited number of sections, for three different technologies, as summarized in Table 2. Table 3 gives the nominal values chosen for each of the input parameters for each case, and the range over which each parameter was individually varied for the sensitivity analysis. Note that the cases do not specify any particular mining technology, because the model is equally applicable to any technology which fits the assumptions of the model.

The results of the computerized sensitivity analysis are discussed below, grouped by the impact each input parameter has on utilization of each of the major mine entities: sections, production crews, and repair crews. Graphs illustrating typical sensitivities are referenced as Figures 3-20, located on pages 24-41.

Table 2. Historical Values of MTBF, MTTR, and $\rho$

| Technology | MTBF (minutes) | MTTR (minutes) | $\rho \equiv$ MTBF/MTTR |
|---|---|---|---|
| Conventional Mining [Ketron] | | | |
| Section 1 | 311.82 | 56.30 | 5.54 |
| Section 2 | 84.48 | 96.40 | 0.876 |
| Section 3 | 115.76 | 77.30 | 1.50 |
| Section 7 | 58.95 | 48.20 | 1.22 |
| Section 8 | 272.25 | 103.0[illegible] | 2.64 |
| Section 9 | 390.87 | 100.80 | 3.87 |
| Section 10 | 541.38 | 76.70 | 7.06 |
| Section 14 | 139.04 | 68.40 | 2.03 |
| Section 15 | 132.41 | 80.70 | 1.64 |
| All Sections | 167.07 | 77.80 | 2.15 |
| Longwall Mining [JPL II,L] | 130.54 | 66.52 | 1.96 |
| Shortwall Mining [JPL II,S] | 44.68 | 39.77 | 1.12 |

Table 3. Nominal Values and Ranges of Input Parameters for Sensitivity Analysis

| Input Parameters / Cases | m (Sections) | | | $s_p$ (Production Crews) | | | $s_R$ (Repair Crews) | | | ρ (Maintainability Ratio) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nominal | Min. | Max. | Nominal | Min. | Max. | Nominal | Min. | Max. | Nominal | Min. | Max. |
| Large Mine | 20 | 15 | 41 | 18 | 5 | 25 | 23 | 5 | 29 | 2.0 | 1.0 | 8.0 |
| Small Mine | 7 | 2 | 20 | 6 | 2 | 10 | 6 | 2 | 10 | 2.5 | 0.5 | 8.0 |
| Poor Balance | 15 | 5 | 21 | 16 | 5 | 21 | 2 | 1 | 13 | 2.0 | 0.5 | 7.0 |
| Optimized Mine | 20 | 12 | 40 | 18 | 5 | 33 | 8 | 1 | 19 | 4.0 | 0.5 | 14.0 |

Utilization of Sections (ENIOS, ENNOS, and US)

In a mine that has approximately 0.85 to 1.0 production crew per section, ENIOS is generally less than 0.01! ENIOS exceeds one section only when the ratio of production crews per section drops below two-thirds (Figure 3). Furthermore, this low value of ENIOS is virtually insensitive to $s_R$, so long as $s_R$ is adequate (see below). Comparison of these statistics against the expected number of non-operational sections (Figure 5) shows a higher idleness of sections due to failure than due to lack of production crews, for $s_p$ greater than 0.5 m.

For a mine with good balance between sections and production crews, improving the maintainability of each section (i.e., increasing $\rho$) increases ENIOS with slightly increasing slope up to about $\rho = 3.5$ in the small mine case, after which the slope decreases slightly (Figure 4). This change in slope occurs at larger $\rho (\rho \approx 7)$ for larger mines. In all cases, however, as $\rho$ increases, ENIOS is less than one-half section idled for values of $\rho$ below the maximum value of $\rho = 7.06$ observed in the data available.

It may be concluded from the above observations that extra sections, and their associated equipment, will not be significantly idle if the ratio of production crews to sections is maintained between 0.85 and 1.0, and sufficient repair crews are available. This conclusion applies without regard to the scale of operation, e.g., the sensitivities were identical for the small mine with seven sections and six production crews. The fundamental observation here is that an extra section or two will not go begging for production crews, if the crews are permitted to move to a new section rather than await the repair of a failed section.

In cases where repair crews are no problem (all but the poorly balanced case), ENNOS rises steeply with increasing $s_p$, then levels off in logarithmic fashion. It is asymptotic to $s_p/\rho$ over the approximate interval 0 to 0.6 m, then bends over during the interval 0.6 m to 0.95 m in order to be asymptotic to $m/(1+\rho)$ thereafter (Figure 5). This latter asymptote is in agreement with intuition, since $1/(1+\rho)$ = MTTR/(MTTR + MTBF) is the fraction of time an average section would spend under repair when there is no waiting for crews.

For the poorly balanced case, however, where a shortage of repair crews forces considerable waiting in the repair (R) queue, ENNOS is asymptotic to 3/4 m (= 12 sections, considerably higher than the 5.33 sections predicted by $m/(1+\rho)$). Confirmation of this sensitivity of ENNOS to the number of repair crews ($s_R$) is shown by Figure 6. ENNOS steeply decreases with increasing $s_R$, and appears to be the function $m - \rho s_R$, until about 0.25 m to 0.35 m, after which it bends up to become asymptotic to $m/(1+\rho)$ after about 0.5 m. The graph shows that ENNOS is extremely sensitive to $s_R$ at the nominal value of $s_R = 2$, and could be improved from 12 to the asymptote of 5.33 by increasing the number of repair crews to at least a less sensitive value like $s_R = 7$. See also the section below on utilization of repair crews.

Sensitivity of ENNOS to m is analogous to that of $s_p$. Again, in systems where repair crew capacity is no problem, ENNOS is an increasing linear function $m/(1+\rho)$ when the system is section-constrained (small m), leveling off to the asymptote $s_p/\rho$ when the system becomes production-crew-constrained (large m). See the small mine case of Figure 7. By comparison, when repair crews are insufficient to avoid a waiting line for repair crews even under normal circumstances, then saturation of repair capacity is manifested in a direct increase in ENNOS of one section for each section added to the system (compare the poorly balanced case in Figure 7). Here, the extra sections just end up waiting in line for repair, because the repair crews are already too busy.

Improving maintainability (increasing $\rho$) decreases ENNOS in a smooth hyperbolic-shaped curve. The small nominal values for the large mine ($\rho = 2$) and small mine ($\rho = 2.5$) cases are still on a fairly steep portion of this curve, suggesting that a small improvement in MTBF or MTTR could significantly reduce the number of sections idled by failures (Figure 8). When there are insufficient repair crews (e.g., in the poorly balanced case of Figure 8), the curvature of this graph is less exaggerated, i.e., the sensitivity to a change in $\rho$ is more uniform over all values of $\rho$. However, the steepness of the curve suggests that significant improvements can be made by improving maintainability even in poorly balanced mine systems.

The proportion of sections producing, or equivalently, the availability of an average section, is measured by the variable US. As expected, US improves with increasing section maintainability ($\rho$) in a logarithmic-shaped (diminishing returns) curve (Figure 9). As before, many of the nominal cases are still on the steep portion of the curve, suggesting that much better utilization of existing equipment could be accomplished by small increases in MTBF and/or decreases in MTTR. However, this curve becomes almost linear for a poorly balanced system, much as the curve for ENNOS did.

Until both the number of production crews, $s_P$, and the number of repair crews, $s_R$, reach adequate levels, US increases sharply with increasing staffing for a fixed number of sections (Figures 10, 11). For $s_P$, "adequate" means at least 0.75 m (see Figure 10). Adequate $s_R$ is at least $s_P/\rho$ (see Figure 11), since the ratio $\rho$ indicates the ratio of mean time spent in the production (P) queue and the repair (R) queue, respectively. For smaller scale systems, these rules of thumb for number of crews must be revised upward somewhat. For example, for the small mine case of seven sections with $\rho = 2.5$, US levels off for $s_P \geq 6$ and $s_R \geq 4$.

Similarly, US drops off dramatically once the number of sections exceeds about 1.17 $s_P$, with that drop-off beginning to level off only after US has dropped below 0.55 to 0.50 (Figure 12).

## Utilization of Production Crews (ENBPC and UPC)

Most of the observations and sensitivities, discussed above for sections, remain true for the utilization of production crews. Performance improves logarithmically with $\rho$, with the most improvement realizable for smaller values of $\rho$ (Figure 13). (Actually, the curve has the shape of $a(1 - e^{-b\rho})$, where a and b are constants.) As before, when $s_R$ reaches the "adequate" level of $s_P/\rho$, the expected number of busy production crews (ENBPC) reaches a plateau (asymptote) of $m\rho/(1+\rho)$, as shown by Figure 14. Note that this asymptote is just

$\rho$ times the asymptote for ENNOS, as one would expect (recall that $\rho/(1+\rho)$ = MTBF/(MTBF + MTTR) is the expected availability of a typical section in isolation, i.e., with no shortage of repair crews). Similarly, as the number of sections increases, for a fixed number of production crews, the production crews asymptotically approach full utilization, except when repair crew shortages limit the number of sections available for any number of production crews to $\rho s_R$ as in the poorly balanced case (Figure 15). As with the sections, expected utilization of production crews (UPC) is asymptotically 1.0 when production crews are in short supply, then drops sharply when $s_P$ exceeds the minimum of either about 0.75 m or $s_R$, and finally starts to level off as poorer utilization levels are reached (UPC < 0.80). See Figure 16.

Utilization of Repair Crews (ENBRC and URC)

The utilization of repair crews (URC), asymptotically 1.0 when repair crews are in short supply compared to the incidence of failures, makes the same sharp drop-off followed by leveling off for increasing values of both $s_R$ and $\rho$ (Figures 17, 18). In other words, utilization of repair crews will decrease dramatically if either the supply $s_R$, of repair crews increases, and/or the demand for those crews decreases due to a larger value of $\rho$ (better maintainability).

As is the case for sections and production crews, utilization of repair crews improves sharply with additional production crews or sections until an "adequate" number are available, at which point a plateau in performance is reached (Figures 19, 20). For increasing $s_P$, the ENBRC curve is asymptotic to the minimum of $s_R$ and $m/(1+\rho)$, where $1/(1+\rho)$ is the expected proportion of time that a section with no shortage of production crews is in the R queue. For increasing m, the ENBRC curve is asymptotic to the minimum of $s_R$ and $s_P/\rho$.

## G. CONCLUSIONS

Four major conclusions can be derived from the above analysis:

(1) Mine performance is theoretically limited by the maintainability ratio, $\rho$ = MTBF/MTTR, even when the number of crews and sections are well balanced. In particular, the expected availability of an average section will not exceed $\rho/(1+\rho)$ = MTBF/(MTBF + MTTR). Furthermore, availability will only achieve this level when there is a sufficient number of production and repair crews such that sections never need to wait for either, which usually implies costly idle time for these crews.

(2) Based upon current industry experience, significant gains in availability appear possible by means of small improvements in the time between failures and/or the time to repair failures. The historical data of Table 2 indicates that many existing mines for which figures are available have a maintainability ratio between 1 and 2.6. Within this range, all performance measures exhibit steep improvement when small improvements are made in the maintainability ratio, $\rho$, and are still far from the region of diminishing returns (see Figures 8, 9, 13). Big payoffs can, therefore, be expected from increases in the time between failures and/or decreases in the time to repair

failures. Hence, research should concentrate on ways to make equipment run longer between failures and/or easier and quicker to repair. Equipment design can facilitate the second objective by providing better service accessibility, modular design and a sufficient inventory of spare modules, completely interchangeable parts, simpler mechanisms, and lighter, more mobile equipment. The first objective would also be aided by simpler machinery, as well as more durable materials, quality control and testing, built-in redundancy in critical components, governors or monitors to prevent over-stressing of equipment, and preventive maintenance tailored to the history of an individual component. It should be noted that, unless properly designed, technologies which are more automated may even regress on both objectives, due to their potentially more complex, heavier, less mobile, and as yet unproven mechanisms [JPL II,L].

3) The number of crews and sections should be properly balanced for any given maintainability ratio, ρ. Specifically, the number of production crews ($s_p$) should be 0.85 to 1.0 times the number of sections (m); the number of repair crews should be at least $s_p/\rho$, where $\rho$ = MTBF/MTTR. Addition of sections, repair crews, or production crews beyond this balance can only decrease utilization of similar entities, and utilization of dissimilar entities will not be significantly improved because of their already near-saturated use. Note especially that a change in the maintainability ratio necessitates a reevaluation of the number of repair crews required.

(4) Main haulage systems closest to the mine mouth require the most attention to reliability. In general, the sensitivity of mine mouth production to the availability of any link in the haulage system is exactly equal to the quantity of coal it is expected to receive from all sections and haulage links feeding into it, times the availability of all haulage links in line between it and the mine mouth. Thus if a reliability choice must be made between two otherwise equal face haulage systems, each serving one section, the face haulage system serving the section having the greater overall production per hour (i.e., including availability) should receive priority.

## H. VALIDATION

Immediate validation of much of the above model, unfortunately, is not currently practical. There is a surprising scarcity of non-proprietary data on performance before and after changes in the number of crews, sections, and/or ρ have been made to a single mine, although at least one study of this is under way [Hayduk]. Experiments to verify the model must be performed on a single mine, in order to ensure that geological differences do not affect the results. Ideally, only one of the input parameters required by the model would be varied. Possible variations include:

- Increasing or decreasing the number of production or repair crews
- Opening a new section of the mine
- An alteration of equipment or maintenance management policies that changed the equipment's MTBF and/or MTTR

- Switching mining methods from, say, conventional to longwall, possibly accomplishing all of the above.

Only the beginning and duration of each idle period for each production and repair crew need be observed. Calculation of the proportions of time that 0, 1, 2,...,m sections were actually busy, and comparison of those predicted by the $\Pi_i$ of the model, would then be straightforward. At a minimum, actual availabilities, before and after the input parameters are changed, should be observed and compared.

Of course, a prerequisite of validation is locating a mine satisfying the majority of the model's assumptions. Because this was a top-level, analytical model, many of the little realistic details that might be incorporated into a large computerized simulation were assumed away. Such simplification allows more exhaustive sensitivity analysis at little marginal cost, but makes the choice of a representative mine and correct definition of input values more critical. For example, in many mines the size and makeup of repair crews is varied according to the severity of the failure and/or the availability of company experts on certain types of failures, such as hydraulic engineers. Some mines assign a mechanic to each production crew to repair minor failures. In these cases, late in a shift, or when hauling coal out of the mine saturates limited transportation routes, production crews do odd jobs on that section rather than move to another section when a failure occurs. Failures of replicated components such as shuttle cars or scoops may not always cause section production to cease altogether, unless all replicates fail simultaneously, or one blocks production by failing in a strategic location. The impact upon the model of these details has yet to be determined.

Some of the conclusions, however, have been substantiated by industry practice. In particular, there exists some evidence that, by trial and error, existing mines have balanced crews and sections in agreement with the rules of thumb suggested by the sensitivity analysis using the model. For example, one mine in Pennsylvania with a MTBF = 9 hours and a MTTR = 1.18 hours operates five sections with only three production crews and one maintenance crew, resulting in a measured availability of 80% [Hayduk]. The rules of thumb given above would suggest (0.85) (5) = 4.25 production crews and 4.25/7.63 = 0.55 repair crews, which when rounded off is only off by one production crew. Another mine, in Kentucky, operates seven sections with six production crews and six repair crews. If the postulated value of $\rho = 2.5$ for this mine is accurate, the rules of thumb indicate it could save money by reducing its repair crews from six to two without significantly affecting production. The assignment of six production crews to the seven sections is in exact agreement with the derived relationship of 0.85 production crew per section. Similarly, the conclusions that main haulage systems and MTBF/MTTR are critical to improving availability are already intuitively understood by most mine engineers; the sensitivity analysis serves to isolate and quantify the extent of their impact so that more rigorous cost trade-offs can be performed for particular instances.

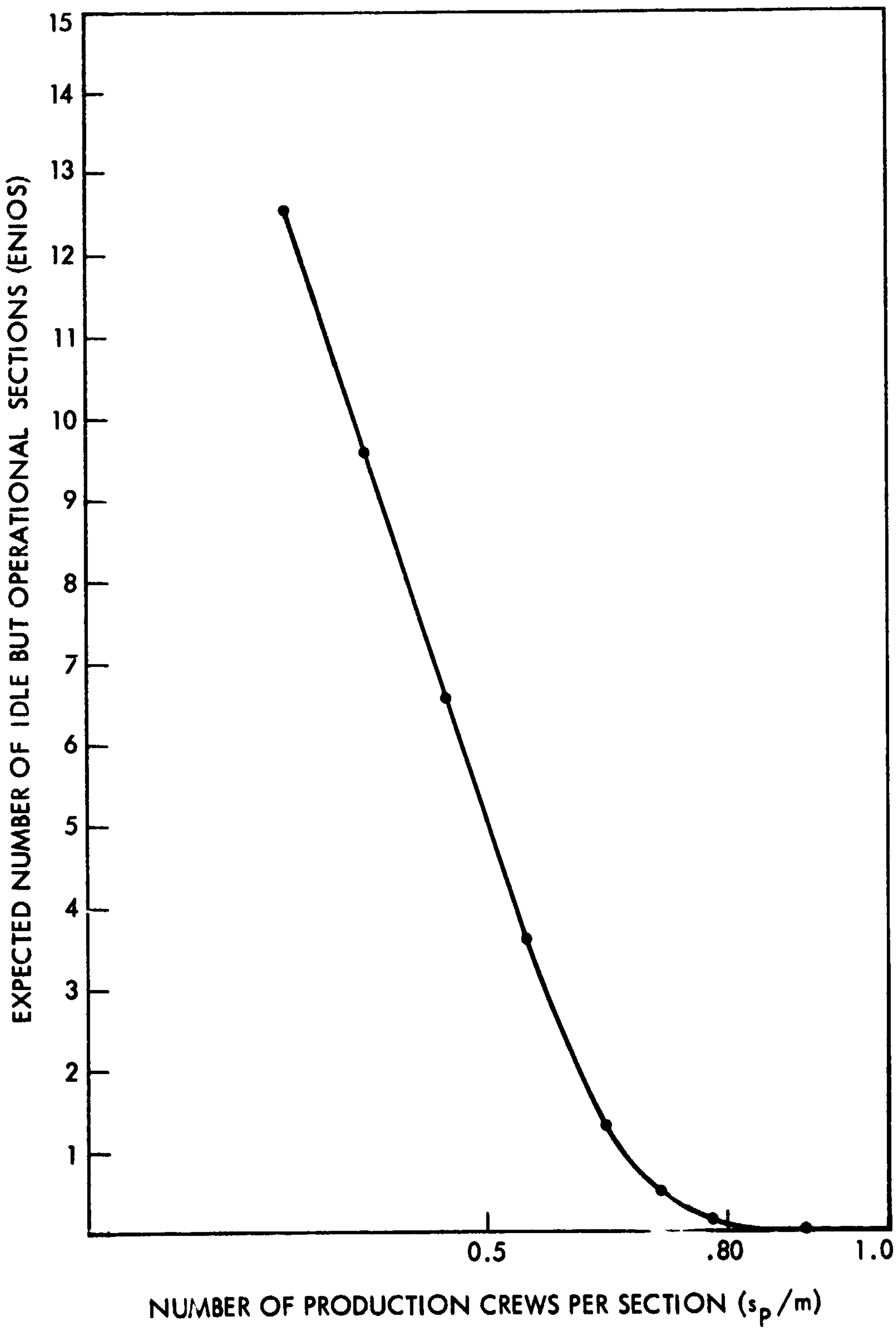



Figure 3. The Expected Number of Idle but Operational Sections (ENIOS) as a Function of the Ratio of Production Crews to Sections ($s_p/m$) for the Large Mine Case ($s_R = 23$, $\rho = 2$)

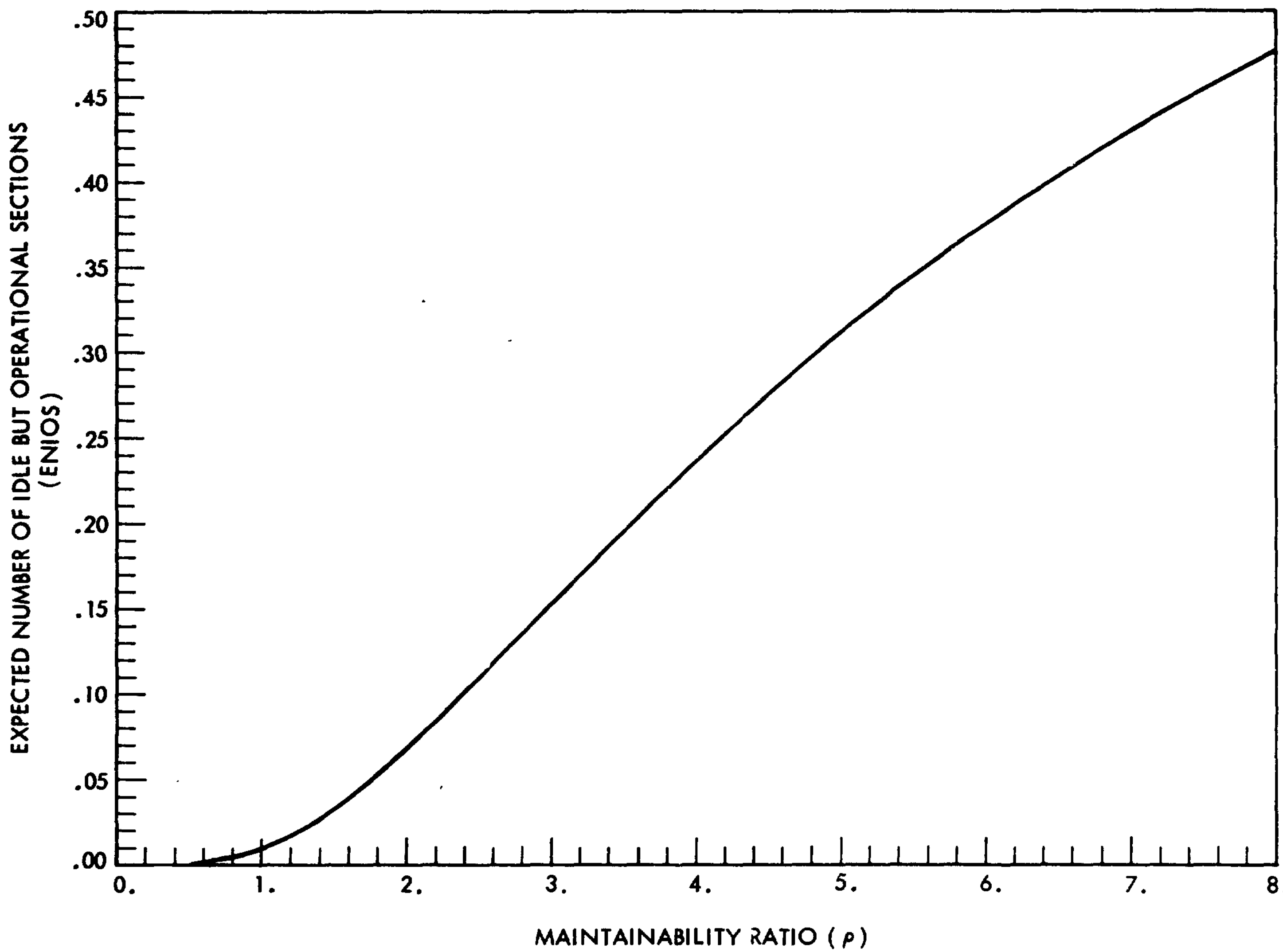



Figure 4. The Expected Number of Idle but Operational Sections (ENIOS) as a Function of the Maintainability Ratio (ρ) for the Small Mine Case ($s_P = 6$, $s_R = 6$, $m = 7$)

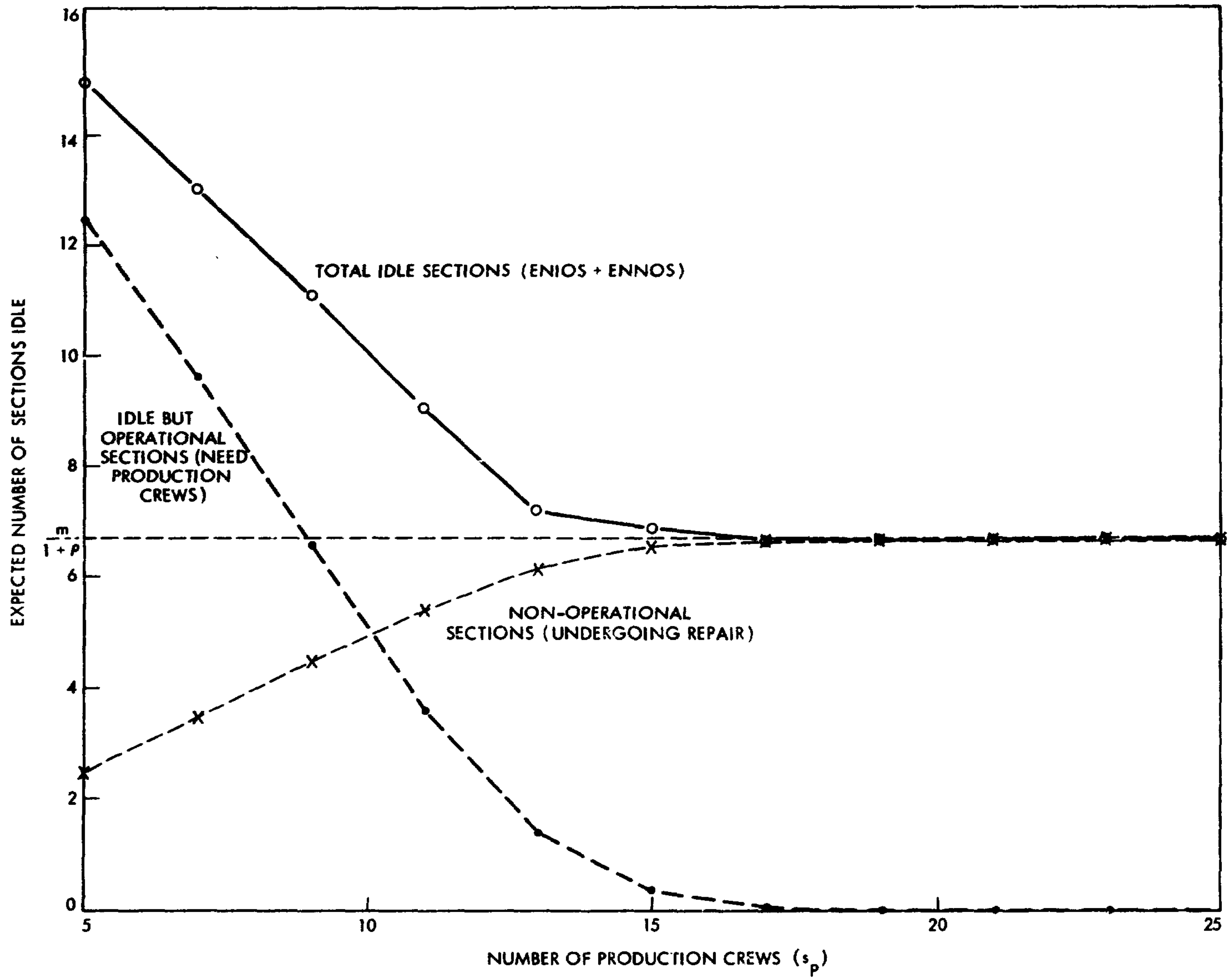



Figure 5. The Expected Number of Idle but Operational Sections (ENIOS), Expected Number of Non-Operational Sections (ENNOS), and Total Idle Sections as a Function of the Number of Production Crews ($s_p$) for the Large Mine Case ($s_p = 23$, $m = 20$, $\rho = 2$)

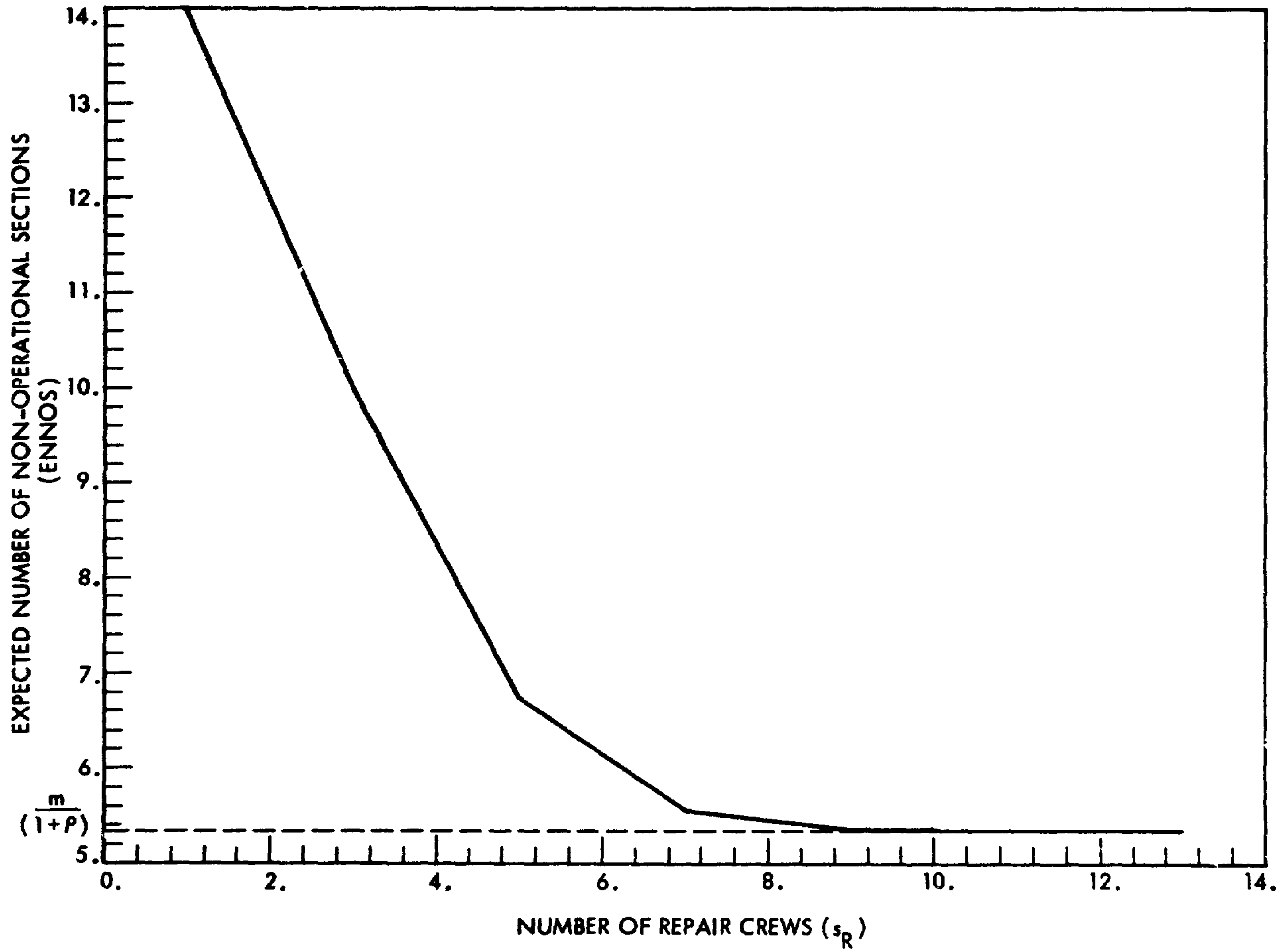



Figure 6. The Expected Number of Non-Operational Sections (ENNOS) as a Function of the Number of Repair Crews ($s_R$) for the Poorly Balanced Case ($s_P = 16$, $m = 16$, $\rho = 2$)

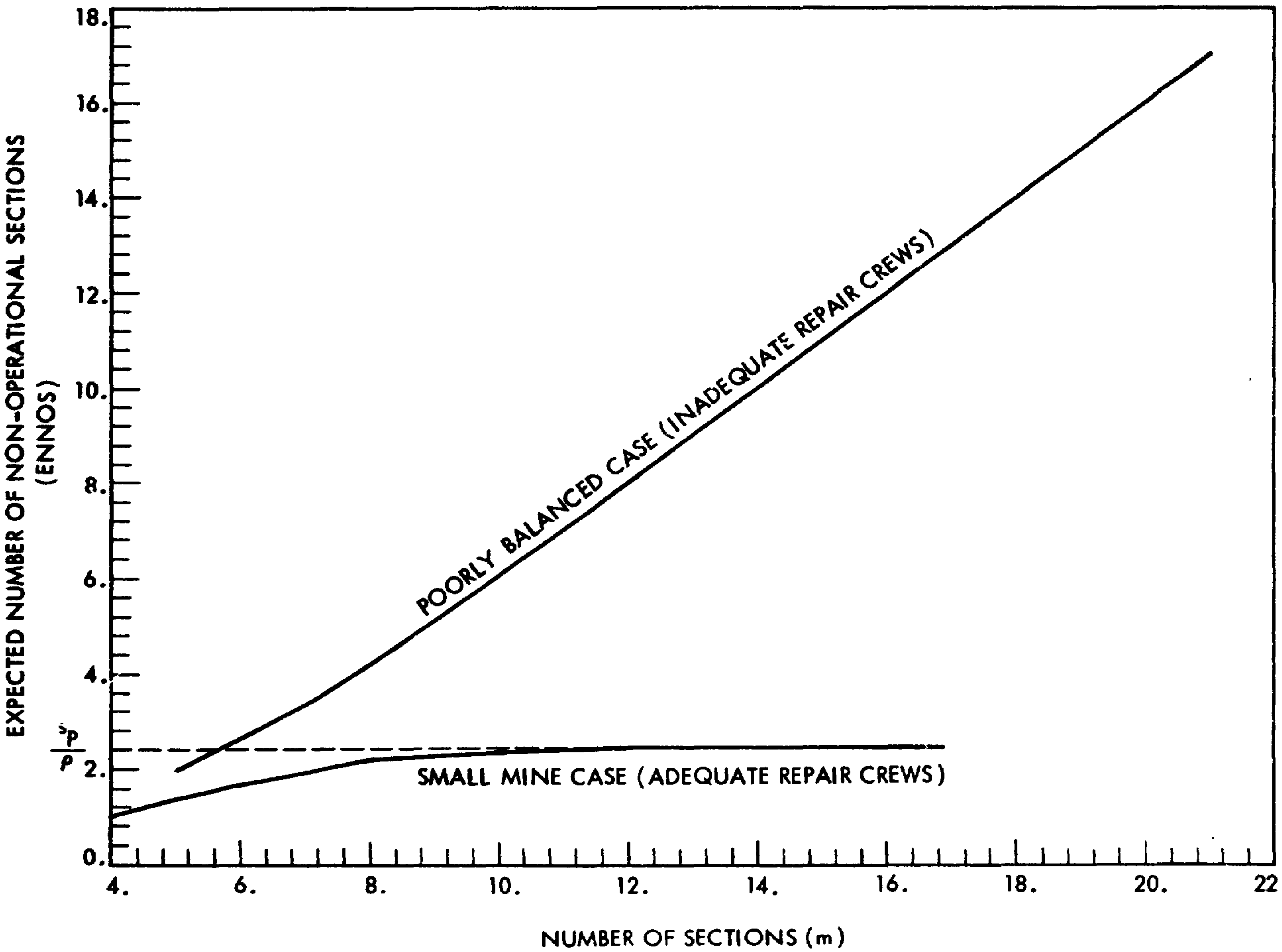



Figure 7. The Expected Number of Non-Operational Sections (ENNOS) as a Function of the Number of Sections (m) for the Poorly Balanced Case ($s_P = 16$, $s_R = 2$, $\rho = 2$) and the Small Mine Case ($s_P = 6$, $s_R = 6$, $\rho = 2.5$)

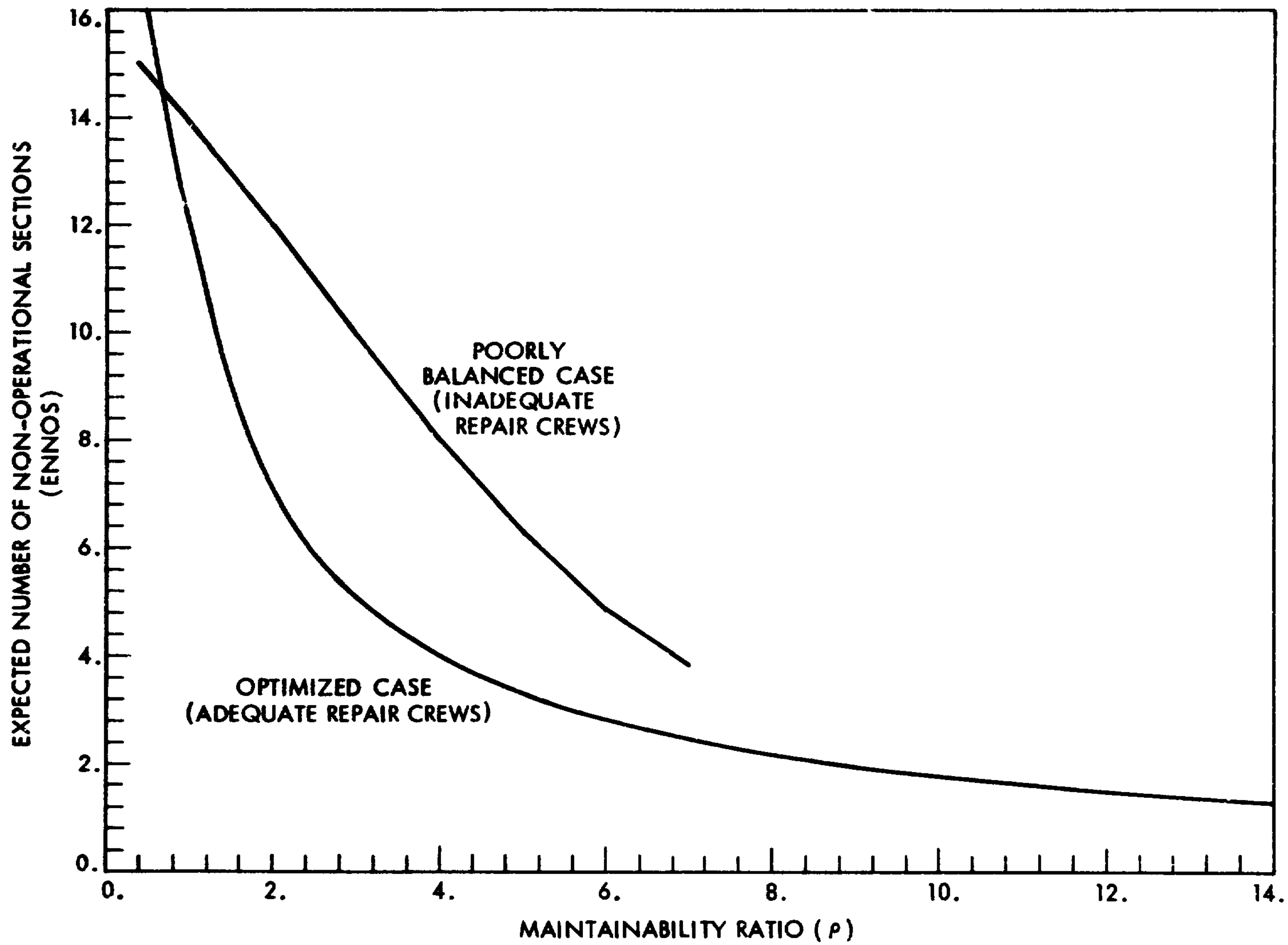



Figure 8. The Expected Number of Non-Operational Sections (ENNOS) as a Function of the Maintainability Ratio (ρ) for the Optimized Case ($s_P = 18$, $s_R = 8$, $m = 20$) and the Poorly Balanced Case ($s_P = 16$, $s_R = 2$, $m = 16$)

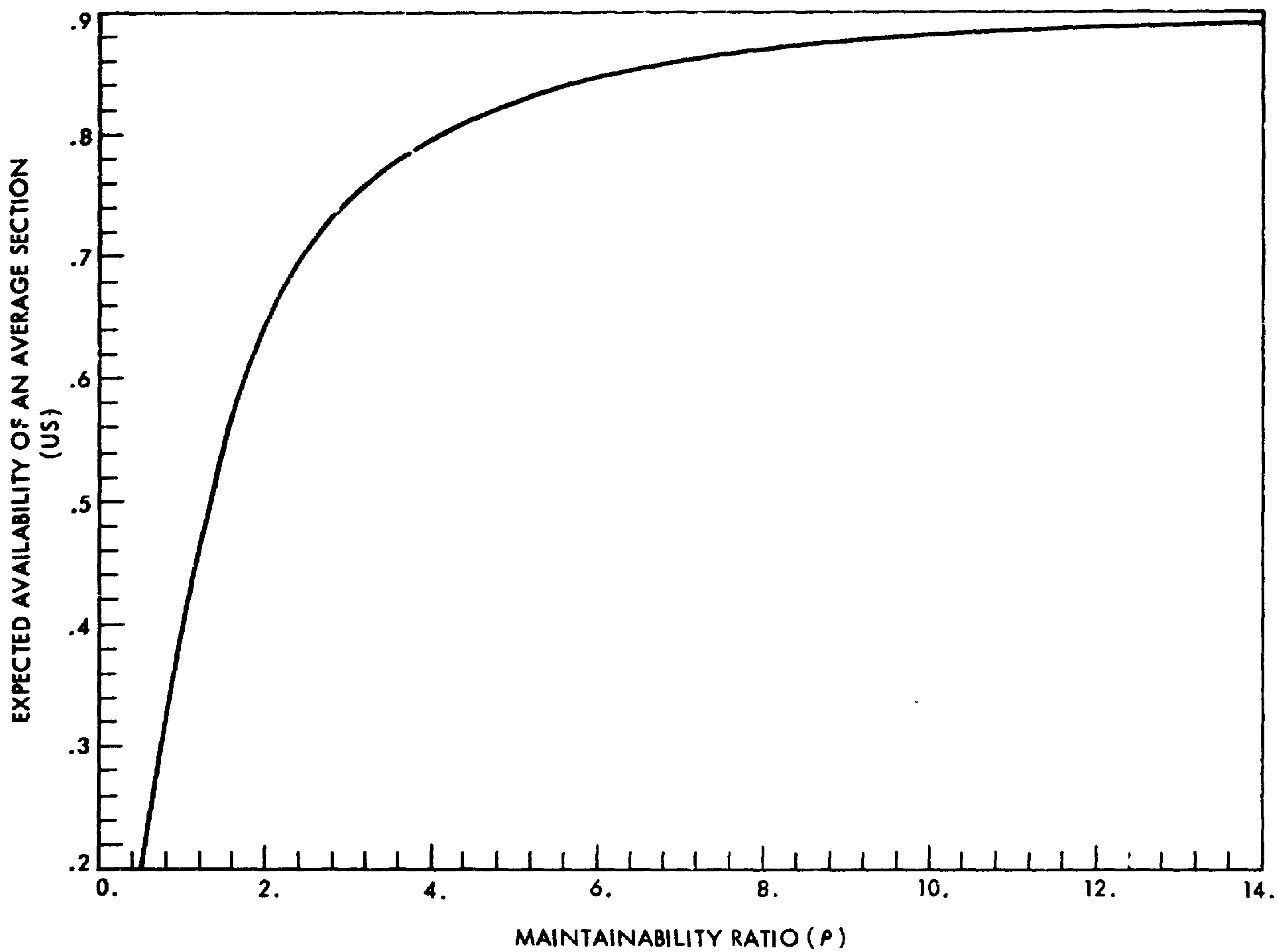



Figure 9. The Expected Availability of an Average Section (US) as a Function of the Maintainability Ratio (ρ) for the Optimized Case ($s_P = 18$, $s_R = 8$, $m = 20$)

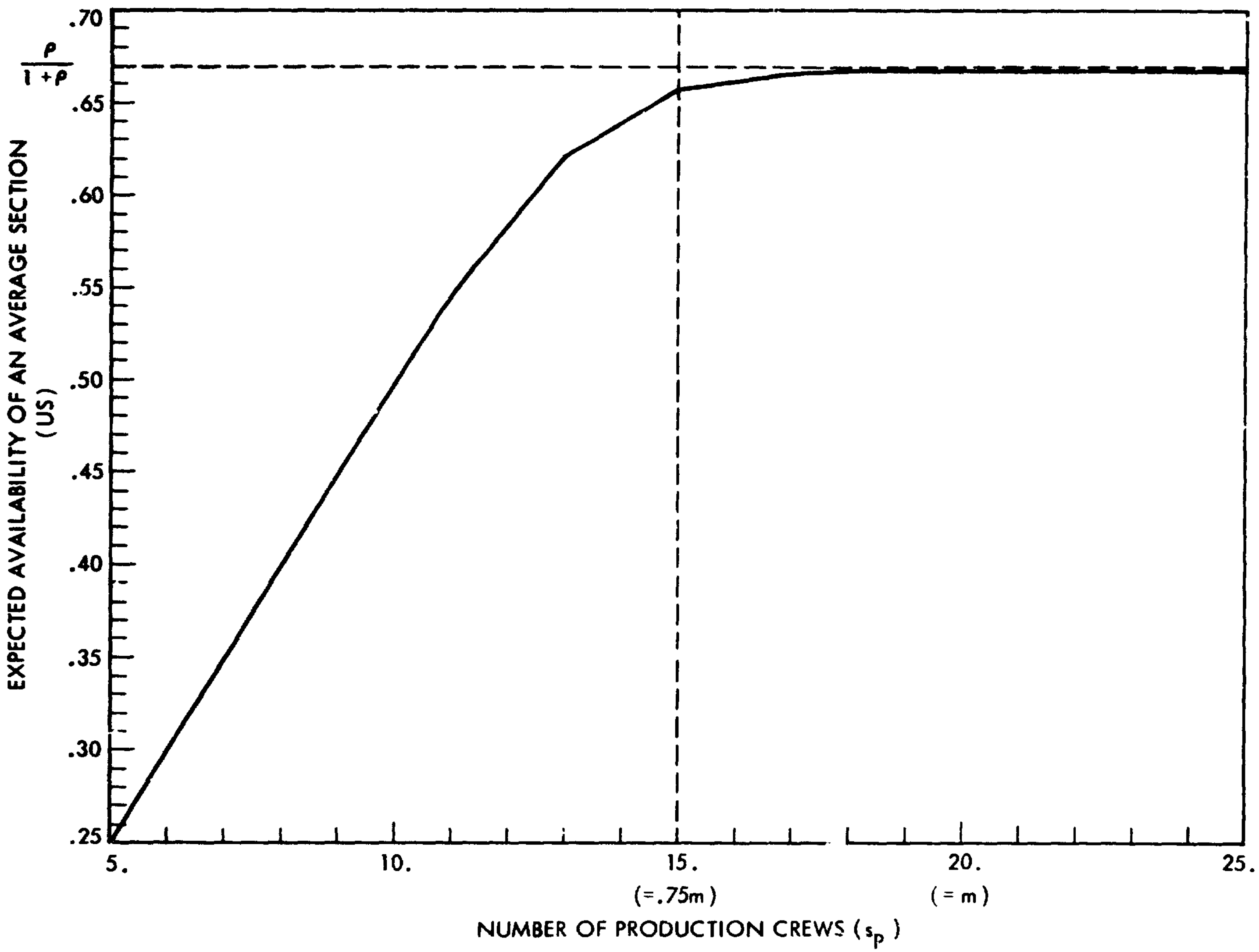



Figure 10. The Expected Availability of an Average Section (US) as a Function of the Number of Production Crews ($s_p$) for the Large Mine Case ($s_R = 23$, $m = 20$, $\rho = 2$)

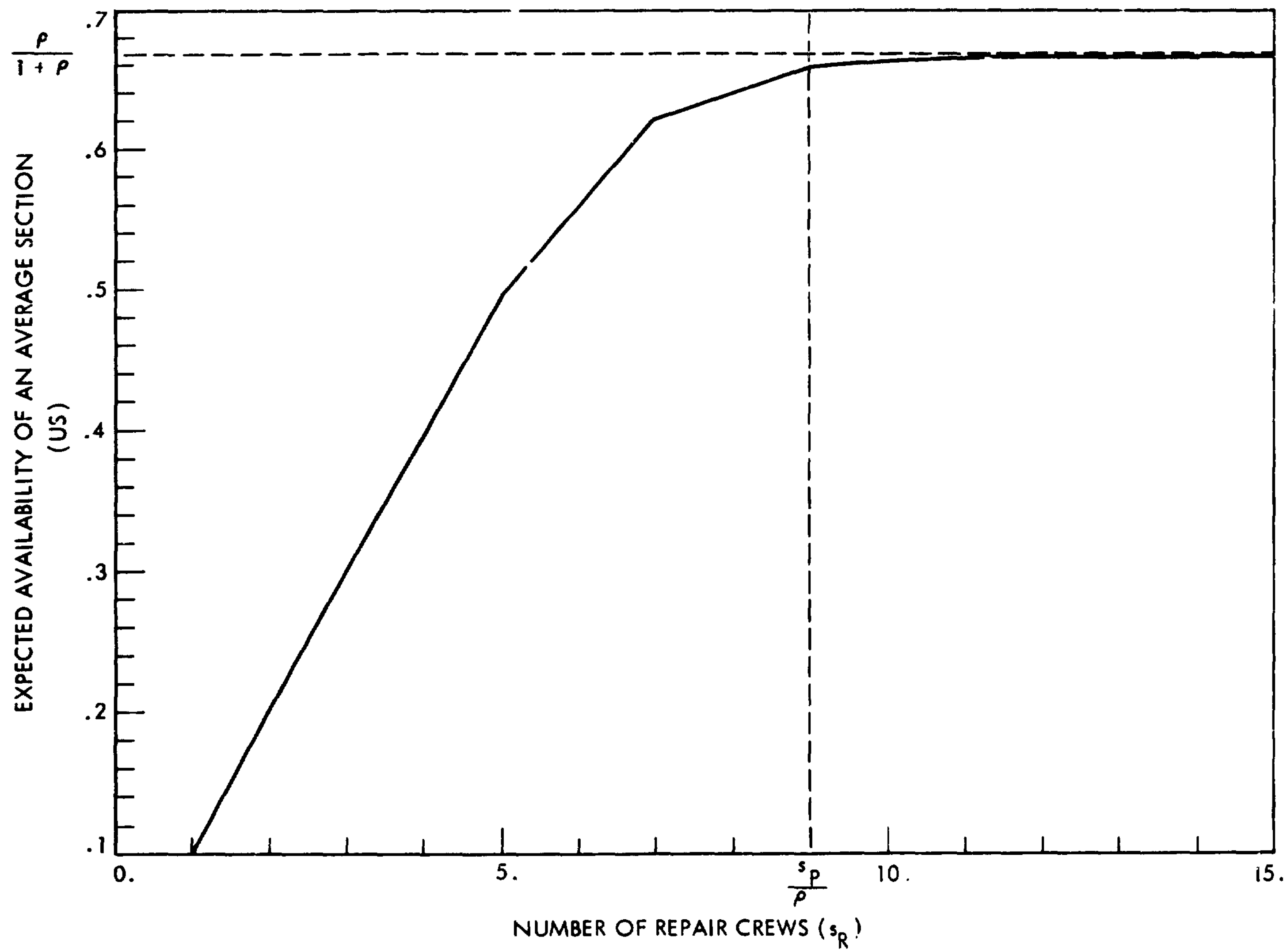



Figure 11. The Expected Availability of an Average Section (US) as a Function of the Number of Repair Crews ($s_R$) for the Large Mine Case ($s_P = 18$, $m = 20$, $\rho = 2$)

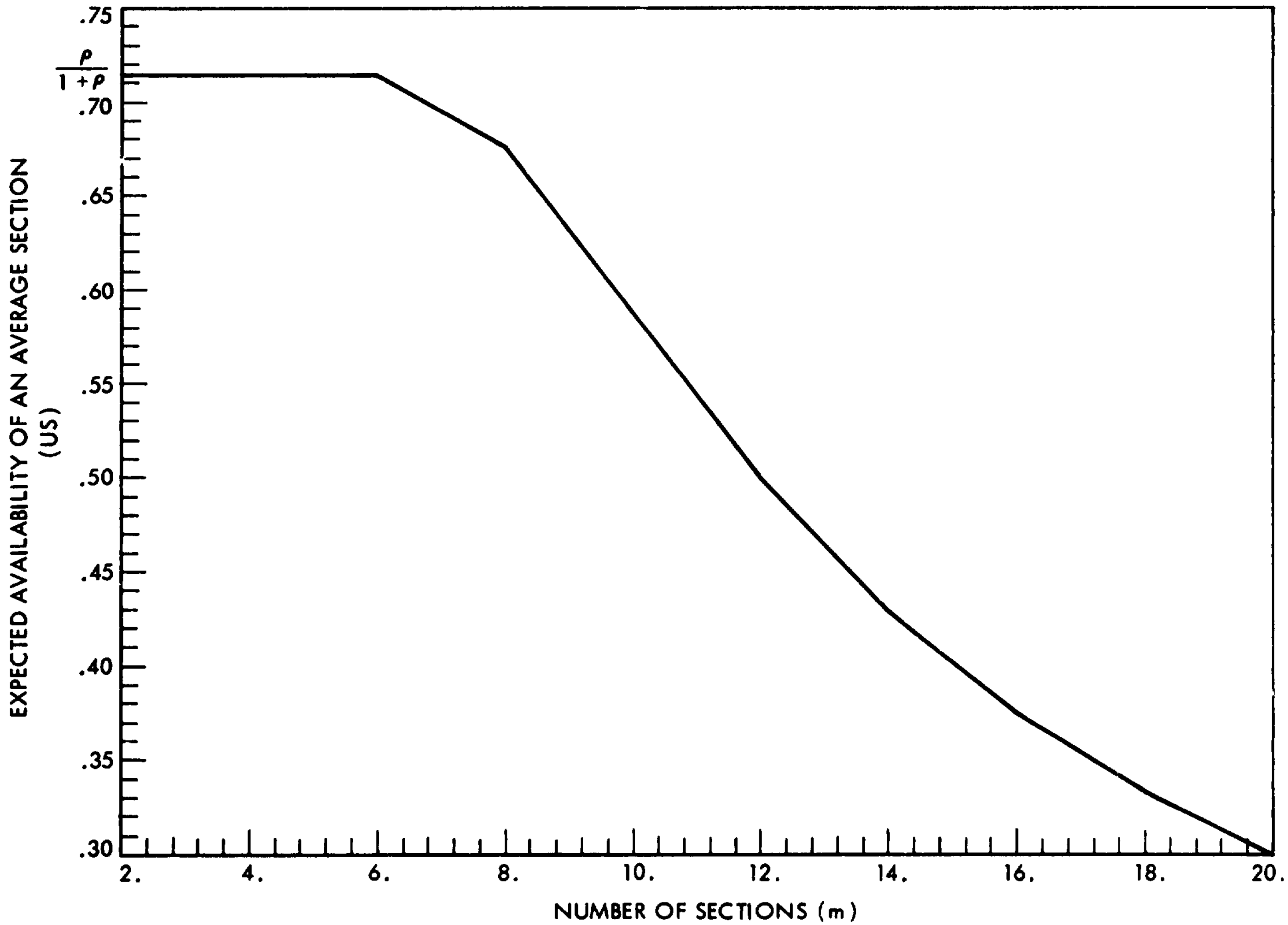



Figure 12. The Expected Availability of an Average Section (US) as a Function of the Number of Sections (m) for the Small Mine Case ($s_P = 6$, $s_R = 6$, $\rho = 2.5$)

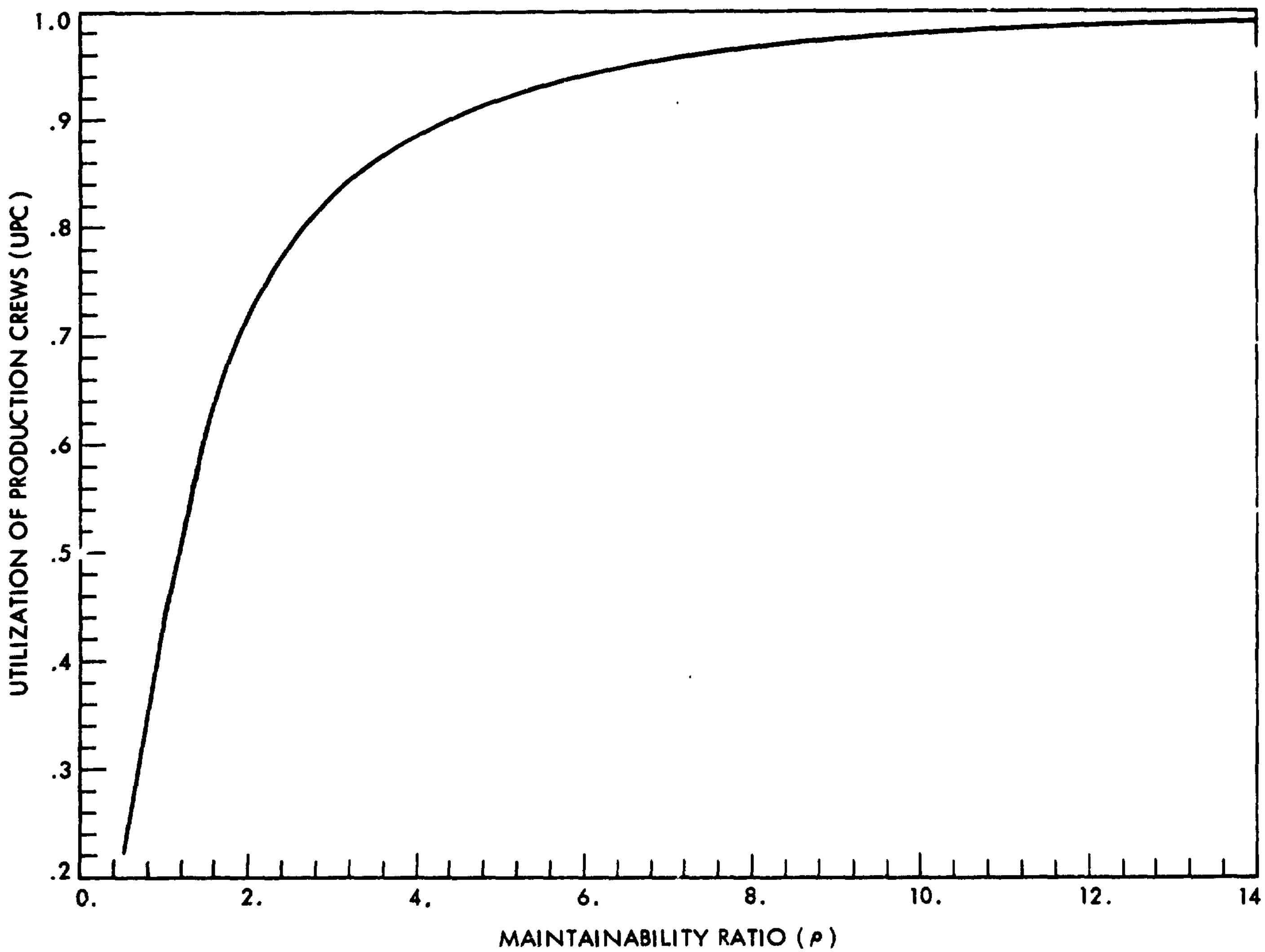



Figure 13. The Expected Utilization of Production Crews (UPC) as a Function of the Maintainability Ratio (ρ) for the Optimized Case ($s_P = 18$, $s_R = 8$, $m = 20$)

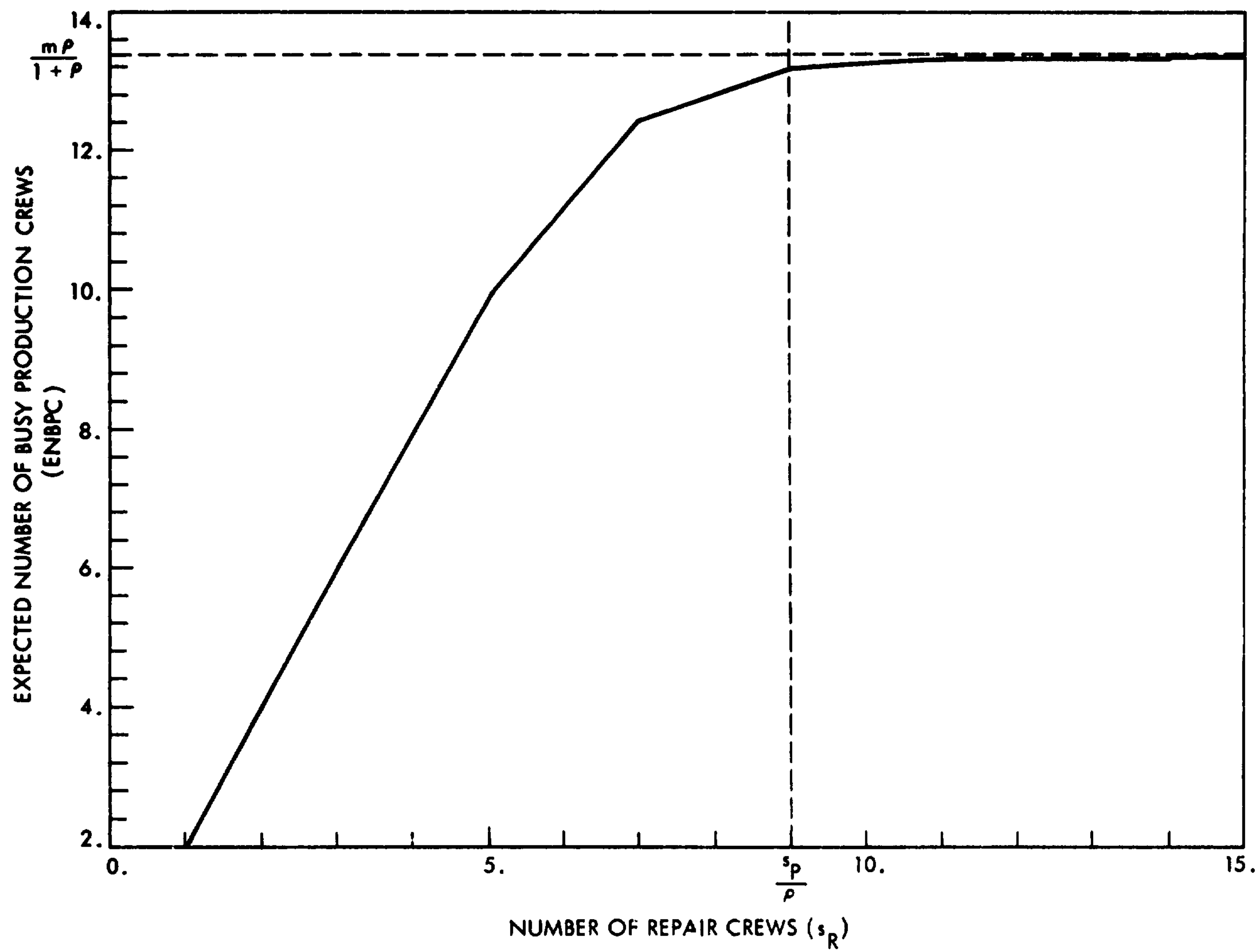



Figure 14. The Expected Number of Busy Production Crews (ENBPC) as a Function of the Number of Repair Crews ($s_R$) for the Large Mine Case ($s_P = 18$, $m = 20$, $\rho = 2$)

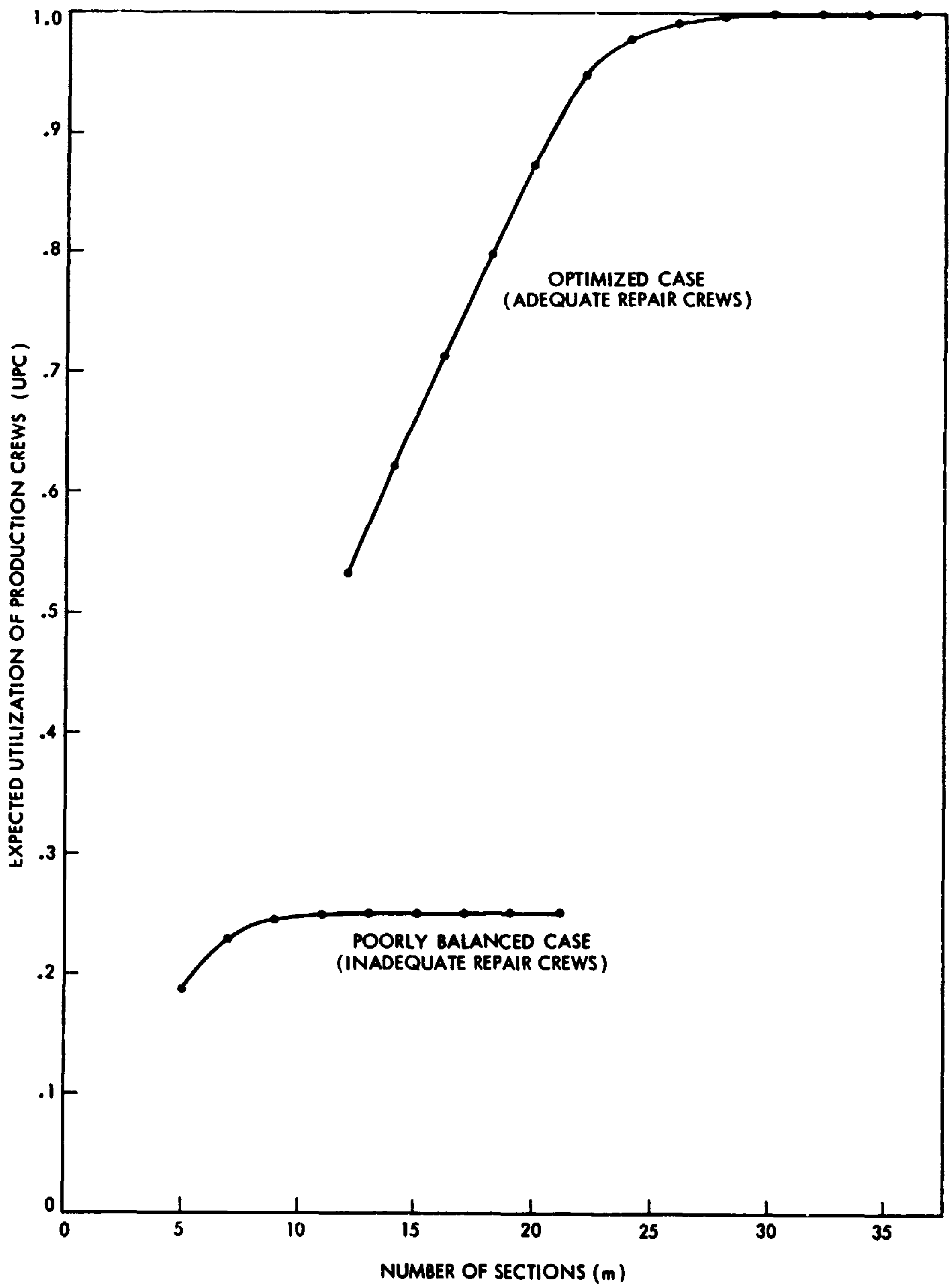



Figure 15. The Expected Utilization of Production Crews (UPC) as a Function of the Number of Sections (m) for the Optimized Case ($s_P = 18$, $s_R = 8$, $\rho = 4$) and the Poorly Balanced Case ($s_P = 16$, $s_R = 2$, $\rho = 2$)

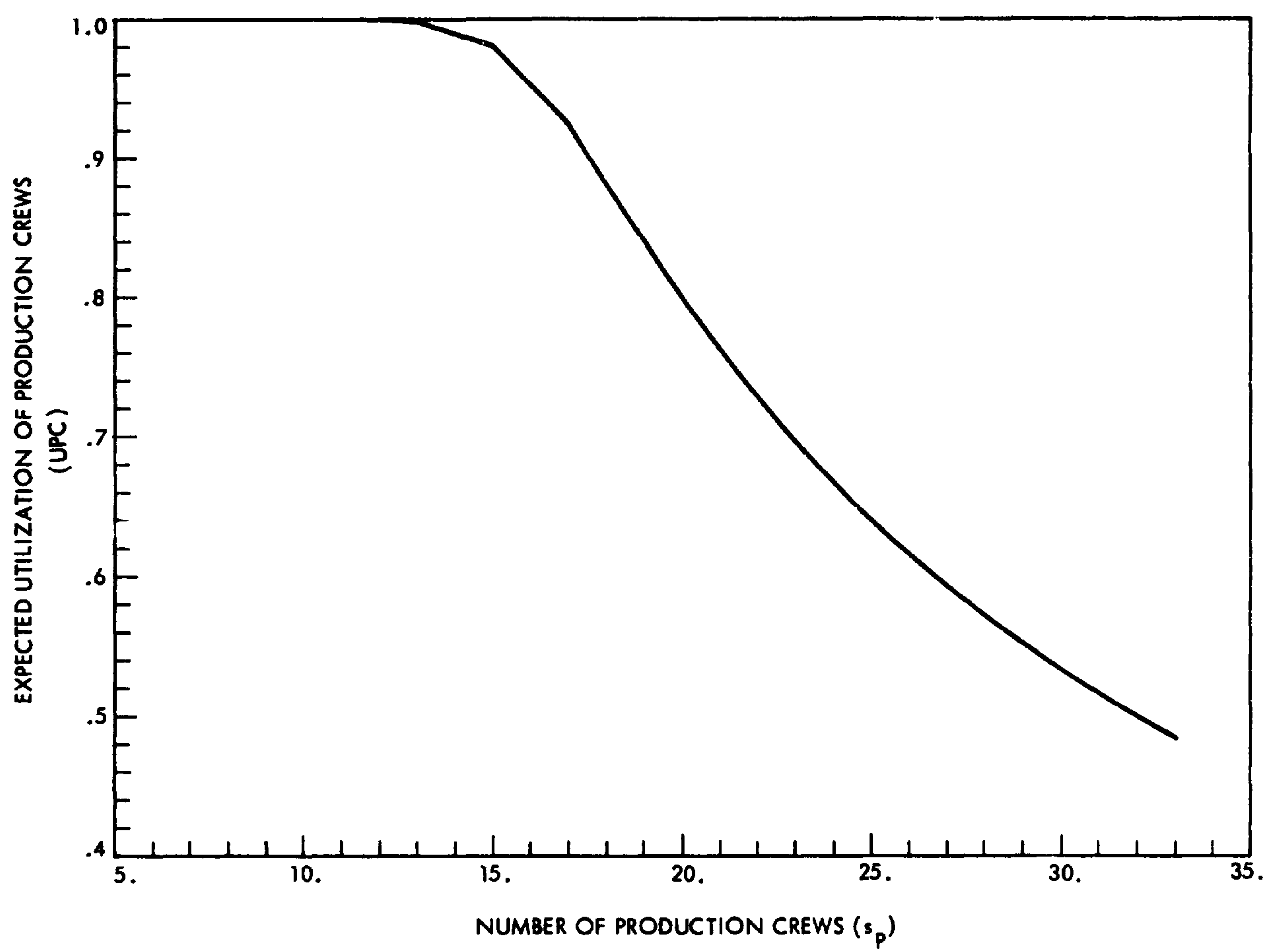



Figure 16. The Expected Utilization of Production Crews (UPC) as a Function of the Number of Production Crews ($s_p$) for the Optimized Case ($s_R = 8$, $m = 20$, $\rho = 4$)

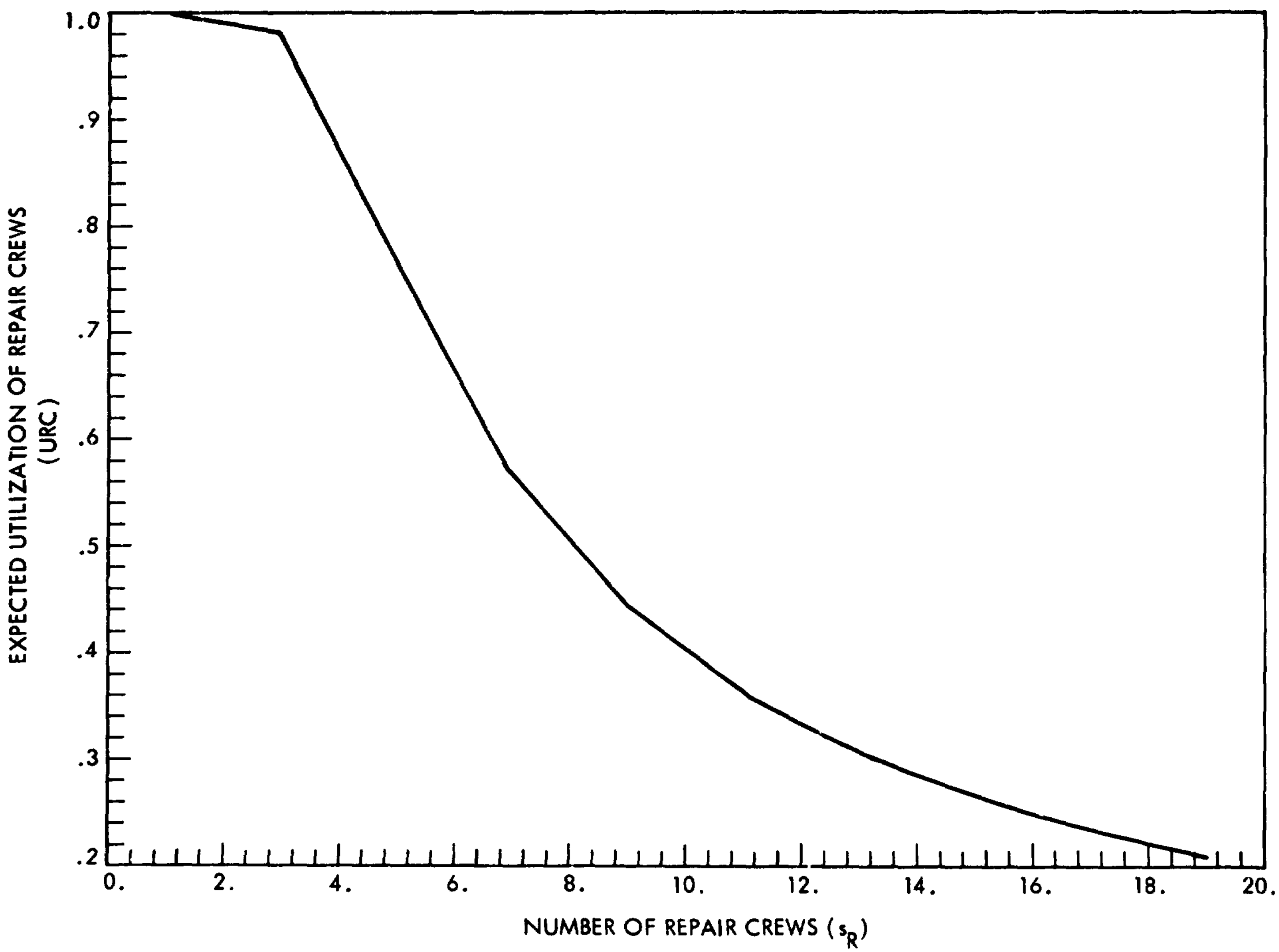



Figure 17. The Expected Utilization of Repair Crews (URC) as a Function of the Number of Repair Crews ($s_R$) for the Optimized Case ($s_F = 18$, $m = 20$, $\rho = 4$)

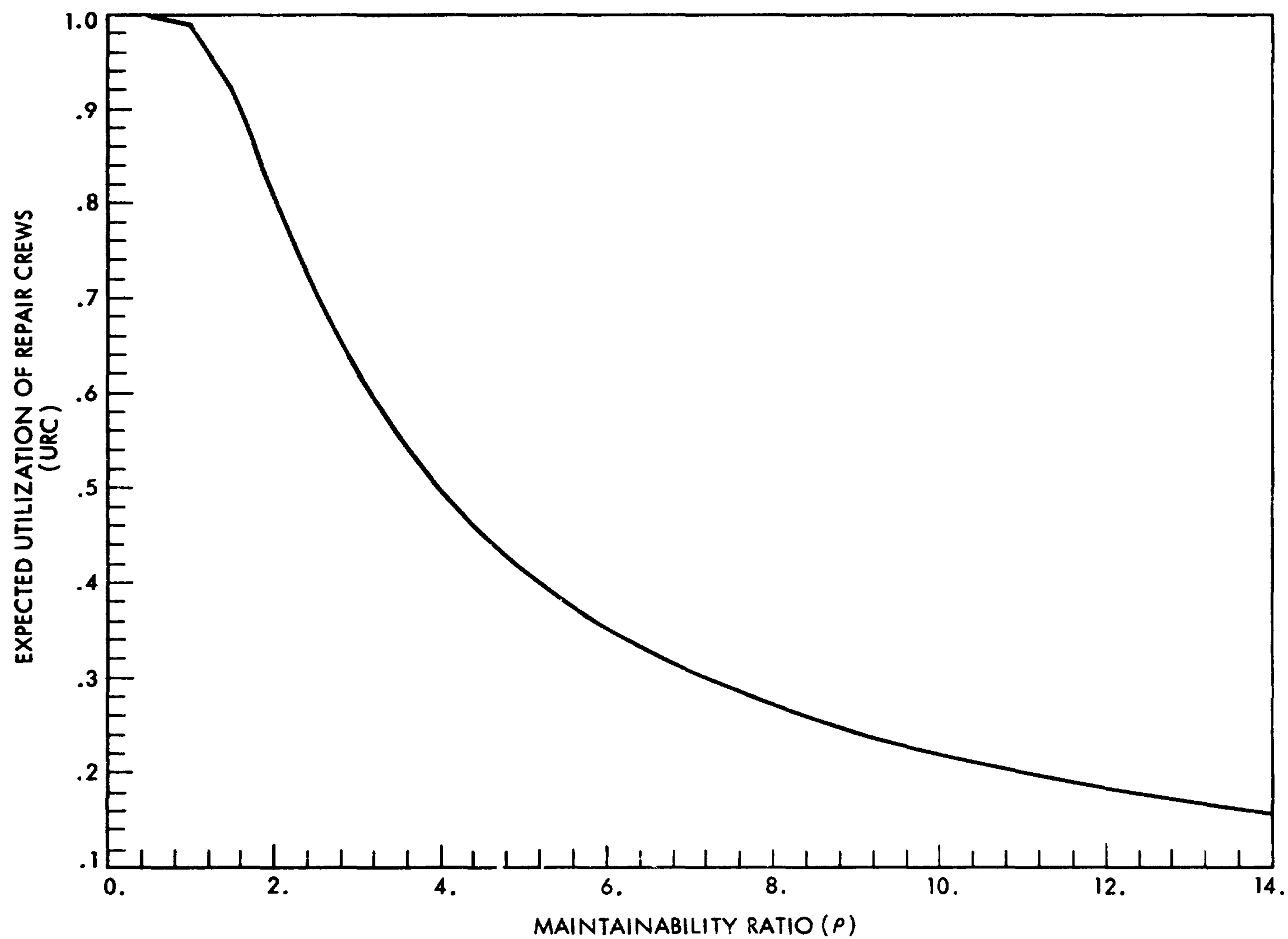



Figure 18. The Expected Utilization of Repair Crews (URC) as a Function of the Maintainability Ratio ($\rho$) for the Optimized Case ($s_P = 18$, $s_R = 8$, $m = 20$)

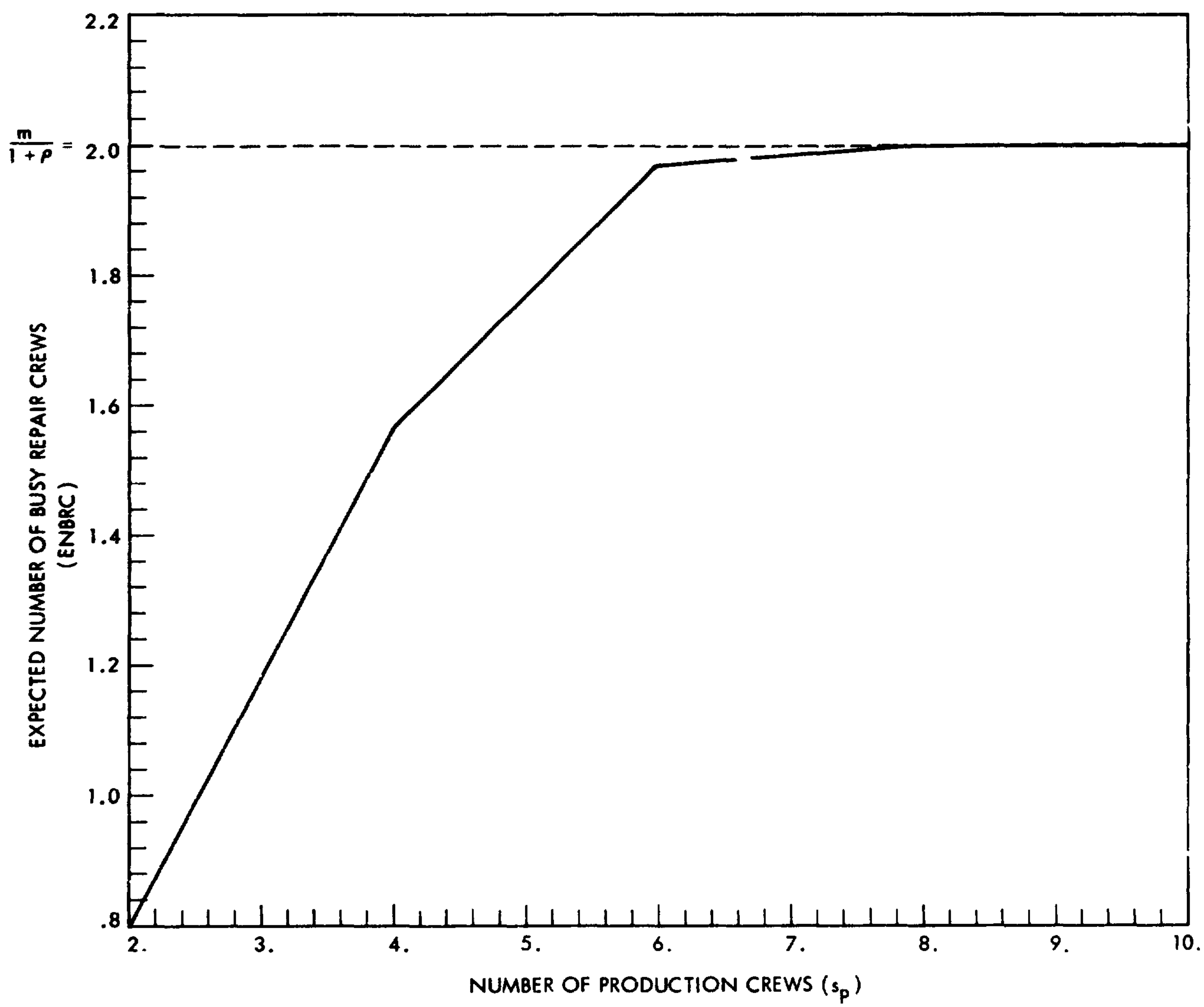



Figure 19. The Expected Number of Busy Repair Crews (ENBRC) as a Function of the Number of Production Crews ($s_p$) for the Small Mine Case ($s_R = 6$, $m = 7$, $\rho = 2.5$)

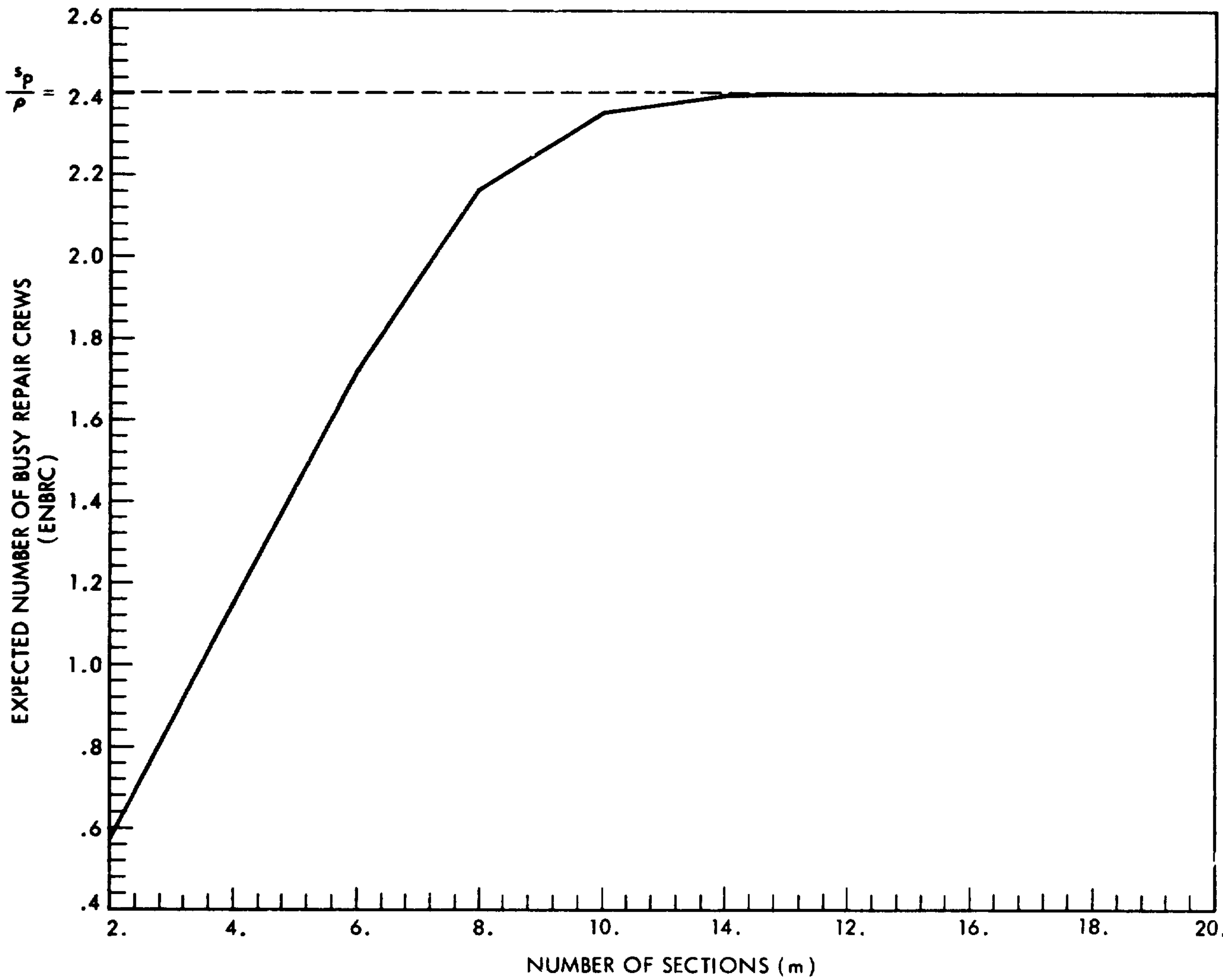



Figure 20. The Expected Number of Busy Repair Crews (ENBRC) as a Function of the Number of Sections (m) for the Small Mine Case ($s_P = 6$, $s_R = 6$, $\rho = 2.5$)

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