

A System Dynamics Model of an Underground Metal Mine

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Abstract

This paper describes the main features of a System Dynamic Model of a mining firm which manages a single underground operation. The model includes mining, development and milling sectors, together with cash flow and finances and pays special attention to the feedback relations between all components. In particular it shows how the management policies of individual company sectors interact and affect the overall system performance.

The aim of the work is to demonstrate that analysis of a company's structure and behaviour when subjected to the perturbing effects of strong and frequent fluctuations from the metal market sector, can lead to recommendations for improved mine management policies. The model is applicable to existing mines and could be a major aid when analysing the feasibility of new projects.

Introduction

As part of a major research project on corporate modelling of large mining firms, currently being developed by the University of Bradford, System Dynamics Research Group, a system dynamics simulation model has been built of the financial and physical interactions in an underground metal mining operation.

The purpose of the study is to analyse the consequences which different operating and financial policies have on the behaviour of a mining firm when faced with the perturbing effects of strong and frequent shocks from its economic environment. Of particular importance are the shocks associated with cost increases and price fluctuations, the latter

being highly relevant to mining firms which sell a big share of their production at prices based on the London Metal Exchange (L.M.E.) price

The model includes mining, development and milling sectors together with cash flow and finances. It takes especial account of the feedback relations that exist between all its components. The use of feedback theory differentiates the model from "ordinary" econometric simulation and assists in the design of "robust" management policies aimed to improve mining company performance.

The model is capable of simulating the entire life span of a mining operation provided that adequate information is given. Its scope is not therefore restricted to analysing the effects of short and long term planning on the performance of an existing mine. It could be a very useful aid for the mine's designer, when deciding between different alternative project designs. Finally since it is possible to simulate the effects of inflation, changing prices and possible additions to the proved reserves, under any set of management policies, it opens a new dimension to the financial analyst when deciding about the economic and financial feasibilities of a new project.

Characteristics of the Mine

The mining firm to be modelled has been chosen to be one which manages a single underground mine whose limited size orebody contains grades of only one metal, that can to some extent, be mined and developed selectively within the limits of its geology. In order to sustain production, new reserves must be developed and, according to the cut-off grade selected, some uneconomic low grades may have to be removed together with waste rock from developments. The waste rock competes with valuable ore for hoisting capacity. This capacity is presently defined to be constant throughout the mine's life. The mill consists of a concentrator, whose capacity can be expanded in discrete steps. This mill capacity imposes constraints on the tonnage and grade of the ores that can be processed. The smelting and refining of concentrates are assumed to be done outside the mine and their influence

on the system behaviour is reflected by the direct costs and time delays incurred on them. The percentage of metal recovered per ton of metal content during the whole processing stage is considered to be constant, but a variable recovery co-efficient depending on grade and volume of ore processed could easily be implemented.

Mine Management Policies

Mine management have various options open to them as regards controlling the performance of the enterprise in order to achieve the desired aims in the most effective way. These aims could differ depending on the type of mining enterprise considered. For example, in the private sector, generally accepted objectives are to maximize the present value of earnings or the minimum dividend per share ratio paid throughout the mine's life, without violating certain constraints, for example the employment level, and the capacity utilization level.

We call the decision rules used in order to select these options, "control policies" or simple "policies".

The control policies implemented in the model can be categorized in four distinguished groups. These are: production, developments, mill capacity acquisition and financial policies.

Production Policies

Before describing the type of production policies that could be simulated it is necessary to clarify certain definitions.

The pay-limit is defined here as the minimum ore grade that can be profitably mined. This parameter not only depends on the physical characteristics and location of the mine and orebody but also on the overall direct costs, fixed assets depreciation, depletion allowances, interest paid and the market price of the metal produced. Secondly, the cut-off grade is defined as the minimum ore grade to be mined, and of course, its selection depends on the grading policy adopted, the current state of developments, the market price and the present pay-limit grade.

Two distinct types of production policies can be analysed by the model. These are concerned with the definition of the desired volume

of ore to be mined and the selection of the cut-off grade. The volume of output policies are based on whether the mining rate should or should not be adjusted to reflect expectation in price and costs. Basically, there are three possibilities all expressed in terms of the divergence of the forecasted market price from what we call a "normal" price for that particular mine. The "normal" price is defined as the metal market price which allows to realize the planned level of return on investment. This price depends on the operation's direct and overhead costs per ton of metal produced and the desired return on investment.

The three options are :-

- 1) Ignore all price fluctuations and always mine at some nominal capacity.
- 2) Increase the mining rate up to some limit (say 20% over nominal capacity) when expected price is above normal and conversely when expectations are below normal.
- 3) Increase production when expectations are above normal but keep it at nominal capacity otherwise.

The grading policy implies the definition of a cut-off grade. This policy is of major economic significance and there seems to be quite contradictory opinions between mine management as the criteria upon which to base grading policy. The spectrum goes from those who sustain the view that a mine should be high graded when prices are depressed to take advantage of the capital cost reductions associated with larger throughput and reduced direct costs to those who say that this should be done when prices are high to maximise present value of earnings.

The model allows the simulation of any grading policy based on the present pay-limit, the developed reserves and the divergence between the forecast and normal price. It makes possible an analysis of the consequences which different grading policies have on the dynamic behaviour of the enterprise, as well as of their effect on the economic life span of the operation.

Reserves and Developments Policies

Because of price fluctuations and variations in costs, the pay-limit may change considerably with time. These variations lead to the necessity of re-assessing the level of both developed and undeveloped economic reserves

available in the orebody at any particular time. In order to be able to perform this dynamic estimation of proved reserves a minimum feasible cut-off grade has been defined. This is the grade of ore below which mining would be unprofitable under any circumstances and has therefore been used to discriminate between waste and possible ore. That is to say, to delimit the maximum size and grade distribution of the mineral body to be considered. The actual definition of what is ore and what should be treated as waste within the mineral body at any point in time is performed by the grading policy adopted.

The development policies decide upon the level of reserves which it is desired to have developed at any time and the administration of the physical resources required to accomplish this target level. The first of these types of policy has been incorporated in the model through the selection of the desired number of weeks of production, covered by the developed reserves. The second kind determines the desired amount of physical resources, i.e. labour, hoisting capacity, etc., to be used for development purposes, comparing the discrepancy between the desired level and the actual level of developed reserves. The actual development rate is eventually determined by the availability of funds and it could be constrained by the physical capacity capable of being used for this particular purpose.

The planning and execution of developments, in most cases, requires considerable amounts of funds and any policy which helps to optimize their use, without detriment to overall system performance when operating within a fluctuating market, would be a very valuable asset. The model, because of its feedback structure and dynamic nature is especially suited to aid the design of such policies and to resolve the conflicting behaviour between different sectors that could arise when trying to suboptimize the performance of an individual sector by readjusting its control policies.

Capacity Expansion Policies

The model has the inbuilt capability of projecting expansions in the mining and milling sectors up to the limit imposed by the hoisting capacity

available at the beginning of the operation's life. (It was assumed that no new shafts were going to be sunk, so no attempt was made to include this type of mine expansion in the model).

The production policies already discussed, set the reference level of ore processing capacity desired to be available for the actual projection of mill capacity additions. The model simulates mill capacity additions in a discrete fashion. That is, it only allows for the addition of certain fractions of the original processing capacity at a time. This reflects the fact that generally, capacity additions consist of some extra units of the kinds already in existence within the operation. When the capacity additions policy, based on the desired ore processing level, indicates that a certain expansion is required, an economic feasibility calculation is made. This compares the expected present value of the additional earnings to be realized by that desired capacity addition, with the present value of the equipment, installation and working capital costs to be incurred on it. Hence an economic viability assessment is made, based on whether the expected rate of return of the investments is greater or less than a minimum economic feasibility return co-efficient. The ultimate decision in order to go ahead with any capacity addition is decided by the financial policies, which deal with the availability of funds for project financing.

Financial Policies

The financial policies are concerned with the uses and sources of funds, actually (or estimated to be) at the disposal of the enterprise. These policies can be classified into three different categories, which respectively control:

- a) The financing of the operational expenditures.
- b) The financing of new expansion projects.
- c) The firm's long term financial strategy.

The first type of policies deal with the utilization of funds on the everyday operation of the mine. They compare the planned level of expenditure on mineral developments and working capital, with a short term forecast of the maximum feasible spending rate and may cut-back or

expand expenditure on those items as a result of this comparison.

The second type of policies act when a particular ore processing capacity addition has been planned and positively assessed by the economic feasibility policy, already described. This financial policy decides whether to go ahead with the projected capacity expansion by comparing the requirement of funds for this addition with a medium term forecast of the funds at the disposal of the enterprise for this particular purpose.

The policies that control the firm's long term financial strategy, decide the level of profits to be retained and the desired value of the equity to borrowed capital ratio. These decisions are taken based on the liquidity situation of the firm and an estimation of the maximum amount of borrowing that could be achieved, at the end of every simulated financial year.

Characteristics of the Model

Because of the dynamic nature of the problem proposed, and the intrinsic feedback interactions that existed between the variables chosen to be analysed, the development of a system dynamic model of the whole enterprise was thought to be the most suitable method to tackle it.

The model has been programmed using DYSMAP, which is a programming language especially designed to facilitate the development of this type of dynamic model. This permits any of the model's variables to be displayed in numerical and graphical form at any point during the simulation time, and poses the very favourable feature of being readily understandable when compared with other simulation languages, presently in use.

Model Structure

The model, whose very simplified influence diagram is shown in Fig. 1, can be divided from the logical point of view, into the following distinguished sections:

Price sector:

This section represents the market. It provides the model with an exogeneous price series that could be whatever the user wants, from the

historical L.M.E. price series to any desired mathematical expression.

Reserves sector:

The size and initial distribution of grades within the orebody to be mined are inputs to this section. An account is kept of the availability of different grades for developing purposes, as well as of the total economic reserves.

Developed reserves:

The present state of developments is described in this section of the model. It includes tonnages and percentages of each separate grade which has been developed. An estimation of the proportion of each different grade, currently being added to the developed reserves is made, based on a selectivity co-efficient, which reflects the amount of selective development capable of being achieved.

Production policies:

In this part of the model an estimation of the cost per ton of ore mined is made. From this and the smoothed market price, the pay-limit grade is defined. The actual implementation of the desired production and grading policies is achieved by the inclusion of appropriate tables, the input to which is the smoothed market price to normal price percentual difference. The output from these tables gives the corresponding multiplier factors which are used to scale the nominal ore production in order to define the desired production rate and to multiply the pay-limit grade to select a cut-off grade.

Production sector:

Using the previously selected desired ore mining rate, the cut-off grade and a mining selectivity co-efficient, the desired mining rate for each of the individual ore grades is calculated. The actual ore mining and milling rate is then established considering the possible constraints on volume and grade that may be imposed by the hoisting and ore processing capacity available.

Waste removing:

Since a dynamic cut-off grade is used, there may exist the need for removing non-profitable grades, developed because perfect selectivity is

not possible.

Capacity additions:

This section incorporates the projection of additional capacity requirements. If a capacity addition is larger than the minimum fraction acceptable for expansions recommended, an estimation of the operational life is made, considering the availability of proved reserves. This fact, together with a forecast of prices and pay-limit allow the prediction of the discounted value of incremental earnings to be produced by the planned expansion. If this value compares favourably with the expenditure to be incurred on it, an economic feasibility switch is set on.

Short and medium term financial policies:

An estimation of the maximum achievable spending rate is based, in the case of short term planning policies, on the present earnings rate, the cash reserves and the possibility of raising funds through borrowing. For medium term financial policies the maximum achievable spending rate is additionally based on the possibility of equity funding.

The ratio between this estimated and the planned expenditure, is used as input to tables which specify the financial policies currently in use. The output of these tables are multipliers that are used to scale up or down the working capital and developments expenditures.

Valuation of the firm:

The model includes a complete accounting section and produces a balance sheet type report at the end of every financial year. The straight line depreciation technique has been adopted to determine the capital allowances due to the initial expenditure on fixed assets. The depreciation of reserves is calculated separately and includes the depletion allowances and the amortization of the developing expenditures.

Profits, tax and dividends

The profits are declared once a year and dividends are paid according to the retaining profits policy adopted, which is based on the liquidity

situation of the firm. If taxes ought to be paid, the model allows for these to be deferred for a period of up to one year since profits were declared.

Cash flow:

The cash flow includes:

- 1) The earning rate, which is defined as the sales revenue less the direct production, processing, marketing and administrative costs plus or minus the interests received or paid.
- 2) The rate of spending on working capital, developments and capacity acquisition.
- 3) The rate of repayment of the long term debt.
- 4) The payment of dividends
- 5) The payment of taxes.

Cost section:

This is essentially an input section which defines the mining, developing, processing and marketing cost per ton of ore, certain fixed costs (excluding depreciation), and the cost of equipment and working capital.

Output section:

The model provides the possibility of printing the numerical value or plotting the dynamics through time of any of its variables.

Control section:

This section includes the characteristics of the simulation runs to be performed, such as duration, printing intervals, etc. It is possible to modify practically all the model parameters and policy tables between contiguous simulation runs.

The Mining Operation Simulated

The firm selected to be modelled in the simulation runs shown in the next section, manages a hypothetical underground copper mine, with nominal metal production capacity of 11,000 tons of recoverable copper content concentrates, in its early life.

The mineral body mined has 20 years of proved reserves at the nominal ore production capacity and initial grade distribution as shown in table 1 below:

Average Grade in % of Cu contained	Proportion of Total
0.5	0.05
0.75	0.10
1.00	0.20
1.25	0.35
1.50	0.25
1.75	0.05

Table 1.

The mine is defined to operate on two shifts, seven days a week, which allows for an expansion of up to 50 percent in ore mining capacity if an extra shift is added. The shaft allows for a maximum daily rock hoisting capacity of 65% in excess of the nominal ore mining capacity. The concentrator has been designed to process ore with an average grade of 1.3 percent of Cu and it is capable of handling up to 10 percent more ore tonnage than the nominal ore mining rate, in a three shift working day. The minimum fraction of ore processing capacity additions allowed is 20%. The average tonnage of waste rock required to be extracted in order to develop one ton of ore is 0.06 tons.

An eight years fixed assets depreciation period has been assumed in order to calculate capital allowances. The depletion allowances are estimated using the unit depletion method. The interest rate paid or received from loans or investments is 12% per year and the same value is used to discount earnings.

Simulation Results

Two separate sets of volume of output and grading policies have been selected in order to illustrate how different production policies affect the dynamic behaviour of the mine chosen to be modelled.

The first set, which we have named Production Policy I incorporates a desired constant tonnage of ore to be mined, irrespective of the metal market price and a low grading policy. By low grading policy, we mean a policy which defines the cut-off grade equal or lower than the pay-limit grade at any time.

The Production Policy II includes a volume of output policy which increases ore production when price expectations are above normal but keeps it at nominal capacity otherwise, and a grading policy which attempts to high grade the mine when prices are above its normal price. To high grade is for us, to define a cut-off grade which is over the pay-limit grade, that is, to say, attempts to increase the profit margin, per ton of ore mined.

Three different price series were selected for the simulation runs, in which all other control policies remained unchanged.

The dynamics shown in figures 3 to 5 have been obtained with the last ten years copper wirebar L.M.E. spot price series, expressed in January 1976 sterling pounds. These simulation runs covered a ten year period, and a summary of some of the overall performance parameters produced is shown in table 2.

Production Policy Type	Discounted Earnings £ x 10 ⁶	Percentage of Increase in Earnings	Copper Production TON x10 ³	Total Dividends £ x 10 ⁶
I	19.4	-	101	4.7
II	22.2	14%	108	6.2

Table 2

The simulation results show that production policy II increases the discounted cash flow by 14% and the cumulative dividends paid, by more than 30% when compared with production policy I. This improved performance is not only the result of an increase in total copper produced that amounts to approximately 8% but also of a reduction in direct production costs due to a higher average grade of ore mined, during most of the simulated period. This fact can be verified comparing the corresponding plots in figures 4 and 5.

The previous simulation runs did not attempt to analyse how the selected production policies affected the mine's behaviour throughout its life span. This fact should not be neglected because the resources available for mining are limited in quantity and quality, therefore, it could happen that what seems to be a better policy when analysing a limited period of operations might not necessarily be an improvement when considering the complete mine life.

The simulation runs whose results are shown in figures 6 to 13 and Table 3 were designed to analyse the dynamic behaviour of the mine throughout its economic life, when operating within two distinct metal markets.

The first type of market is represented by a fluctuating price series, with a 2.5 years oscillation period and 30% variations around a constant average price of £1000 per ton of copper. This price series was adopted to compare the effectiveness of the selected policies when the system is subjected to strong and continuous fluctuations from its environment. The dynamics obtained can be seen in figures 6 to 9.

The last price series implemented includes a sudden increase in price with the purpose of analysing how effectively the selected control policies re-adjust the system operation to the new market conditions. The dynamic behaviour produced by these policies can be seen in Figures 10 to 13.

Policy Type	Price Series	Mine Life Years	Discounted Earnings £ x 10 ⁶	Copper Production TON x 10 ³	Total Dividends Paid £ x 10 ⁶
I	30% osc.	20	28.7	195	29.8
II	30% osc.	18	31.5	189	29.7
I	Step, 33% incr.	21	51.3	200	66.5
II	Step, 33% incr.	15	61.4	194	64.4

Table 3.

The results obtained show that production policy II gives a much better rate of return on investment, especially if operating in a market with an increasing trend in real term prices. Production policy I may be superior though, if a smoother mine's operation is desirable for strategic reasons, such as availability of labour force or a greater metal recovery.

Conclusions

From the results obtained it is possible to conclude that there will be appreciable performance variations between one set of mine management policies and another. That the model could be a very valuable aid to the decision maker because it is capable of producing synthetic experience about the consequence the decision rules used or planned to be used will have on enterprise performance under any set of hypothesis about future economic climates.

Since the model can be adjusted to simulate any underground metal operation, which reasonably fits the assumptions under which it was developed, during its entire operative life, its scope is not only restricted to analysing the effects management policies have on mine performance but also it could be used as a design aid for new projects.

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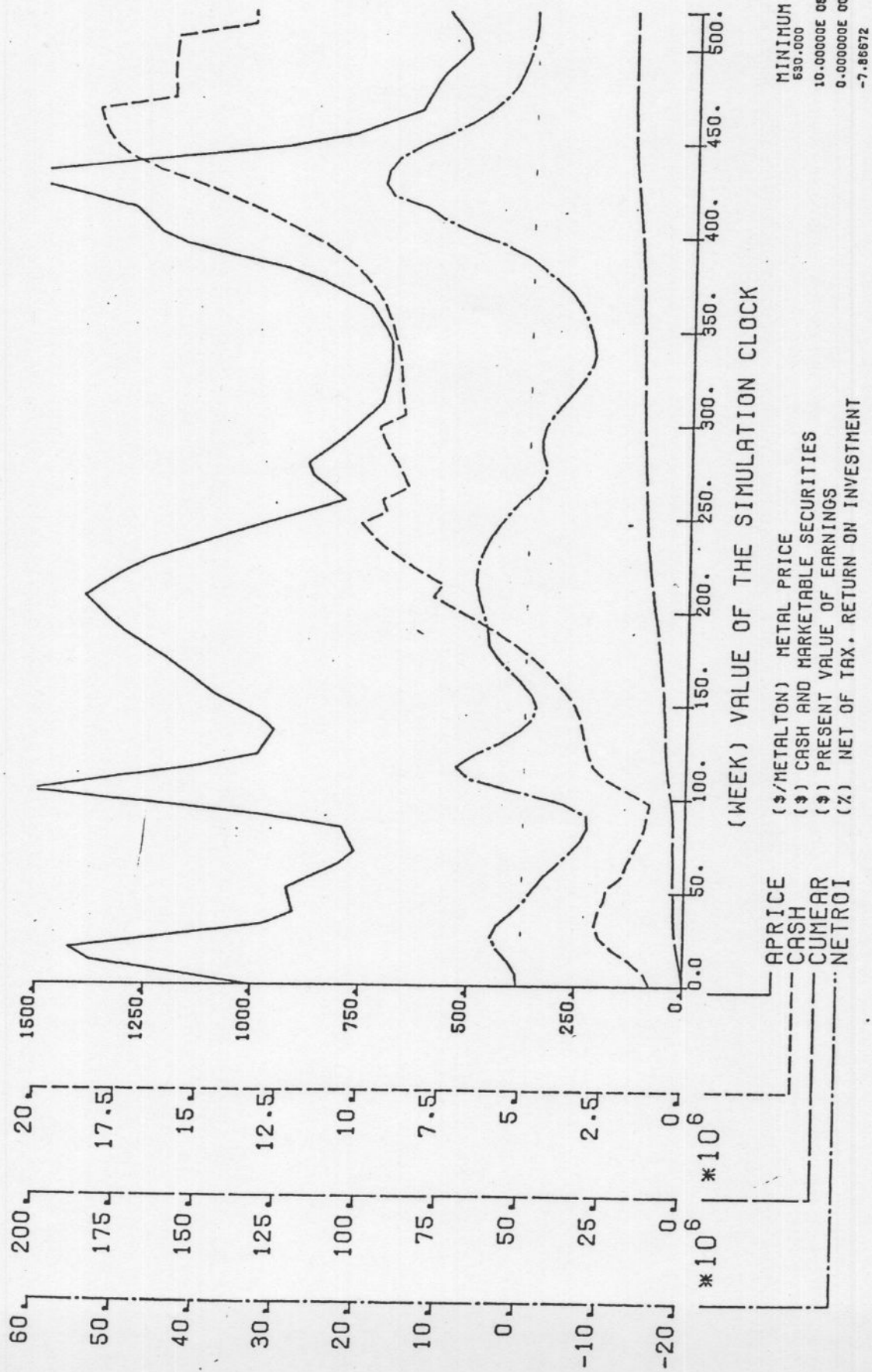
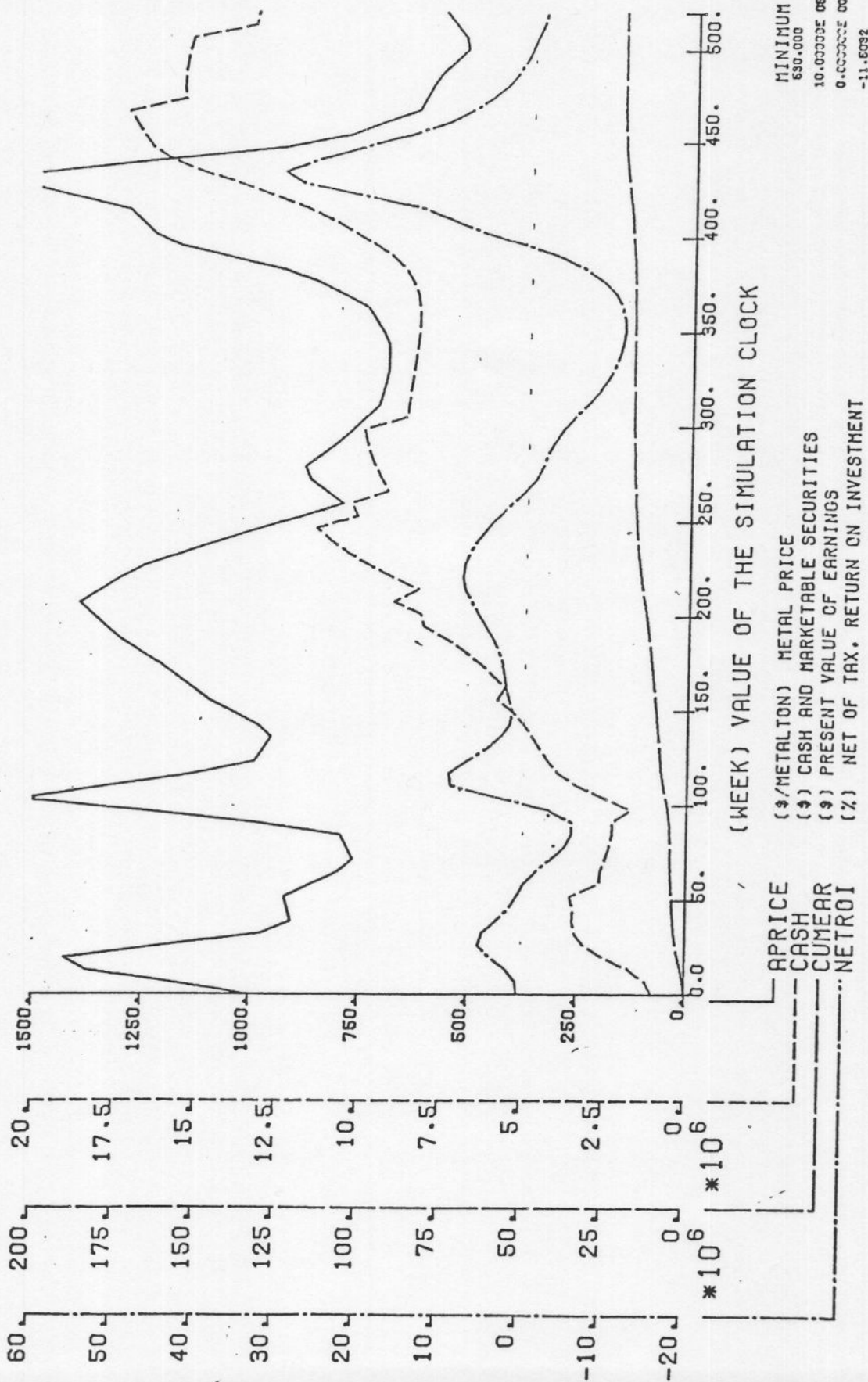


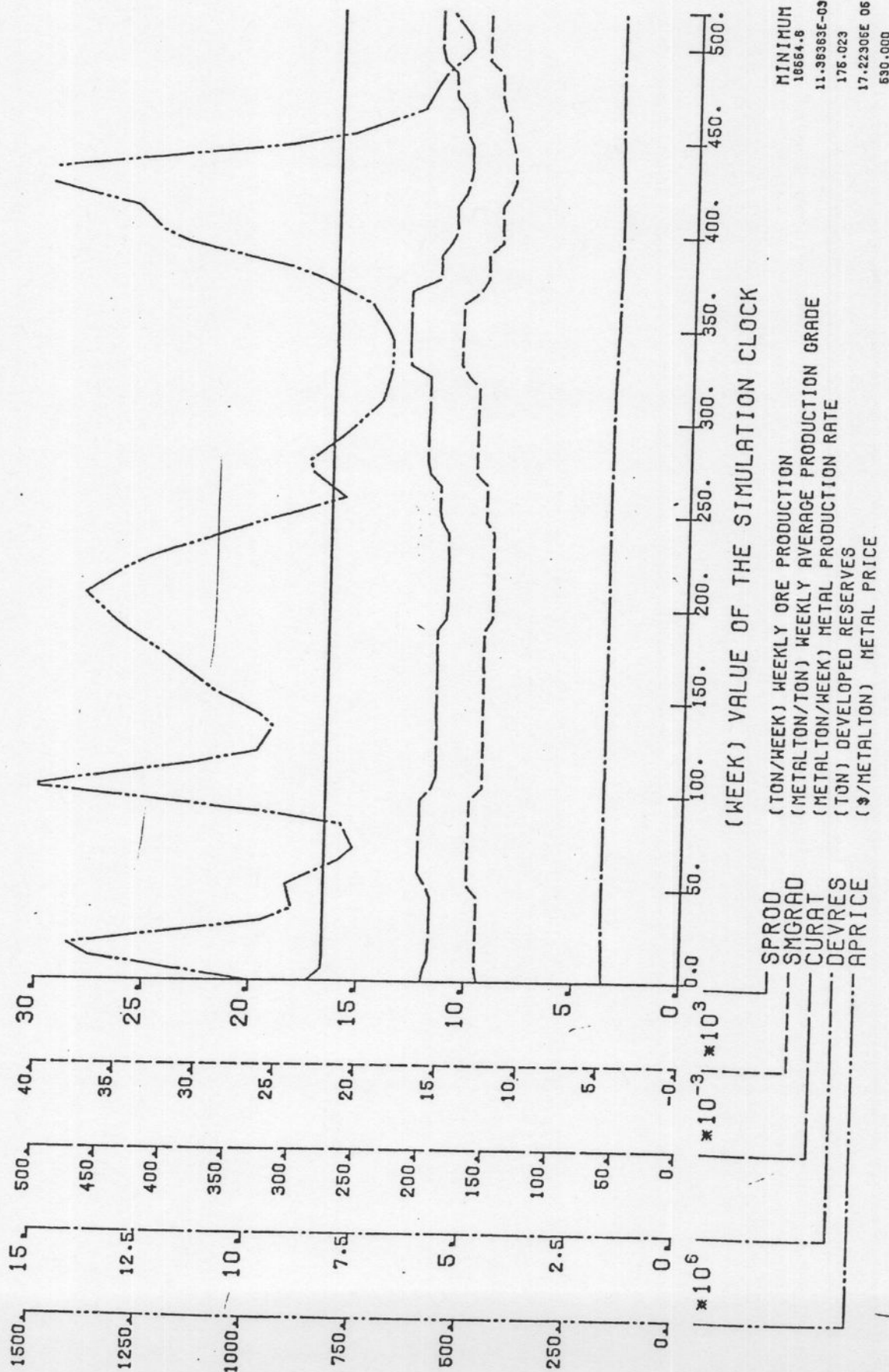
Fig. 2

PROD. POL. I, L.M.E. PRICE
MODEL OF AN UNDERGROUND MINING OPERATION

Fig. 3

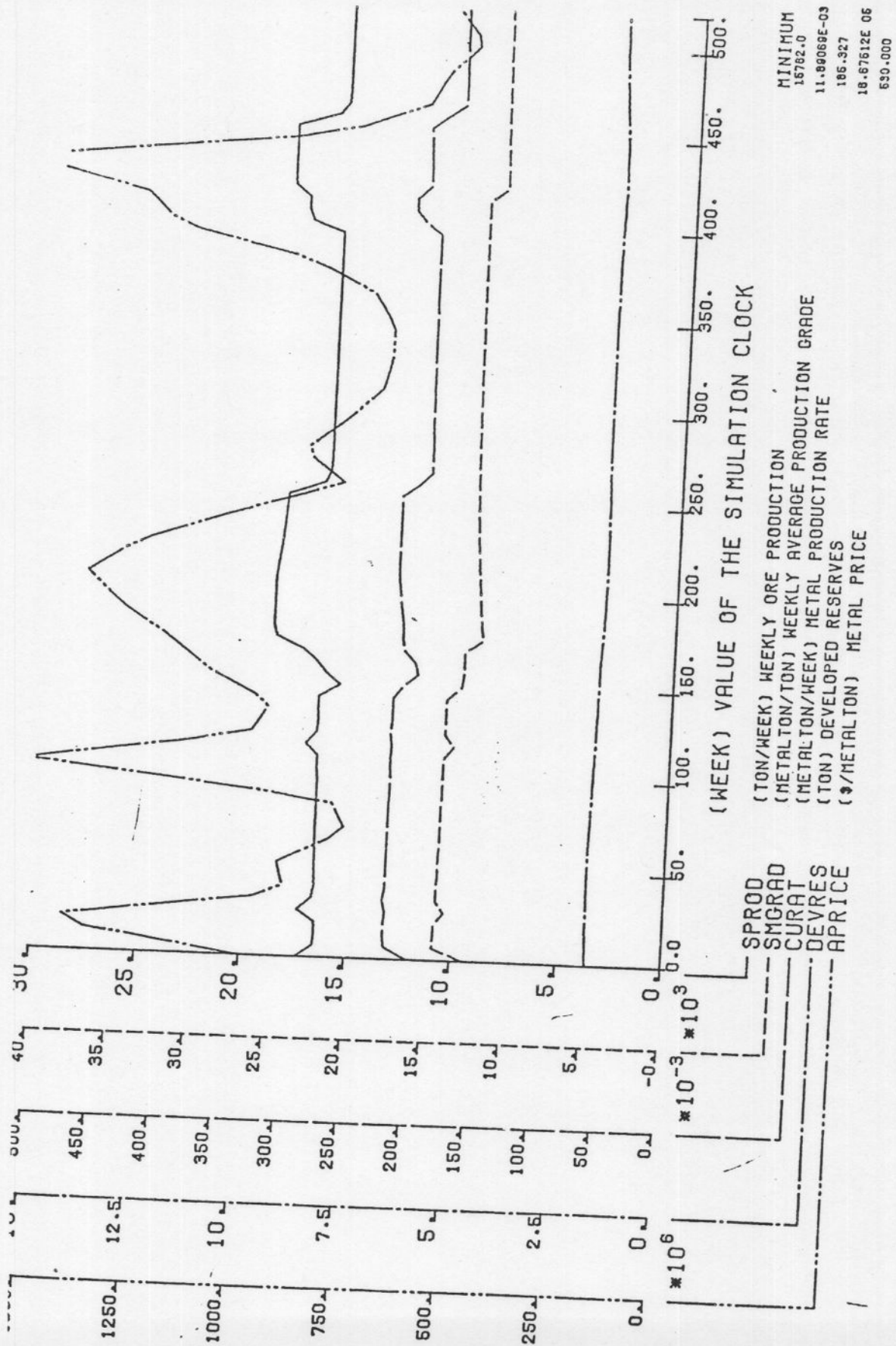


PROD. POL. II, L.M.E. PRICE
 MODEL OF AN UNDERGROUND MINING OPERATION

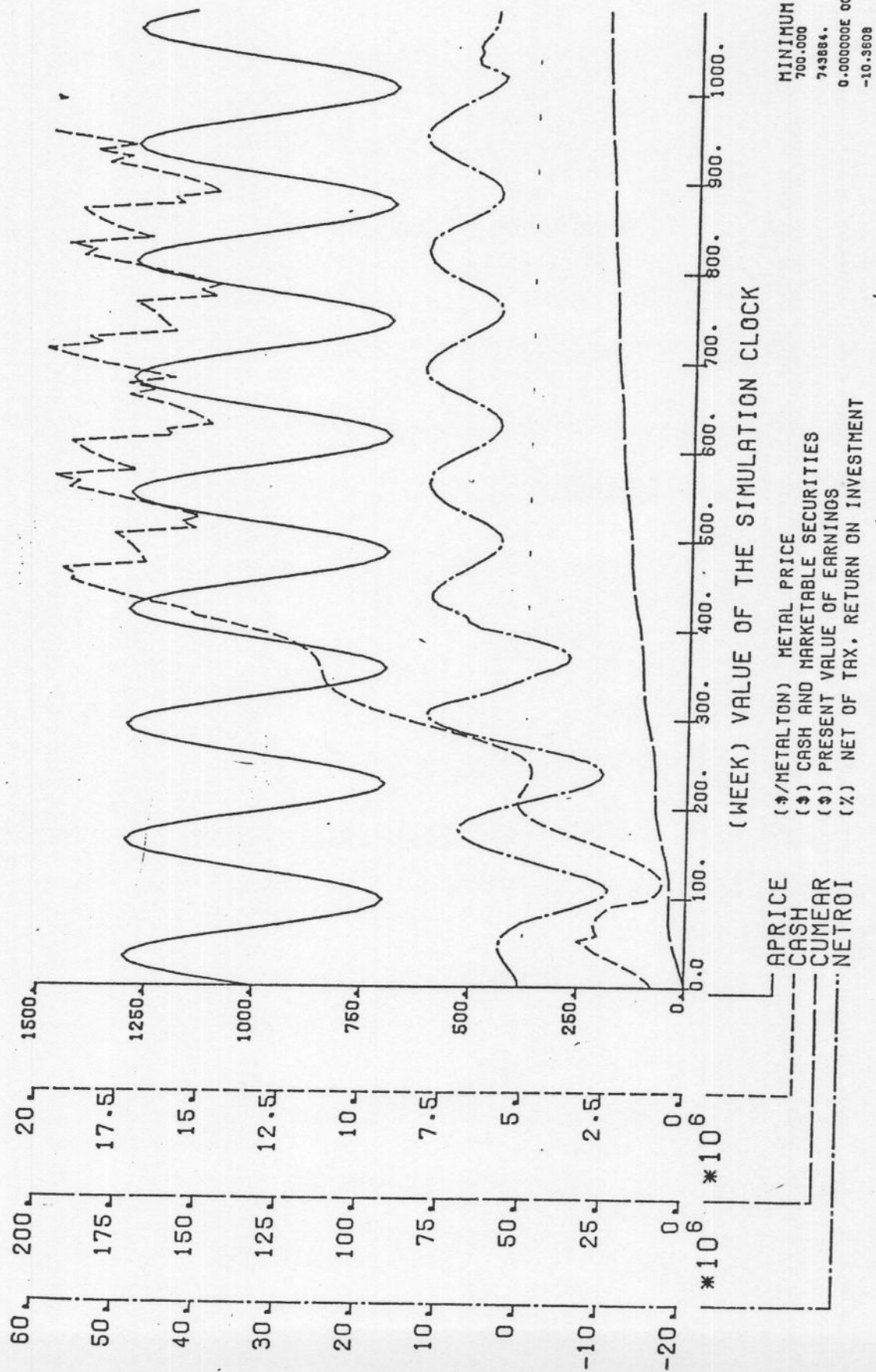


PROD. POL. I, L.M.E. PRICE
MODEL OF AN UNDERGROUND MINING OPERATION

Fig. 5



PROD. POL. II, L.M.E. PRICE
MODEL OF AN UNDERGROUND MINING OPERATION



PROD. POL. I, LOW GRADING, 30% OSCILLATIONS
MODEL OF AN UNDERGROUND MINING OPERATION

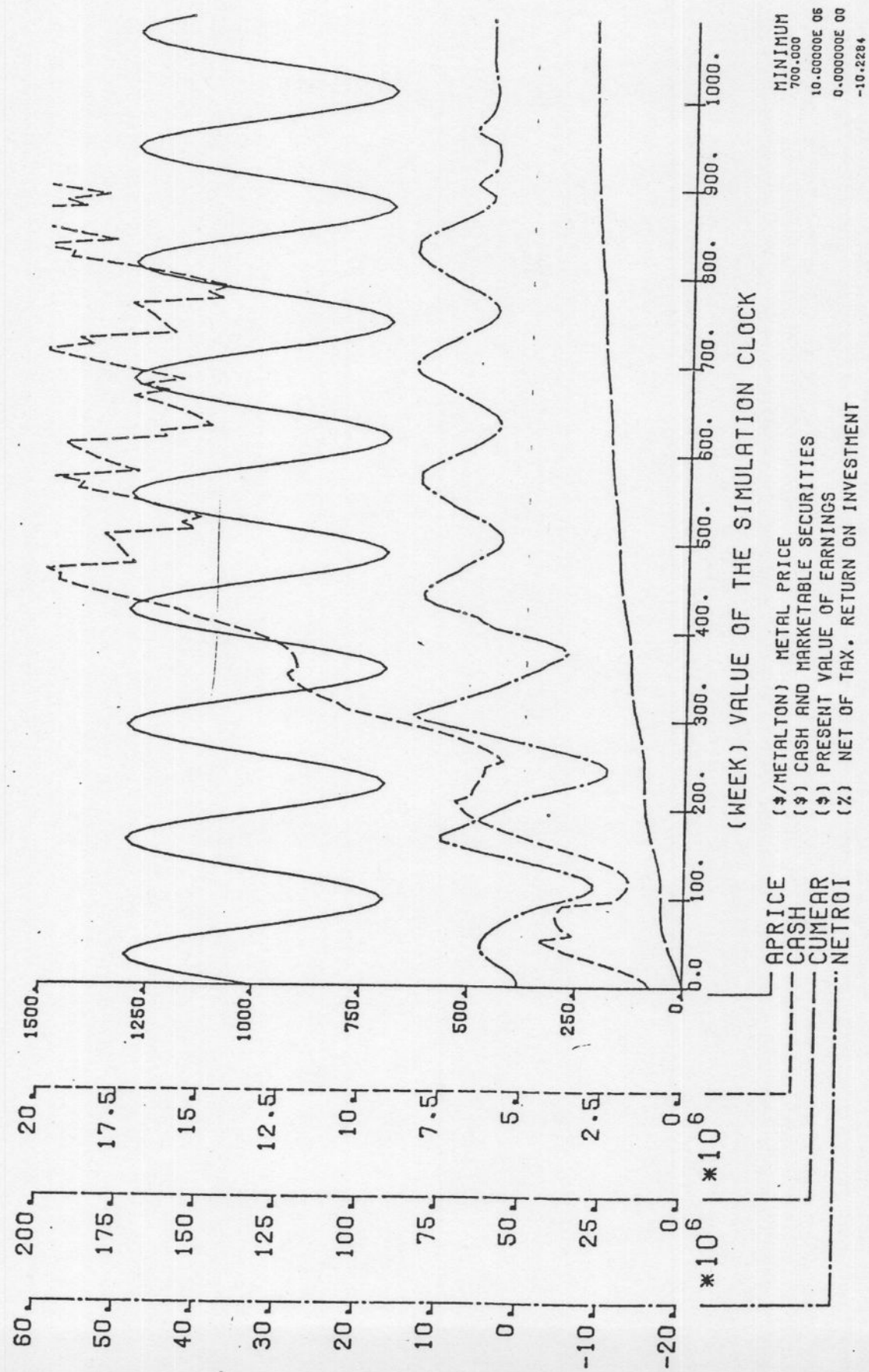


Fig. 7

PROD. POL. II, 30% OSCILATIONS IN PRICE
MODEL OF AN UNDERGROUND MINING OPERATION

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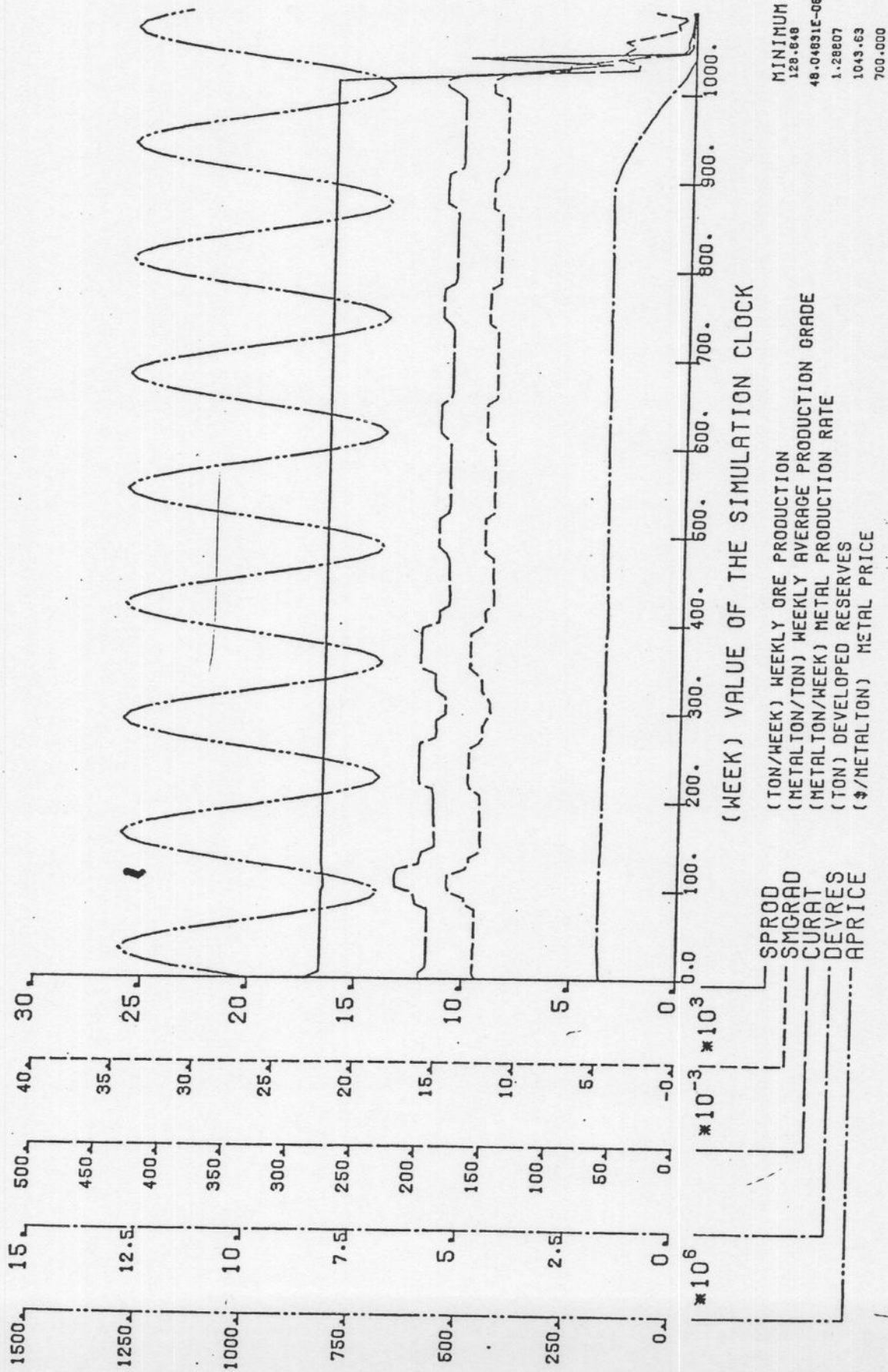
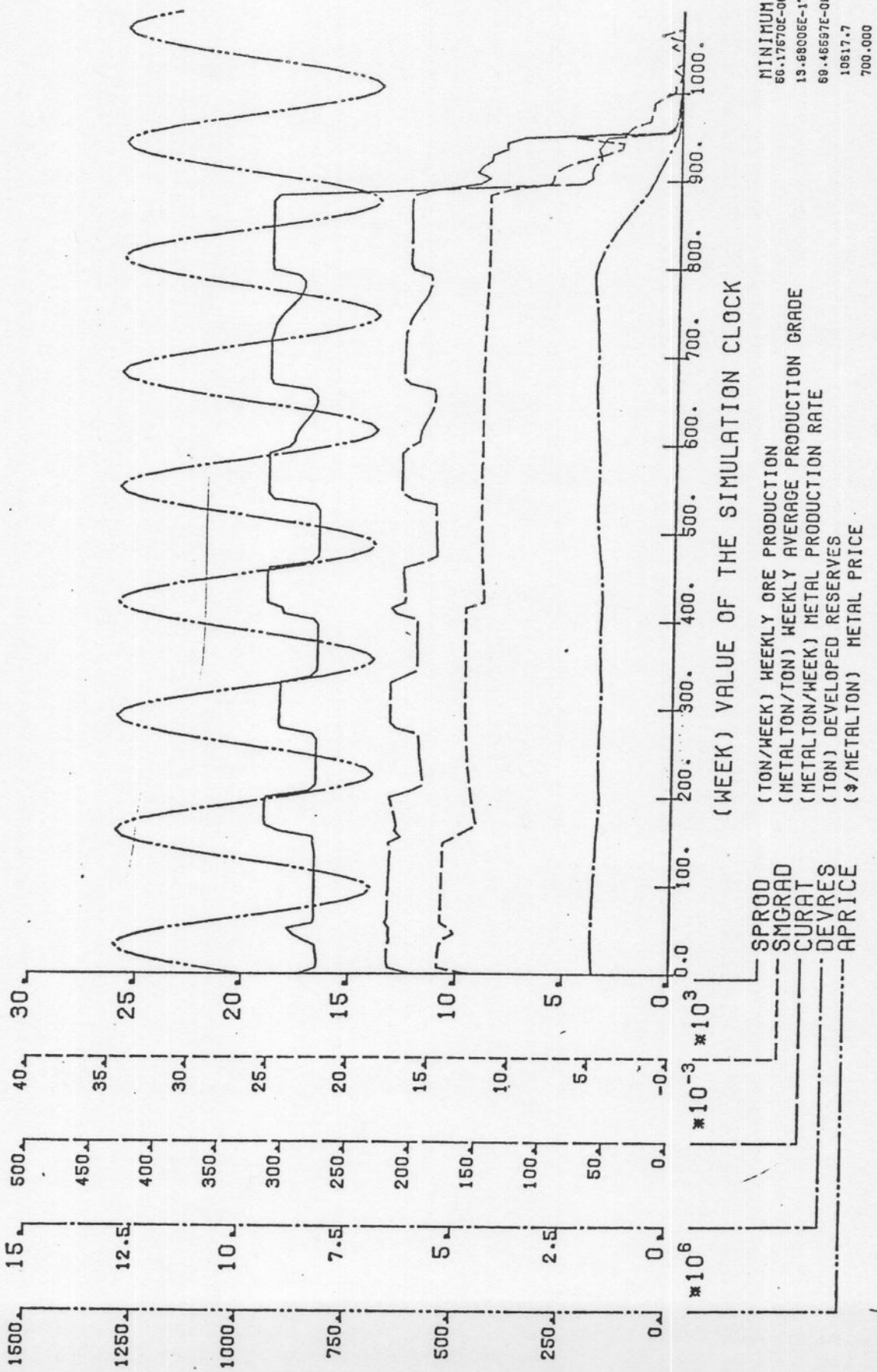


Fig. 8

PROD. POL. I, LOW GRADING, 30% OSCILATIONS
MODEL OF AN UNDERGROUND MINING OPERATION



MINIMUM	MAXIMUM
56.17670E-06	19027.0
19.68005E-17	14.49931E-
68.46597E-08	221.619
10617.7	19.76365E
700.000	1300.00

PROD. POL. II, 30% OSCILLATIONS IN PRICE
 MODEL OF AN UNDERGROUND MINING OPERATION

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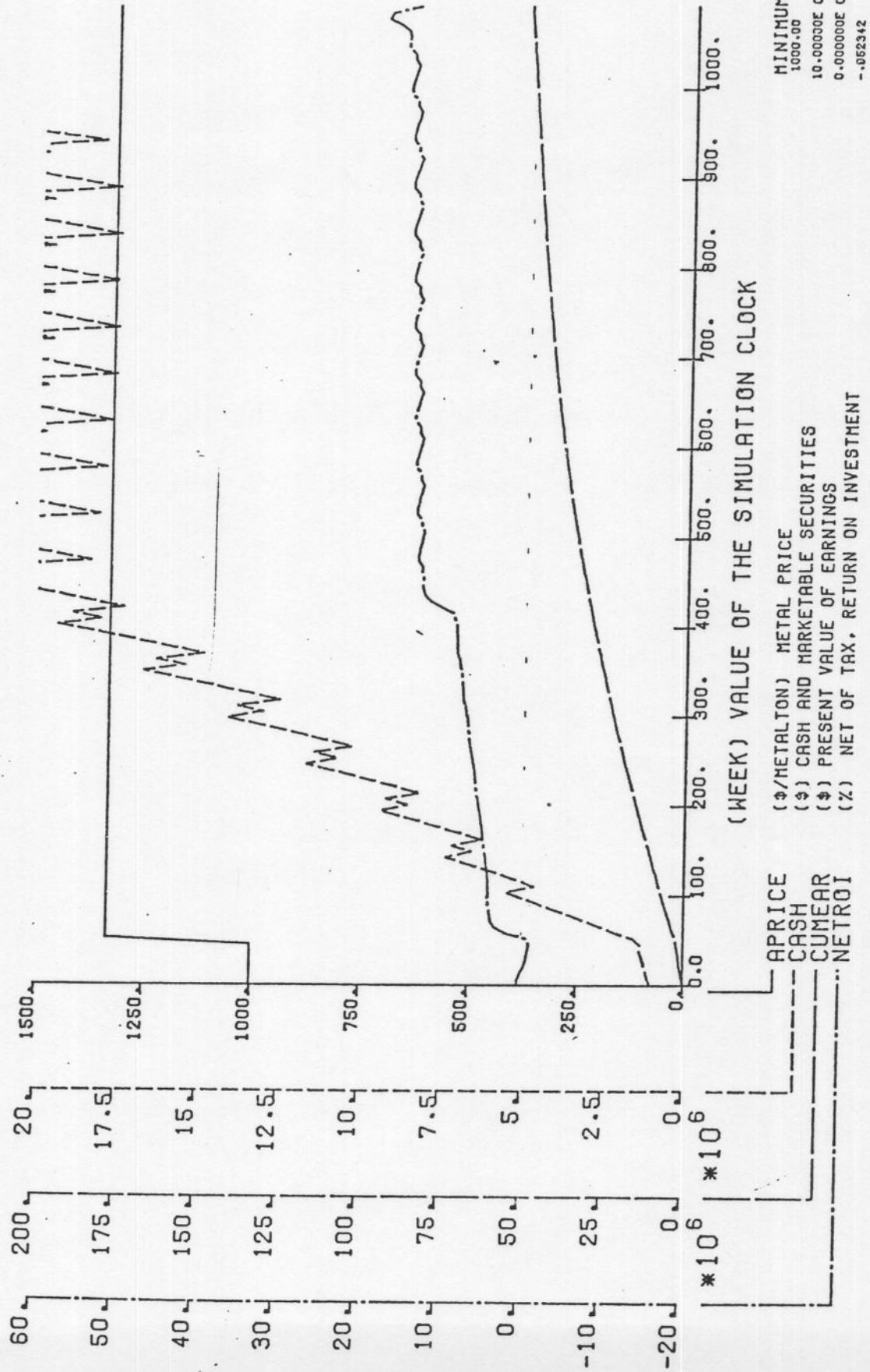


Fig. 10

PROD POL. I. STEP RESPONSE
MODEL OF AN UNDERGROUND MINING OPERATION

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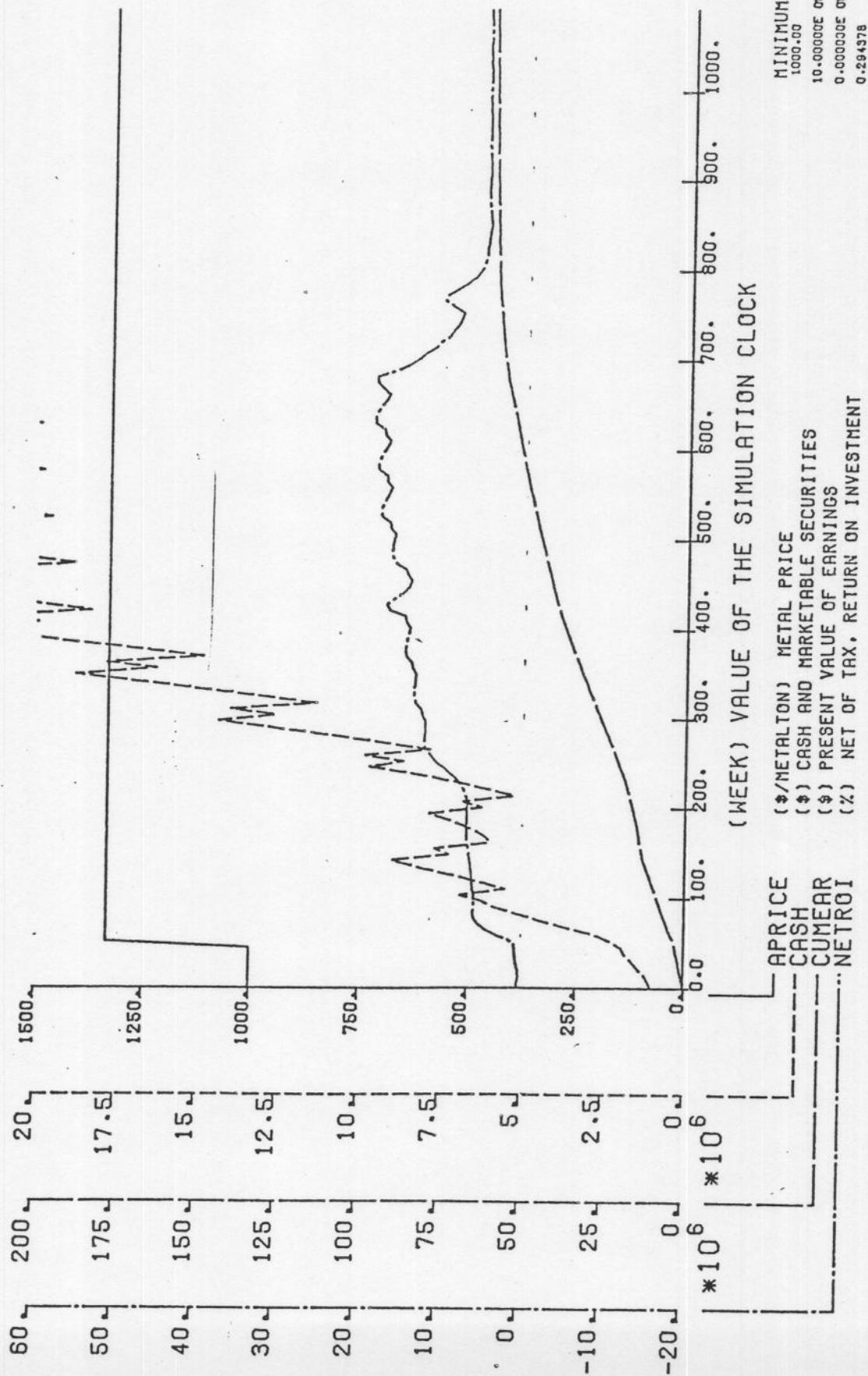


Fig. 11

PROD. POL. II, STEP RESPONSE
MODEL OF AN UNDERGROUND MINING OPERATION

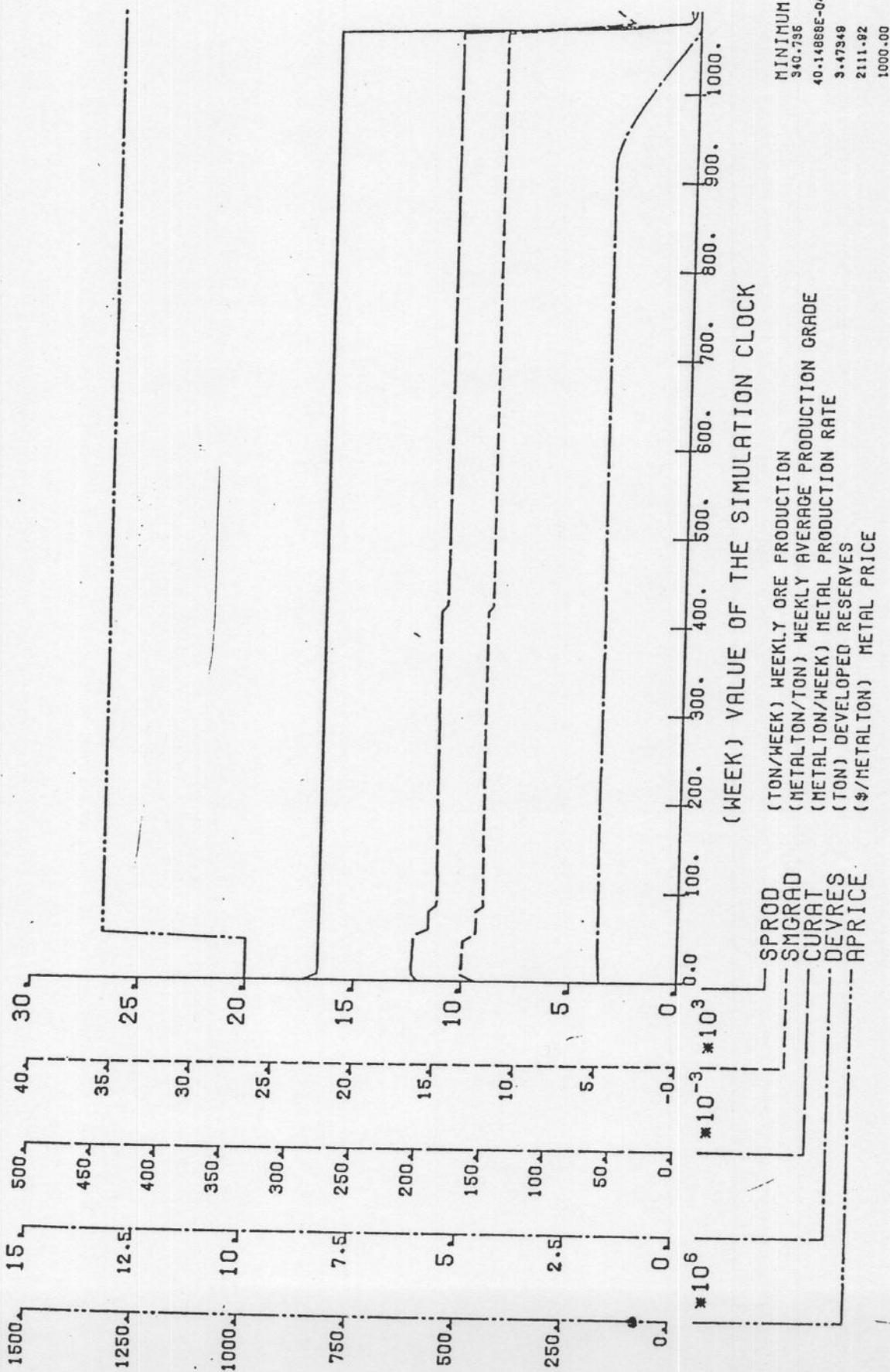
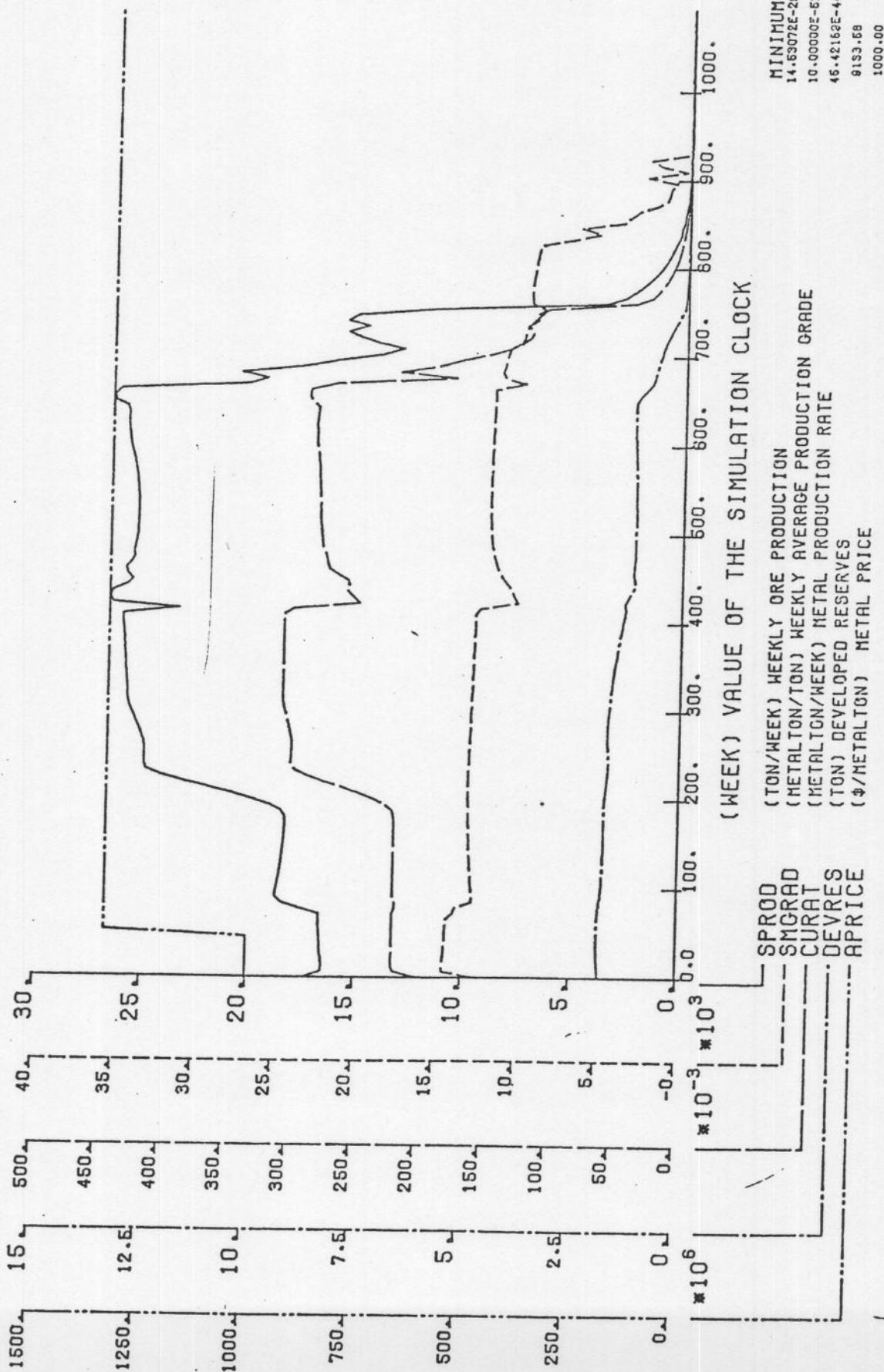


Fig. 12

PROD POL. I, STEP RESPONSE
MODEL OF AN UNDERGROUND MINING OPERATION

Fig. 13



PROD. POL. II, STEP RESPONSE
MODEL OF AN UNDERGROUND MINING OPERATION

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