A RELIABILITY-BASED DESIGN PROCEDURE FOR MINE DEWATERING SYSTEMS

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ABSTRACT

The presence of groundwater in the form of large aquifers can have an important influence on investment decisions for underground mines. The design for such mines requires development of special mining methods, and mine dewatering infrastructure to avoid hazards during shaft sinking and underground development. The costs associated with mine drainage control and mine dewatering systems (MDS) are relatively small compared to the huge consequential losses that can occur in case of an uncontrolled inflow and subsequent flooding of the mine. The design of MDS needs consideration of accurate prediction of the maximum uncontrolled inflow rate, availability of the system during an uncontrolled inflow while the inflow is mitigated, and decision on pumping system technology to have capability to operate under water. The research presented in this paper provides a theoretical framework for a reliability-based design procedure which takes into account the uncertainty in the estimate of the maximum uncontrolled inflow, performance of the system during the period of an uncontrolled inflow and a methodology to decide on appropriate pumping technology considering the reliability of the system and available underground storage. The reliability-based mine design procedure integrates the ideas of Effective Reserve and Hydraulic Reliability Index to come up with a unified methodology for design of Mine Dewatering Systems.

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INTRODUCTION

The presence of groundwater in the form of large aquifers can have an important influence on the investment decisions for underground mines. The possibility of water flow into the mine workings, depending on magnitude, can increase the capital cost of mine development and reduce operating efficiency. The design for such mines requires development of special mining methods, and mine dewatering infrastructure to avoid hazards during shaft sinking and underground development

Development of underground mine workings below aquifers or surface water bodies will invariably change the hydraulic gradient, with the possibility of flow of water from the surrounding rock mass towards the mining excavations. Seepage from adjacent aquifers, localized inflows along faults and major fissures, changes in permeability and storage from caving, and, subsidence due to mining are the few ways water will make its way into the underground workings. Water control measures such as cementitious grouting and ground freezing are routinely applied to limit the amount of water seepage to underground workings. However these measures act as hydrogeological barriers and any potential breach or loss in their effectiveness can result in either increased seepage or a major uncontrolled inflow to the mine workings. In case of an uncontrolled inflow the possibility of flooding the mine does exist. Therefore accurate estimation of the groundwater inflow quantity to the mine workings with and without the presence of hydrogeological barriers is of great importance in the design of the mine dewatering systems (MDS).

The importance of mine drainage control and the need for detailed design of mine water systems at the planning stage have been highlighted by various researchers [1-2]. The costs associated with mine drainage control and MDS are relatively small compared to the huge consequential losses that can occur in case of an uncontrolled inflow. However, controlled inflows to the mine working can also add significant pumping costs. Konkola Mine (Zambia) once was the wettest mine in the world, pumping more than 15,500 m^3/hr, with a peak of 17,700 m^3/hr [3-4]. Bridgwood et al. [1] defined four distinct modes of underground water inflow which would have most important influence in designing pumping capacity. These inflow modes are: constant rates of inflow over a long period; occasional large inflows from a finite source of underground water; drainage of large solution cavities in Karst aquifers; water inflow through erosive protective layer. An accurate estimate is therefore required for the design of underground drainage control installations such as pumping stations, sediment settlers, and underground pumping equipment [5].

Predicting inflow rate to an underground excavation is one of the most challenging tasks for a mine hydrogeologist. The quantity of water which can make its way to an underground mine can be attributed to surface hydrology, size and shape of source of water, recharge area and hydraulic characteristics of the intervening strata between the source of water and mine workings [3]. Various analytical and numerical methods can be used to predict these inflows, e.g. see [5-7]. Mathematical models, either analytical or numerical, use simplifying assumptions and available hydrogeological and hydrologic data to make mine water inflow estimates. These methods can either underestimate or overestimate the inflow values. In case of an under prediction the consequential cost of an unexpected flooding may be in the order of millions of dollars [5]. Therefore for larger projects, having capacity in excess of estimated maximum uncontrolled inflow rate can be justified. However in cases where either the excess capacity is not built into the system or the uncontrolled inflow persists for a long period of time, available capacity of the system over the inflow period becomes very important. This can be addressed by having redundancy in the system, which is a duplication of critical components of a system with the intention of increasing the system reliability. Building either active or passive redundancy in the system improves the overall reliability of the system but does not necessarily address the standby failures or failures on demand, a situation that is very relevant to the contingency MDS, which essentially are expected to work at full capacity in event of an uncontrolled inflow as the inflow is mitigated.

The discussion in the previous sections highlights three important points, (i) accurate prediction of the maximum uncontrolled inflow rate so that MDS of sufficient capacity can be made available, (ii) availability of the system during an uncontrolled inflow while the inflow is mitigated.

The research presented in this paper provides a theoretical framework for a reliability-based design procedure which takes into account the following:

1. Uncertainty in the estimate of the maximum uncontrolled inflow;
2. Performance of the system during the period of an uncontrolled inflow;
3. Probability of flooding of underground pumping systems taking into account the underground storage.

THEORY

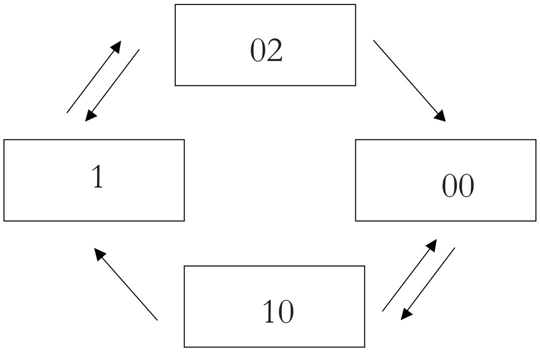
Effective Reserve

For mines that already have significant amount of development underground with production progressing to high-risk inflow areas, another form of redundancy in the term of effective reserve can be considered. Kulakov and Frolov [8] presented the idea of effective reserve as an alternative way of increasing the reliability of the underground mechanized extraction systems. They proposed that the rigid link between the subsystems can be weakened by providing one or more subsystems a reserve (redundancy) in the form of an identical equivalent "effective reserve," which temporarily replaces the defective system. Kulakov and Frolov [8] cite an example from the mining industry in which effective reserve is a system of bunkers (capacities) at the loading points, which can temporarily replace the operation of the transport and avoid stoppage of the extraction faces owing to the transport failure. In this particular case, the time of operation of the effective reserve (failure operation) can be determined by the productivity of the extraction faces, volume of the reserve capacity, and by the time of the throughput of the transport. It should be noted that restoration of the effective reserve is only possible after restoration of transport subsystem, a feature of the effective reserve that its restoration involves the protected subsystem and can only occur after it is repaired.

Underground water storage in the mine workings can act as an effective reserve to the MDS. An uncontrolled inflow is analogous to the productivity of the extraction face and, in the event of a pump failure(s) in a MDS (pumps connected in parallel), underground storage at a particular level can act as an effective reserve to compensate for the lost pumping capacity until the system is back to its full operational capacity. As explained in the previous example, unlike the reserve (redundant pump), effective reserve (underground water storage) can only be restored if the failed subsystem (in this case the pump) is repaired and the uncontrolled inflow is less than the total dewatering capacity of the system. The failure rate of the effective reserve (in this case, rate of depletion of underground storage) can be determined by the inflow rate, available pumping capacity, and the available underground storage. Figure 1 shows the possible states of the subsystem in the form of possible states of the protected system. The coefficient of operational readiness (K_r) of the protected subsystem can be expressed by the following equation [8]:

$$K_r(t) = 1 - K_{f_1}(t) K_{f_2}(t) \tag{1}$$

where K_{f1} and K_{f2} are the coefficients of failures of the subsystem and effective reserve. A closer look at the Eq. [1] indicates a lower failure rate of effective reserve will warrant higher coefficient of readiness of the protected subsystem.



`1 : The subsystem is operating.`

`02: The subsystem is not operating, but the effective reserve is operating.`

`00: Neither the subsystem nor the effective reserve is operating.`

`10: The subsystem is operating, but the effective reserve is not operating.`

Figure 1 – Diagrams of states of the subsystem

Hydraulic Failure and Hydraulic Reliability Index

The concern about a MDS being flooded either due to the potential failure of the pumps operating over the period of inflow mitigation, or an underestimated inflow rate can be addressed by introducing the notion of hydraulic failure and hydraulic reliability index. Most of the pumping station reliability models focus on the reliability of pumping stations in water supply systems. Emolin et al. [9] pointed out that the reliability of an object is defined as its ability to provide continuous, long-term operation without the need for overhauls and can be mathematically measured as probability that an object meets these requirements. They argued that the above-mentioned definition of probability is of limited use as a performance criterion for a sewage pumping station (SPS) functionality which remains functional, albeit to a limited extent, even when one or more of its components fail. In support of their argument they pointed out that definitions of both mechanical and hydraulic failures introduced by Mays et al. [10] should be used for SPS. Mechanical failure considers a SPS failing due to pump failure or power outages, whereas a hydraulic failure occurs when a SPS cannot pump out all the sewage entering its input at all times.

In this paper it is proposed that the reliability of MDS is analogous to Emolin et al.'s [9] concept of reliability of SPS, based on the following rationale. Most sewage disposal systems are designed on the concept of head-gravity, where sewage passes through the sewers by gravity and pumping stations lift sewage in areas where gravity flow is impossible. This is analogous to the uncontrolled mine inflow where water moves under the action of gravity to the lower mine workings and dewatering systems pumps it out of the mine. The other similarity between the SPS and MDS is the idea of hydraulic failure. Based on the analogy by Emolin et al. [9], the hydraulic failure of a MDS will occur when the system cannot keep up with the mine inflow water due to unserviceability of pump unit(s). In other words, hydraulic failure will occur when MDS cannot pump out all the uncontrolled inflow entering its input at all times. Emolin et al. [9] also argued that it is not always the case that a mechanical failure gives rise to a hydraulic failure, but each hydraulic failure is usually the result of a mechanical failure. We propose that the last part of the statement is not universally true for MDS because a less conservative deign value of an uncontrolled inflow rate estimate can also result in a hydraulic failure when all the pump units are working.

Based on the above discussion it becomes evident that the idea of hydraulic failure has merit to be used for MDS. Moreover, it is also proposed that integrating the idea of hydraulic failure and underground storage a methodology to decide on the availability of the MDS over the period during which inflow is mitigated can be made.

Proposed Methodology

The idea of hydraulic failure can be expressed in terms of hydraulic reliability index (γ) [9]. For a MDS this index can be quantitatively determined by:

$$\gamma = \frac{Q_d}{Q_{in}} = \frac{\int_o^T q_d(t)dt}{\int_o^T q_{in}(t)dt} \tag{2}$$

where Q_d is the total volume of the water not pumped out of the mine over the time interval T (where T is the time from start of the inflow to time when inflow is mitigated), and Q_{in} is the total volume of the uncontrolled mine inflow. Equation 2 indicates that the value of hydraulic reliability index γ can vary between *0* (absolutely reliable mine dewatering system) and 1 (completely failed pumping station); the intermediate values would reflect the degree of ability of a system to fulfill its specified function of pumping out the inflow water in an easy-to-perceive, palpable form. Therefore γ can be used as the reliability measure for MDS.

In order to address the concern regarding flooding of the underground MDS as the inflow is mitigated or additional pumps are installed, another aspect of hydraulic failure can be used. Combining the ideas of effective reserve and hydraulic failure, reliability calculations can be performed to predict the time to possible flooding of MDS.

The total volume of the water not pumped out of the mine as result of the unavailability of the pumping units can be estimated by the following equation:

$$q_d(t) = q_{in}(t) - q_c(t) \tag{3}$$

where q_d is the deficiency in pumping capacity in terms of discharge, q_c is the current discharge capacity and q_{in} is the discharge entering the mine as a result of uncontrolled inflow. It should be noted that all the variables are random functions of time t. The deficiency in pumping capacity during the period of time over which the uncontrolled inflow persists is a function of operationally available and unavailable pumping unit(s) over that period. The combination of operationally available and unavailable pumping units can be denoted by the different states of the mine dewatering system. The possible number of states is equal to 2^n, where n is the number of identical and perfectly switched pumps in a dewatering system. The probability of dewatering system residing in the s^{th} state $p_{s(n,i)}$ can be expressed by:

$$p_{s(n,i)} = \left(\frac{n!}{(n-i)!}\right)(1-p_N)^{n-i} p_N^i \tag{4}$$

where p_N is the operational availabilities of the pumping units and $p_{s(n,i)}$ is the probability of i out of n pumps operating at any given time, respectively. In addition the following equation is true:

$$\sum_s p_s = 1 \tag{5}$$

which reflects the fact that the mine dewatering system resides in one of the possible states at all times. The probability of each MDS state can be calculated from Eq. 4. As the MDS will reside in any of these states depending on the availability of the pump(s) and these states will change occasionally the amount of water that will not be pumped out (q_d) is the discrete random variable and an equivalent flow rate $(q_d)_e$ can be estimated as the expectation of this variable i.e.

$$(q_d)_e = \sum_{s \in k} \left[(q_{in})_{av} - (q_c)_s \right] p_s \tag{6}$$

The term $\left[(q_{in})_{av} - (q_c)_s\right]$ in Eq. 6 equals zero for all values of $\left[(q_{in})_{av} < (q_c)_s\right]$.

The estimation of equivalent flow rate requires operational availability functions for the various pump(s) in the MDS and can be estimated from the expressions of the form:

$$p_N(t) = \exp\left[-\lambda_N t\right] \tag{7}$$

where λ_N is the failure rate of each pumping unit and $p_N(t)$ is the availability of the pump at time ‘t’. The failure rates can be determined from the service records of the pumps.

The total volume of unpumped inflow that occurs due to pumping deficiency and pump failure can be estimated from:

$$Q_{d(n,t)} = \sum_{i=0}^{n} \int_0^t \left[(q_{in})_{av} - (q_c)_i \right] p_s(t) dt \tag{8}$$

Remembering that the term $\left[(q_{in})_{av} - (q_c)_s\right]$ in Eq. 8 equals zero for all values of $\left[(q_{in})_{av} < (q_c)_s\right]$.

$$Q_{d(n,t)} = \sum_{i=0}^{n} \left[(q_{in})_{av} - (q_c)_i \right] \int_0^t \frac{n!}{(n-i)!} p_n^i (1-p_n)^{n-i} dt \tag{9}$$

Fig. 2 shows a conceptual diagram from above described framework. In this figure it can be seen that for a given inflow rate, the time it would take to utilize all the underground storage can be estimated considering the reliability of the MDS

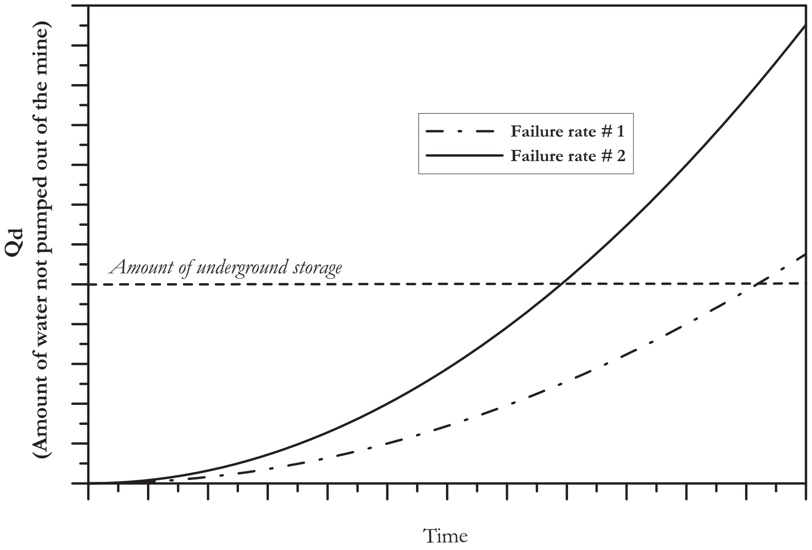


Figure 2 – Schematic of conceptual framework to determine possibility of MDS flooding

PROOF OF CONCEPT CALCULATIONS

For the proof of concept calculations we consider a hypothetical underground mine with an uncontrolled inflow potential of $q_{in} = 1000\ m^3hr^{-1}$. In case of an uncontrolled inflow the incoming water will report to the sump located at the lowermost level of the mine at the depth of 500 m ($H_{so} = 500\ m$) from the ground surface. The main pumping station located at this level is capable of pumping in excess of $1000\ m^3hr^{-1}$ to the ground surface, where water is released after treatment. The pumping system is composed of $n = 1 \ldots 6$ pumps of equal capacity and the degree of redundancy is dependent on the actual inflow rate. The pump discharge curves are given in Fig. 3. The head discharge curves for a single pump can be approximated by the quadratic equation:

$$H_p(q) = H_{po} - aq - bq^2 \tag{10}$$

where $a = 161.68$, $b = 55133$ and $H_{po} = 781.19$ are the least square estimates of the quadratic coefficients. The system head losses can be approximated by the equation:

$$H_s(q) = H_{so} + \alpha q^2 \tag{11}$$

where α is calculated as outlined in the following paragraphs.

The hydraulic constants are taken as ρ = 1000 kg m^{-2}; $\gamma_{water} = 9807\ Nm^{-3}$; μ= 0.00152 N s m^{-2}; ν = 1.52 x 10^{-6} m^2s^{-1}; g = 9.807 ms^{-1} . The diameter of the effluent pipe is calculated to keep the flow velocity in the pipe below 2.5 m s^{-1} at the maximum inflow rate. Therefore, 2 effluent pipes of standard pipe diameter d = 0.31 m each are selected. In this analysis, it is assumed that the friction factor, f_{Qin}, observed at Q_{in} is constant and applies for all flow rates. It is also assumed that the head loss due to pipe valves, fittings and entrance and exit losses are equal to 20% of the head loss due to wall friction. Therefore, head loss is calculated as:

$$h_L(q) = \alpha q^2 \tag{12}$$

where α is the friction coefficient and calculated as follows:

$$\alpha = \frac{c\mathrm{f}_{\mathrm{Qin}}L}{2gd\left(\frac{\pi}{4}d^2\right)^2} \tag{13}$$

where, the friction factor (f_{Qin}) is calculated from the Blassius formula as:

$$f_{Qin} = \frac{0.316}{R_e^{0.25}} \tag{14}$$

and the Reynolds number (R_e) is calculated as:

$$R_e = \frac{\rho Q_{in} d}{\mu\left(\frac{\pi}{4}d^2\right)N_p} \tag{15}$$

and $c = 1.2$ is a constant multiplier to account for the minor losses in the piping system and N_p is the total number of effluent pipes provided .

Stable operation of a pumping unit occurs under the condition:

$$H_s(q) = H_p(q) \tag{16}$$

For n number of pumping units under operation, the flow capacity $q_{c(n)}$ is calculated from Ermolin et al [9] as:

$$q_{c(n)} = \frac{n}{2\left(b+\alpha n^2\right)}\left[\sqrt{a^2+4\left(b+\alpha n^2\right)\left(H_{po}-H_{so}\right)}-a\right] \tag{17}$$

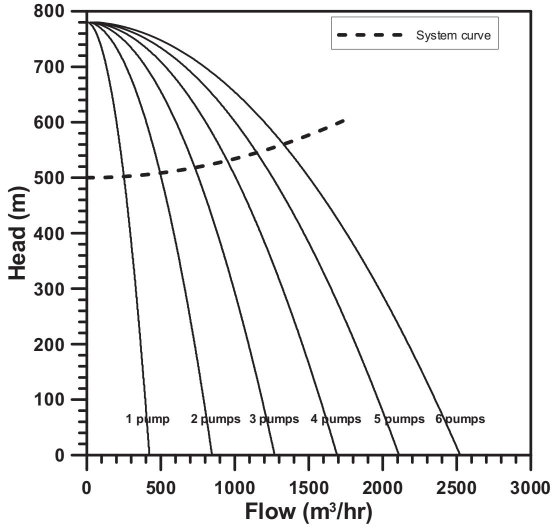


Figure 3 – Pump discharge curves

Assuming a pump failure rate of $\lambda_N = 0.5 \times 10^{-4}$ hr^{-1} for each identical parallel pumping unit, the availability of a single pumping unit can be calculated as:

$$p_N(t) = \exp[-\lambda_N t] \tag{18}$$

The failure rate or availability function in this preliminary calculation has been estimated. However, a detailed maintenance history of similar pumps will provide a better estimate of system reliability.

Figure 4 was produced by solving Eq. 9 using the Maxima Computer Algebra System (Li. and Racine, [11]), and shows the amount of water that will not be pumped out the mine if the inflow is to persist over a period of one year. Although the calculations were performed for all the permutations as described by Eq. 4, however for the sake of brevity results are shown for a limited number, with the assumption that results for rest are either subset or simple extrapolation of the results presented here. From this figure it can be seen that if the pumping system comprises of 6 pumps the amount of water that will not be pumped out of the mine after 6 months of operation is minimal. The quantities for less number of pumps are more and increase as the times progresses. It should be noted that all these estimates depend greatly on the availability function used for the calculations described by Eq. 17., therefore a good definition of failure rates for the relevant pumps is very essential.

Fig. 4 can also be used to assess the time available to either mitigate the inflow or increase pumping capacity before the MDS becomes totally unavailable due to flooding. As an example, if the underground storage for the hypothetical case is 4×10^5 m^3 and the pumping system comprises of 4 pumps, the available time for inflow mitigation/installation of excess capacity is around 6 months.

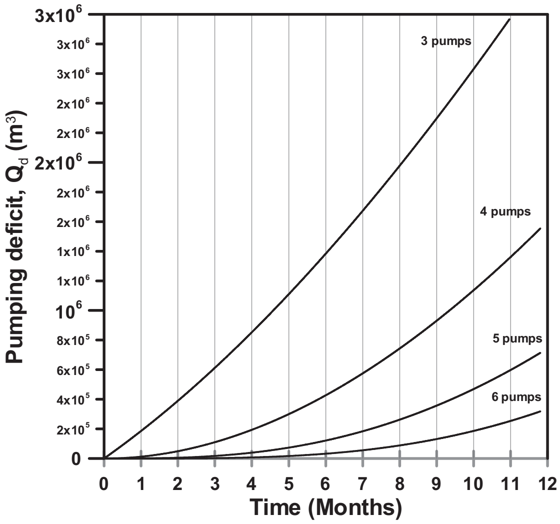


Figure 4 – The potentially unpumped inflow volume as a function of time

An alternative way of presenting the results is the plot of hydraulic reliability index as a function of time as shown in Fig. 5. This figure can be used more intuitively as one can clearly calculate that 10 % of the total mine inflow will not be pumped out over a six month period for pump station comprising of four pumps. However, for pumping scenarios with five and six pumps, the time for 10% of the inflow water to accumulate underground is more than a year of continuous inflow with no mitigation or additional pumping capacity.

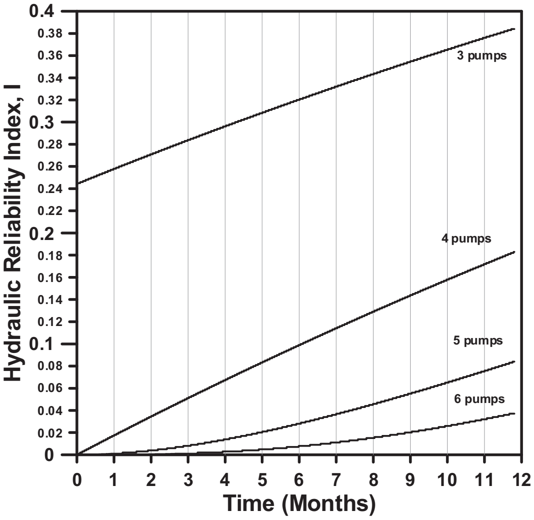


Figure 5 – Change in the value of hydraulic reliability index with prediction time

CONCLUSIONS & RECOMMENDATIONS

The research presented in this paper provides a theoretical framework for a reliability-based design procedure which takes into account the uncertainty in the estimate of the maximum uncontrolled inflow, performance of the system during the period of an uncontrolled inflow. The proposed methodology predicts the amount of inflow water that will not pumped out of the mine taking into consideration the failure of pumps over the time it take to mitigate the inflow. The comparison of predicted inflow water accumulated with the available underground storage clearly quantifies the risk of possible flooding of the MDS. Calculation of the hydraulic reliability index provides a credible scientific approach to help foster sound decision-making for excess capacity of pumping that needs to be provided underground. It should be noted that the idea of effective reserve is only loosely tied with hydraulic reliability index in the mathematical sense. The two can be integrated mathematically to calculate coefficient of operational readiness of the MDS using the approach described by Makhinin [12]

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