Energy Proceedings
Vol 43, 2024
ISSN 2004-2965

A Methodology to Determine the Maximum Allowable Repair Time for Critical Units of Natural Gas Pipeline Systems Using Gas Supply Reliability Theory

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ABSTRACT

As an essential part of the natural gas supply chain, the safe and reliable operation of the natural gas pipeline system is vital to energy supply security. When accidents occur in the natural gas pipeline system, determining the maximum allowable repair time of the failed unit is a crucial factor in balancing maintenance resources against risks of gas shortage. Therefore, this paper proposes a methodology to determine the maximum allowable repair time for critical units of natural gas pipeline systems using gas supply reliability theory, considering system uncertainties as well as the line-pack effect. The methodology is composed of three parts. Firstly, the supply reliability indicators are proposed from the perspective of gas shortage. Secondly, the gas supply reliability evaluation model for the natural gas pipeline system is developed considering system uncertainties and the line-pack effect. Finally, the maximum allowable repair time is determined based on gas supply reliability and target reliability. Furthermore, a real natural gas pipeline system located in China is applied to confirm the feasibility of the methodology. The results demonstrate that the proposed methodology can serve as part of a Reliability Centered on Maintenance (RCM) analysis and provide guidance to support maintenance managers in making data-driven decisions.

Keywords: natural gas pipeline system, supply reliability, Reliability Centered on Maintenance, maximum allowable repair time

NONMENCLATURE

Abbreviations	
SPS	Synergi Pipeline Simulator
RCM	Reliability-Centered Maintenance
Symbols	
R_{system}^{Q}	The gas supply reliability of the natural gas pipeline system from the quantity dimension
R_{system}^{T}	The gas supply reliability of the natural gas pipeline system from the time dimension
$R_{system,j}$	The gas supply reliability of the natural gas pipeline system for the j^{th} simulation
T	The mission time of the natural gas pipeline system
K	The number of consumers;
X_{ik}	The amount of natural gas supplied on the i^{th} day supplied by the natural gas pipeline system to the k^{th} consumer
D_{ik}	The demand of the k^{th} natural gas consumer on the i^{th} day
$T_{\max}^{repair}$	The maximum allowable repair time of units
R_{target}	Target gas supply reliability

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

1. INTRODUCTION

The natural gas pipeline system plays a vital role in ensuring the stability and security of the energy supply, making its safe and reliable operation critically important for energy security [1]. With the rapid development of the natural gas industry, the total mileage of in-service transmission natural gas pipelines in China is now nearly 50,000 kilometers, with more than 600 stations [2, 3]. Furthermore, the interconnectivity capability of the pipelines is becoming increasingly robust, leading to a progressively more complex and dynamic network structure and operating conditions. Natural gas pipelines and compressors, as critical components of natural gas pipeline systems, can significantly impact the gas supply capacity of the system when they fail stochastically [4, 5]. However, the natural gas pipeline system operates as an open system, and significant difficulties are encountered in determining the repair times of units, which arise from uncertainties associated with unit failures, user demand, and resource availability [6, 7].

Determining the maximum allowable repair time for each individual unit becomes a key factor in effectively managing maintenance resources and reducing the potential risk of natural gas shortages. Therefore, determining the repair time for pipelines and compressors has been the focus of engineering applications and academic research. Traditionally in China, the repair time of critical units in natural gas pipeline systems is determined empirically, usually 72 or 96 hours. With the application of hydraulic simulation software such as SPS and TGNET in China, the self-rescue times of systems are analyzed by modeling on the software and applied to maintenance strategies [8]. However, hydraulic simulation software cannot take into account the uncertainties associated with the system.

Furthermore, reliability theory has been employed to establish maintenance strategies for pipelines and compressors. Mulenga constructs a time-dependent failure probability assessment model for corroded pipelines to determine the optimal maintenance strategy for corroded pipelines [9]. Safiyullah developed a compressor degradation model using genetic programming to provide support for compressor maintenance strategy.[10]. Nevertheless, the aforementioned studies did not consider the risks associated with the system and did not take into account hydraulic characteristics.

To solve these problems, this paper proposes a comprehensive methodology for determining the maximum allowable repair time for critical units in natural gas pipeline systems using the gas supply reliability theory of natural gas supply reliability while taking into account system uncertainty and line-packing effects.

2. METHODOLOGY

2.1 Overview

The Maximum Allowable Repair Time for a unit refers to the maximum duration after the occurrence of the unit failure, during which the natural gas pipeline system remains capable of meeting customer demand. The supply capacity of the natural gas pipeline system will be reduced or even interrupted due to unit failures. Due to the hydraulic characteristics of natural gas pipeline systems, the impact of different units on the system's gas supply capacity varies significantly, taking into account flow optimization and line-packing effects. In addition, stochastic failures of other units are important influences on the system's ability to supply gas, which can give rise to the risk of widespread gas shortages.

In order to support the system's maintenance strategy development, this paper proposes a comprehensive methodology for determining the maximum allowable repair time for critical units. This methodology consists of three parts.

Firstly, the gas supply reliability indicators from the time dimension and quantity dimension are proposed. Second, the gas supply reliability evaluation model of the natural gas pipeline system is constructed. The gas supply reliability evaluation model comprises two parts: a system state transition model and a gas supply capacity calculation model. Finally, the maximum allowable repair time for units based on target reliability is determined.

2.2 Establishment of gas supply reliability indicators

The gas supply reliability of the natural gas pipeline system refers to the ability to meet the gas demand of consumers under specified times and conditions. In this study, the indicator for the system is established based on time dimension and quantity dimension.

In accordance with the definition of system reliability, the ratio of the actual amount of natural gas supplied by the natural gas pipeline system to the gas demand of consumers is used to calculate the gas supply reliability indicators. The formula for the gas supply reliability indicator is as follows:

$$R_{system}^{Q}=\frac{\sum_{i=1}^{T}C_i}{T}, C_i=\begin{cases}1, \sum_{k=1}^{K}X_{ik}\geq\sum_{k=1}^{K}D_{ik}\\ \frac{\sum_{k=1}^{K}X_{ik}}{\sum_{k=1}^{K}D_{ik}}, \text{ else}\end{cases} \tag{1}$$

$$R_{system}^{T}=\frac{\sum_{i=1}^{T}C_i}{T}, C_i=\begin{cases}1, \sum_{k=1}^{K}X_{ik}\geq\sum_{k=1}^{K}D_{ik}\\ 0, \text{ else}\end{cases} \tag{2}$$

Moreover, the gas supply reliability indicators for the k^{th} consumer, R_k, can be expressed as the following formula.

$$R_{k}^{Q}=\frac{\sum_{i=1}^{T}C_i}{T}, C_i=\begin{cases}1, X_{ik}\geq D_{ik}\\ \frac{X_{ik}}{D_{ik}}, \text{ else}\end{cases} \tag{3}$$

$$R_{k}^{T}=\frac{\sum_{i=1}^{T}C_i}{T}, C_i=\begin{cases}1, X_{ik}\geq D_{ik}\\ 0, \text{ else}\end{cases} \tag{4}$$

Where the subscript *i* denotes the moment, day; the subscript *k* denotes a particular consumer.

The proposed gas supply reliability indicators reflect the risk of gas supply shortages [11]. In accordance with Equations (1-4), a higher gas supply reliability indicates a smaller risk in gas shortage of the system, and vice versa.

2.3 The development of the gas supply reliability evaluation method

The critical functional units of a natural gas pipeline system include natural gas pipelines and compressors. To assess the gas supply reliability while taking into account the stochastic failures and repair of these units, an evaluation model has been developed. The detailed construction methodology is described in Sections 2.3.1, 2.3.2, and 2.3.3.

2.3.1 Stochastic state transition model of the natural gas pipeline system

The failure rates and repair rates of natural gas pipelines and compressors can be obtained from historical failure databases. The state transition rate matrix for gas resources can be derived from historical gas supply data based on stochastic process theory. On the basis of the state transition rate matrix of gas resources and the failure and repair rate of units, the state transition model of the system is established based on the Sequential Monte Carlo method, and the state stochastic transition of the system is simulated. More details of the model can be found in our published article [11].

Based on the results of the simulation, the operational state of the system throughout the mission duration, along with the moments of state changes and the respective durations for each state, are determined.

2.3.2 The calculation of the gas supply of the natural gas pipeline system

The gas supply capacity of the natural gas pipeline system is contingent upon the hydraulic characteristics and the operational state of the system. The latter is ascertained utilizing the system state transition method delineated in Section 2.3.1. Subsequently, an optimization model is devised to compute the quantity of gas supplied by the natural gas pipeline system, accounting for the diverse operational scenarios.

Within the optimization model, the primary aim of the objective function is to maximize the daily distribution of natural gas to each consumer by the system during the mission time. The inlet and outlet throughput and pressures are the decision variables of the model. The model's constraints encompass flow, pressure, and hydraulic constraints, which can refer to our previous study [11]. Using the GUROBI solver, the optimization problem can be solved, and the gas supply to each consumer node of the system can be determined.

2.3.3 The calculation of the gas supply reliability of the system

Considering the uncertainties of the system, the expected value of the gas supply reliability indicators is evaluated based on *N* (*N* is a large number) times of Monte Carlo simulation.

The gas supply reliability of the system for each Monte Carlo simulation is calculated according to Eqs. (1-4), and the expected value for gas supply reliability is calculated as follows:

$$R_{system}=\frac{\sum_{j=1}^{N}R_{system,j}}{N} \tag{5}$$

Where *N* represents the total number of Monte Carlo sampling.

2.4 Determination of maximum allowable repair time for critical units

Gas supply reliability indicators are calculated for each moment after the time of failure of a unit, using the proposed gas supply reliability evaluation method. Evaluation periods and time intervals can be determined as needed for practical applications.

In addition, the value of the target reliability is critical to the determination of the maximum allowable repair time. The formula for calculating the target gas supply reliability is as follows:

$$R^{Q}_{system,target} = \frac{\sum_{i=1}^{T} C_i}{T}, C_i = \begin{cases} 1, \sum_{k=1}^{K} \mathrm{E}(D_{ik}) \geq \sum_{k=1}^{K} D_{ik} \\ \dfrac{\sum_{k=1}^{K} \mathrm{E}(D_{ik})}{\sum_{k=1}^{K} D_{ik}}, \text{ else} \end{cases} \tag{6}$$

Where $\mathrm{E}(D_{ik})$ represents the expected minimum gas demand of the k^{th} natural gas consumer on the i^{th} day. Expect minimum gas demand can be obtained through energy policy and user contracts.

The maximum allowable repair time for one unit can be defined as follows:

$$T^{repair}_{\max} = \max_{0 \leq i \leq n}(t_i) \ \left(\forall R(t_i) \geq R_{target}\right) \tag{7}$$

Depending on Equation (1-4), it is possible to ascertain the maximum allowable repair times from both the system perspective and the consumer perspective.

3. MATERIAL AND METHODSCASE STUDY

3.1 Description of the Case-Study Natural Gas Pipeline System

In this section, the maximum allowable repair time for a specific unit of the SJD pipeline system is determined to confirm the feasibility of the developed methodology. The schematic representation of the test natural gas pipeline system is presented in Fig. 1, featuring 6 compressor stations, 46 block valve stations, and 3 terminal or offtake stations. Within the SJD pipeline system, there are nine consumer nodes, numbered from U01 to U09, with corresponding information provided in Table 1. The properties of pipelines and gas sources are shown in Tables 2-3. The configuration of compressor stations is shown in Table 4. The SJD pipeline system encompasses a total of 54 segments of natural gas pipelines, and you can find detailed pipeline properties in Table 5. In addition, The failure and repair rates of pipelines, compressors, and sources are shown in Table 6 [12].

Table 1 The information of user nodes

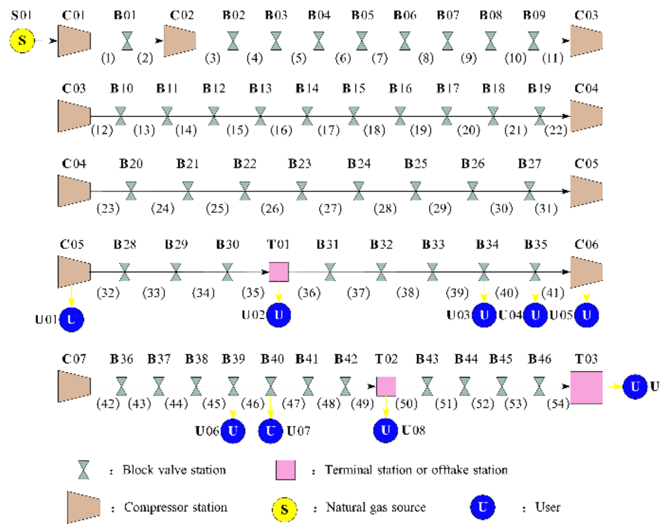

Fig. 1. The schematic of the SJD pipeline system

User node	Location (km)	Q_{demand} (10^4*Nm^3/h)	P_{min} (MPa)
U01	665	115.2	4
U02	734	213.6	4
U03	819	26.4	4
U04	839	28.8	4
U05	847	144	4
U06	914	120	4
U07	928	28.8	4
U08	975	273.6	4
U09	1063	3830.4	4
System	-	4780.8	-

Table 2 Properties of pipelines

Parameters	Value
Diameter(mm)	1219
Thickness(mm)	22
Design pressure(MPa)	12
Maximum amount of line-pack of the pipeline(10^4Nm^3/km)	5.8
Minimum amount of line-pack of the pipeline(10^4Nm^3/km)	17.5

Table 3 Properties of gas sources.

Gas source node	Type	Capacity (10^4Nm^3/h)
S01	Natural gas field	4780.8

Table 4 Configuration of compressor stations.

Compressor station node	Location (km)	Configuration
C01	0	1+1
C02	33	3+1
C03	261	3+1
C04	474	3+1
C05	665	3+1
C06	847	2+1

"1+1": the former indicates that there is 1 operating compressor and the latter indicates that there is a standby compressor in the station. "3+1": the former indicates that there is 3 operating compressor and the latter indicates that there is a standby compressor in the station. "2+1": the former indicates that there is 2 operating compressor and the latter indicates that there is a standby compressor in the station.

Table 5 Length of pipelines.

Pipe	Length (km)	Pipe	Length (km)	Pipe	Length (km)
1	16.40	19	25.83	37	27.99
2	16.90	20	23.92	38	22.79
3	23.91	21	7.70	39	22.04
4	19.75	22	21.88	40	20.24
5	26.35	23	19.77	41	7.49
6	27.84	24	23.71	42	16.01
7	31.28	25	25.70	43	21.19
8	26.57	26	17.42	44	11.82
9	29.86	27	19.44	45	17.92
10	16.24	28	35.04	46	14.26
11	26.59	29	14.35	47	10.67
12	20.04	30	11.21	48	22.01
13	22.30	31	24.65	49	14.24
14	16.21	32	27.64	50	20.96
15	19.25	33	14.23	51	22.22
16	24.08	34	14.14	52	21.98
17	11.75	35	12.60	53	16.40
18	19.74	36	12.60	54	6.73

Table 6 The failure and repair rate of pipelines, compressors, and sources.

Component	Failure rate (1/h)	Repair rate (1/h)
Compressor unit	7.7×10^{-4}	0.0250
Pipeline segment	1.46×10^{-8}/km	0.0139
Natural gas field	1.39×10^{-6}	5.952×10^{-3}

3.2 Determination of maximum allowable repair time for critical units of the Case System.

According to Section 3.1, a model for evaluating the gas supply reliability of the SJD system is established. The Monte Carlo simulation times are 10,000.

This study analyzes the pipeline and compressor unit with a mission time is 240 hours. It is assumed that the system is normal at moment 0h and the unit fails at moment 1h. Pipeline segments 4, 41, 50 and a compressor in the C04 compressor station are analyzed. The gas supply reliability curves for each unit are shown in Figs. 2-5.

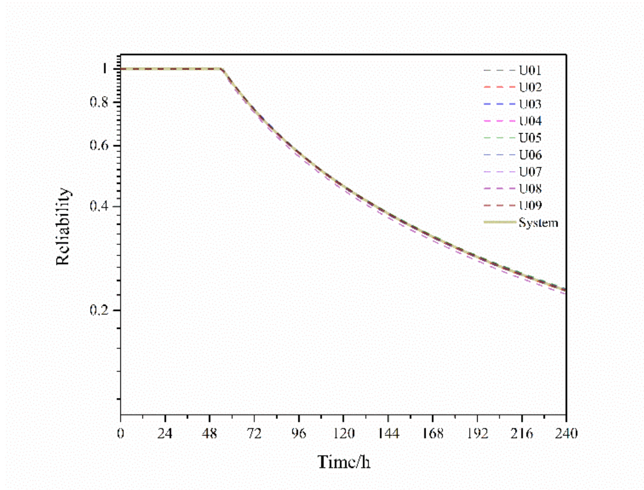

Fig. 2. The gas supply reliability curve after the failure of pipeline segment 4

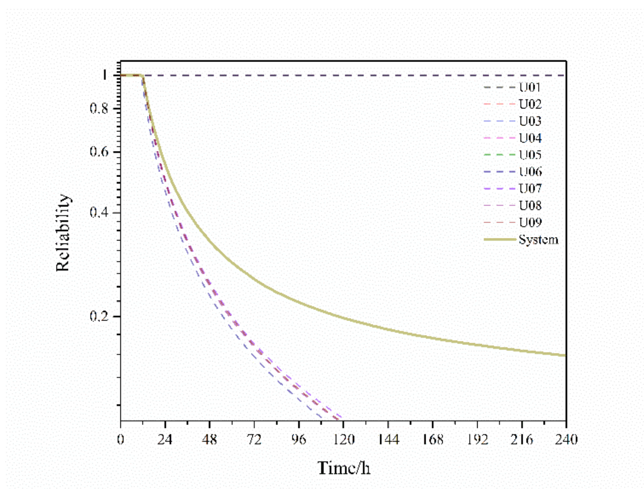

Fig. 3. The gas supply reliability curve after the failure of pipeline segment 41

Based on the historical supply data of the system, the historical average gas supply reliability is obtained as 97.7%, and the target reliability is assumed to be equal to the historical average gas supply reliability in this paper. According to Figs. 2-4, the maximum allowable repair times for pipeline segments 4, 41, and 50 are 56h, 13h, and 4h, respectively. It can be analyzed that as the failed pipeline segment gets closer to the gas source, the maximum allowable repair time is instead longer, due to

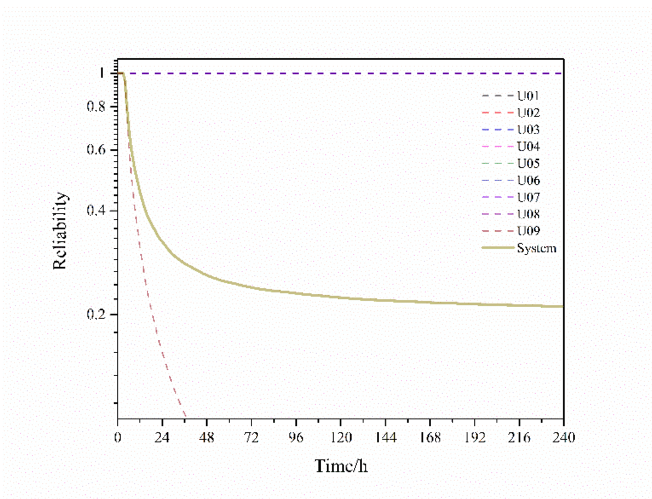

Fig. 4. The gas supply reliability curve after the failure of pipeline segment 50

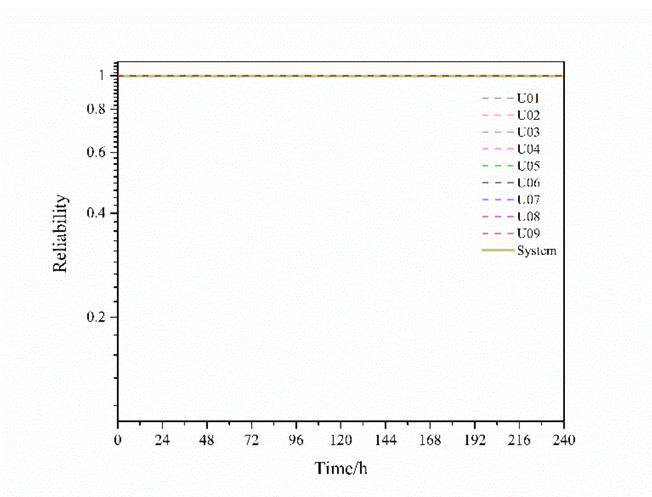

Fig. 5. The gas supply reliability curve after the failure of compressor in station C04

the increase in pipeline line-pack. According to Fig. 5, the failure of one compressor does not have an impact on the gas supply reliability, due to the availability of backup compressors at several stations of the system.

4. CONCLUSIONS

In this paper, a methodology to determine the maximum allowable repair time for critical units of natural gas pipeline systems. The methodology is composed of three parts, namely the establishment of gas supply reliability indicators, the development of the gas supply reliability evaluation method, and the determination of maximum allowable repair time for critical units. Moreover, the methodology's practicality was confirmed through an application to a real gas pipeline system in China. The results illustrate that the suggested methodology can function as a component of the RCM analysis, offering valuable insights to assist maintenance managers in formulating data-informed decisions. This research contributes to enhancing the reliability and security of natural gas supply systems.

ACKNOWLEDGEMENT

This work is supported by the Basic Public Welfare Research Program of Zhejiang Province [LQ23E040004]; Science Foundation of China University of Petroleum, Beijing [Grand number: 2462020YXZZ045]; Science Foundation of China University of Petroleum, Beijing, [No.2462023YQTD001], all of which are gratefully acknowledged.

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