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Leak Detection in Water Pipeline by Means of Pressure Measurements for WSN

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***Abstract*—During the last decade, many types of research have put prominence on the potential feasibility and sustainable management of water pipeline leakage. Unlike the traditional methods, using wireless sensors networks is greatly helpful in terms of high performance, low cost and simple exploitation. However, many researchers have concentrated their efforts on solutions based on WSNs for pipeline monitoring in relation to sensing techniques, mathematical formulation, reading acquisition techniques, and information processing methods. This study investigates various leakage detection formulations based on WSN in order to identify, locate and estimate the leak size. In addition, a computerized techniques based on the analysis of pressure measurement in water distribution system is presented to find the defective pipe.**

Keywords*—Pipeline monitoring ; Leak detection ; Localization; Wireless sensor networks

I. Introduction

Currently, millions of kilometers of pipelines are used extensively to transport vast volumes of fluid and gas in industrial as well as residential areas, all over the world. The involuntary release of oil or water from pipelines is considered as a leak. Pipeline leaks may occur due to a multiplicity of reasons including damage and manufacturing flaws, bad workmanship or pipe erosion, sudden changes of pressure, cracking, internal and external corrosion, and defects in pipes or lack of maintenance. According to statistical study, the pipelines experience at least one leak every year [1]. Indeed, fluid-transporting pipelines have been an important subject through the last few years as any breakdown to pipeline could influence the quantity and quality of water. In fact, there are up to 60 % of water waste in the world each year due to leaky pipelines [2]. On the national ground, some cities across the Kingdom of Saudi Arabia such as Riyadh, Jeddah and Medina require to desalinate more than 90 % of their water needs [3]. Researchers have declared that 30 % of the water imparted across the Kingdom of Saudi Arabia (KSA) is waste through leakage [4]. The desalination cost losses are estimated to the amount of 820 million USD per year. This amount does not comprise transportation, distribution and other losses. In most cases, the decrease of leak can also guide to an economic gain associated to purchasing and producing water as well as increasing energy conservation which is essential to treat and pump water for distribution. Therefore, to ensure the continued secure process of the pipelines in real-time, leaks should be rapidly identified, localized and repaired. However, the existing patrolling system of pipeline monitoring is difficult and reacts to leaks on classic methods, responding to apparent leaks and bursts by repairing infrastructure as necessary. Consequently, there is a need for more coherent techniques for administrating pipelines leakage. Furthermore, Wireless Sensor networks (WSN) can be extremely useful in giving a widespread, economic and successful key [5]. Numerous factors could menace the pipeline infrastructure, decrease the water quality and cause some other damages. Some factors are related to human intervention and lack of protection. Some others are related to the pipeline itself such as size and material. Many methods have been investigated to check the damages in the pipeline and to detect and locate a leak. In this paper, we would focus particularly on methods applied in WSNs. Some of these techniques are described in this work. Then, the rest of this paper is planned as follows:

- Section 2 explores the existing pipeline leakage detection approaches,
- Section 3 talks about the potential ways for pipeline monitoring and leak localization applications used in the context of WSNs,
- Then, in Section 4 the leak test bench is described and simulated results are analyzed,
- Finally, the work is concluded in Section 5.

II. Related Work

A. Monitoring Techniques Based on Sensors Outside Pipelines

These kinds of sensors determine many factors such as temperature, humidity, and properties of the soil in the surface of underground pipelines. These motes are entombed underground along the pipelines hence, can provide high granularity for leakage detection and localization. Current outside leakage identification sensors are detailed as follows:

1) Visual Inspection: These classical supervising methods for above ground pipelines used both image and video motes to detect any leakage or another outliers type along the pipelines [6]. However, this technique is unsuitable to supervise underground pipelines.

2) Ground Penetrating Radar (GPR): The ground penetrating radar (GPR) is useful to detect the leakage of underground pipelines [7]. This technique is capable to cover some miles pipeline per day. However, it requires severe human participation and a leakage may not be identified in real-time.

3) Soil Properties Sensors: The leaky pipe can be identified through the detection of outlier value of the transported fluid properties. Thus, the choice of motes types is correlated with the transported fluid such as temperature sensors, soil humidity, and hydrocarbon vapor sensors. The supervising application based on soil property sensors supply accurate and real-time leakage identification and localization. However, it is extremely costly to deploy a wire-based system for underground pipeline supervising. Furthermore, the system is not strong since the communication is interrupted if at any point the wire is broken.

B. Monitoring Techniques Based on Sensors Inside Pipelines

These kinds of sensors determine many factors such as pressure, velocity as well as the acoustic vibrations caused by the leakages in the water flow. In underground pipelines, the increase of leakage is caused by the high densities of junctions. Consequently, the sensors can be only deployed inside the pipeline at the checkpoints or the pump stations. Current inside leakage identification sensors are detailed as follows:

1) Acoustic Devices: A small leakage when the fluid escapes from the pipeline can produce high-frequency oscillations in the pipeline. Therefore, a high density of acoustic sensors is usually installed to cover the entire pipeline network. However, this solution is not suitable for underground pipelines which the exploitation and maintenance are difficult. In addition, large leaks do not generate vibrations; here the acoustic sensors are unavailing [8].

2) Negative Pressure Wave: This technique has been extensively used for identifying leaks in lengthy space with stationary operation mode [9]. Moreover, this method establishes that many factors influence the detectable leakage flow rate computation such as speed of the wave and instrument noise as well as outlet and inlet pressure.

3) Mass Balance Methods: A leak can be detected by auditing the network in order to force equality between water placed into the distribution system and water taken out [10]. In addition, mass balance can identified small leaks which do not provide a high rate of modification in flow pressure. Moreover, the cost of this method is very low. However, the identification of detection rate is low. Thus, this technique is enabling to localize the position of the leakage.

4) Transient-based methods: Another category is the transient-based methods that have been extremely presented. These methods determined the measurement of transient signals to identify leaks. Colombo et al. [8] present a summary of transient-based leak detection techniques and divided them into three groups: inverse-transient analysis, frequency-domain techniques and direct transient analysis. Most of them are unsuitable to be implemented on complex water distribution systems and cannot supply enough leakage identification information and localization accuracy.

III. FRAMEWORK FOR WATER PIPELINE MONITORING USING WIRELESS SENSOR NETWORK

The earlier networking technology used in leak detection suffered from inadequate real-time communication between the sensors. Therefore, the system had a slow response, high false alarms, and it is difficult to detect multiple leaks. Furthermore, in the case of a wired network, it may not be easy to access the whole pipeline area, and also if any damage happens, it becomes shard to fix the wired network. Wired networks present several others limits such as cost, installation and repair. In fact, maintaining or repairing underground wire break is a painful, time-consuming and costly mission. To overcome the challenge of continuously monitoring water system performance to detect any failure or security breach, WSN seems a accurate and efficient technique. Unlike the traditional methods, using wireless sensors networks is extremely advantageous in terms of high performance, low cost and easy infrastructure. Hence, many researchers have put emphasis on the potential and achievability of WSNs for pipeline supervising in terms of sensing techniques, mathematical formulation, data acquisition methods, and data processing algorithms. Furthermore, each kind of sensor can capture only one transient effect that is created in the system. Then, there has been a rising trend of deploying a network of heterogeneous wireless sensors to supervise pipelines and detect any leakage with a diversity architecture node. This technology can offer an excellent level of safety assurance, operational efficiency, and real-time leak detection and localization. Various experimental WSN projects using field tests for leak detection have been investigated.

PipeTECT architecture has been presented in [11]. This network is modeled with sensing nodes equipped with up to three MEMS accelerometers attached by 40 PVC pipes of 1-inch diameter in the company of seven valves in order to check the consequence of several ruptures. In addition, four pressure gauges are installed to supervise the stable level of flow. The system calculates the acceleration change on the pipe surface with alliance of a digital filter to identify rupture events and to locate the various rupture points. Three techniques are tested including the contour maps, time-correlated acceleration data analysis, and frequency domain analysis.

MISE-PIPE system has been introduced in [12]. This project uses a metal pipeline and offers low-cost and real-time solution to detect and localize leak in underground pipelines. Authors have proposed clustered architecture of heterogeneous sensors. However, inside sensors determine pressure, velocity and flow measurement of fluid, as well as others parameters such as acoustic vibrations caused by the leaks. In addition, outside sensors are used to determine temperature, humidity value, and properties of the soil around all pipe. Then data are transmitted using the magnetic induction (MI) to the cluster heads which collect all the measurements and drive the collected observation to a distant data center.

WaterWise has been developed in Singapore since 2009 [13] and some authors aim to improved the network monitoring system like [14] [15]. This platform controls and analyses data collected from network by supervising hydraulic, acoustic and water quality factors. Authors use a mixture of model based prediction (water demand and hydraulic state) and data stream analyses to detect events such as pipe leak in online manner. The efficiency of this system in tiers of burst repair and pump optimization is demonstrated by [14].

Rashid et al. [16] propose a novel distributed technique. Authors aim to archive a trade-off between event (leakage/burst) detection accuracy and energy efficiency. This work presents a wavelet transform based technique coupled with transient pressure wave to achieve reliable detection and localization of bursts and leakages in liquid pipeline distribution systems. The wavelet transform is used for feature extraction and adjustment of noisy signals. The proposed algorithm has many advantages such as outstanding performance in terms of distance range, detection time and accuracy.

Some projects tend to combine and/or improve various methods in order to benefit from the advantages of each one such as SmartPipe [17]. This work describes the design and the development of a smart wireless sensor network for leak detection in underground water pipelines. The proposed method mixed the measurement of relative indirect pressure changes and soil property technique. In addition, authors investigate a novel pressure sensing method. As a result, the accuracy performance and capabilities of the system are improved by both laboratory and field trials.

In [18], a new water pipeline leak detection technique is presented. This work is based on time-correlated acceleration data sensed by means of a Micro-Electro-Mechanical Systems (MEMS) based wireless sensor network (WSN) from diverse joints of a water distribution application. MEMS accelerometers are incorporated for determining the change in water pressure caused by rupture and localized the damage. The discussed technique is the most economical alternative. This system uses MEMS sensors, which is the less expensive, or other acceleration sensors. To improve the accuracy of identifying damage location in wide area water distribution applications, much amelioration are needed.

WaterBox[19] is a well-kown small-scale testbed for emerging, monitoring and controlling algorithms in a fail-safe area for water distribution systems. This project has a supple hydraulic hardware and software infrastructure that enables an anomaly scenarios representation including leaks and bursts. To provide further development enhancements, Kartakis et al. [19] tried to improve this project in-mote data processing and decision making, energy optimization, event-driven communication, and automatic control.

WML is described in [20]. This work described the steps of designing, developing and testing of a smart wireless sensor network (WSN). This application is introduced to detect leakage pipeline and estimate its size in long range pipelines. This system investigate wireless communication and machine learning approaches to learn, make decisions and identify the critical events like slow /small leakages in pipeline autonomously. Some machine learning is used in this work such as K-nearest neighbor (KNN), support vector machine (SVM) as well as Naive Bayes and Gaussian mixture model (GMM). These techniques mentioned above are performed to classify events based on raw data gathered by individual sensor node in the network. The combination of machine learning and wireless sensor network provides a reliable, autonomous and robust monitoring.

EARNPIPE, presented by Fatma et al. [21], is a hybrid technique in which a laboratory testbed has been constructed using plumbing components. This project allows the detection and localization of leaks with an efficient wireless sensor node System on Chip (SoC) architecture. The authors based their method on pressure measurements and used Predictive Kalman Filter (LPKF) and Modified Time Difference of Arrival (TDOA). This prototype reaches a high accuracy and optimizes the power consumption of the node and the network. Almazyad et al. [22] propose a novel approach called Velocity Integration Method (VIM) for classifying the leakage. The authors integrate velocity by using Trapezoidal Area Method to calculate the leakage location. This work is simple to employ with lower cost and with high accuracy compared to other techniques currently existing. However, the network structure needs to be improved.

IV. SIMULATION TOOLS AND RESULTS

EPANET was developed by the Water Supply and Water Resources Division of the U.S. Environmental Protection Agency?s National Risk Management Research Laboratory. This computerized simulation software is used to analyze the hydraulics and quality performance of water distribution systems. In terms of data collection techniques, there are several parameters that are required to be determined to ensure running system. By using EPANET and its Programmer's Toolkit in MATLAB, it is easy to trail various parameters of water in each pipe like flow, velocity and headless. Then, users are able to save data pressure at each node for the duration of a multi-time phase simulation and prevent error. We have presented a test section with EPANET in order to approximate the consequence of a leak in a water pipeline. This scheme consists of a U-shaped fragment made of 35 mm PVC pipe with a virtual leak. Water was distributed through the network by a common water pump that supplies up to 3 bars of pressure. Likewise, a valve with a variant diameter was implemented in the pipe in order to simulate leak. Our system, as shown in Fig 1, is composed of six nodes attached to the PVC pipe sections at 100 m intervals. Sensors A, B and C were positioned before the leak and Sensors D, E and F were positioned after the valve. We have used various sizes of

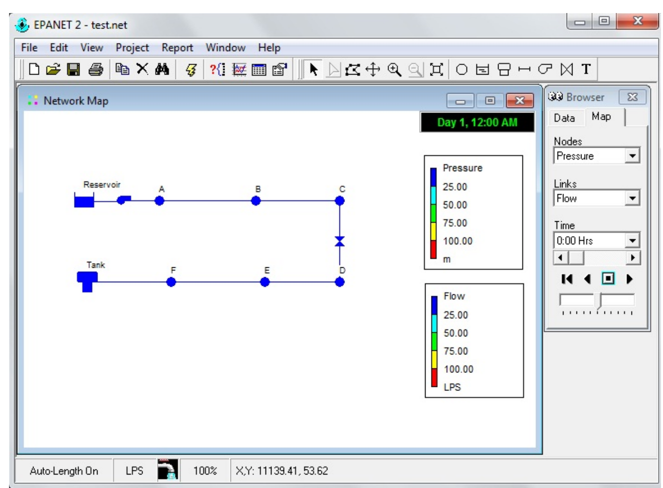

Fig. 1: EPANET simulation

valves in pipe 3 to create false leaks. We presented the signal recorded to four different valves diameters 10, 20 , 25 and 30 millimeters measured in 24h during the simulated rupture case. The detection of large leaks is comparatively easy then small leak. However, the deflection in the pressure curve becomes less important when the leakage size decreases as shown in Fig 2, 3, 4 and 5.

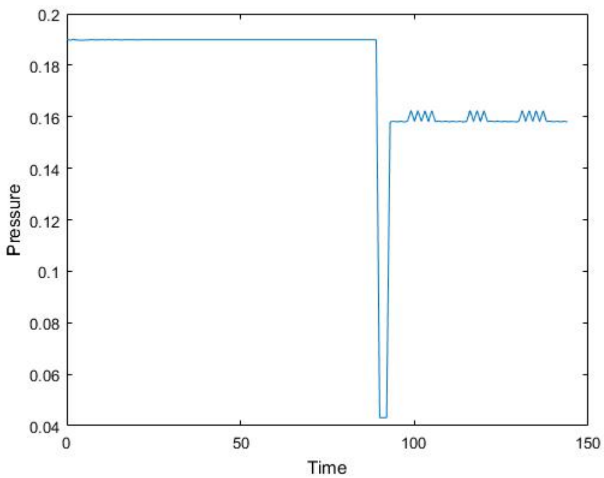

Fig. 2: Traces of pressure for 10 mm of leak

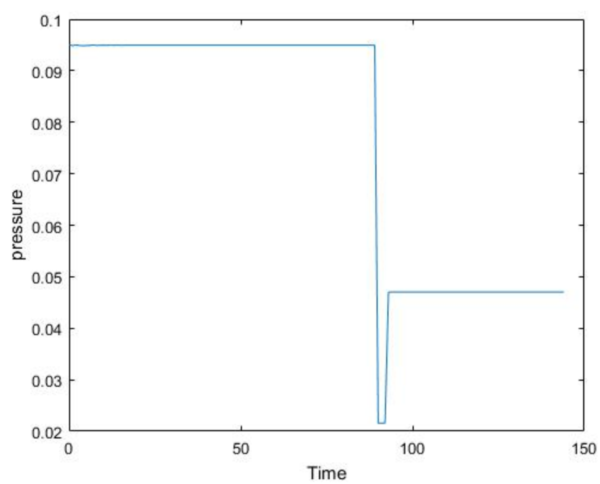

Fig. 3: Traces of pressure for 20 mm of leak

The detection of leak depends on pipe geometry and materiel used (PVC, IRON, plastic, copper), controls parameters and the nature of transported fluid. According to these tests, it can be obviously shown that simulated leak can be identified from the sensors flow output as a sudden flow down in the system as shown in Fig 6. The most important phases of the experiment consist of the pressure before the pump was switched on, the augment in pressure after the pump was switched on, the variation in pressure to the development of the leak and lastly the decrease in pressure due to the switching off of the pump, are presented in Fig 7. Although, based on Fig 7 it is hard to identify the accurate position of the leak that all nodes in the network emerge to respond in the same time to the leak. To determinate the exacted pipe leaked, we presented in Fig 8 a close viewer of the pressure deviation caused by the leak. It can be consider from this figure that the

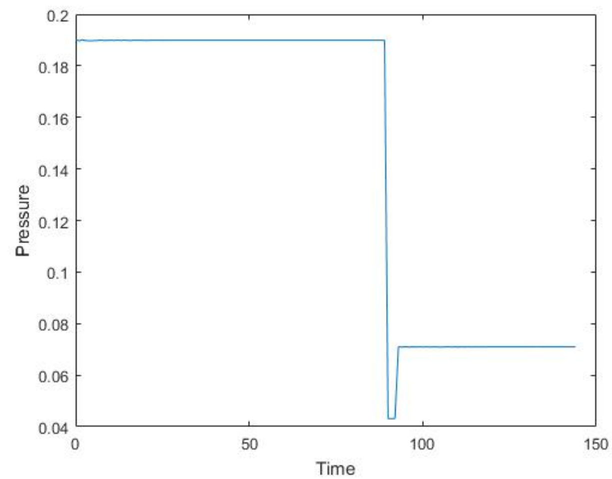

Fig. 4: Traces of pressure for 25 mm of leak

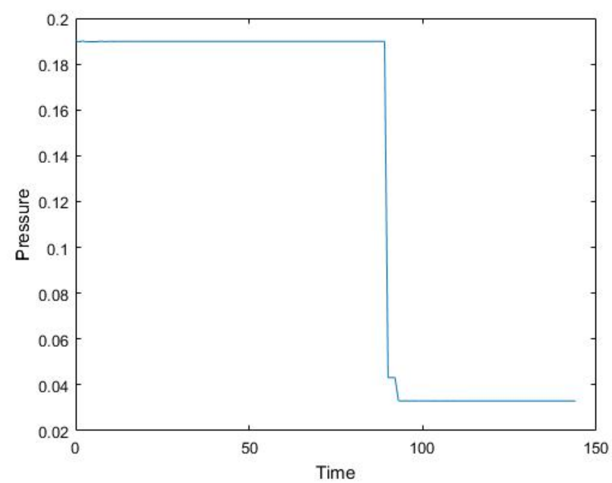

Fig. 5: Traces of pressure for 35 mm of leak

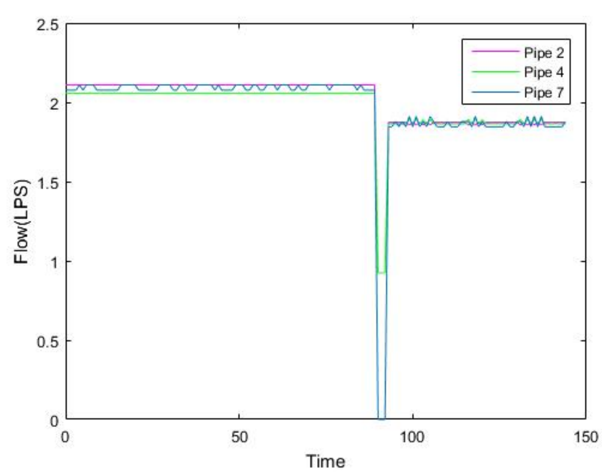

Fig. 6: Flow profile of the network

pressure profiles of Sensors A, B and C, which are upstream to the leak point, are different to the ones downstream of the leak. The profile for theses sensors exhibits a gradual pressure rise shape than the ones after the leak which presented a drop shape. This differentiation can be investigated to find out the approximate location of the leak. Then, it can be clearly seen that is somewhere between Sensors C and D in this case. In addition, we are using EPANET software to

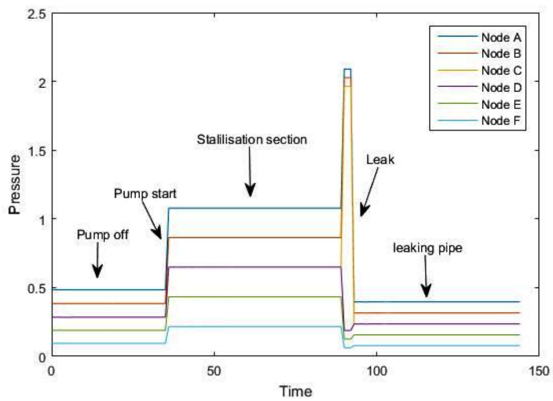

Fig. 7: Pressure profile for all sensors network

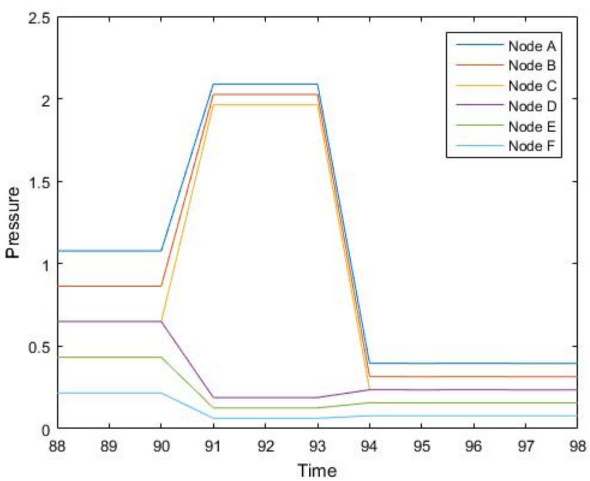

Fig. 8: Raw sensor output measured of the leak

obtain a set of training data that can be helpful to find a good classification result with high accuracy (network with leak or without leak). By means of MATLAB software, we used the EPANET model and construct modifications for the leak dimension and position, 32 leaks sizes with 1000 leaks locations consequently we obtain about 3200 scenarios, we exploit 2400 scenarios for training and another 800 scenarios for testing. The collected data about pressure are collected from the six sensors. In the current paper, the effective data were trained and tested using three different classifiers: Naive Bayesian Network, Decision Tree and Kth Nearest Neighbors.

To calculate the precision of different techniques, we examine the detection rate and the false positive rate for all data points of the experiment database. The higher TPR and the lower FPR value, the more accurate classification results. The TPR and FPR value can be measured by the formula as follows:

$$TPR = \frac{TP}{TP + FN}$$

$$FPR = \frac{FP}{FP + TN}$$

where:

TP:	Number of true positive
FN:	Number of false negative
FP:	Number of false positive
TN:	Number of true negative

The comparison of the classifiers has been described in table below.

TABLE I: Experimental results for various classifiers

Methods	**DR**	**FDR**
K^{th} Nearest Neighbors	82.45%	17.55%
Naive Bayesian Network	66.31%	33.49%
Decision tree	48.9%	51.10 %

In our binary classification problem (network with leak or without-leak), Kth Nearest Neighbors outperforms Naive Bayesian Network and Decision tree. The average detection accuracy in detection leakages is 82.45% for KNN, 66.31 % for Nave bays network and 48.90% for Decision tree. The results of classification for these various techniques are still small. This is due to the insensitivity from EPANET software in data processing. In our future studies, we will try to use a real data to obtain high accuracy.

V. Conclusion

Pipelines are one of the most widely used means for water transportation worldwide. These pipelines are often subject to failures. Therefore, detecting leakages and locations is very important. This paper aims to evaluate the performance of a network in the case of leak water pipeline. We use EPANET software to simulate the leak test bench by processing the pressure measurement obtained at each node (junctions) with different leak sizes in the water distribution networks. The simulated data showed that the measurements of the pressure have different behavior before and after the leak. Furthermore, this hypothesis is investigated for determining the leaked pipe. To enhance the accuracy of identifying damage and localize it in a larger-scale network, we need to used a preferment algorithms .Further study is needed to correctly differentiate between leak and other events happened in the pipeline. As a future work, we plan to investigate more technique based classification to classify data and detect event in water pipeline by means of small datasets or a combination of these classifiers.

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