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Development of an end state vision to implement digital monitoring in nuclear plants

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ABSTRACT

Cloud-based services affords many new opportunities for transitioning to an off-site centralized maintenance and diagnostics (M&D) center by added additional computing power and storage, but this also produces new challenges in terms of networking and security. This report covers everything required for enabling such a transition, including data processing and uploading to cloud services, feature selection, model creation, and result visualization for decision making. Despite the various cloud-based services (e.g., Amazon Web Services and Google Cloud) available, this report specifically centers around Microsoft Azure so as to simplify the nomenclature and maintain a consistent focus. Many of the features offered by Microsoft Azure are also available from other cloud-based services, and comparisons have been made in other related literature. In this report, those Azure services most relevant to nuclear power plants (NPPs) (i.e., those pertaining to networking and security, storage and databases, and artificial intelligence [AI]) are reviewed. Networking covers all communications-related aspects of Azure resources, including security, privacy, and redundancy measures. Storage and databases includes data storage, upgrading, patching, backups, and monitoring. AI services enable users to access the machine learning (ML) techniques developed in Azure, including automated ML, anomaly detection, computer vision, and natural language processing (NLP). This report summaries, in a user-friendly manner, the features, capabilities, and challenges of cloud-based services.

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CONTENTS

FIGURES

TABLES

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ACRONYMS

DevOps	development and IT operations
DNS	domain name system
HTTP	hypertext transfer protocol
IP	internet protocol
M&D	monitoring and diagnostics
ML	machine learning
NPP	nuclear power plant
NLP	natural language processing
O&M	operations and maintenance
SHAP	Shapley Additive Explanations
SQL	structured query language
VIF	variance inflation factors
VPN	virtual private networks

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1. INTRODUCTION

Despite the nuclear industry's excellent safety records, it is experiencing premature closures of nuclear power plants (NPPs) for economic reasons [1]. Such reasons include the exorbitant operations and maintenance (O&M) costs associated with legacy light-water reactors [2]. By reducing O&M costs, nuclear energy can become more economically competitive with other energy sources, and premature closures can be avoided. From a maintenance standpoint, this can be achieved by leveraging machine learning (ML) and artificial intelligence (AI) technologies to develop data-driven algorithms to better diagnose potential faults within the system [3]. Improved model accuracy can lead to reductions in unnecessary maintenance, thus lowering the costs associated with parts, labor, and unnecessary planned, forced, or extended outages. From an operations perspective, cost savings can be generated by shifting from onsite- to cloud-based computing and storage services. Cloud computing services would generate cost savings by reducing the amount of hardware needing to be purchased and maintained—all while scaling to both computational and storage demands.

1.1 Scope of this Report

The overall goal of this report is to provide an end-to-end summary of how NPPs can acquire, analyze, store, and visualize data to in a manner that reduces O&M-related costs. This report is the last in a series of documents covering online monitoring, wireless communication networks, diagnostic and prognostic modeling, and data visualization [4]–[10]. Previous documents in this series evaluated potential wireless technologies and communication networks for use in NPPs, based on their performance and economics [5-7]; assessed vibration sensors with wireless capabilities [7]; developed formal methodologies for cleaning data and objectively comparing ML prognostic models [8]; performed fault diagnostics and preventative maintenance optimization [9], and reviewed various data visualization techniques [10].

This report highlights the major contributions of the previous documents, while expanding on how these technologies can be implemented using cloud computing services. It reviews the basics of cloud computing before delving deeper into the three topics that are of particular interest to the nuclear industry: networking and security, storage and databases, and AI.

1.2 Organization of this Report

Section 2 investigates the use of cloud computing services. Section 3 summarizes how feature selection can aid in choosing the best possible variables when conducting diagnostics and short-term forecasting. Section 4 details how data visualization is utilized to support decision making at NPPs. Section 5 discusses the economic benefits of implementing cloud services for a centralized M&D center. Section 6 summarizes the report and details both ongoing and future work.

2. CLOUD COMPUTING SERVICES

Cloud computing refers to on-demand delivery of services over the internet. Cloud computing services offer flexible resources in terms of computing power, servers, software, and AI. Cloud computing is available from several providers, including Microsoft, Google, and Amazon. It has gained in popularity as a way to save money, reduce physical IT footprints, and enhance operations [11]. Some customers have reported a 30–50% reduction in IT-related costs by switching to cloud-based services, thanks to cutbacks in IT infrastructure and workloads [11]. The fact that these clouds are comprised of web-connected servers means that their storage capabilities, computing power, and services are accessible anywhere with internet connectivity. Once a cloud provider has been selected, various frameworks, tools, and infrastructures are available on a quickly scalable, pay-for-what-you-use fashion in the form of infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS).

2.1 Other Cloud Computing Services

Although this report primarily focuses on Microsoft Azure as a potential cloud computing solution, several other viable options exist, including Google Cloud and Amazon Web Services. Each cloud computing provider offers similar services in terms of IaaS, PaaS, SaaS, integrated development environment support, databases, virtual machine types, operating systems, and pricing types. And since a comparison of Microsoft Azure, Google Cloud, and Amazon Web Services can be found in other papers [12]–[14], this report focuses on Microsoft Azure, thereby enabling consistent nomenclature in explaining the intricacies of cloud computing. A monitoring and diagnostics (M&D) center or utility should conduct a proper comparison of the available cloud computing providers prior to selecting the preferred option.

2.2 Microsoft Azure

Microsoft Azure first became generally available in 2010, and has since expanded into 52 regions, ranging from the U.S. to China to South Africa [13]. Utilization of Microsoft Azure's computing resources is accomplished via a virtual machine hosted on Microsoft's servers. Azure offers several virtual machine types, including general purpose, compute optimized, memory optimized, storage optimized, and high-performance computing [13]. Virtualization of hardware is accomplished via a hypervisor, which is similar to an emulator. Users provide details on the amount of computing power and storage they need, and the cloud adjusts to provide the requested amount. This engenders inherent flexibility, as the services can scale to needs; there is also a virtually limitless amount of storage and computing resources, as these resources can be pooled as necessary. Microsoft Azure's services can fundamentally be divided into nine categories: compute, networking and security, storage and databases, mobile, web, Internet of Things, big data, AI, and software development and IT operations (DevOps). These are summarized in Table 1.

Table 1. Summary of Microsoft Azure services.

Service Name	Description
Compute	The computation capabilities provided include general purpose, compute optimized, memory optimized, storage optimized, and high-performance computing.
Networking & Security	Involves the manner in which computational access/capabilities are linked and secured, both internally and in regard to the outside world."
Storage & Databases	How files, queues, and tables are stored in a manner that supports high availability, redundancy, security, scalability, maintainability, and accessibility.
Mobile	The ability to create iOS, Android, and Windows apps for connecting to Azure features.
Web	Building and hosting web-based apps and hypertext transfer protocol (HTTP)-based web services.
Internet of Things	Allows any device with internet capability to connect to and access information.
Big Data	Managing and processing very large amounts of data in every format. Uses open-source clustering techniques to manage these larger datasets, but can support a broad range of technologies.
AI	ML for forecasting, vision, speech, knowledge mapping, and natural language processing (NLP).

DevOps	Resources that aid in the development pipeline that extends from the building of an application to its release.

These services could all play a role in the implementation of maintenance algorithms at M&D centers or utilities. However, it is the three services that seem of greatest interest to the nuclear field that are explored further: networking and security, storage and databases, and AI.

2.2.1 Networking and Security

Networking covers components and services that enable communication between the on-premises computers and the virtual machines hosted in Azure. Once connected, Azure has multiple ways of interfacing with web applications, databases, virtual machines, etc., over the internet. Security ensures that the information passed between applications or stored on databases remains protected. By default, virtual machines are linked to the internet and made accessible via Azure's command line interface, remote desktop protocol, or secure shell. Incoming connections from the internet can be defined by a public Internet Protocol (IP) address or public load balancer. Connections between the virtual machine to other virtual machines, subnets (subdivisions of an IP network), Azure databases, storage accounts, and other Azure resources can be made by using a virtual network. Within these virtual networks can be multiple subnets, distributed denial of service protection, and optimized (or custom) routing between resources. This added flexibility enables M&D centers or plant sites to customize the virtual network's inner workings in a manner that best fits their needs.

Because Azure also enables the linkage of on-premises resources, a network can be created that expands over both a local and cloud environment. And since Azure enables point-to-site virtual private networks (VPNs), computers outside the premises or organization can still connect to the local Azure virtual network via an encrypted link generated by the VPN. Azure also has site-to-site VPNs, which provide encryption and operate over the internet. In the case of site-to-site VPNs, the on-premises computers or gateway link to the Azure virtual network at which point they would then show up as being on that network. The user can define custom protocols and routing for all network traffic among virtual networks, on-premises networks, and the internet. Default options are also available. Network traffic between subnets can also be filtered and screened via a network security group, which can allow or block traffic in accordance with multiple inbound/outbound security rules (e.g., the source IP, destination IP, port, or protocol). Virtual machines can be connected to other virtual machines through virtual network peering, enabling the machines to communicate with each other. Peering is controlled via user-defined routing, thus allowing for greater control by the network administrators. Figure 1 shows an example of virtual machine networking with Azure. In Figure 1, two virtual networks are connected to a hub network. Peering enables communication between the virtual networks. Virtual network A also has a user-defined routing that connects it to the hub's network virtual appliance. A remote gateway connects virtual network B to the hub network, while the VPN gateway connects the hub network to the on-premises computers. Such a configuration could potentially connect multiple plant sites to a M&D center that provides maintenance oversight and recommendations. Having a M&D center provide analysis for multiple plant sites would generate overall cost savings, as such expenses would be shared among the participating sites.

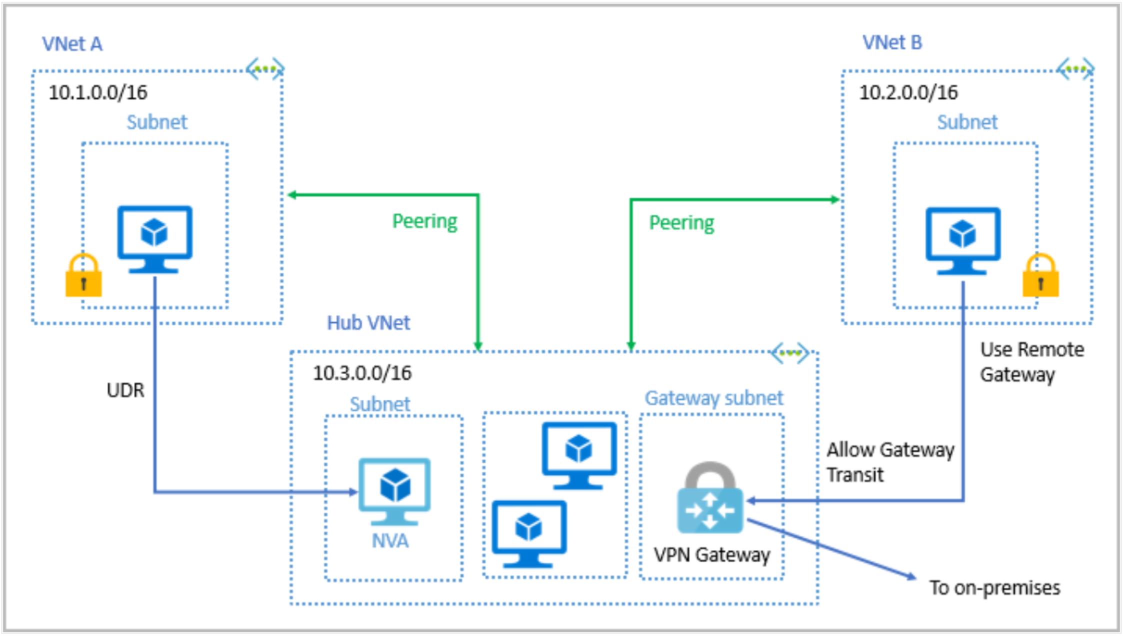

Figure 1. Example of Azure virtual machine networking [15].

Connecting to Azure entails inherent security risks, as all the data must cross the internet. However, these data are encrypted in a private tunnel as they are sent out, as seen in Figure 1. This encryption helps block attacks and prevent eavesdropping while traveling over untrusted networks. The VPN gateways can be used for connecting to other virtual networks or on-premises computers through either policy- or route-based VPNs. Both of these VPN types rely on Internet Key Exchanges and Internet Protocol Security. Internet Key Exchanges establish the encryption agreement between the two endpoints, while Internet Protocol Security encrypts and decrypts the information being sent. Policy-based VPNs evaluate every data packet against a set of IP addresses, while route-based VPNs rely on IP routing to determine which tunnels to interface with. In total, the VPN gateway can connect up to 30 site-to-site or network-to-network tunnels while providing a throughput of up to 1.25 Gbps.

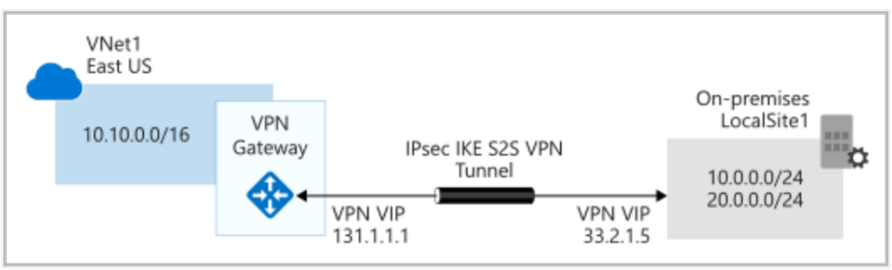

Figure 2. Example of on-premises connection to the Azure virtual network through a VPN gateway and private tunnel [15].

Azure ExpressRoute is one way to avoid the security risks of connecting to the internet, as ExpressRoute connections do not travel over the public internet. ExpressRoute connects on-premises networks to Microsoft Azure through a private connection by means of an any-to-any (IP-VPN) network or a point-to-point Ethernet network, or through a connectivity provider at a colocation facility. Data centers at different locations can connect to ExpressRoute and then communicate with each other via ExpressRoute Global Reach. The cross-data-center traffic travels through Microsoft networks, allowing for a more secure method via which plant sites can communicate with a central M&D center. ExpressRoute's built-in redundancies afford multiple ways of routing nodes on a multi-node network.

Although the data are not sent over the public internet, ExpressRoute still requires that Domain Name System (DNS) queries, certificate revocation list checking, and Azure Content Delivery Network requests take place over the public internet. Consideration for loss of connectivity should be included in your company's Business Continuity and Disaster Recovery Plans If the built-in redundancies fail, each plant site should be able to maintain safe operability and a consistent maintenance schedule without connecting to a central M&D central via the Azure virtual network.

2.2.2 Storage and Databases

Microsoft Azure offers a relational database, Azure structured query language (SQL) Database, as a PaaS. Relational databases manage predefined relationships among data across different databases. The primary advantage of using Azure SQL Database is the reduced amount of hardware required on-premises. Storing large amounts of data can require the purchasing and maintaining of expensive equipment. Azure SQL Database manages database upgrades, patching, backups, and monitoring—all without involvement from the user. This includes all updates to SQL and the operating system code, enabling users to focus less on system/data maintenance, and more on optimizing or utilizing the data. The amount of storage available scales as needed, and access to these data is provided at a 99.99% availability. Microsoft uses the latest stable version of Azure SQL Database to ensure high performance without sacrificing reliability and security.

Microsoft Azure also offers services for accessing and analyzing the data stored in the SQL database: Azure Synapse Analytics, Azure HDInsight, Azure Databricks, Azure Data Lake Analytics, and Azure Data Factory. Azure Synapse Analytics (previously Azure SQL Data Warehouse) is used for data warehousing and big data analytics. This service provides data integration, exploration, and preprocessing for ML needs. Azure Synapse Analytics is coupled with Azure ML, Azure Cognitive Services, and Power BI and can be coded in several different languages (e.g., Python, Scala, Spark SQL, T-SQL, .NET, and KQL) [15]. Azure HDInsight is fully managed and runs many popular open-source frameworks (e.g., Apache Hadoop, Spark, Hive, Apache HBase, and Oozie) for more cost-effective processing of tremendous amounts of data [16]. These open-source frameworks allow for big data clustering and autoscaling. By properly managing and clustering the data, useful insights can be obtained while simultaneously reducing overall computational costs. This leads to cost savings, as PaaS costs are based on use. Azure Databricks provides an interactive workspace for building AI and fostering collaboration [17]. Azure Databricks supports data science frameworks (e.g., Python, R, Scala, SQL, and Java) and ML libraries (e.g., scikit-learn, PyTorch, and Tensorflow). Version control for projects within Azure Databricks is provided via Github and Azure DevOps. Azure Data Lake Analytics is an on-demand service that simplifies big data prior to preprocessing and providing overall analytics [18]. This service performs parallel data transformation so as to be able to manage and process petabytes of data, using programs such as U-SQL, Python, R, and .NET. This processing can include data extraction, transformation, loading, and analytics, as well as ML, image processing, and NLP. Azure Data Factory provides an automated method for moving the data from Azure Data Lake Storage and over to Azure Databricks for preprocessing in anticipation of generating readily available analytics via Azure Synapse Analytics [17].

2.2.3 Artificial Intelligence

Microsoft Azure also offers a wide variety of readily available off-the-shelf AI tools. Applications for these tools include conversational AI, ML, anomaly detection, computer vision, and NLP. Of these areas, conversational AI is probably the least relevant to NPPs. It involves methods of teaching AI agents to converse with humans, and is typically implemented in service industries (e.g., the airline and restaurant industries) to record reservation bookings or provide costumer support. One potential use case for conversational AI is in the nuclear field is that of public engagement via an onward-facing website.

Microsoft Azure has both ML and anomaly detection capabilities. Its services support the entire end-to-end ML lifecycle, from data labeling and preprocessing to building and training models to validation and deployment. This process is streamlined through built-in integration of Azure's storage and database services (e.g., Azure Synapse Analytics, Azure HDInsight, Azure Databricks, Azure Data Lake Analytics, and Azure Data Factory) [19]. Azure can create and train classification, regression, deep-learning, and time-series forecasting models [20]. Azure also offers many tutorials to help users explore and analyze data before training and evaluating ML models. It has prebuilt models that can be used, or these can be substituted for user-defined models. It also contains features for calculating feature importance and disparity metrics in order to improve model efficiency and reliability. Azure utilizes Git, Github, and a central registry system to store and track an auditable trail for data, models, and metadata. Azure's anomaly detection can also indicate upward or downward data trends, thus aiding users in preventing measurements (e.g., temperature and flow rates) from reaching hard-coded alarm limits.

Microsoft Azure offers AI tools pertaining to computer vision and NLP. Computer vision enables AI to visually make sense of the world by using cameras, images, and video [21]. Computer vision for image classification entails training the model on existing images and then making and evaluating predictions. The Azure service called Custom Vision aids in uploading, labeling, training, and evaluating the models, whereas the Azure service called Cognitive Services deploys the model for predictions. Computer vision also includes image analysis for extracting descriptions, tags, and text, or can be used to identify and extract information from forms and invoices. For example, this type of form recognition can be used to automatically extract information from work orders not created electronically. Computer vision can also be used to build face recognition/detection software. It can be used for security purposes or to track operator eye movements in order to improve human-machine interfaces. NLP involves extracting information and insight from text [22]. Azure utilizes many techniques (e.g., tokenizers, stemming and lemmatization, entity extraction, part-of-speech detection, and sentence boundary detection) in attempting to extract the meaning and context of a text. This process can be applied to both real-time message ingestion or to a database prior to analysis and reporting. Azure offers prebuilt models with Microsoft Cognitive Services, or the ability to train custom models using Azure HDInsight with Spark NLP. But whether using prebuilt or custom models, data preprocessing and feature selection should take place prior to deployment of ML or AI techniques.

3. FEATURE SELECTION

NPPs collect and store large amounts of heterogenous data from across each plant site. These data vary in terms of frequency, amount, and type (e.g., plant process parameters, maintenance logs, online monitoring data, and equipment failure data). These data can be leveraged via ML and AI technologies to create diagnostic and prognostic models for solving or predicting problems within the site. However, the unstructured nature of this information can cause challenges when developing reliable and scalable models, making data preprocessing a necessity. Feature selection is an integral aspect of data preprocessing and entails choosing the best combination of features from the original input feature space for the task at hand. Feature selection can improve training speeds and model efficacy. In a previous report, Shapley Additive Explanations (or SHAP values) and variance inflation factors (VIFs) were utilized for feature selection [8].

SHAP values are based on a game-theoretic concept that considers input features as "players" on a "team" of features that work together to influence the model's overall output [23]. The baseline model output is determined by averaging over all predictions and then using a simplified model to solve for each feature's contribution to the model's actual output. SHAP values use an additive feature approach, meaning that the model output is a linear combination of the inputs. By solving for the SHAP values, the feature's influence on the model output can be determined. This method can also be used to rank feature importance, as features that largely affect the model output will have large SHAP values.

VIFs measure the amount of the multicollinearity between the predictor variables. Multicollinearity occurs when two or more variables are highly correlated, potentially leading to unforeseen variability in regression analyses. The strong relationships between independent variables distort the relationship with the dependent variable. Once multicollinearity between the variables is identified, the problem can be rectified via regularization techniques or by simply removing the offending variables [24]. Using either SHAP values or VIFs, features from the original dataset can be selected in order to improve model performance. Both these methods have been used to select the optimal features for short-term forecasting of plant parameters [8].

4. DATA VISUALIZATION

Once the data have been collected, stored, processed, and modeled, the results must ultimately be conveyed to humans for use in making timely decisions. Visualizations of model/system outputs should keep the human user in mind; this concept, known as information visualization, refers to the use of charts, graphs, or other graphical representations to make information or data more easily digestible to humans. For every additional sensor and model, the data landscape becomes more complex, and effective use of information visualization becomes of increasing importance, as operators must make appropriate decisions by balancing a multitude of factors. A previous report covered many of the considerations behind effective visualization, including colors and salience, information density, patterns, guided attention, visualization recommendations, and commercial off-the-shelf solutions [10].

5. ECONOMICS

The report focuses on the three topics that are of particular interest to the nuclear industry: networking and security, storage and databases, and AI. These three topics forms the basis for automation of large number of maintenance activities within NPPs. This not only enhances equipment reliability but also allows optimization of resources, scheduling, supply chain, and minimizes unplanned outage duration, ensuring availability of the power plant. Therefore, understanding the economics of automation achieved by transitioning to a cloud-based M&D center coordinating plant sites maintenance activities is important. Some of the work in this area involves coupling Markov chain risk models and a prognostic model by using a proportional hazard model to derive probabilities reflecting NPP state (i.e., full-load operation, derate, and trip) [25].

To evaluate the economics of automation, it is important to understand the costs spend on the current maintenance activities and the costs of ownership of technologies required to enable cloud-based M&D center. The transition can reduce costs associated with current maintenance activities by reducing staffing, inventory, and reducing/eliminating periodic labor-intense preventive activities, and dose (associated generation of nuclear waste). However, there are capital and maintenance costs associated with the transition that needs to be incurred upfront. The internal rate of return (IRR) is a metric used in financial analysis to estimate the profitability of potential investments. IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis. IRR is not the actual dollar value of the project rather it is the annual return that makes the NPV equal to zero. NPV, as a financial metric, was used to perform the techno-economic analysis of wireless network in NPPs [5, 26, 27].

6. SUMMARY AND PATH FORWARD

This report demonstrates an end state vision for online monitoring as data are collected, stored, preprocessed, and visualized. Cloud computing offers potential cost-savings opportunities, as the responsibility of purchasing, updating, and maintaining IT-related equipment for storage and computing is offloaded to the cloud provider. Additional savings can be incurred by having a single M&D center provide analysis for multiple plant sites, as the expenses of such analysis could be shared among the participating sites. However, these cost-savings opportunities must not come at the expense of availability or cyber security, so added emphasis is placed on these features. The available data can then be preprocessed before being modeled using off-the-shelf ML and AI techniques from the cloud provider, or by using custom user-defined models. These diagnostic and prognostic models can help determine when and where maintenance may be required. Finally, the model results must be adequately conveyed to the human users ultimately responsible for the necessary decision making.

Future work will focus on expanding the end state vision to wireless monitoring in order to enable continuous online monitoring. More work must also be done in quantifying the expected cost saving value generated by transitioning from on-premises storage and computing to a cloud-based approach.

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