SAND2022-0102R

Literature Review of Electromagnetic Pulse (EMP) and Geomagnetic Disturbance (GMD) Effects on Oil and Gas Pipeline Systems

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October 2021

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ABSTRACT

This document summarizes the findings of a review of published literature regarding the potential impacts of electromagnetic pulse (EMP) and geomagnetic disturbance (GMD) phenomena on oil and gas pipeline systems. The impacts of telluric currents on pipelines and their associated cathodic protection systems has been well studied. The existing literature describes implications for corrosion protection system design and monitoring to mitigate these impacts. Effects of an EMP on pipelines is not a thoroughly explored subject. Most directly related articles only present theoretical models and approaches rather than specific analyses and in-field testing. Literature on SCADA components and EMP is similarly sparse and the existing articles show a variety of impacts to control system components that range from upset and damage to no effect. The limited research and the range of observed impacts for the research that has been published suggests the need for additional work on GMD and EMP and natural gas SCADA components.

ACKNOWLEDGEMENTS

The authors wish to thank Peter Schuck and Sean Blake from the NASA Goddard Spaceflight Center for their assistance obtaining the GMD benchmark data associated with the TPL-007 standard. The authors also wish to thank Matthew Sneddon for his assistance with the preparation and editing of this document. Also, thank you to Nathan Schoenkin from the Pipeline Hazardous Materials Safety Administration at the Department of Transportation and John Ostrich from the Office of Cybersecurity, Energy Security, and Emergency Response at the Department of Energy for funding this effort.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
CP	Cathodic Protection
DTRIAC	Defense Threat Reduction Information Analysis Center
EM	Electromagnetic
EMP	Electromagnetic Pulse
ESP	Electrical Submersible Pump
GIC	Geomagnetic Induced Current
GMD	Geomagnetic Disturbance
HANE	High-Altitude Nuclear Explosion
HEMP	High-altitude Electromagnetic Pulse
HPEM	High-Power Electromagnetics
PLC	Programmable Logic Controller
SAIC	Science Applications International Corporation
Sandia	Sandia National Laboratories
SCADA	Supervisory Control and Data Acquisition

1. INTRODUCTION

A review was conducted by Sandia National Laboratories (Sandia) staff of published literature regarding electromagnetic pulse (EMP) and geomagnetic disturbance (GMD) impacts on oil and gas pipeline systems. The literature review was used to determine where a significant amount of research had been done and where additional work was needed to help guide the team's further analytic efforts.

Staff searched IEEXplore, the Web of Science database, Elsevier's Engineering Village database, Google Scholar, the Advanced Technologies & Aerospace Index, and the Defense Threat Reduction Agency Information Analysis Center (DTRIAC) during this review. Where specific authors were found publishing relevant material, a more in-depth search on those authors was also performed.

During the search a list of keywords was developed, and the keywords then used in pairs with one word taken from an electromagnetic (EM) column and one word from an infrastructure column. The keywords are listed in **Error! Not a valid bookmark self-reference.**. Articles specific to EMP and GMD effects on oil and gas pipeline systems and their control system elements were rare, so the search focused more generally on pipeline and control system elements and EMP/GMD impacts to them.

Table 1-1. Keyword List Developed for Search Criteria

Electromagnetic	Infrastructure
GIC	Pipeline
Geomagnetic induced current	Oil
Solar storm	Gas
Geomagnetic disturbance	Natural gas
GMD	SCADA
EMP	Control system
Electromagnetic pulse	Supervisory control and data acquisition
HANE	Compressor
HEMP	Pumping station
High-altitude nuclear explosion	Cathodic protection
High-altitude nuclear detonation	Programmable logic controller
High-altitude electromagnetic pulse	PLC
Telluric	Corrosion

1.1. Natural Gas System Overview

The keywords developed as part of the literature review come from oil and gas infrastructure design and operation information developed from site visits and modeling of oil and gas networks worldwide. Future work on the project will focus on the natural gas system, so a brief overview of that system is provided here for reference.

Major elements of the North American natural gas system are shown in Figure 1-1. There are three major classes of pipeline comprising the natural gas transportation route: production, transmission, and distribution. Production pipelines move raw gas from oil and gas wells to processing facilities. Transmission pipelines transport processed gas from producing regions to areas of high demand, which may be hundreds or thousands of miles away. As shown in Figure 1-2, the U.S. transmission pipeline network extends across the entire country.

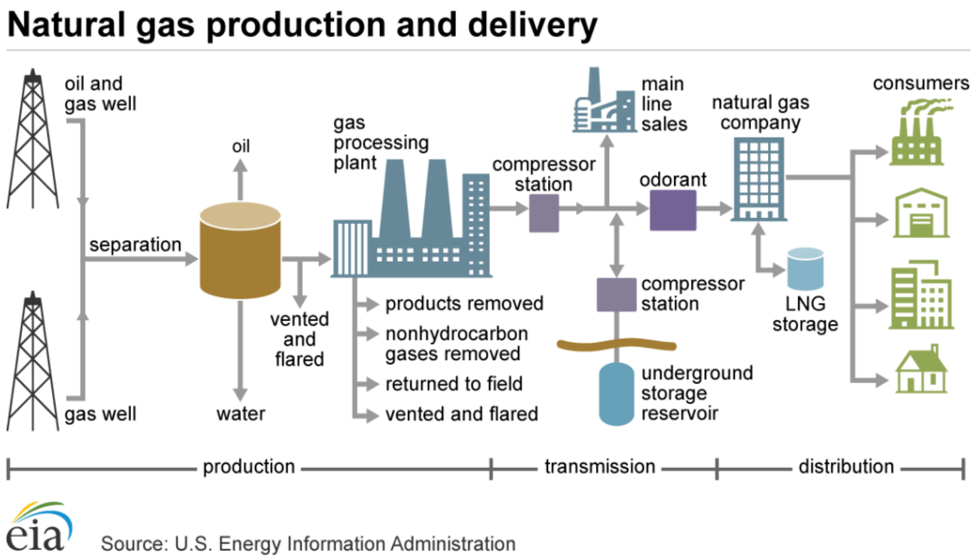

Figure 1-1. Major elements of the North American natural gas system.

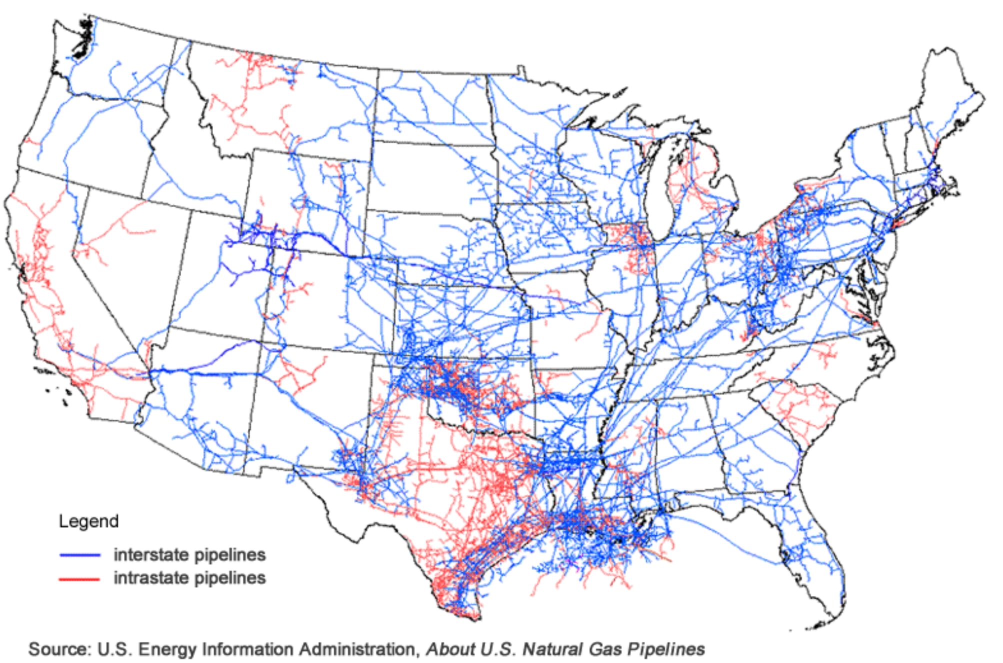

Figure 1-2. U.S. natural gas transmission system pipeline network.

Transmission pipe, also called 'line pipe,' is constructed of carbon steel and engineered to meet industry standards. The pipe is covered with a special coating, often a fusion bond epoxy on modern pipes, to prevent corrosion after placement in the ground. To further protect the pipe, active cathodic protection is often used, which runs an electric current through the pipe at a specific electric potential relative to the ground, to prevent corrosion.

To maintain natural gas pipeline pressure and flow within required bounds, compressor stations are usually situated at 40- to 100-mile intervals along the pipeline. Metering stations are placed along pipelines to track the flow of gas into, along, and out of the transmission network. Large valves placed every 5 to 20 miles along a transmission pipeline enable segments of the system to be isolated for maintenance or to control of leaks in an emergency.

To monitor and control the flow of natural gas through the pipeline, centralized control stations collect and manage data received from compressor stations, metering stations, and other remote facilities. Most of this data is handled by Supervisory Control and Data Acquisition (SCADA) systems. These SCADA systems collect data along the pipeline and transmit it to a centralized control station. Flow rate, pressure, temperature, and other equipment readings are used to constantly assess pipeline status. A SCADA system may also remotely operate pipeline equipment, such as individual valves or entire compressor stations. This enables operators in the central control center to quickly respond to both emergencies and to routine changes in supply and demand throughout the pipeline.

1.2. EMP and GMD Overview

A specific concern for natural gas system EMP vulnerability is a high-altitude electromagnetic pulse (HEMP) created by a nuclear detonation in the upper atmosphere. The HEMP environment is generally described in terms of three components: early-time (E1), intermediate-time (E2), and late-time (E3). For the purposes of vulnerability assessments, E2 fields are considered to occur on the same timeframe as fields generated by nearby lightning, but at lower field levels; therefore, E2 is considered low risk due to existing lightning mitigation measures. Of the remaining two HEMP components, the E3 component is most like a GMD and will be discussed as a common GMD/E3 environment consideration, although the events creating these fields are very different. In contrast to an intentional HEMP event, GMD is created when a natural coronal mass ejection from the sun interacts with the Earth's magnetosphere, inducing quasi-dc electrical voltages on conductors near the Earth's surface; where closed electrical circuit exist, quasi-dc currents can develop.

Impacts associated with E1 occur quickly and can insult equipment directly via radiation or can couple to wires or cables and insult electrically connected equipment with a high voltage and current pulse. The E1 component of a HEMP is less than a microsecond in duration and can create voltage pulses up to tens of kilovolts (kV) on wires and cables as short as a few hundred feet.[1] For wires and cables measuring kilometers in length, the coupled voltage pulse can reach several hundred thousand volts.[2] While the wires carrying the coupled pulse are themselves rarely at risk, electrical damage could occur for any connected susceptible equipment. Building materials and earth provide some degree of EM shielding that will reduce the magnitude of an incident EM pulse.[3] Components that are located behind significant amounts of shielding or are buried underground (especially in moist higher conductivity soil) will receive a lower radiated EMP insult and have a lower probability of

[1] B. J. Pierre, R. T. Guttromson, J. Eddy, R. Schiek, J. Quiroz, and M. Hoffman, "A framework to evaluate grid consequences from high altitude EMP events," Sandia Nat. Lab., Albuquerque, NM, Technical Paper SAND2020-7323C, July 2020.

[2] R. Schiek and M. Halligan, "Statistical Profiles of EMP E1 Coupling to Single Conductors," Sandia National Laboratories, SAND2020-10738, September 2020.

[3] S. Hyun, et. al., "Analysis of Shielding Effectiveness of Reinforced Concrete Against High-Altitude Electromagnetic Pulse," IEE Transactions on Electromagnetic Compatibility, Vol. 56, No. 6, December 2014.

failure based on local attenuation of the HEMP fields. However, only limited number of the cable coupling scenarios have been quantified, although more could be developed. Furthermore, components still may receive a conducted insult if a portion of the shielded wires connected to them are exposed to an EMP.

GMD (and by association E3) has a history of negative effects in the electric power system. The primary problem is transformer core saturation caused by GMD/E3 in power systems is due to grounded transformers located between very long transmission lines. The coupled GMD/E3 signal can create a voltage bias on wire conductors between approximately 8 volts per kilometer (V/km) (for a 100-year storm GMD), with local peaks of up to 12 V/km, and 40 V/km for E3a (blast) and 25 V/km for E3b (heave)[4], though benchmark waveform testing recommends double the anticipated HEMP threat level. However, the closed electrical path created by grounded transformers, which leads to voltage suppression (GMD and E3) and thermal damage (GMD only) in power systems does not exist in the natural gas system. For short conductors that exist at natural gas compressor stations or junction points, this could amount to a few volts, which would likely not pose significant risks to electrical equipment in use. Longer conductive pipelines in the gas transmission system would provide a scenario for higher coupling of GMD/E3 fields, but it is unlikely that GMD/E3 would have an acute effect on corrosion. The timeline for corrosion to result is measured in years so the impacts build up over time rather than happen from a single GMD event that lasts up to two days, or about two minutes for E3. Furthermore, cathodic protection on the pipeline isolates segments of the pipe in lengths typically ranging from 10 to 40 miles, which reduces the possibility for long distance coupling of GMD/E3. It may be possible for a coupled pipeline voltage (with respect to ground) to accelerate corrosion if the proper pathways were present from the pipeline to ground. However, since E3 can create voltages of up to 40 V/km for less than a few seconds and up to 25 V/km for less than two minutes, it is unlikely to have a significant damaging effect in that short duration.

1.3. EMP and GMD Benchmarks

As part of the tasking under the literature review, the team also researched benchmarks that could be used for analyzing EMP and GMD effects.

The following benchmarks will be used for Task 2 of the study:

- For the EMP portion of the study we are planning to use the E1 and E3 benchmarks as described in the following Department of Energy (DOE) memorandum published in January 12, 2021:

  https://www.energy.gov/sites/default/files/2021/01/f82/FINAL%20HEMP%20MEMO_1.12.21_508.pdf

  The E1 definition was provided by the previously published IEC-61000-2-9 E1 waveform, and the E3 definition is based in part on earlier work from Oak Ridge National Laboratories (ORNL) and the EMP Commission as described in the memorandum. The E2 definition in the DOE memorandum linked above was assumed to be sufficiently accounted for by lightning protection systems unless said systems were determined either to be insufficient for protection or nonexistent.

[4] D. Brouillette, Secretary of Energy Memorandum, Physical Characteristics of HEMP Waveform Benchmarks for Use in Assessing Susceptibilities for the Power Grid, Electrical Infrastructures, and Other Critical Infrastructures to HEMP Insults. Department of Energy.

- For the GMD portion of the study we propose using the GMD benchmark data from the TPL-007 standard with a reference benchmark peak of 8 V/km and supplemental peak of 12 V/km. Our initial look will use the 60° latitude base benchmark since this is higher than any regional adjustment would provide.

1.4. Structure of the Document

The following sections discuss the publications that were found and examined for the literature review. They were divided into four categories. The first category includes papers that were specific to EMP and GMD effects on pipelines without constraining that set to just oil and gas pipelines. The second category contains papers that discussed EMP and GMD on control system components and circuits; again, not constraining the set to those specifically used in natural gas or petroleum systems, since there can be a great deal of overlap in manufacturers and specific control system components across different utility sectors. The final category includes a small selection of articles related to GMD measurements in northern regions and cathodic protection on non-pipeline systems. This category was included for completeness though they are generally less relevant to the follow-on work.

This report summarizes the findings of this review as an annotated bibliography. Each article identified is briefly described, and conclusions are summarized where available. In many cases, the papers describe the development of methods or the gathering of data and no specific conclusions are available. Each section contains a summary of the articles within it and any conclusions that can be drawn. Overall conclusions are provided at the end of the document.

Section 2 – Articles Specific to EMP/GMD and Pipelines
Section 3 – Articles on EMP/GMD and Control System Components
Section 4 – Additional Cathodic Protection and Telluric Current Articles

2. ARTICLES SPECIFIC TO EMP/GMD AND PIPELINES

The articles included here specifically focus on EMP/GMD or telluric currents and pipelines and indicate that cathodic protection systems can be designed to mitigate the impacts of GMD and where those impacts do occur the corrosion occurs over a time horizon of years. While the E3 component of EMP is not addressed specifically, given its shorter timescale it is unlikely to have a significant impact on corrosion. The impacts of E1 have not been well explored and warrant further study.

There is a significant body of work that discusses telluric currents, in some cases without explicitly specifying GMD, on various pipeline systems. This includes observed measurements on pipeline systems and mathematical models for calculating the induced voltage and currents on the pipeline. Many of the papers that focus on telluric current discuss the impacts on corrosion of the pipeline and corrosion protection systems. Several also discuss possible mitigations with respect to cathodic protection system design. A significant amount of work has been done on cathodic protection and pipeline systems to compensate for variations in telluric currents and their impacts on pipeline corrosion. Many of the articles here detail those impacts and several also provide strategies for cathodic protection system design and mitigation to account for those variations.

Included are a smaller number of articles looking at EMP on both buried and above ground pipelines.

Boteler, D.H. and Trichtchenko, L. (2001). ***Observations of Telluric Currents in Canadian Pipelines*****. Corrosion 2001, Paper No. 01316.**

This report provides valuable findings regarding the correlation between geomagnetic activity and voltage variations measured on pipelines. Two different pipelines in Canada were found to have voltage variations corresponding to geomagnetic activity in the area. The information contained in this paper does not include the effects that the induced voltage had on the pipelines, only that there was a correlation between the geomagnetic activity in the area and the fluctuations in voltage on the pipeline relative to the earth surrounding it. The correlation in voltage variations began to drop off at several hundred kilometers from the source of the geomagnetic disturbance.

Boteler, D.H. (2003). ***Geomagnetic Hazards to Conducting Networks*****. Natural Hazards 28, pp. 537-561.**

The effects of geomagnetic disturbances on power systems and pipelines are described using evidence from real-world scenarios and analyzed using typical measures employed to provide protection. While this paper primarily focuses on the effects of a GMD on power systems, it provides little focus on the effects of GMDs on pipelines. A possible result of a GMD on a pipeline is corrosion. To prevent corrosion, pipelines are kept at a small negative voltage relative to the earth surrounding it, and this voltage fluctuates during a GMD. A possible long-term result of this is corrosion to the steel pipeline.

Boteler, D.H. (2004). *Telluric Currents and Their Effect on Cathodic Protection of Pipelines.* NACE CORROSION 2004, Paper No. 04050.

Authors examine how GMD can cause variations in pipeline voltage relative to the surrounding earth and the associated impacts of those variations. Positive variations of voltage in a pipeline can lead to corrosion, and negative variations in voltage can cause the cathodic coating to lose adherence. The voltage variations are larger when the cathodic coating has a higher resistance. Variations in voltage can also damage survey equipment connected to the pipeline.

Boteler, D.H. and Trichtchenko, L. (2005). *A Common Theoretical Framework for AC and Telluric Interference on Pipelines.* NACE CORROSION 2005, Paper No. 05614.

Calculations are used to estimate how GMD and power transmission lines interact with pipelines. This information could be used to assist with design of cathodic protection systems to assist with mitigation. How pipelines are affected by EM disturbances is dependent on the frequency of the disturbance and the resistivity of the surrounding earth. Higher frequency interferences cause significant theoretical values for coating capacitance and pipeline inductance. Coating capacitance and pipeline inductance are insignificant at lower frequencies. A multi-layer conductivity model is used to determine the electric field at different depths of the earth caused by electromagnetic interference. The complex image method is used to calculate the size and area-of-effect of electric fields for EM disturbances with sources at different heights.

Boteler, D.H. (2007). *Assessing Pipeline Vulnerability to Telluric Currents.* NACE CORROSION 2007, Paper No. 07686.

A methodology is presented showing how certain features can alter telluric effects on pipelines, which could prove valuable for knowing possible mitigation strategies for EM disturbances near pipelines. Variations in pipeline voltage relative to the surrounding earth are greatest where telluric currents are disrupted, such as at flanges, turns, and ends of pipeline. A pipeline coating with a greater resistance value causes a higher voltage between the pipeline and the earth. Telluric effects on pipelines can be mitigated by grounding both ends of the pipeline, rather than only one end.

Boteler, D.H. (2013). *A new versatile method for modelling geomagnetic induction in pipelines.* Geophysical Journal International 193, pp. 98-109.

This paper creates an expansive mathematical model using equivalent-pi circuits, leveraging distributed-source transmission line and Thevenin equivalent circuit work as described in Pirjola et al (1999) (with mathematical detail missing from the prior article). The authors then describe combining a series of equivalent-pi circuits that represent elements of a pipeline network to develop a complete pipeline representation. This modeling could prove useful for a better understanding of the possible currents that could be present on a pipeline and contribute to cathodic protection system design.

Campbell, Wallace H. and Zimmerman, James E. (1980). *Induced Electric Currents in the Alaska Oil Pipeline Measured by Gradient Fluxgate and SQUID Magnetometers.* IEEE Transactions on Geoscience and Remote Sensing GE-18 (3), pp. 244-250.

Observations at several sites resulted in a mathematical formulation of currents at points along the Alaska oil pipeline that may be useful for cathodic protection system design to compensate for the fluctuations. In the formulation, current is a function of the north-south geomagnetic field amplitude and its apparent period. The paper highlights current surges of 500 amperes (A) during geomagnetic storms.

de Moraes, JF. et al (2019). *Evaluation of Possible Corrosion Enhancement due to Telluric Currents: Case Study of the Bolivia-Brazil Pipeline.* Annales Geophysicae, Vol. 38, Issue 4, pp. 881-888. DOI: 10.5194/angeo-38-881-2020.

This paper establishes a model to calculate the corrosion effects of telluric currents on Brazilian gas pipelines that likely is applicable to other pipeline systems. The authors concluded that currents that didn't exceed the pipeline's rated protection nevertheless contributed to long-term corrosion. Thus, the effect of geomagnetically induced currents (GICs) on pipelines can reduce the lifetime of a pipeline.

Demirel, B and H. Yalcin (2013). *Investigation of the Telluric Effects Arising Along the Cathodically Protected Natural Gas Pipeline between Karadeniz Eregli and Duzce.* Turkish Journal of Electrical Engineering and Computer Sciences 21, pp. 758-765. DOI: 10.3906/elk-1108-13.

This paper presents measurements for telluric currents affecting a Turkish pipeline. The study found that values did not significantly change daily, and peaks and drops could be the result of fluctuating soil resistivity. The article shows that telluric currents can have an impact on the cathodic protection system and that insulating flanges and grounding techniques can mitigate those impacts.

Dimmock, A. P., Rosenqvist, L., Hall, J.O., Viljanen, A., Yordanova, E., Honkonen, I., André, M., and Sjöberg, E. C. (2019). *The GIC and geomagnetic response over Fennoscandia to the 7–8 September 2017 geomagnetic storm.* Space Weather 17, pp. 989–1010. https://doi.org/10.1029/2018SW002132.

Analysis of a geomagnetic storm impacting network areas described in Pirjola et al (1999). The authors observed that the maximum peak of the GIC did not coincide with the storm commencement nor did that peak occur during strong driving conditions. This suggests that more work is needed to understand the precursors of GIC peaks. They also found good temporal agreement between a 1D and 3D model with significant difference in amplitude. This provides for justification for the use of 1D models and suggests that accurate ground conductivity values are important for modeling.

Edwall, H. and Boteler, D.H. (2001). *Studies of Telluric Currents on Pipelines in Southern Sweden.* Corrosion 2001, Paper No. 01315.

This paper is useful for understanding how pipeline length effects the location of potential variations in voltage. Telluric currents were observed in different lengths of pipeline in Sweden, and researchers found that changing the length of the pipeline changes the locations of the largest variances in voltage. The results of testing the telluric effects on different lengths of pipeline were consistent with the modeling techniques mentioned, which also indicates that the modeling technique used is effective for predicting telluric effects.

Favetto, A. and Osella A. (1999). ***Numerical Simulation of Currents Induced by Geomagnetic Storms on Buried Pipelines: An Application to the Tierra del Fuego, Argentina, Gas Transmission Route.*** **IEEE Transactions on Geoscience and Remote Sensing, Vol. 37, No. 1, January 1999.**

Geomagnetic fields and currents on buried pipeline were measured to produce a correlation between geomagnetic activity and the measured pipeline currents. A numerical simulation was performed using a previously developed theoretical formulation to estimate the current induced by a geomagnetic storm. The theoretical model produced an upper bound of the possible measured values. The authors conclude that the tool can be used to predict the current that could be produced on a pipeline and that that information could be used to improve protection in regions with a higher risk of corrosion.

Fernberg, P. et al (2007). ***Telluric Hazard Assessment for Northern Pipelines.*** **NACE CORROSION 2007, Paper No. 07654.**

Telluric activity was studied in Canadian pipelines over the course of a year to improve modeling long-term variations in geoelectric fields. The authors conclude that models coupled with statistics can provide information on the total time in a year that pipeline to soil variations can exceed the safe range for steel pipelines. This paper provides data on the pipeline to soil potential variations over the course of a year and deals with the natural geoelectric variations of Earth in the northern hemisphere, but does not account for events such as solar storms or HEMPs.

Gummow, R. A., and Eng, P. (2002). ***GIC Effects on Pipeline Corrosion and Corrosion Control Systems.*** **Journal of Atmospheric and Solar-Terrestrial Physics, pp. 1775-1764. https://doi.org/10.1016/S1364-6826(02)00125-6.**

A discussion of the impacts of telluric current on corrosion control systems and pipeline corrosion. The authors explore the fact that the pipeline corrodes during positive cycles of telluric events and experiences coating damage during negative cycles. Recommended mitigations include maintaining good electrical continuity, integrating cathodic protection, and monitoring pipe-to-soil potentials.

Kim, W., Kim, S., and Yook, JG (2018). ***Analysis of Water Pipe Structures Considering EMP Shielding Effectiveness.*** **USNC-URSI Radio Science Meeting (Joint with AP-S Symposium), pp. 33-34.**

The authors propose design guidelines for water pipes used in septic tanks to maintain the function of the pipe and provide protection from an EMP without the need for an additional shielding structure. Traditional systems installed with additional shielding inside the pipe restrict the flow of the drainage system. Impurities also restrict that flow by accumulating on the shielding thus limiting the effectiveness of the drainage system.

Lax, K., Boteler, D. H., Charalambous, C. A., and Pirjola, R. (2019). *Practical Application of Telluric Modelling for Pipelines.* European Federation of Corrosion, pp. 1-11. http://eurocorr.efcweb.org/2019/abstracts/16/179136.pdf.

The authors discuss the use of an integrated model to show the variations in potential that can occur from GMD. These methods allow for the informed use of telluric modeling techniques in system design and mitigation decisions. Two example calculations are presented. The first regards a single, straight pipeline. The second is of a typical pipeline network that includes elements such as junctions, bends, and changes in pipeline diameter. The second model is the same used in the draft ISO standard 21857.

Ma, C. and Liu, C. (2019). *Influence of Pipeline Insulation Leakage Points on the Distribution of Geomagnetically Induced Current and Pipe-Soil Potential.* IEEE Access 7: pp. 147470-147480.

The authors leverage Boteler's previous models (2013) of pipeline networks, then extend those to design resistance models of a pipeline insulation leakage point in the pipeline's conductor. 3D pipeline simulation modeling is performed in ANSYS engineering simulation software to solve for equivalent resistance. Findings demonstrate the changes to the calculation of GIC when the diameter of leakages varies and how geomagnetic storms impact such leakage points. The authors conclude that the closer to the end of the pipeline and the larger the radius of the leakage point, the greater the impact on the distribution of the GIC on the pipeline.

Pirjola, R., Pulkinnen, A., Vijanen, A., Nevanlinna, H., and Pajunpaa, K. (1999). *Study Explores Space Weather Risk to Natural Gas Pipelines in Finland.* Eos 80 (30).

This study expands on the authors' previous work estimating the GIC risk of the Finnish high-voltage power system and highlights corrosion risk as the main concern for pipelines. Distributed-source transmission line theory and Thevenin's theorem describe the nature of GIC for a segmented pipeline, as well as the impedance and voltage for each connection. Leveraging the magnetometer concepts applied by Campbell, calculations of GICs are compared to observations, with good association. Coating resistance is found to be critical to measurement.

Pirjola, R., Pulkkinen, A., and Viljanen, A. (2003). *Studies of Space Weather Effects on the Finnish Natural Gas Pipeline and on the Finnish High-Voltage Power System.* Advances in Space Research 31 (4), pp. 795-805.

This report studies the effects of pipeline corrosion and power transformer damage from GICs on Finnish power systems and natural gas pipelines. The findings for corrosion on oil and natural gas pipelines due to GICs are consistent with those found in other papers and articles. This paper provides good information on the effects of GICs on power system transformers, as well.

Pulkkinen, A. et al (2001). *Modelling of Space Weather Effects on Pipelines*. Journal of Applied Geophysics 48, pp. 233-256.

A theoretical model is used to determine the voltage and current values along a buried pipeline using the known external electric field. The theoretical model was used to predict the electrical characteristics of a Finnish pipeline. Those theoretical values agreed with measurements taken of the pipeline after a GMD. The information in this paper is very useful for modeling voltages and currents along a buried pipeline due to an electromagnetic disturbance.

Rix, B.C. and Boteler, D.H. (2001). *Telluric Current Considerations in the CP Design for the Maritimes and Northeast Pipeline*. Corrosion 2001, Paper No. 01317.

Methods for mitigating telluric effects in pipelines were used in the design of cathodic protection (CP) for two northern pipelines. Telluric current fluctuations can be mitigated with rectifiers on the ends of the pipeline, a bond switch between sea and land pipelines, interruptible test coupons for reading data without interfering with the rectifiers, and 4-wire IR-drop spans for reading telluric current. This paper is good for evaluating mitigation strategies to prevent the effects of electromagnetically induced currents in a pipeline that can lead to corrosion.

Trichtchenko, L. and Boteler, D.H. (2002). *Modelling of Geomagnetic Induction in Pipelines*. Annales Geophysicae 20, pp. 1-10.

A theoretical model is used to find the voltage and current values along a buried pipeline using the known external electric field and pipeline characteristics. Distributed source transmission modeling was used to estimate the pipeline voltage relative to the surrounding earth. The electrical characteristics of the pipeline were taken into consideration for this modeling technique. This paper would be useful for modeling the telluric effects of a pipeline and estimating the induced pipeline voltage.

Tsurutani, B.T. and Hajra, R. (2921). *The Interplanetary and Magnetospheric Causes of Geomagnetically Induced Currents (GICs) > 10 A in the Mäntsälä Finland Pipeline: 1999 through 2019.* Journal of Space Weather and Space Climate 11 (23) DOI: 10.1051/swsc/2021001.

This paper (and erratum) focuses, as do several of the papers in this review, on the GIC data set associated with the Mäntsälä natural gas pipeline. The authors find that super-substorms and intense substorm auroral electrojet intensifications are the most frequent causes of GIC events of greater than 30 A. Solar wind plasma particle impingement and forward shocks were the second and third most frequent cause of these events.

Viljanen, A. et al (2006). ***Recordings of Geomagnetically Induced Currents and a Nowcasting Service of the Finnish Natural Gas Pipeline System*****. Space Weather-The International Journal of Research and Applications, Vol 4, Issue 10. DOI: 10.1029/2006SW000234.**

This paper discusses measurements of geomagnetic currents on a Finnish natural gas pipeline. The well-established GIC Now! system was used as the primary means for collecting measurements. The GIC Now! service uses calculation methods validated through previous works on GICs and geoelectric fields. The service is easily transferable to other pipeline systems and provides a near-real-time identification of a GIC.

Yoon, Sangho et al (2020). ***Electromagnetic Pulse Shielding Effectiveness of Circular Multi-Waveguides for Fluids*****. Results in Physics 16, pp. 102946.**

Metal multi-waveguide pipe can be installed in certain regions of large-scale piping facilities to prevent EMP penetration, and this paper provides a theoretical analysis of the effectiveness of using multi-waveguide pipes for mitigating EMP penetration in a piping facility. Protection from EMPs ensures continuous operation for pipeline facilities supplying natural gas, water, or oil.

Yu, Z., Hao, H., Liu, L., and Wang, Z. (2019). ***Monitoring Experiment of Electromagnetic Interference Effects Caused by Geomagnetic Storms on Buried Pipelines in China.*** **IEEE Access 7: pp. 14603-14610.**

Data analysis of GIC resulting from a geomagnetic storm occurring on 7 September 2017. The effects of GICs on buried pipelines is observed in middle and low latitude regions in China. The difference in voltage between the pipeline and the surrounding earth can cause corrosion when driven outside the desired range by GMDs. Greater distances between insulating flanges on the pipeline result in larger corrosion effects of the GIC on the pipeline. The authors conclude that medium or small geomagnetic storms can lead to significant corrosion in protected pipelines.

Zhang, J. and Liang, Z. (2017). ***Effects of High-Altitude Electromagnetic Pulse on Buried Pipeline*****. International Journal of Applied Electromagnetics 55, pp. 507-522.**

This paper establishes a model to calculate the effects of a HEMP on a buried pipeline. The authors observe that increasing the depth of a buried pipeline can decrease HEMP effects, and as HEMP effects are directly related to an external surface area, smaller pipelines experience less HEMP effects than larger pipelines.

Zhang, J. and Liang, Z. (2018). ***Effects of High-Altitude Electromagnetic Pulse on Overhead Pipeline.*** **International Journal of Applied Electromagnetics and Mechanics 57, pp. 309-324.**

The authors establish a model to calculate the effects of a HEMP on an overhead pipeline in contrast to their previous examination of HEMP effects on buried pipeline. The author's findings are almost identical for both overhead and buried pipelines. Length has little-to-no impact, and height and outer radius have a positive relationship with HEMP effects.

3. ARTICLES ON EMP/GMD AND CONTROL SYSTEM COMPONENTS

There were no articles found in the general literature specifically studying the effects of EMP/GMD on natural gas control systems; hence, the papers listed here involve impacts on different control system components. Supervisory Control and Data Acquisition (SCADA) systems have a limited number of vendors, so many of the components in natural gas systems are likely to exist in other infrastructure control systems. This section captures control system components that have been explored for EMP/GMD impacts to serve as possible reference material. The results from the articles are mixed, with some systems showing levels of upset or damage and others showing no impact. Given the varying results, additional research, and analysis of control system elements in natural gas systems is warranted.

Boteler, D.H. (1999). *Calculating the Voltages Induced in Technological Systems During a Geomagnetic Disturbance*. IEEE Transactions on Electromagnetic Compatibility 41, No. 4.

Two approaches are given for calculating the voltage induced in a horizontal conducting loop at the Earth's surface. This paper focuses more on the calculations rather than the effects of a GMD. Overall, this calculation strategy is supplemental to other works regarding the effects of induced voltage on technological systems.

Dou, L. et al (2014). *Simulation Study on Coupling Effect under HEMP of Shielding Control Box*. Applied Mechanics and Materials 551, pp. 309-314.

The effectiveness of a HEMP shielding control box was tested and analyzed. It was found that a HEMP with an incidence perpendicular to the long side of a gap in the box had the highest penetration effectiveness. This paper is a useful source for information regarding shielding of control systems from an EMP. The authors note that a gap in the shielding box can be filled with conductive rubber to increase the effectiveness of the EM shielding capabilities.

Ericson, D.M. et al (1983). *Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems Volume 2*. Sandia National Laboratories Technical Library, SAND82-2738 vol. 2.

This paper analyzes the effects of HEMPs on nuclear power plant systems and provides a breakdown of power plant shutdown procedures in response to a HEMP. The study generally found that damage thresholds of sensitive components are robust enough that arcing and breakdown will occur before direct HEMP damage.

Lanzrath, M. et al (2017). *HPEM Vulnerability of Smart Grid Substations; Coupling Paths Into Typical SCADA Devices*. 2017 International Symposium on Electromagnetic Compatibility – EMC Europe.

This paper presents test results of the effects of high-power electromagnetics (HPEM) on typical SCADA devices. The authors report that vital smart-grid components were extremely vulnerable to EMI, but no SCADA devices showed permanent or long-term damage from the test.

Lanzrath et al (2018). *HPEM Vulnerability of Smart Grid Substation Secondary Systems.* 2018 International Symposium on Electromagnetic Compatibility, pp. 799-804.

This paper assesses HPEM susceptibilities in secondary systems used in smart grids. Bulk current injection and irradiation tests are conducted on protection and telecontrol devices both as individual devices and in a system configuration. Details on the specific devices are not provided. Various devices suffered critical failures at varying frequencies.

Tian, L. et al (2020). *Failure Mechanism of Integrated Circuits Investigated Experimentally and Theoretically under Electrical Fast Transient.* Proceedings of SPIE, Vol.11565, Article# 115650J. DOI: 10.1117/12.2576124.

This paper presents results of an experiment measuring the potential weak points in a circuit when hit with a high-power microwave. High current produced by the high-power microwave caused the junction temperature of the transistor in the circuit to rise, resistivity to fall, and current density to increase. This led to a positive feedback cycle that ultimately caused the transistor to melt. A simulation model was also developed and compared favorably to the testing results.

Wang, Q.G. et al (2013). *The Modeling and Experimental Investigation on Coupling of Transmission Line Network with Electromagnetic Pulse (EMP).* IEEE International Conference on Smart Energy Grid Engineering (SEGE), 2013.

This paper presents a model of the coupling of an EMP on electric power transmission lines. Equations are specifically modeled for double-parallel conductor lines and other typical networks. The models also account for the network structure's height from the ground. The authors believe the developed models could also be used to explore coupling impacts on SCADA systems.

4. ADDITIONAL CATHODIC PROTECTION AND TELLURIC CURRENT ARTICLES

This section contains articles related to the measurement of telluric currents or GMD activity in areas proposed for pipelines and independent of the pipelines themselves. It also includes articles that discuss cathodic protection and telluric current for buried elements other than pipelines. These articles are included here for completeness of the literature search, though they may have limited relevance to natural gas pipeline systems.

Metwally, I.A. et al (2007). *Stray Currents of ESP Well Casings.* Engineering Analysis with Boundary Elements, Vol.32, Issue 1, pp. 32-40. DOI: 10.1016/j.enganabound.2007.06.003.

This paper analyzes a simulated model of an electrical submersible pump (ESP) well casing to test the effectiveness of a pulse cathodic protection system. The simulation found no significant difference between cathodic protection and pulse cathodic protection systems.

Metwally, I.A. and Al-Badi, A.H. (2009). *Factors Affecting Pulsed-Cathodic Protection Effectiveness for Deep Well Casings*. Anti-Corrosion Methods and Materials, Vol.56, Issue 4, pp. 196-205. DOI: 10.1108/00035590910969329.

This paper assesses the effectiveness of pulse cathodic protection for deep well casings. This technology could be similar to cathodic protection means used for oil lines.

Metwally, I.A. and Al-Badi, A.H. (2010). *Analysis of Different Factors Affecting Cathodic Protection for Deep Well Casings.* Materials and Corrosion-Werkstoffe und Korrosion, Vol.61, Issue 3, pp. 245-251. DOI: 10.1002/maco.200905272.

This paper analyzes both cathodic protection and pulse cathodic protection systems for deep well casings and how different factors affect casing corrosion. The study takes an in-depth look at how different systems interact with soil resistivity, which can limit the currents produced by cathodic protection systems.

Nikitina, L., Trichtchenko, L., and Boteler, D.H. (2016). *Assessment of Extreme Values in Geomagnetic and Geoelectric Field Variations for Canada*. Space Weather 14, doi:10.1002/2016SW001386.

Geomagnetic activity was recorded in Canada over the course of 40 years to evaluate extreme scenarios for geoelectric field variations. A generalized extreme value distribution was applied to obtain criteria for assessing vulnerability to geomagnetic activity. This paper could be useful for risk mitigation and design when installing new pipelines, since the long-term geomagnetic activity for areas in the northern hemisphere could be predicted.

Trichtchenko, L. (2012). *Assessment of Telluric Activity in the Area of the Proposed Alaska Highway Pipeline*. NACE – International Corrosion Conference 2, pp. 1289-1298.

In this report, telluric activity is observed at different latitudes in Alaska to determine the risks of a pipeline being placed in the region. Data was taken over the course of 30 years in the area of the proposed pipeline, and it was found that the area had 80% higher geomagnetic activity than lower latitudes. This paper focuses on the analysis of data for geomagnetic activity in the area, not on telluric effects on pipelines or mitigation strategies.

5. SUMMARY

The impacts of telluric currents on pipelines and their associated cathodic protection systems has been well studied as evidenced by the large body of literature on this topic that was discovered through the literature review process. The articles include development of mathematical models of the induced current and voltage, and measurement of telluric currents on various pipeline systems. Induced voltages caused by an EM disturbance in the atmosphere can cause variances in pipeline-to-soil potential. These variances can cause corrosion due to an electrochemical process in the pipeline steel. Protective coatings on the pipeline can also be damaged leading to further potential for corrosion. The literature describes implications for corrosion protection system design and monitoring to mitigate these impacts.

Effects of an EMP on pipelines is not a thoroughly researched subject. Most directly related articles only present theoretical models and approaches rather than specific analyses and in-field testing. Literature on SCADA components and EMP is similarly sparse, and the existing articles show a variety of impacts to control system components that range from upset and damage to no effect.

While EMP has not been specifically studied on cathodic protection systems for pipelines, due to the long-term nature of corrosion impacts to pipelines it is not an immediate concern but a longer-term impact occurring over years. Thus, we don't suggest additional work specific to cathodic protection and EMP at this time. The limited research and the range of observed impacts for the research that has been published suggests the need for additional work on GMD and EMP and natural gas SCADA components.