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Sleeman biogas boiler system design

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Energy costs represent a significant expense in the brewing of beer, and it is in a company's best interest to minimize these costs. Due to the high organic loading processed by the on-site wastewater treatment plant at Sleeman Breweries in Guelph, Ontario, a large amount of biogas is generated, which could be used as an energy source and revenue stream for the brewery. The purpose of this project is to design a system that will make use of the wasted biogas to benefit the company. First a preliminary analysis of several design alternatives was conducted in order to determine the best option. Through this analysis it was determined that a pretreatment and piping system, along with boiler modifications would be the most cost effective method of dealing with the biogas. This system would save the brewery approximately $134,000 in the first year it was implemented, and have a payback period of approximately 5 years. Therefore, it is recommended that Sleeman Breweries consider moving forward with the proposed biogas recovery system. This report describes the detailed research, calculations, and modeling completed to design this system in order to present with confidence the optimal solution to Sleeman Breweries.

The Sleeman Breweries Guelph facility is currently treating their wastewater on-site using an anaerobic digester and flaring off the biogas. The biogas, mainly consisting of methane, is a potential fuel source for the brewery. The system designed makes use of this methane in a biogas powered steam boiler, which will save the brewery money on natural gas costs. Due to more stringent regulations and environmental concerns, it is important that the brewery find a more sustainable way of running their operations by using a biogas recovery system.

This report includes a system model of the design and demonstrates the cost savings with the use of the biogas system. The model was based on current production values and considers growth and efficiency changes to approximate the payback period. A sensitivity analysis is completed, which shows the effect of changes in inputs on biogas production and natural gas savings. The constraints, criteria, and modeling analysis were used in design evaluation and optimization. This analysis allowed for a recommendation that Sleeman Breweries can feel comfortable in pursuing.

BACKGROUND

Biogas is generated when organic compounds containing carbon, hydrogen, and oxygen are consumed by bacteria in the absence of oxygen, which produces carbon dioxide and methane [1]. The existing anaerobic digester has been in place since 2004, and operates at approximately 50% to 67% capacity, with an average flow rate of 606 m^3/d and a hydraulic residence time of about two hours, depending on the inflow rate. The biogas produced by this process is made up of approximately 78% methane, 0.5% hydrogen-sulphide, trace hydrogen, water vapour and the remainder carbon dioxide. The flow rate of this gas stream is approximately 1,150 m3 per day on average [2]. Currently, the biogas stream is flared off to remove the methane, without making use of the available energy. The brewery consumes large amounts of natural gas, 87% of which is used for steam production, using two 300 hp and one 500 hp fire tube boilers at typically 30 to 50% load. Since the biogas can be used in place of natural gas, it is valuable as a combustion fuel in one of the steam boilers, to reduce costs at the plant.

The design constraints that must be met by the final design are presented in the list below:

- The payback period must be less than 10 years
- The design must accommodate the predicted growth rate for the next five years
- The system must be flexible in order to deal with fluctuations in pH, flow rates, and diverse compositions of influent in the wastewater stream
- All applicable regulations and laws must be met regarding installation and operation

Additionally, the system should maximize the following design criteria, in order to provide maximum benefit for the brewery:

- Maintenance requirements should be low, and it should be possible for a single person to operate the system
- The design should be flexible, modular, and capable of

being relocated due to future expansion

- The system should be reliable, and capable of lasting for a long period of time
- The payback period should be as low as possible
- The system should have a low risk of failure
- The system should be as simple as possible, including installation with minimal interruption and a minimal number of additional components required
- The system should minimize negative environmental impact with respect to waste, emissions, energy and water consumption

In order to create a design, it was necessary to make several assumptions for information that was not available. Regarding the digester it is assumed that the hydraulic residence time is 2 hrs, the design loading rate is 20 kg TCOD/m^3day and the optimal efficiency is at 2/3 of this loading rate. It is also assumed that the relationship between the biomass and biogas production is constant, the composition of the wastewater is constant, the biogas is saturated with water prior to treatment and that 1 m^3 of biogas is equivalent to 0.778m^3 of methane since the average methane content is 77.8% [2]. The biogas production is assumed to be constant at 0.4464 (kg COD)/(kg VSS)day. Additionally the growth rate is assumed to be constant for the next five years with the amount of energy, and water used as well as wastewater produced to increase proportional to growth and the cost of natural gas to be \$0.3753/m^3 of methane [2].

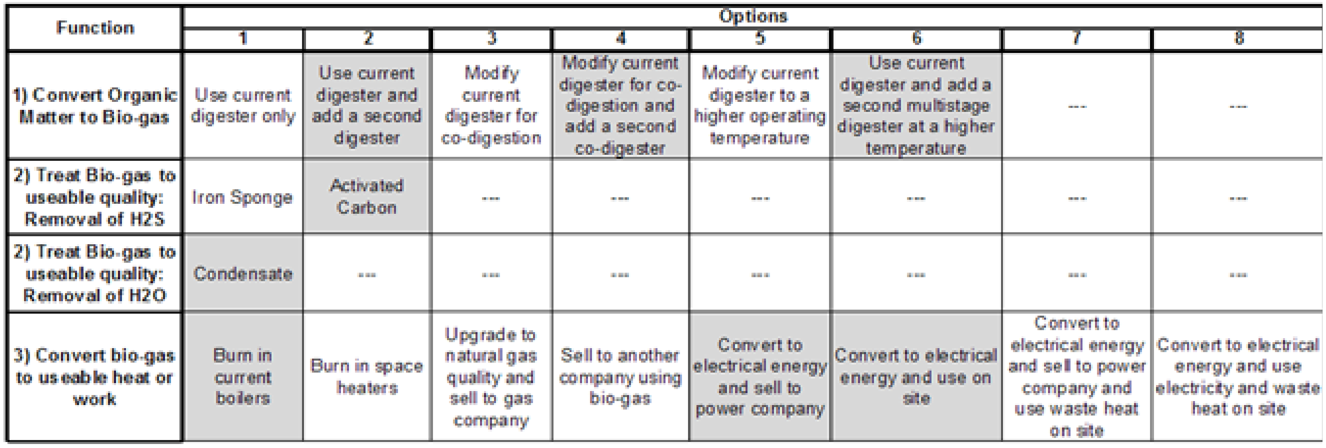
DESIGN CONCEPT

The system was analyzed and designed based on three main functions: convert the organic matter into biogas, treat the biogas and convert the biogas into useful heat or work. Some of the options initially considered for these three functions are outlined in Figure 1. The first options were to consider how biogas was to be produced. These options included the current single digester, additional digester, modifications to the digester for co-digestion, upgrading the digesters to thermophilic conditions and the introduction of multiple stage digesters. The second options focused on the treatment of the biogas, utilizing either a combination of activated carbon and an iron sponge or a condensate.

The third options considered the use of the biogas once it was treated. These options included burning it in the current boiler system, burning it in space heaters, selling the biogas directly, treating the biogas and selling it as natural gas, and converting it to electricity for onsite use or sale to a power company. Other additional options that were considered were the use of waste heat on site.

Through cost analysis and evaluation of the options against the constraints and criteria it was determined that the best alternative is to add a second digester for growth, use activated carbon and a condensate for the biogas treatment and to burn the biogas in the boilers on site.

The system designed consists of four main components as seen in Figure 2. Currently wastewater from the brewery is piped to the treatment facility, enters the conditioning tank where chemicals are added to adjust the pH and then flows into the digester where the biogas is produced. These steps will not be altered in the proposed design except that a second conditioning tank and digester will be added after 5 years to take into account predicted growth. The biogas produced in the digesters will then flow through a PVC piping system to one of the boilers after passing through two treatment systems, one activated carbon scrubber and one condensate system where H_2S, water vapour and suspended solids are removed. The burner on this one boiler will use an automatic controller to mix natural gas and biogas to produce enough fuel to keep the 300 hp boiler between 30-50% load. With the biogas being used in the boiler system, it will reduce the natural gas consumption by an average of 9.8%, leading to about \$134,000 saved in the first year. If by chance the boiler shuts down or in any way the biogas cannot be used continuously, the flow can be re-directed to the flare currently installed.



Function	Options							
	1	2	3	4	5	6	7	8
1) Convert Organic Matter to Bio-gas	Use current digester only	Use current digester and add a second digester	Modify current digester for co-digestion	Modify current digester for co-digestion and add a second co-digester	Modify current digester to a higher operating temperature	Use current digester and add a second multistage digester at a higher temperature	---	---
2) Treat Bio-gas to useable quality: Removal of H2S	Iron Sponge	Activated Carbon	---	---	---	---	---	---
2) Treat Bio-gas to useable quality: Removal of H2O	Condensate	---	---	---	---	---	---	---
3) Convert bio-gas to useable heat or work	Burn in current boilers	Burn in space heaters	Upgrade to natural gas quality and sell to gas company	Sell to another company using bio-gas	Convert to electrical energy and sell to power company	Convert to electrical energy and use on site	Convert to electrical energy and sell to power company and use waste heat on site	Convert to electrical energy and use electricity and waste heat on site

Figure 1. Summary of Design Alternatives Analyzed

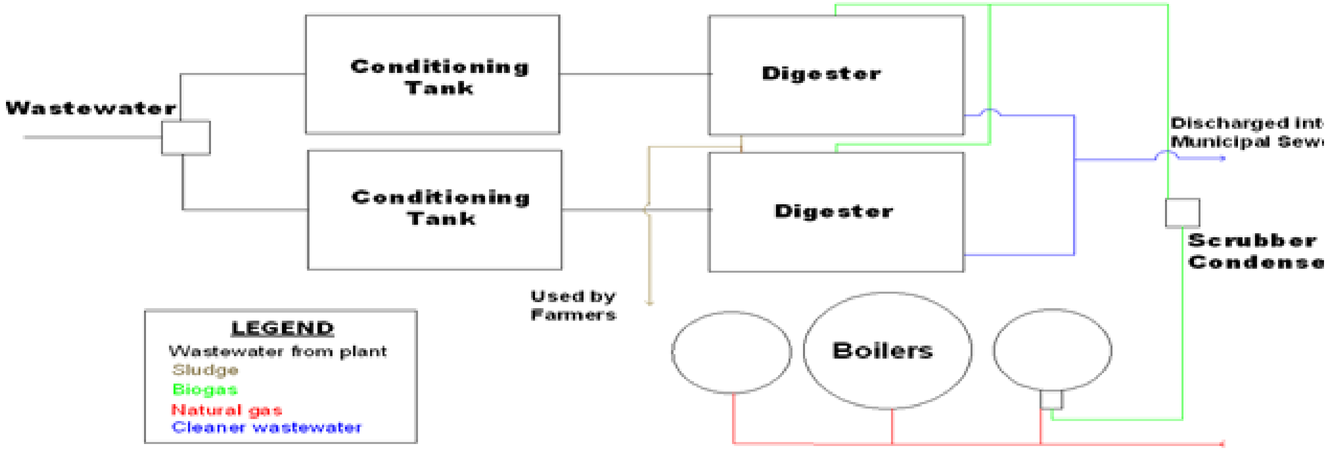


Figure 2. Designed System Layout

DETAILED DESIGN & ANALYSIS

Anaerobic Digestion System

The current Expanded Granular Sludge Bed (EGSB) digester is running at 2/3 capacity, 13.5 kgCOD/m^3day of the 20 kgCOD/m^3day the tank was designed for [2]. Assuming 20kgCOD/m^3day is the average loading rate and the predicted growth over the next five years leads to a corresponding increase in the wastewater flow, it was determined that the brewery would need to add a second digester at the beginning of year 5. Given that the digester becomes less efficient as it reaches capacity and it is assumed to be currently operating near optimal conditions, a digester of 200 m^3 was chosen.

The size of the new conditioning tank is approximately 75% of the volume of the existing digester, providing a slightly shorter hydraulic retention time. Since the size of the second digester will be 200 m^3, the conditioning tank will therefore need to be 150 m^3 to achieve 75% of the conditioning tank volume. The additional digester and conditioning tank are estimated to cost $600,000 and $200,000 respectively based on the costs of the current digester [2].

Biogas Pretreatment System

When the methane is extracted from the digester it will contain a trace amount of hydrogen sulphide and water vapour, which will be removed with activated carbon and a condensate trap, respectively. The current concentration of H_2S being produced by the digester is between 0.3-0.6 ppm. Since even small amounts of H_2S can cause corrosion in pipes and boilers that the biogas comes in contact with [3], the H_2S gas will be removed with the use of a Purafil DS-100 drum scrubber. This scrubber will remove a minimum of 99.5% of the H_2S gas present in the biogas stream, is corrosion resistant, and is able to filter at a rate of up to 100 cfm[4]. This is more than adequate to treat the amount of biogas currently produced, as well as the amount produced after the 5-year growth period. The unit will cost $3,000, and replacement media will cost $190 per bag, with 5 bags required for operation [4].

The Varec Biogas 233 Condensate/Sediment Trap will be installed inline after the digesters, in order to remove water vapour before it cools and condenses in the piping. Removal of the water vapour will prevent corrosion and firing issues in the boiler burner, ensuring that maintenance and long term reliability are optimized [5]. The condensate trap itself is easily cleaned and removes condensation through a sudden decrease in velocity and high centrifugal force [6].

Piping

For the biogas piping system, a PVC piping material will be used, as PVC is low cost, easy to install, and resistant to corrosion [7]. PVC is also beneficial in that it is easier to stop the flow by pinching the tube in the event of a gas leak, and can be used in low to moderate gas pressure applications [7]. PVC pipe can also be safely buried underground, with a tracer wire to aid in locating the pipe at a later time, as it will be installed underground outside [8]. The system will require approximately 133.6 m of 4-inch PVC piping, along with six 90-degree PVC elbows, and one PVC tee that will connect the two digesters to a single outlet pipe. The total cost, including installation for the piping system will be approximately $8,400 [9]. The piping will be installed to carry the biogas from the digesters to the boiler room. The existing pipes will be used to carry fuel to the backup flare.

The piping system was designed to convey at least the 85th percentile biogas flow, after the projected 5-year growth. This was done due to the fact that sizing for this flow will still capture nearly all flow overall, but will allow for the use of a commonly available pipe size of 4 inches. This means that after five years of company growth, the pipes will still be able to convey all of the biogas to the boilers on 85% of days, according to the sizing chart for natural gas on Engineering Toolbox [10]. On days where this level is exceeded, the pipes will convey most of the flow, while excess will be flared. The design flow for this requirement is 2,410 m^3 of biogas per day, assuming constant flow over the entire day. A curve of best fit was created for maximum flow rate vs. length of pipe, and the maximum flow rate for the required pipe length of 133.6 m was found. According to this chart, a pipe of size 4-inches would be acceptable for piping the biogas at a flow rate of 2,470 m^3 /day. With this size pipe, capacity will account for all biogas produced by the digester on approximately 85% of all days.

Biogas Steam Boiler

Currently, the company is relying fully on natural gas to run their boiler systems. With three boilers, one 500 hp and two 300 hp, 30 years and 8 years old, respectively, and running continuously, Sleeman Breweries is using roughly 500,000 m^3 a month of natural gas, or over $2 million annually [2]. The current boiler burners, however, are not designed to burn biogas [2]. Therefore, for biogas to be utilized in this system, the burners in the boilers will need to be replaced. Since all three boilers run on a 2-pass system, the water is only in contact with the heat twice, so the temperature must be high to ensure the correct amount of steam is being created. The new boilers being considered to replace the two smaller boilers would have a 4-pass system. With this system, water is in contact with the heat twice as much as the previous system, meaning that the temperature of the air can be reduced and effectively reduce the natural gas consumption. With the new boilers in place it will increase efficiency nearly 4%, bringing the boilers efficiency up to 80-85% [11].

The burner chosen for consideration is the MPG series, manufactured by Midco International, since it can run on biogas [12]. This burner's control system will measure the amount of incoming biogas and adjust the natural gas flow to allow the efficiency of the boiler to remain constant. The options of either replacing the boiler and burner or replacing simply the burner in one or two of the boilers were compared against the criteria and constraints. This analysis found that the replacement of a burner rather than upgrading the entire boiler was the best option. Since flows would not exceed the capacity of one 300 hp boiler only one burner would need to be replaced. This will optimize the boiler system by minimizing the initial cost to the brewery, and reduce the risk of failure and additional maintenance needed while costing only $15,000 [11].

To ensure the correct ratio of air to fuel and natural gas to biogas at the burner, a Honeywell ABC900 control system will be installed. This system will be able to monitor and adjust the air-fuel ratio, as well as the biogas to natural gas ratio of the boiler as the biogas composition changes with time [13]. This will allow the boiler to operate at maximum efficiency as the methane concentration of the fuel changes.

Modeling

Modeling of the system designed was completed in order to assess the costs and payback period. The model consists of two sections; the first regarding the digester, which relates the inflow of waste water to the biogas production and the second regarding the boiler, which relates the biogas production to the amount of natural gas saved.

Due to the complexity of the system this design analysis, a simplified model relating the change in volume and flow to the production of biogas was developed rather than a more complex model as described in the literature since one could not be determined reliably. The model captures the relationship between the changing inputs (change in influent flow), changing system (change in biomass and addition of second digester) and changing outputs (change in biogas production). Refer to Figure 3 for a diagram of the model.

A relationship between the biomass concentration, biogas production, natural gas required and natural gas saved was determined based on data from the existing system and previous modeling of anaerobic digesters [14][15]. A direct and reliable relationship however between the change in inflows and change in biomass could not be found. Therefore for simplification, it is assumed that each unit increase in flow would result in an equal increase in average biomass and consequently, an increase in biogas production. To account for the decrease in production as the tank fills, as mentioned by Pontes & Pinto [16], a factor proportional to

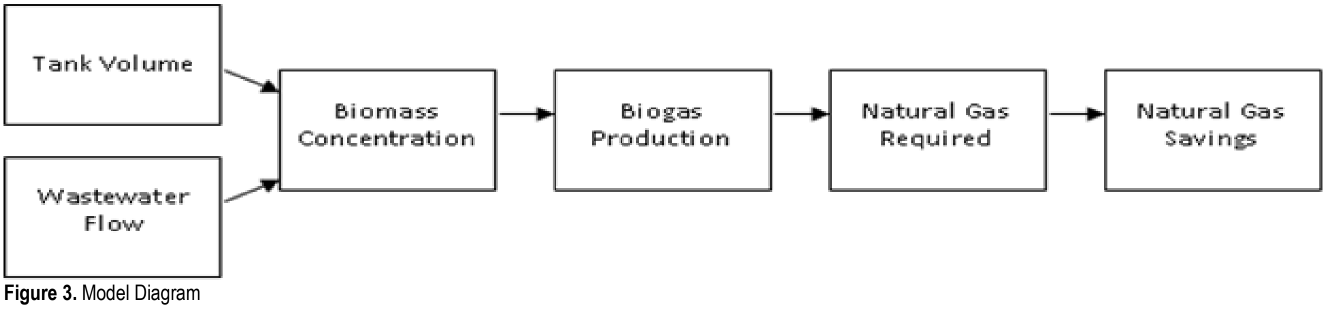


Figure 3. Model Diagram

the change in loading rate is added. For this case (referred to as Case 2) this factor is assumed to be 33.3%. The validity and effect of this assumption was tested and is described in the following sections by changing the factor and examining the effect on the payback period. Modeling of the system found that the payback period, given the above assumptions and the second digester is installed in year 5, to be 5.3 years.

Additionally, sensitivity analysis was carried out in order to determine the effect of certain parameters and assumptions in the model on the cost of the design. It was determined that the payback period was not very sensitive to either a change in the growth rate or the assumed 33.3% factor but was very sensitive to the digester and conditioning tank costs. Any reduction in these costs would significantly affect the payback period.

Sensitivity of the digester to varying operating conditions was determined using the Expanded Granular Sludge Bed (EGSB) Reactor Model, which resembles linear performance model. This sensitivity analysis was mirrored off one performed by Pavlostathis and Gossett [17]. The parameters being addressed are the growth rate of the bacteria (μMA), the initial concentration of the bacteria (X_{MA}), the bacterial yield (Y_{MA}), reaction rate in the reactor (Rs_{CH4}) and the volume of digester tanks 1 (V1) and 2 (V2) individually. The results of this sensitivity analysis found that the reaction rate to be the most sensitive parameter, followed by the Initial Concentration and Bacterial Yield, respectively. Conversely, the volume of the second digester is the least sensitive parameter. As an example, as the Reaction Rate decreases by 10%, the overall biogas production will decrease by 11.85% if all other parameters are held constant.

TESTING AND EVALUATION

Testing

The model described in the previous section was validated by comparison with a second independent model. In the paper Analysis of integrated Kinetic and Flow Models for Anaerobic Digesters by Pontes and Pinto, several models are suggested for use with expand granular sludge bed (EGSB) reactors [15].

The EGSB model is quite different than the linear growth models, in that rather than approximating the biogas production from the flow rate of the wastewater, it is based on a bacterial reaction rate and the volume of wastewater under digestion. The reaction rate, however, is still derived from the wastewater flow data.

The results of this model closely reflect those of the previous case, where on average about 1,572 m^3/d of biogas is produced over a 10-year period. Two other cases which are variations of Case 2 (described previously using the 33.3% factor) were also tested to evaluate the model under different scenarios. In case 1, optimal conditions were assumed, where a 1:1 relationship between wastewater flow and biogas production exists, and increasing the flow per unit volume does not inhibit the growth or biogas production in anyway. Case 3 assumes the increase in volume does inhibit the growth of biogas as in Case 2 but to a lesser degree and therefore the factor is assumed to be 90%. A payback period between 5 and 6.5 years for each model was produced as seen in Table 1 and Figure 4.

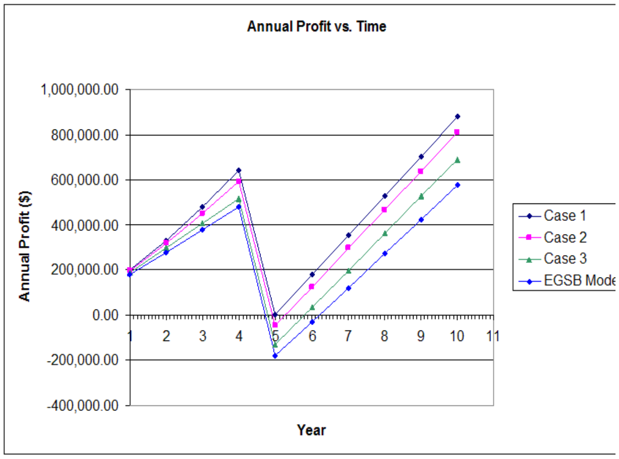


Figure 4. Net Payback Periods for Analytical Models

Design Evaluation

Overall the system proposed in this report is simple and reflects the needs of Sleeman Breweries. The system was optimized with the understanding that the purpose of the anaerobic digestion system at the brewery is primarily for treatment of the facility's wastewater, and that the company is interested in obtaining the highest possible economic gain, while improving their environmental image. Cost modeling as described in the previous section gives confidence that the system will provide a reasonable payback period under different scenarios. As well, the sensitivity analysis gives confidence that a variation in growth rate will have a minimal effect on the payback period and thus the system will still be profitable given a year of decreased growth. It also indicates areas of opportunity, for example in reducing the digester and conditioning tank capital cost, where the company can significantly decrease the payback period for the project. Model testing gives some confidence to the model as the overall payback period is not changed significantly under different cases. However, it should be noted that all the models contain several assumptions and are very simplified.

Consideration of Constraints & Criteria

The design is evaluated against the criteria and constraints in supplementary information and shows that the biogas utilization system design meets all the constraints outlined. The payback period is less than the maximum allowable 10 years, at 5.0 to 6.2 years. The backup natural gas supply allows the biogas boiler to be completely flexible to changes

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in biogas flow rate. The high growth rate of the company will be allowed for by the design, which is sized to handle flows for the company's growth over the next 5 years. Applicable regulations will be met during installation and operation of the design.

CONCLUSIONS

In this report, the use of biogas in Sleeman Breweries' Guelph facility operations was investigated, and a final system design was presented. The design itself is optimized based on the constraints and criteria of the brewery. The system will include an additional digester in year 5, a piping and treatment system for the biogas, and a replacement burner for one of the existing boilers. The design will benefit the brewery by offsetting approximately $134,000 in natural gas costs annually, and it will reduce the amount of natural gas consumed and the amount of air pollutants released. As production grows, the annual savings will grow to reflect the increased biogas production, as the system is sized to accommodate future growth. Additional modeling and reviewing of the design by experts working with the current system and in the field to ensure its reliability should be completed. It is recommended that Sleeman Breweries pursues further development of the design presented in this report.

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