Analysis of Potential Power Sources for Inspection Robots in Natural Gas Transmission Pipelines

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INTRODUCTION

Strategic Center of Natural gas's (SCNG) Natural Gas Infrastructure Reliability Product Team has undertaken the development of a prototype robot that would inspect and possibly repair transmission pipelines. NETL has granted a contract for this purpose to New York Gas Group (NYGAS) and Carnegie Mellon University's (CMU) National Robotics Engineering Consortium (NREC).

The purpose of this study is to analyze various onboard power supply options for such a commercially viable robot that can operate in a transmission pipeline for extended period. The primary power sources considered are wind turbines, rechargeable batteries, fuel cells and radioistotopic thermoelectric generators (RTGs).

ROBOT REQUIREMENTS

It is quite clear that requirements of robot power source cannot be properly evaluated in isolation, as they are intrinsically linked with those of robot itself. This means we need to consider

(a) Robot's dimensions and mass, its means and methods of locomotion, speed of its locomotion, and its energy requirement, etc.

(b) The mission of the robot (what type of sensors, what method of communication, what type of repair, etc.), and

(c) The range of robot's activities, i.e., pipe diameter(s), length of travel, and obstacles to overcome, etc.

The items stated in the previous paragraph are unspecified at this stage of the development, as they are evolutionary in nature. For example, initially robots would probably be meant for inspection. Later on, robots for repair work would be introduced. Even within the limited mission of inspection there are a wide variety of sensors available. It is reasonable to expect that robots would have multiple sensors as they evolve increasing their mass, dimensions and energy requirement. Robots designed for repair work would be much more complex and will require much more maneuverability and ability to carry repair tools and material. Thus they would be heavier and larger, and would require more energy.

As to the range of robot activities, it is probably appropriate to limit them to transmission pipelines. There are about 300,000 miles of transmission pipelines plus more than 1 million miles of local distribution lines. It is worth noting that transmission lines are often run in parallel. In such cases each one of the parallel line would have to have its own robot. There are 98 interstate transmission companies and 57 intrastate transmission companies. There are 10,610 delivery points, 48 service hubs, and 1528 compressor stations in the main lines. There may be additional 6,500 compressor stations that supply natural gas from the main transmission lines to distribution lines through the delivery points and "laterals."

A critical question about the transmission pipelines that need to be addressed is the extent to which these lines contain sharp turns or bends, such as 90^{O} and 180^{O} elbows, steep slopes, flanges, and vertical rises. This information is needed to identify to what extent robots can function in the pipelines and what their designs should be. For example, information supplied by David Damon of Dominion shows that about 60 percent of Dominion's block valve stations in its transmission lines have vertical risers to the block valve, with lengths ranging from 6 to 9 feet. Several of Dominion's transmission lines are in hilly terrain with slopes of 30 - 45 degrees and contain welding ells, sag bends, overbends, and sidebends, etc. This clearly indicates that a single robot design may not fit applications for all pipelines.

While a wide range of variation exists between the operations of various pipelines, one can generalize the operations as follows. Typically, the pipe diameter ranges from 3 to 36 inches, bulk of pipes being 12 to 24 inches in diameter. Typical operating pressure ranges from 100 to 2,000 psig. Compressor stations are spaced about 20 to 60 miles apart. Questions regarding types of valves, their internal designs, and their spacing remain unanswered at this point. In particular, knowing the internal design is crucial in determining the suitable mode of locomotion of the robot.

Much of the missing information outlined in the previous two paragraphs can be obtained only in statistical form. Only the operating companies are in a position to supply this information. Having the information will allow us to make further refinements in our understanding of requirements of robot and its power source. However, some general specifications of a truly innovative robot can be stated as follows. The robot should function under the operating conditions of the pipe for an extended period, possibly several years, without disruption and without needing human intervention. This would allow uninterrupted supply of natural gas while robot continues to carry out its mission.

The robot should be able to overcome obstacles and irregularities in the line such as valves, reducer segments, or flanges. It should be maneuverable to get around turns and bends in the pipe and climb or descend a sloped pipe. (Climbing or descending a vertical rise may offer a special challenge.) The robot should be able to move through any pool of condensate that may be present in the line. The robot should be able to move in either direction within the pipe. The robot should be programmable and be also able to accept overriding commands.

It may be preferable to have the power supply of the robot, locomotion unit of the robot and the robot as a single unit rather than modular units that are linked together. This is because the modular units may not be able to overcome as easily as a single integrated unit the obstacles described in the previous paragraph.

A reasonable estimate of maximum number of in-pipe robots would be about 8,000 since the largest distance a robot can move is from one compression station to another. For the purposes of setting specifications, robots may be limited to pipes that have at least 8” diameter from one compression station to another. It may be much more difficult to develop a robot that can navigate itself through smaller pipelines, which are also likely to have sharp bends or turns and even vertical rises. Based on the information compiled by the Energy Information Agency (EIA), as of 1997 this restriction would eliminate only about 10% of transmission lines from robot application.

The speed of the robot locomotion partly depends on its mission and the sensors’ response times and thus cannot be quantified. However, if robot speed is set somewhat arbitrarily at 1 mile per hour or 1.47 ft per second, a round trip between compressor stations twenty miles can be completed in about 2 days and sixty miles apart in about 5 days.

ROBOT POWER SOURCE ALTERNATIVES

Robot power requirements consist of five parts, viz., power needed by

(a) the sensors,
(b) the communication system,
(c) the on-board computer,
(d) repair tools, if any, and
(e) The locomotion unit.

The total power requirement as well as the distribution of the power load among the five parts will depend on the mission of the robot and on the mass of the robot. The total power requirement will also depend on the energy density of the power source since the power source will also move along the robot. (One exception to this is if the robot draws power from an electric line installed within the pipe.) For preliminary design calculations, it was estimated that the robot would require 200 Watts of electric power.

The four alternatives considered for a robot power source are wind turbines, rechargeable batteries, fuel cells, and radioisotopic thermoelectric generators (RTGs).

What follows is an assessment of each of these options to identify the positive and negative aspects of each of them.

Wind Turbine

The robot movement is much slower than that of the natural gas. Therefore, it has been proposed that a small onboard wind turbine/generator set, driven by the transport velocity of the natural gas moving past the robot, could supply the energy robot's energy needs. The power that could be generated using a state-of-the-art multi-blade wind turbine was estimated using data from *Marks' Standard Handbook for Mechanical Engineers* (8th Edition, page 9-164).

Given that the turbine would have to be shrouded to prevent the blade tips from hitting things, a 1-foot turbine blade diameter was estimated to be the largest practical size. Based on a transport pipeline capacity spec of 530 BSCF/year for a 56" pipeline, 10 ft/sec was estimated to be the maximum transport velocity. At 10 ft/sec and operating pressure of 1500 psia, a 1-foot diameter turbine would produce approximately 32 watts according to the *Marks' Handbook* data. This maximum power is only 16 percent of the estimated robot power need of 200 watts.

Moreover, since the wind turbine's power output is proportional to the cube of the transport velocity, the power produced would drop drastically under reduced flow conditions. For example, at 60 percent of the pipeline maximum flow, with 6 ft/sec transport velocity, the same wind turbine would only produce 7 watts. Based on these calculations, it was concluded that a wind turbine could not produce sufficient power to run the robot and therefore was dropped from further consideration.

Rechargeable Batteries

Within the generic class of "rechargeable batteries" there are many choices. By their very nature, in this application the selected battery must store enough energy for the robot to complete its journey from one charging station to another. The charging is envisioned to be carried out with a DC power source introduced through keyhole size openings in the pipe that are separated by appropriate distance. Since the compressor stations already have a power source, it would be desirable to locate these DC power sources there. This would minimize extensive electrical work. Thus, under this scenario the robot would be expected to have enough energy to make the trip from one compression station to the next, get charged and then make the return trip.

A key factor in selecting a rechargeable battery for a robot is its energy density. Both types of energy density measures, viz., kWh/kg and kWh/L, need to be considered. Firstly, the robot's power source is mobile. Therefore, the required between-recharging capacity (kWh) depends partly on the mass of the battery, which in turn depends on the energy density (kWh/kg). Secondly, the robot and its power source need to move and maneuver in confined space. Therefore, the space constraints of the pipeline require taking into account the volume of the battery or its energy density in terms of kWh/L.

The cost of the battery has also to be factored in, but in general higher energy density batteries would be preferred. A list of alternative batteries with their energy densities is provided in the Appendix. (This information is taken from the web site: http://www.energyadvocate.com/batts.htm.)

As the energy density is one of the key considerations in battery selection, of the batteries listed, magnesium hydride with Ni-catalyst appears to be a front runner, as its energy density is more than 100 times that of the lead-acid batteries. However, this and other hydride batteries are unsuitable for this application because they only serve the purpose of hydrogen carrier, not of electricity generation.

The operating condition of the selected battery must also be consistent with the ambient temperature, high-pressure natural gas environment in which the battery must operate. This may preclude selection of a sodium-sulfur battery, for example, as it operates at 350^{O} C. Maintaining this battery operating temperature in the pipeline would be problematic. Lithium-sulfur battery, having 10-times the energy density of a lead-acid battery, appears to be a suitable candidate for this application. It also enjoys the advantage of flat discharge curve, low internal resistance, and operating safety record.

On the basis of the assumptions that (a) robot's crawling action is similar to walking of a human being and (b) thermodynamic efficiency of a human body is about 20%, the stored energy requirement of a 50-kg robot crawling a horizontal distance of 40 miles at 1 mile per hour before having to be recharged is estimated to be about 1 kWh. Therefore, the mass of a lithium-sulfur battery, which has energy density of 220 watt-hrs/kg, for this hypothetical application is projected to be about 5 kg. (Robert Gross of OSPS/NETL has provided some original computations that are consistent with the numbers given in this paragraph and some insight into the underlying principles of mechanics.)

This is a very rough, back-of-the-envelope type estimate of the battery mass. Secondly, it does not take into account (a) energy requirement for the operation of the robot, (b) resistance encountered by the robot when it is crawling against the flow of natural gas, and (c) energy required for the robot to crawl uphill, etc. Therefore, the estimate should be viewed only as indicative of the feasibility potential.

An alternative and more realistic assessment of lithium-sulfur battery mass is based on projected 200 watt power requirement of the robot for all of its operations. For a one way distance of 40 miles traversed by the robot at 1mile per hour, robot will need 8,000 watt-hrs of energy, which corresponds to about 40 kg battery mass.

The last key factor in rechargeable battery decision is its recharging characteristics, i.e., recharging period, overcharge protection, and cycle life (i.e., total practical recharging cycles), etc. The recharging period impacts the robot operation itself, disrupting its mission(s) during the charging period. The cycle life determines the frequency with which the battery needs to be replaced. A battery such as silver-zinc battery, which has a poor cycle life - typically only 5 to 50 cycles for high rate cells and operating life of only 2 to 18 months once filled, will require frequent replacement and thus negate the chief advantage of robotic technology, viz., uninterrupted service over an extended period without needing human intervention. Even the best cycle life of batteries does not generally exceed the limit of 500 cycles. Thus, depending on the frequency of recharging, they may need to be replaced as frequently as every two years.

Dr. Joon Kim of Moltech Corporation (Tucson, AZ) (www.moltech.com) has reported that his company plans to start producing by the end of the year 2003 rechargeable Li-S batteries with mass energy density of 300 Wh/kg and volume energy density of 400 Wh/L. The operating temperature of the battery is in the range of $-40^{O}C$ to $50^{O}C$ and the battery can operate and can be recharged in oxygen-free environment. According to Dr. Kim, Moltech's Li-S batteries would require 4 to 5 hrs for recharging and their cycle life is expected to be 500 cycles (up from current 300 cycles), i.e., they could be charged 500 times. PolyPlus Battery Company (Berkeley, CA) (www.polyplus.com) is another company active in the Li-S battery technology. Its batteries are claimed to have energy densities of 420 Wh/kg, and 520 Wh/L.

No significant regulatory or public acceptance issues are anticipated in the use of rechargeable batteries for robots in the natural gas transmission pipelines.

Fuel Cells

In principle, fuel cells as a power source for robots in a natural gas pipelines can use the natural gas surrounding it as a fuel. However, the fuel cell also needs an oxidant, which has to be supplied from an external source. Separation of small quantity of oxygen that may be present in the natural gas stream for the operation of a fuel cell has been proposed. Generally, there is very little oxygen present in natural gas. Secondly, means of separating oxygen from natural gas have not been developed as yet. Carrying high-pressure oxygen in a natural gas environment is extremely hazardous, as it has the potential to explode, and is hence unacceptable. Additionally, robot's oxygen supply would have to be replenished periodically. This would be a much more hazardous task as compared to recharging of a battery power supply.

Hydrogen peroxide (50% aqueous solution) may offer a somewhat safer option. (Fuel cells using 50% hydrogen peroxide solution have been developed for their application in marine environment.) Hydrogen peroxide needs catalyst to produce oxygen, usually potassium iodide or more often manganese dioxide. One of the limitations of hydrogen peroxide solution as a source of oxygen is that the available oxygen is only 23% of the mass of the solution. Secondly, when it is depleted, the depleted solution has to be removed and fresh peroxide solution has to be supplied. This would be much more cumbersome than recharging of batteries of robots in natural gas pipes. Furthermore, any leakage of peroxide solution in the pipe would pose a serious hazard, as it is a source of oxygen.

For a 50-kg robot crawling a horizontal distance of 40 miles at 1 mile per hour nominal speed and requiring 200 watts of power for its locomotion, and diagnostic, data transmission, and other functions would require a minimum of 30 kg of fresh 50% hydrogen peroxide solution at the end of the trip, if (a) fuel cell thermodynamic efficiency of 40% and (b) ~20% safety margin for robot energy needs and fuel cell functioning are assumed.

There are few other commercially available non-gaseous sources of oxygen, viz., ammonium perchlorate, potassium permanganate, potassium dichromate, magnesium peroxide, potassium bromate, and ammonium persulfate. This list is not comprehensive. Ammonium perchlorate is used in rockets and is considered extremely hazardous by several US Government agencies (OSHA, DOT, DOD, and FEMA, etc.). Heat, friction, shock may cause it to explode, especially when contaminated with carbonaceous material. To release molecular oxygen needed for the fuel cell operation, it needs to be heated, but heating causes it to decompose violently. Therefore, it is not a suitable source of oxygen.

Potassium permanganate and dichromate normally provide oxygen in ionic form, not molecular form, in an aqueous medium. They may be suitable candidates as source of oxygen; however, their use does not readily fit into the existing fuel cell designs. Entirely new type of fuel cell will, therefore, have to be designed. Magnesium peroxide would function in a similar manner as hydrogen peroxide. The same frequent and cumbersome replenishment issues exist for these oxygen sources (potassium permanganate, potassium dichromate, and magnesium peroxide) as for aqueous hydrogen peroxide.

Potassium bromate and ammonium persulfate in solid form are also used as source of oxygen. Upon heating they release oxygen. Supplying heat for these and other chemicals to free oxygen needed for fuel cell may pose hazard in natural gas environment that exists in the pipeline. Creating a source of heat will need additional component that needs to be added to the fuel cell, making its design more complex. Possibly, the waste heat from the fuel cell can be used to generate oxygen. If this is not feasible, electricity generated by the fuel cell is another source of heat, but this will increase duty or load of the fuel cell. Replacing solid depleted bromate or sulfate with fresh supply (as compared to replacing liquid peroxide solution, for example) will be technically much more challenging.

There are four types of fuel cells, either commercially available or under development, viz., phosphoric acid fuel cell, molten carbonate fuel, solid oxide fuel cell, and proton exchange membrane fuel cell. Of these, only proton exchange membrane fuel cell has the suitable operating temperature (~90^{O}C), but it uses hydrogen, not natural gas, as fuel. Its performance degrades due to poisoning of anode by carbon monoxide and sulfur-containing gases, which can be a major handicap in this application.

At present, for reasons cited above this option is probably unfeasible.

Radioisotopic Thermoelectric Generators (RTGs)

RTGs enjoy the distinct advantage of long and uninterrupted service life over the other options. Strontium-90 and plutonium-238 are two radioisotopes, with half-lives of 28 years and ~87 years, respectively, that are used at present for RTGs. These long half-lives are the bases for the chief advantage of RTGs. RTGs are powered by the decay heat of these long-lasting radioisotopes. The decay heat generates power by sustaining a large temperature gradient across a thermocouple junction. The long half-lives of radioisotopes result in a practically flat discharge curve for an extended period though strictly speaking power output of RTGs is a function of time. (Since thermal energy of RTGs is the result of its radioactivity, as time proceeds radioactivity declines and so does thermal energy output.) RTGs have no moving parts and has been found to be a highly reliable source.

In the USA most of the RTG applications have been in space missions to outer planets, with at least one case of military-related remote, unattended monitoring application in Burnt Mountains of Alaska. Soviet Union (now Russia) has apparently made extensive use of RTGs on the earth as well as some in their space missions.

In spite of this track record, public acceptance of their use in natural gas transmission pipelines is a huge question mark. Recent news items of discarded RTG units in the Republic of Georgia causing radiation-related sicknesses in hunters who accidentally found them further dim prospects of public acceptance. Potential does exist for these RTG units to be stolen from the pipelines by terrorists and used to make "dirty nuclear weapon" even though radioisotopic material in RTG is not nuclear weapons grade material.

Operating temperature of RTG's hot junction is 1,300 K and at the cold junction about 500-600 K, with efficiency of less than 10%. Though radioisotopic material in a RTG is always well shielded, more than 90% of heat, which is not converted into electricity, has to be dissipated. In natural gas pipeline, the convective heat transfer provided by the gas flow itself may be inadequate to ensure that the gas or the pipe material does not get excessively hot. This is a particular cause of concern if the possibility exists that robot may remain stationary for some time at a particular location – during repair work, for example. Any localized heating could cause weakening of the pipe material or natural gas pressure build-up. For this reason heat transfer considerations need to be analyzed quantitatively and if necessary, provide a cooling fan. The energy for the fan would have to be supplied by RTG.

One serious drawback of RTGs is their relatively low power densities (power to mass ratio) though their energy densities are very high. For example, the RTG used in the Galileo spacecraft weighed 56 kg of which 11 kg was plutonium dioxide and it generated ~285 watt electric power. (The excess mass is made of iridium, lead, or tungsten and is for the purpose of radiation shielding to reduce it to about 10 millirem/hour at a distance of 1 meter.) This corresponds to about 6% thermal efficiency and power density of ~5 W/kg. (The RTGs located in Burnt Mountains of Alaska have even lower power densities, as low as 0.053 Watt/kg, due to the large mass of the lead shielding used for these land-based units.)

Another drawback of RTGs is that once fabricated they can not be turned off. They are also reportedly difficult to handle because of the precautions that must be taken to due the high temperature and radiation effects. To install or remove them from pipelines would require specially trained operators and special equipment.

Since all RTGs are manufactured for the military or space missions, i.e., for government use and they are typically custom-manufactured, their cost information is not readily available. Pu-238 is extremely expensive and fabrication of RTG is very complex and dangerous – almost certainly involving robotic technology. An estimate put forth by the Atomic Energy Insights is that the price of a 50-watt plutonium-238 powered RTG unit would be close to a million dollars. Another Internet source reports $3,000/Watt thermal for Pu-238, which leads to an estimated price of $1,500,000 for a 50-watt RTG unit, assuming 10% efficiency. For strontium-90, reported cost is $250/Watt thermal, corresponding to $125,000 for a 50-watt RTG unit, assuming 10% efficiency. (However, it has been suggested that strontium-90 RTGs would have lower efficiency because they operate at lower temperature.)

Since the RTGs for robots in pipelines would be fabricated for and used by private companies, their fabrication, ownership, and use would be subject to the Nuclear Regulatory Commission (NRC) regulations. The interstate pipelines may be subjected to additional regulations involving jurisdictional aspects of different states, as NRC has authorized some states to manage some regulations on its behalf. Similarly, the intrastate pipelines located in states that have NRC authorized regulatory authority will have to obtain licenses from that state's regulatory authority.

The manufacturer/distributor of RTGs would need to obtain a license for possessing strontium-90, a byproduct material, and/or plutonium-238, a special nuclear material, as well as distributing RTG devices. (Each model of RTG device will have to have separate distribution license.) NRC reviews the safety aspects of fabrication and conducts device review prior to issuing registration certificate to the manufacturer of RTGs. Each operating company that employs RTG powered robot(s) in its pipeline(s) also needs to obtain NRC license for receiving and possessing RTGs. This license is applicable for all the RTG units owned by the company, i.e., no separate license for each RTG unit owned by a company is required. This license also requires prior end use review by NRC. There are various application fees as well as annual renewal fees, which would add to the cost of robot operation.

More in-depth analysis of RTG viability as a power source for a robot in a natural gas pipeline will have to incorporate failure mode analysis. Any feasibility study could include as a first step experiments to ensure adequacy of locomotion and maneuverability of a robot powered by RTG by loading on a robot excess mass equal to that of RTG but powered by an external power source through electric wires.

The high cost of RTG, its low energy density, extreme handling difficulties, major regulatory requirements, and anticipated public resistance to it may make RTG usage as a power source in a natural gas transmission pipelines highly unlikely in spite of its long service life.

CONCLUSIONS

At present rechargeable batteries should be considered as the front runners in the application of robot in the natural gas transmission pipelines. They are probably going to be much less expensive and easier to manage than RTGs, and would have wider public acceptance and fewer regulatory constraints, but would require much more frequent replacement.

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Appendix

Batteries

Batteries are not *sources* of energy	Batteries, like hydrogen, are not a source of energy. They are useful *carriers* of energy. The table below shows how much energy (both in watt-hours and in joules) is stored by one kilogram of battery (exclusive of its case) for batteries of various types.

Battery Type	**Energy Density** **W-hr/kg** **(watt-hour per kilogram)**	**Energy Density** **J/kg** **joules per kilogram**
Lead-acid	22	79,200
Nickel-cadmium (Ni-Cd)	44	158,400
Silver-Zinc (Ag-Zn)	110	396,000
Sodium-sulfur (Na-S)	220	792,000
Lithium-Sulfur (Li-S)	220	792,000
Iron-titanium hydride (Fe-Ti-H)	590	2,124,000
Magnesium hydride with Ni catalyst (Mg-H (Ni))	2300	8,280,000
Gasoline (not a battery!) (for comparison)	13200	47,500,000

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