SODIUM HYPOCHLORITE GENERATION FOR HOUSEHOLD WATER DISINFECTION IN HAITI

by

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ABSTRACT

Currently, owners of the Gift of Water, Inc. (GWI) household water filters use imported commercial chlorine bleach for disinfection as part of the GWI initiative in Haiti. Problems associated with adequate supply, high costs, and limited shelf life of the bleach have led to the need for an alternative chlorine source, i.e. using a sodium hypochlorite generator to manufacture a disinfectant locally. Dumay, the site of the largest and longest-running GWI program, was chosen for the pilot project, and the projected chlorine needs within 2 to 5 years were estimated. During a field visit in January, availability of the hypochlorite generator's requirements, salt, fresh water, and electricity, was assessed, as were conditions in Dumay for such equipment.

A study of generator mechanism was performed, and the most appropriate unit determined through the use of a weighted factor comparison where non-monetary, subjective qualities are incorporated into the selection process. It was key in this analysis that factors such as ease of use and manufacturer support be given equal importance as economic considerations. Based on this comparison, the SANILEC-6 unit, made by Exceltec International Corporation, was found to be the most suitable for Dumay.

Guidelines for project implementation, both for generator operators and filter owners, were created, and simplified with the lowering of the chlorine concentration in the GWI filter. The generated solution has a lower chlorine concentration and thus higher stability than chlorine bleach, and the time span between manufacture and use is reduced to a matter of weeks. Therefore previous practices dosing the filters to compensate for bleach degradation will no longer be necessary. It is thus recommended that the filter's chlorine concentration be reduced from 16 mg/L to 5 mg/L, corresponding to adding 2 standard capfuls (12 ml) of solution instead of 1. This practise should facilitate the transition to the generated solution while maintaining complete disinfection of the raw water.

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1.0 Introduction

The non-profit group Gift of Water Inc. (GWI), based in Satellite Beach, Florida, has been working to improve the quality of drinking water in Haiti since 1995. GWI provides rural Haitians with simple point-of-use water systems, enabling them to treat their own drinking water in an effective and appropriate manner. The seven Haitian communities with GWI programs have achieved significant measures of success regarding water treatment, yet some problems continue to hinder the progress and efficacy of this initiative. A critical issue involves drinking water disinfection, i.e. the filters' source of chlorine is inconvenient and expensive, and current practices impede the program's self-sufficiency. The purpose of the following thesis is to provide a solution to the difficulties associated with the generation, transportation, and longevity of chlorine sources used in Gift of Water purifiers in Haiti.

Currently, commercial chlorine bleach is used as a disinfectant in the GWI filter, bought locally by technicians or filter-owners. All commercial bleach in Haiti, however, is imported from the United States or the Dominican Republic. This practice is becoming increasingly problematic due to issues of availability and stability of the bleach, as well as problems associated with Haiti's dependence on foreign products. Recent escalation of political instability has further jeopardised GWI's source of chlorine, and the future looks to be no less difficult. The solution I propose here is to generate sodium hypochlorite as a chlorine source within Haiti, replacing imported chlorine bleach, thus alleviating the above problems. Moreover, in-country chlorine generation gives Haitians a greater stake in the GWI initiative, provides jobs and skills, and represents a move towards a self-sufficient and sustainable water purification project.

In order to ascertain the most appropriate hypochlorite generator and implementation of it, I have structured the project so as to assess Haiti's particular needs and how they might realistically be met. A study of appropriate technology is important in pinpointing the most effective ways of introducing this technology to Haiti, and in balancing technological and social factors in such an intervention. Further, I have studied the context of the GWI project, i.e. the current situation in Haiti with respect to its economy, politics, and environment. This field study involved a site visit in January 2001, where I visited six communities with GWI programs.

In this thesis, the mechanics of chlorination as a disinfection method are investigated, as well as the operation of point-of-use hypochlorite generators. The requirements of a generator, including brine solution and electricity, are reviewed under Haitian conditions, as are the economic and project comparison evaluation methods of selecting a specific generator. Finally, a generator is recommended and I provide guidelines for its implementation and use in the community of Dumay as a pilot project.

2.0 Appropriate Water Quality Technology

Before researching and recommending action with respect to sodium hypochlorite generation in Dumay, I thought it important to study the concept of "appropriate technology" and how to factor this concept into my project decisions. The best technical solution is not necessarily the best overall solution, and cost cannot be the ultimate measure in project evaluation. Some criteria are more qualitative than others, such as cultural appropriateness and ease of use, however I strove to consider them equally with numerical aspects including cost and system life cycle. It was my goal to balance each of these criteria and develop a solution and implementation plan specifically appropriate for Dumay, Haiti. Although this type of project will be readily transferable to other communities in Haiti, as well as to other developing countries, some factors (e.g. community support and availability of fresh water, salt, and power) will demand reassessment.

The success of a new facility primarily depends on proper and effective operation, as well as acceptance and use by its beneficiaries. Technology must be in balance with the circumstances under which it operates, and appropriateness must be considered on a long-term basis. Common problems associated with projects in developing countries include lack of qualified and motivated labour, lack of community support, bad management, and limited financial resources (Lawrence and Block, 1968). The use of sophisticated methods and expensive imported equipment is less likely to be locally accepted or sustainable over the long term.

An important benefit of sodium hypochlorite generation is its effect on Haiti's dependence on imported products. A Haitian dollar is better spent on Haitian-made salt and labour than on imported commercial bleach. Such initiatives will allow Haiti to grow in a sustainable and realistic manner, and work toward gaining self-sufficiency. Local production is associated with questions of local skills and materials, however, but a well-chosen system should not be hindered by such conditions. The training and employment of community members to operate the generator and distribute sodium hypochlorite solution further place the project in local hands. Because sodium hypochlorite generation gives Dumay's residents the responsibility of disinfecting their water as well as producing the disinfectant, it progresses towards GWI's ultimate goal of putting the entire project under Haitian control.

3.0 Haiti

3.1 History and Politics

Of all the countries in the Caribbean, Haiti has remained closest to its African roots. Unfortunately, this connection includes the degree of poverty experienced by the Haitian people, as well as its widespread political instability and corruption. Haiti is an unexpectedly beautiful and vibrant country, however in addition to economic and social turmoil, much of its population is struggling with basic survival.

Haiti gained independence from France in 1804, and since that time has been in a continual state of flux marked by a lack of infrastructure and severe poverty. Its history has seen corrupt political leaders, dictatorships and international, primarily US, intervention and occupation. The most recent political activity is centred on Jean-Bertrand Aristide, first elected president in 1990. This election was followed by ten years of upheaval, with a coup, condemnation by the United States and the Organisation of American States (OAS), and subsequent sanctions and embargoes. Ultimately such actions were most felt by the innocent Haitian population. Although the US was heavily involved in returning Aristide to power in 1994, doubts were beginning to circle regarding his mental stability.

In November 2000's heatedly contested election, Aristide was again elected President of Haiti. Both violence and apathy have marked the period between Aristide's election and inauguration in February 2001. In the cities, primarily the capital of Port-au-Prince, clashes occurred between Aristide supporters and opposition parties, whereas in the rural areas, even during our field visit in January, little was mentioned regarding Haiti's political situation. Perhaps the rural population believe that the government, regardless of who holds power, has no real influence over their lives as virtually no infrastructure exists, and the little that has been implemented is due to efforts by international aid organisations.

3.2 Environment and Economy

Occupying roughly one third of the tropical island Hispaniola, Haiti is 27750 square kilometres in area, over 60% of which lies on a gradient of above 20% (Dogget and Gordon, 1999). As one of the most densely populated countries in the Western Hemisphere, the combination of human stress on the land and demand for charcoal as fuel has caused severe deforestation. It has been estimated that from 2 to 5% of the country's original forest cover remains (Dogget and Gordon, 1999), associated with massive erosion and significant loss of rich topsoil. Further, 1998's Hurricane Georges catastrophically affected the country, virtually destroying communities such as Fonds Verets, a southwestern village with a GWI program. Environmental degradation is not the most pressing issue in Haiti however; first and foremost problems associated with poverty and overpopulation must be addressed.

Approximately 80% of Haiti's population are rural, living off agriculture within the lower of the two Haitian economies. This agrarian peasant economy relies on subsistence farming and the selling of produce (maize, rice) at local markets. At the other end lies Haiti's business class, located in Port-au-Prince and primarily involved in import and export activities. Being the poorest country in the Americas, Haiti is greatly dependent on foreign aid and as the government remains unstable and the economy continues to fall, this dependence will most likely continue. To a significant extent, Haiti's economy relies on its extensive population living throughout North America. In 1999, Haitians abroad sent an estimated US$300 million to their families who remain (Dogget and Gordon, 1999).

In 1999, the World Bank listed Haiti's population as 7.7 million, with a growth of 2.4% and doubling time of 31 years (World Bank, 2001). Average life expectancy was 54 years, with an infant mortality rate of 71 in 1000 live births. Of this population, 28% had access to "safe water". According to the Economist Intelligence Unit (1999), Haiti's 1998 GDP growth, which had been negative in 1994, was 2.7%, with 24% of it coming from agriculture. Haiti's main exports are manufactured goods while the principal import is food, and the primary destination of imports and exports is the United States. As political chaos continues, there is little hope of recovering millions of dollars worth of unreleased aid from the US and elsewhere. Despite the GDP growth, the continuing Haitian political crisis is preventing passage of legislation, such as a new budget, thus much external funds cannot be disbursed and the government must rely on the central bank.

The Economist's outlook for 2001 is dominated by Haiti's recent elections, local and presidential, because of the associated and unceasing turbulence (The Economist Intelligence Unit, 1999). This tense social climate leads to little confidence in business opportunities, and Aristide's return is unwelcome to local businesses because of his socialist leanings. Moreover, uncertainty surrounds Aristide's economic policies, labour relations and relations with the US, particularly as the Republicans now hold power. The Economist predicts a dip in the GDP growth below 2% and a widening of the already high trade deficit. From 1998 to 1999, growth in exports fell from 46% to 10% while import growth grew from 24% to 32% (The Economist Intelligence Unit, 1999). The Haitian dollar, once fixed to equal a US dollar, was worth approximately 20 cents during our trip in January 2001.

3.3 Water Management

Although the focus of this project is drinking water quality, I cannot address this issue without first discussing Haiti's severe water resources problem. The GWI purifiers are of no use if owners are unable to fill them with raw water. Even during our short stay in January, not considered one of the driest months, we witnessed water shortages in some GWI communities. It was fairly common to find wells or fountains running dry over the course of a week's stay in an area, and some purifier owners resorted to buying water from other community members, usually those with private cisterns. According to GWI, even those with cisterns occasionally purchase large quantities of water from tanker trucks.

Essentially, Haiti's water problem lies in its management for a population that continues to grow in cities and rural areas, with an increasing agricultural water demand. Water supply is a significant problem for both rural and urban areas; however some Haitians believe that the situation should be viewed in terms of water resources management, not water scarcity. A 2000 World Health Organisation (WHO) report stated that Haiti's national services for the provision of drinking water were meeting 46% of the population's needs (WHO, 2000). In an April 2000 interview with the Panos Institute, members of Haiti's National Service of Water Resources (SNRE) claimed that this situation is linked to the lack of investment in water exploitation as well as the lack of resource management policies (Octave, 2000). No legal framework exists for the authorisation of one broad-based institution, capable of implementing the necessary studies for water exploitation and management. Current regulations give several institutions the right to exploit water resources, regardless of experience or technical abilities. The SNRE is a part of the Ministry of Agriculture, Natural Resources and Rural Development, while other water management companies include:

- the National Service of Drinking Water (SNEP), covering ten cities throughout the country;
- the Metropolitan Autonomous Station for Drinking Water (CAMEP), a commercial organisation covering the Port-au-Prince area:, and
- national and international non-governmental organisations that implement drilling and capturing activities throughout the country, installing public wells, reservoirs, and fountains.

SNEP technicians speak of projects where drilling is done seemingly without consideration of available reserve levels. Fountains, including every one visited in six Haitian communities, run day and night with no collection systems for the water that is unused.

The serious water resource problem in Port-au-Prince is worsening as the population continues to increase more than anywhere else in the country. CAMEP can provide 120,000 cubic metres of water per day to the metropolitan area, but recent assessments indicate that over 200,000 m^3/d are needed (Octave, 2000). While in Dumay, we noticed the beginnings of a project that will pipe water from Dumay to Port-au-Prince. Although I was not able to obtain any concrete information on this project, it is unlikely that its effects on Dumay's water supply were considered.

Such water-related problems do not include those associated with treating drinking water, and the lack of infrastructure impedes a centralised program. Therefore initiatives such as GWI’s are the most feasible solution in Haiti, relying on small community organisations to introduce and monitor water programs. Giving individual households control over the quality of their drinking water better ensures that treatment is regularly and effectively performed.

3.4 Haiti Field Study

During the month of January, I had the opportunity to see the GWI project and experience its problems and successes first-hand. Our team spent three weeks in Haiti (Figure 1), travelling to six of the seven communities with GWI water purification projects. In each community, I met the technicians and spoke with project leaders as well as local purifier owners.

Figure 1: Map of Haiti

The villages and towns with GWI initiatives differed notably in their locale, community structure, wealth and availability of fresh water. In the northeastern region, Ferrier's project was very well organised, and water is readily available for the vast majority of the year. Seventy filters are now in place, and over three hundred families have signed a list expressing interest in obtaining a filter. The scheme in Bas Limbe, however, nearer Cap-

Haitian, had been much less successful, with disorganised technicians, a lack of community cohesion, and only forty filters in place. Some of these filters were not in use due to problems with water supply, and of those that were being used, owners seemed to have difficulty with adding sufficient chlorine for disinfection.

In southeastern Haiti, we visited the two communities of Fond Verets and Barasa, struck by serious problems with water supply. In fact, Pere Belneau, a local priest and community leader, cited water supply as Fonds Veret's most pressing concern. The lack of fresh water is so serious that some people had been buying water from other community members with cisterns (for rainwater collection). Barasa's project had similar problems, and approximately 50 filters have been distributed in each community. Les Palmes is located in a very mountainous part of the country west of Port-au-Prince, thus even visiting the remote homes with filters is a daunting task. Some filter owners receive little attention because of the inaccessibility of their homes, and the fact that approximately 600 filters are in place with only ten acting technicians to guide their use.

Dumay, situated slightly south of Port-au-Prince, began its GWI program in 1996. This community is by far the most experienced and saturated with water filters, with estimates ranging from 1800 to well over 2000 purifiers in use. The filter distribution covers a great physical distance, and only eleven technicians monitor the project. Strategies such as monthly community meetings help in educating locals about the importance of drinking water disinfection and the correct usage of the GWI filter. The water committee is in charge of selling chlorine bleach to the community: ten stations throughout the area sell 250 ml bottles of bleach for 3 gourdes (approximately $0.12 US). Generally, Nathan Dieudonné, a local pastor and community leader as well as GWI's Co-ordinator of Haiti, buys bulk quantities of chlorine bleach from Port-au-Prince as is needed, with prices averaging at 6 gallons for 52 Haitian dollars (equal to 260 gourdes or $10.40 US). In selling bleach to the community, M. Dieudonné claims that the scheme usually comes close to breaking even. The strong community support, history with GWI and regulation of bleach distribution make Dumay ideal for the pilot hypochlorite generation project. In other villages, it is more common to find people supplying their own bleach than in Dumay, which would further complicate the shift to generated hypochlorite solution. The system of community meetings should also be helpful in easing this transition.

In addition to assessment of chlorine demand and bleach prices, our visit to each community included a random check for bacteria in GWI filter treated water, in order to ascertain how successfully the purifiers are preventing water-related illnesses, and to monitor the correct use of the system. Results varied considerably, with some filter owners having erroneous ideas of how and when to add bleach. In a few cases no bleach whatsoever had been added to the raw water. Most technicians were able to provide instruction to community members on correct filter usage, but this type of problem is especially relevant to the proposed plan of using a generated hypochlorite solution. Because the generated solution contains a lower concentration of chlorine than commercial bleach, an increased amount will most likely be required per disinfection treatment in the GWI purifier.

4.0 Chlorination

4.1 Disinfection Using the GWI Filter

The GWI water purification system consists of two 20 L opaque plastic buckets, one placed atop the other (Figure 2). Treated water is obtained from a spigot attached to the bottom bucket. The water purifier removes both particulate and chemical contaminants from raw water and commercial chlorine bleach provides disinfection. In the purifier's top bucket, containing a porous cotton core for sediment removal, a 5.25% chlorine bleach solution is added for source water disinfection. This practice serves to prevent bacterial growth in the granular activated carbon contained in the bottom bucket, which removes chemicals, including chlorine, by adsorption. As the bottom bucket's effluent is chlorine-free, additional bleach is added after filtration in order to continue disinfection until the water is consumed.

Figure 2: GWI Filter

A standard dispensing bottle (approximately 250 ml volume) and small squeeze dropper are provided with each water purifier, as are detailed instructions outlining when and how to add the chlorine bleach. Purifier owners are directed to add 5 drops to the bottom bucket, and pour a full capful of bleach (approximately 6 ml) from the dispensing bottle into the top bucket. The entire purification process requires approximately 2 hours for complete filtration and disinfection. Users are further instructed to store the bleach-dispensing bottle in a cool, dry place, away from sun and heat.

4.2 Chlorination Fundamentals

The fundamental purpose of drinking water disinfection is to prevent waterborne diseases by destroying pathogenic organisms. Populations in undeveloped countries, primarily young children, are vulnerable to such diseases as typhoid, dysentery and diarrheal illnesses. The practice of drinking water chlorination represents one of the most significant public health advances of the 20th century. Formation of chlorine by-products is a serious concern associated with chlorination; however the greatest priority is the microbiological quality of drinking water. Cancer is a critical concern associated with chlorine by-products but the risk of microbial disease is more certain, serious, and immediate an issue. Thus chlorination remains an appropriate disinfection method.

Chlorine is the most widespread disinfectant meeting the following criteria for a public drinking water disinfectant (Faust and Aly, 1998):

- It must destroy the kinds and numbers of organisms present, within the available contact time, water temperatures and fluctuations in condition of raw water.
- It must be dependable and available at a reasonable cost, in a safe and convenient form.
- It must possess the ability to disinfect without rendering the water toxic or objectionable.
- It must persist as a residual, particularly in cases of considerable time lag between disinfection and consumption.
- It must allow for practical, accurate and quick assessment methods for determining its concentration, efficiency and effectiveness.

Before chlorine, a strong chemical oxidant, can disinfect, the chlorine demand of the water must be satisfied, that being the difference between the added oxidant dose and the residual oxidant concentration. In water, free available chlorine can be found in one of three forms: chlorine (Cl_2), hypochlorous acid (HOCl) and the hypochlorite ion (OCl^-). Hypochlorite is the most widely used active chlorine compound in disinfection, due to its powerful germicidal action, non-toxic nature at "at-use" concentrations, economic advantages, and ease of use. Chlorine bleach, sodium hypochlorite (NaOCl), forms the hypochlorite ion in water through the following reaction:

$$NaOCl \rightarrow Na^+ + OCl^-$$

Species distribution is dependent on water pH, temperature, and total chlorine concentration. Industrial strength bleach is 12 to 15% available chlorine, household commercial bleach is 3 to 5.75%, and sodium hypochlorite produced by a generator contains a maximum of 1% available chlorine. "Available chlorine" is an empirical measurement of a compound's oxidising power in terms of an equivalent quantity of pure chlorine; i.e. Cl_2 is 100% available chlorine. It is calculated as though Cl_2 were the oxidising agent in a reaction between free chlorine and the iodine ion. In a titration reaction to assess available chlorine, I_2 acts as an indicator due to its brown/yellow colouring and either Cl_2 or ClO^- oxidises I^- (ASTM, 2001). This comparison is valid because both of the two active forms of chlorine's react with the iodine ion with a 1:2 stoichiometry:

$$Cl_2 + 2I^- \rightarrow 2Cl^- + I_2$$
$$ClO^- + 2I^- + H_2O \rightarrow I_2 + Cl^- + 2OH^-$$

Some commercial chlorine products list the solution's percent chlorine by weight; commercial bleach contains 5.25% chlorine by weight, and (given a bleach density of 1.084 g/ml) approximately 5.7% available chlorine.

Sodium hypochlorite of high chlorine concentration is impractical due to its increasing instability with chlorine concentration. At ambient air temperature, the half-life of sodium hypochlorite is approximately 60 days for an 18% available chlorine solution and 1700 days for a solution of 3% available chlorine (Lawrence and Block, 1968). Heat and light also significantly affect a hypochlorite solution's stability: its rate of decomposition nearly doubles with a temperature increase of 10 degrees Fahrenheit (approximately 5.5 degrees Celsius) (Sconce, 1962). At temperatures reaching 85 degrees Fahrenheit (30 degrees Celsius), the rate of decomposition can be high enough to deplete the solution's available chlorine (Sconce, 1962). Further, as chlorine is a strong oxidant, high concentrations are hazardous and require an extra degree of precaution.

4.3 Hypochlorite generation

The costs and benefits of drinking water disinfection by chlorination depend on site-specific factors such as power costs, availability of brine/sea water, safety, and ease of use. Disinfection using hypochlorite is often the least expensive and most appropriate option.

On-site sodium hypochlorite generators produce a solution of strengths below 1%, usually between 0.6 and 0.8%. These concentrations are under the threshold for hazardous classification, therefore no containment requirements or process safety management concerns are necessary. This provision considerably minimises safety concerns of the facility operators as well as its neighbours. The only raw materials required by the generator are salt and water (or seawater) and electricity. Generated sodium hypochlorite has a pH of 9 as compared with commercial hypochlorite's pH of 13, making it less likely to cause scaling.

Additional benefits of on-site sodium hypochlorite generation involve the elimination of import and transportation issues, as well as the rising costs of imported goods as Haiti's economy continues its downward trend. Haiti's climate is challenging for chlorine storage, with its mean yearly temperature of 26 degrees Celsius (Dogget and Gordon, 1999). Sodium hypochlorite's low chlorine concentration and the reduced storage needs of on-site generation resolve such degradation concerns. The simple nature of the generator further increases its appropriateness for a less developed country. Experience by rural communities in other developing countries indicates that such units are effective and locally accepted and understood, with generator operators needing no technical background. After an outbreak of intestinal illness in La Esmeralda, Guatemala, a portable generator supplied by Exceltec International Corporation was purchased by the Pan American Health Organisation (PAHO) to provide the town a 0.8% hypochlorite solution. The unit is located in the community centre and a local work committee capably operates it, with only a one-day training session by PAHO.

A standard generating system produces 0.6 to 0.8% sodium hypochlorite through electrolysis. The generating cell itself consists of a series of electrodes contained inside a protective shell. With the application of an electric current, the electrodes start an electrochemical reaction where the brine solution (or seawater) is converted into sodium hypochlorite and hydrogen. With respect to brine solutions, the water used in the tank should be as particle free as possible, although microorganism presence is not a concern. Salt impurities may increase calcium build-up on the cathode and necessitate more frequent maintenance, however. Household white vinegar can be used to clean the cell. Most generator models are available using either alternate current (AC) or direct current (DC) electricity. During the electrolysis of a brine solution, chlorine is generated at the anode and hydrogen at the cathode. The following reactions occur in the generator (Exceltec, 2001):

$$2Cl^- \rightarrow Cl_2 + 2e^-$$
$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$
$$Cl_2 + H_2O \rightarrow HOCl + HCl$$
$$2NaCl + H_2O \rightarrow NaOCl + NaCl + H_2$$

The essential processes and requirements of a hypochlorite generator are relatively simple with respect to North American standards. In Haiti, however, such technology is not in any way widespread, thus a pre-engineered system is most feasible. A number of companies that produce such units, designed for easy installation, operation, and the meeting of specific requirements, were contacted. Each firm expressed interest in working on this project and company representatives were extremely co-operative, answering specific questions and providing recommendations and guidance.

4.4 Assessment of Dumay's Chlorine Demand

Deciding on the generator capacity required for Dumay, allowing for future expansion of GWI's filter distribution without over-designing the project and making it prohibitively expensive, was an extremely difficult task. The prediction of future water purifier use is problematic in itself, but the uncertainty was increased by the contradictory information collected on Dumay's current demand. Chlorine requirements were based on technician surveys to determine the number of purifiers in the area as well as the frequency of chlorine dispenser bottles refilling. Technicians had differing estimates of the numbers of purifiers in the Dumay area, and GWI's estimate was based on parts shipped to Haiti and was much higher. Further, GWI has manufactured parts for an additional ten thousand water filters to be distributed throughout Haiti, with approximately one third designated for Dumay. The most common estimate for Dumay's filters currently in place was between 1800-2000, and I used the conservative figure of 2000 in my calculations. The frequency of bleach bottle refill was assessed through surveys of individual purifier owners, and once per month was the most common estimate. Even this information was questionable, however, because although some families claimed to use their filters every day, the majority responded that they treated water approximately five times per week. Considering a 250 ml bottle being refilled once every 30 days, and the addition of approximately 6 ml of chlorine per use, the frequency of filter use is over once per day:

- filter use per month = (250 ml per bottle)/(6 ml per filter use)
  $\cong$ 42 times per month

In light of these contradictions, I conservatively held that the bottles were filled once per month, in order to ensure adequate chlorine supply. These discrepancies do beg the question of how much of this chlorine bleach is actually being used in the filters.

In determining a capacity for Dumay's generator, I assumed that 2000 filters are currently in use, and in the relatively near future another 3000 would be distributed from the pending GWI shipment. I explicitly acknowledge, however, that assumptions are worth little in Haiti, and with the continued political instability and tensions between Haiti and the US, the GWI program could be hindered. Optimistically, I predict that within the next few years, the number of filters in Dumay will be roughly 5000.

Currently, GWI's practice is to maintain a filter chlorine concentration much higher than that recommended by the Centres for Disease Control and Prevention (CDC). In similar projects using generated sodium hypochlorite, the CDC encouraged a treated water concentration of 0.5 to 2 mg/L (Centres for Disease Control and Prevention, 2001), whereas GWI practice results in approximately 16 mg/L:

- Cl_2 concentration = $(0.0525 \text{ kg/L})(10^6 \text{ mg/kg})(0.006 \text{ L})/(20 \text{ L})$
  $\cong 16$ mg/L

This is done to satisfy the chlorine demand of the raw water, which varies considerably throughout the year. Further, as the chlorine is obtained from imported commercial bleach of 5.25% chlorine, degradation interferes with its ability to disinfect, therefore high chlorine doses are needed to compensate. Roughly three years ago, Phil Warwick, GWI's founder, conducted a trial where the chlorine concentration was reduced to 8 mg/L (corresponding to the addition of 3 ml per treatment). According to his account, this action resulted in a decrease in the clean water produced, and although the exact cause was not identified it was suspected to be bleach degradation.

Based on both the CDC and GWI's experiences, I recommend a trial period using a filter concentration of approximately 5 mg/L, corresponding to adding 12 ml (2 capfuls) of generated sodium hypochlorite solution. (If the raw water's chlorine demand is not satisfied with this dose, it can readily be increased to 7 mg/L with the addition of another 6 ml per treatment (corresponding to 3 capfuls). This will require further study in Dumay.) I believe that the issues responsible for decreased clean water in GWI's previous tests will not be similarly problematic with the 0.8% chlorine hypochlorite solution. Because sodium hypochlorite stability increases with decreased chlorine concentration, and the transportation and storage times are reduced to a matter of weeks, degradation will not affect the disinfection capabilities of the solution. Thus raw water will be effectively treated with a 5 mg/L chlorine concentration, while still providing a margin of safety to account for chlorine demand.

As commercial bleach currently in use contains 5.25% chlorine, the maximum available chlorine requirement in Dumay, maintaining a 16 mg/L chlorine concentration, is calculated as follows:

- filter number = 5000
- dispensing bottle size = 250 ml = 0.25 L
- 5.25% bleach needed = (5000)(0.25 L/ month)
  = (1250 L/month)(month/30.4 days)
  ≅ 41 L/day
- available chlorine needed = (41 L/d)(0.0525 kg Cl/L)
  ≅ 2.2 kg/d

The amount of available chlorine needed to maintain a 7 mg/L filter concentration (the conservative estimate, corresponding to the maximum amount of chlorine required) is determined assuming that filters are used once per day:

- available chlorine needed = [(7 mg/L) / (16 mg/L)] (2.2 kg/d)
  ≅ 1 kg/d
- 5.25% bleach needed = (1 kg/d) / (0.0525 kg/L)
  ≅ 18 L/d

Therefore Dumay requires a sodium hypochlorite generator with a capacity of 1.0 kg/d of available chlorine, based on the maximum chlorine demand. Ideally, if the 5 mg/L concentration is sufficient, chlorine requirements will be even lower, but as this is not certain I am assuming the conservative amount.

5.0 Brine in Hypochlorite Generation

5.1 Brine Solution

Although some commercial units can generate sodium hypochlorite using seawater, the use of brine solution is more common and can achieve higher concentrations of available chlorine (some seawater systems produce solutions of only 0.2% chlorine). Moreover, salt is more readily transported than seawater, particularly important as Dumay is located over 30 km away from the coast, and road conditions are extremely poor. Because of Dumay's location on flat plains near a mountainous region, water supply is not the problem it tends to be in other GWI communities. Adequate fresh water is available to supply the community with household and irrigation water as well as run a sodium hypochlorite generator. The effect of a new project transporting water from the Dumay area to Port-au-Prince, currently in the construction phase, may impact water availability for brine in the future. Neither the scale of this project nor its predicted effect on Dumay's water supply is known, and information on such projects is difficult to obtain. During our January field visit, construction workers were not willing to speak about their work. GWI has considered such uncertainties regarding water supply, however, and is currently exploring plans to collect rainwater for use in the sodium hypochlorite generator.

5.2 Salt

Salt is essentially sodium chloride (NaCl), a crystalline compound commonly found throughout nature. Sodium chloride has a cubic structure and is colourless to translucent, depending on its purity. It is a hygroscopic substance, absorbing water from the atmosphere. Seawater's average salinity is 35 parts per thousand (ppt), and NaCl makes up over 77% of the dissolved salt. Other species include $MgCl_2$, $MgSO_4$, $CaSO_4$ and KCl, with trace amounts of MgBr and $CaCO_3$ (Kaufman, 1960). Salt purity strongly depends on the type of process used for recovery, as well as the quality of its source. Regulated production methods for evaporated and solar salt normally yield a salt of over 99% NaCl.

5.3 Solar Evaporation

The world's most basic salt supply is obtained from natural deposits due to solar evaporation of shallow seawater pools (See, 1960). Deliberate confinement of seawater in shallow lagoons increases such evaporation, where salt crystals form on the brine surface and are held by surface tension until they either become too large to float or are disturbed. Salt produced in this manner is commonly known as “solar salt.” It is never found absolutely pure because the majority of salt is deposited from ocean water that contains many dissolved and suspended materials. In addition to salts other than NaCl, insoluble impurities such as anhydrite, dolomite, iron oxides, and quartz are often found, as well as silt and clay (See, 1960).

Populations have practised solar evaporation for centuries, and methods have improved steadily and significantly. In developing countries such as Haiti, however, production methods remain crude and simple. The type of solar salt produced here is commonly impure because the evaporating stages are not separated and each brine batch is reduced as nearly to dryness as possible. The end product is often damp, with a bitter taste due to a high content of bittern salts. ("Bittern" denotes the liquid remaining after evaporation and crystallisation of NaCl from seawater, containing concentrated forms of calcium and magnesium chlorides and sulphates, bromides, and iodides.) The NaCl concentration of such salt can be as low as 65%, with 28% hydrated magnesium salts, 4% gypsum ($CaSO_4 \bullet 2H2O$), and small amounts of other compounds found in seawater (See, 1960). Another issue is that the product obtained by evaporating seawater to dryness strongly tends to absorb water vapour from the atmosphere. Practically, the use of seawater involves problems of sanitation and transportation; sand and grit are commonly found as solar salt constituents.

The solar evaporation method can be improved, relatively simply, by removing salt from the pond before all the brine has evaporated, thereby eliminating bittern salts. After evaporation has proceeded until salt-tasting crystals are found at the surface, the brine is transferred to a second pond where it continues to evaporate until only a small amount of brine remains. The salt is then raked into piles along the edges of the pond for further drying. Although the end product is still impure, its quality is notably improved by the separate stages in the process.

In a rigorous purity analysis of solar salt, the following determinations are commonly made (Marciniak et al., 1960):

- moisture content,
- water insolubles (including foreign substances such as paper fibre, lint, ash, and sand),
- calcium and magnesium,
- sulphate,
- iron, alumina and silica,
- alkalinity as calcium carbonate ($CaCO_3$), and

- total sodium chloride.

The American Society for Testing and Materials (ASTM) provides standard test methods for the chemical analysis of sodium chloride, testing for moisture, water insolubles, calcium and magnesium, and sulphate (ASTM, 2001).

5.4 Salt Production in Haiti

In Haiti, salt is produced by solar evaporation along the northern coast in semi-agricultural operations. Small units function with minimal organisation or quality control, as producers have little financial means or access to technical assistance. Salt purity in developing countries tends to be low, with estimates ranging from 80-90%, often with visible contamination (Vil, 1999). Production statistics are generally unavailable, however; therefore such estimates have little basis.

A 1999 interview with a 50 year-old Haitian woman conducted by the Panos Institute provides some insight into salt manufacture (Vil, 1999). This woman lives in northeastern Haiti in a small community called Jacquesyl, very close to the centre of salt production in Caracol. According to this interview, salt production occurs for six months of the year, usually April to September, and is generally considered women's work. During the other months, most women take odd jobs and/or produce charcoal. The more fortunate Haitians dig holes into the seashore where seawater will penetrate, and after a few months of drought salt is ready for piling and harvesting. At this time the owners of these "salt pans" call for women willing to collect the salt. Collection itself is described as a painful activity, with continual bending and back strain. Depending on depth, three to four days may be needed to collect the salt from one lagoon and bank it in "bates," piles of approximately 25 kilograms. At the end of a working day, a salt pan owner will usually give the women one quarter of the salt they have collected. The women in turn sell their salt in local markets; 3 kg can costs 10 to 15 gourdes (Vil, 1999). Haiti's government has provided no aid in establishing or regulating salt production.

I was able to personally visit Caracol as part of my field research in Haiti. The road was poor and our group took a lengthy detour to avoid the more direct main route that had been completely washed out. People in nearby communities were aware that salt is made in Caracol, however very few people knew its location or how to get there. Our trip occurred in mid January, during a rainy spell in the north. The frequent rainfall had prevented brine evaporation, and thus the lagoons were quiet and full, most likely with a mixture of seawater and rainwater. The solar salt operation consists of approximately three large lagoons dug close to the seashore (Figure 3), and essentially uses the method described in the Panos Institute's interview. One man was clearly in charge of the salt production, and he welcomed us and readily provided a large sample from his stockpile, locked away in a wooden hut. The salt was unrefined and very damp, with visible impurities including sand and wood (Figure 4).

Figure 3: Salt Lagoon

Figure 4: Raw Salt

The presence of impurities in Haitian-made salt will not be problematic with respect to sodium hypochlorite generation. In response to questions regarding the effects of impure salt on the generator, suppliers indicated that impurities would affect the efficiency and maintenance schedule of the electrodes. As these units generate chlorine on a very small scale, however, the impact of such effects on overall performance is minor. The efficiency of a small generator is not particularly high to begin with, and efficiency is not the paramount concern regarding point-of-use water disinfection. Ed O'Sullivan of Equipment & Systems Engineering, Inc. pointed out that crude sea salt is used around the world, and suggested adding an additional 10% salt to the brine solution as compensation.

6.0 Photovoltaic Power

Photovoltaic power essentially describes the conversion of solar energy to electricity. Its use is appropriate for this project due to its lack of a highly specialised or technical nature, minimal polluting effects, and ability to function in the absence of infrastructure. Solar power systems contain no moving parts and are fairly easy to maintain. Their modular nature allows for added capacity as power needs increase. Currently, solar power is used in some parts of rural Haiti, but diesel generators are more commonly found than photovoltaic panels. I wish to encourage solar energy's use for the sodium hypochlorite generator, because it is a sustainable, non-polluting energy source, and it prevents Haitians from needing to buy imported fuel. Further, Dumay is located in an area that receives more than adequate sunlight to generate solar power. Monthly averages over a ten year period indicate that the amount of solar radiation incident on the earth's surface in this location varies between 4.30 and 6.04 $kWh/m^2/day$ (McGinnes, 2001). Despite its prime location for solar power, no solar panels are currently used in Dumay; the little community power that does exist comes from a diesel generator that provides up to 46.5 kilowatts.

A typical solar cell is manufactured from a thin silicon wafer, with a patterned metal layer partially covering the side exposed to sunlight, making an electrical contact to it, and a second metal contact covering most of the rear surface. When sunlight hits the cell, electrical output is generated between the contacts, allowing the cells to be used as a battery. Generally, thirty-six cells are connected within a weatherproof package (a solar "module"), with a sheet of glass forming the top surface, providing protection from the environment. Several manufacturers warrant their modules for up to twenty-five years, and technically the cells could last forever because of the absence of processes causing wear. The cells are very costly, however; thus the electricity produced is relatively expensive but cost is offset to some degree by photovoltaic (PV) power's environmental and social benefits.

In rural areas, PV power is usually used in conjunction with "lead-acid" batteries, similar to ordinary car batteries, to store electricity overnight and during periods of low sunshine. The simplest remote power system requires a PV panel connected across a battery, with a fuse to protect the battery from short circuits. This system is problematic because in sunny weather, the panel may supply enough electricity to the battery so as to overcharge it, causing the acid and water mixture to decompose into hydrogen and oxygen, reducing the acid level and eventually destroying the battery. In addition, explosive hydrogen is a serious safety hazard. The battery can go "flat" in conditions of little sun or high electricity demand, where more electricity is drawn from the battery than is being replaced by the panel. In this case the battery will be unable to supply electricity until it is recharged, and flattening reduces battery life. A solution to these problems involves the use of a charge controller, preventing the solar panel from overcharging the battery as well as protecting it from going flat. With a charge controller, either an alarm light is triggered or loads are automatically disconnected from the battery. Another refinement of the simple system is the addition of an inverter, between the battery and electrical load, to convert direct current (DC) to alternating current (AC) electricity (Green, 2000).

Technically speaking, PV panels themselves are seldom problematic, but local components can be unreliable. Usually car batteries are used for power storage, as they are affordable and locally available, but only a fraction of the total stored charge can be drawn out of this battery without reducing its life, only two to three years under ideal conditions. (Battery life measures the number of times a battery can be charged and discharged before it stops performing, and depends primarily on construction, type of charging, maintenance and use.) A better but less accessible choice would be the heavy-duty batteries used in trucks and buses.

Even the smallest-scale systems can cost up to US$500 (Green, 2000), which is extremely expensive for rural areas of the developing world. Capital costs are the most significant, but maintenance costs can also be as high as US$2 to $3 per month (Green, 2000) because high quality components (batteries, charge controllers, etc.) cannot be afforded and those that are available can need frequent repair or replacement. In weighing costs and benefits, one must remember that the high capital cost is somewhat offset by the elimination of ongoing fuel expenses. Fuel prices as well as inflation affect these savings. The constraint is, however, that despite the ultimate benefits to be gained with a PV system, sufficient capital must be available for the initial investment.

There are some additional considerations regarding the feasibility and efficacy of PV power. Spare parts for panels and components must be available locally, and with reasonable cost and quality. Battery recycling must be addressed to minimise unnecessary environmental contamination; in the Dominican Republic, with considerable help from non-governmental organisations, roughly 50% of batteries used in PV systems are recycled (Cabral et al., 1996). Finally, some degree of local technical support is needed, even if this consists of minimal training of users to perform simple maintenance functions.

Communities such as Ferrier and Fonds Verets currently use photovoltaic power, with panels obtained from Port-au-Prince.

7.0 Economics and Generator Selection

The selection of a sodium hypochlorite generator for Dumay involves many factors, both quantitative and qualitative. Economic concerns play a significant role, however it is important not to emphasise these aspects over the social and environmental ones. Given this combination of numeric and less objective criteria, traditional cost-benefit analysis is not sufficient to make a reasoned decision. Ultimately, a blend of common sense and economic analysis was necessary in selecting a specific generator for Dumay. My major areas of concern involved using a cost-benefit analysis with non-monetary criteria, the selection of a discount rate for Haiti, and the high degree of uncertainty surrounding this project, both now and in the future.

The selection of engineering projects among alternatives is commonly done using a logical methodology, the primary criterion being economic effectiveness. Often, however, multiple criteria must be considered such as quality, safety, environmental impact, community attitudes, cash flow positions, risks, system operability and flexibility, and training requirements. Many of the above factors can be expressed in monetary values, but others, such as community attitudes, are impossible to quantify. These elements, affecting the project's outcome but inexpressible in monetary terms, are often called intangibles and are involved in all selection processes.

7.1 Cost-Benefit Analysis

A cost-benefit analysis (CBA) compares the advantages and disadvantages (traditionally and most commonly in monetary terms) of a project, and the alternative with the most positive answer, i.e. the greatest benefits and least costs, is selected. Generally, the following steps are taken in a CBA (White et al., 1998):

- Define a set of feasible alternative, including all of their effects (e.g. health, safety, economy-oriented).
- Define a planning horizon over which to compare the alternatives.
- Develop the costs and savings in monetary terms. This step may be difficult and subjective where non-monetary factors are significant.
- Specify an interest rate. Again, this may be difficult, especially in developing countries with unstable economies.
- Compare the alternatives.
- Perform supplementary analyses (risk / sensitivity).
- Select the preferred alternative.

The discount rate/interest rate question poses a problem in developing countries, particularly in Haiti because of its unstable government and economic uncertainty.

Suggested rates for this type of situation range from 0% to 15%; thus the effect on net present worth of cash flows is significant. In an ideal market, the interest rate that equilibrates savings and investment is equal to the marginal rates of return on capital (White et al., 1998). In practice, however, factors such as government policy distortions and market failures create divergences between these rates. In countries like Haiti, the urgency of satisfying immediate needs is a higher priority than long-term security; therefore projects with social costs over the long-term and benefits in the near-term are attractive and favoured by a higher discount rate. Projects with long-term benefits are less likely to be undertaken with a high discount rate. As the majority of environmentally sustainable actions are geared to long-term benefits, it is often argued that a lower discount rate should be chosen. A lower rate can be problematic because by lowering the cost of capital, more is consumed in the near term than might be the case otherwise. This degree of detail is not necessary for the CBA of hypochlorite generator alternatives, because the project is on a very small scale, and the alternatives are very similar. Yet the selection of an appropriate discount rate is an important and difficult issue.

Inflation (the decrease in purchasing power of money caused by an increase in general price levels of goods and services without an accompanying increase in the value of goods and services) also affects the interest rate. In 2000, USAID estimated Haiti's inflation rate to be 10% (USAID, 2001), but a Haitian interest rate has been much more difficult to find. In a telephone interview, a representative of the Haitian Consulate in Boston claimed that in February 2001 the interest rate in Haiti was 18% (Haitian Consulate interview, 2001). Unfortunately this information could not be confirmed by another source, but was the only estimate I was able to find.

The combined interest rate should reflect both the time value of money and inflation, and a number of methods exist for combining the two factors. Due to the great uncertainty surrounding Haitian rate information, I have used the simple combined interest rate formula as was used in a comparable project in Nigeria, with the same range of interest and inflation rates (Adeoti, 2000):

$$i = [(100 + p) / (100 + a)](100) - 100$$

where i = interest rate
p = market interest rate
a = inflation rate

Based on the above formula and data, the Haitian combined interest rate is 7.3%.

Risk and uncertainty are inherent in project decisions, particularly in those regarding this project, and must be addressed. Estimating the expected value of costs or ensuring against unknown possibilities is essentially impossible, and the complex and variable interactions between environmental, political, and economic systems demand consideration. The traditional method of handling uncertainty on a project-level CBA is the use of a sensitivity analysis to determine which variables most affect the project's benefits and costs. A sensitivity analysis is most often used when one is fairly confident in the possible values of a parameter, but unsure of each value's chances of occurring. It examines the effects of errors in parameter estimation, as the worth of an investment is affected differently and to different degrees by errors in the various factors involved. In the extreme case of complete uncertainty of possible parameter values, a break-even analysis can be used to determine a set of values for which the project is economically justified, and the set for which the project is not justified. Both analyses' objective is to reduce the amount of information needed to make a sound decision (White et al., 1998). The acknowledgement of uncertainties makes economic comparisons more realistic because any assumption about future information is risky.

7.2 Alternative Project Analyses

The importance of non-economic factors in the analysis of this project is vital, and although some literature discusses ways to quantify such factors, a measure of subjectivity is then added to the CBA. I decided that rather than try to put all factors into monetary terms, I would explore project evaluation methods that deal more explicitly with qualitative elements of project selection.

Other methods of selecting the "best" alternative are less focussed on maximising economic worth, and based on satisfying a set of multiple criteria. Any complex selection process involves multiple measures of quantitative and qualitative natures, as well as risks and uncertainties regarding the future outcome. We often try to gauge all costs and benefits in monetary terms, but the reduction of factors such as safety and operability can become almost arbitrary. "Weighted factor comparisons" are used in decision-making with multiple attributes, where each alternative is assigned a numerical value in proportion to a set of factors (e.g. operator safety, net present worth) according to specified degrees of importance (White et al., 1998). Based on alternatives' performances with respect to each factor, a numerical score is given. This step is the most difficult and subjective aspect of the process, and the most likely to be disputed. Scores are multiplied by the factor's weight, and products are then summed over all factors to determine each alternative's total weighted score. The highest score identifies the preferred alternative, but scaling difficulties are involved, such as a halo effect, where a very high or low ranking regarding one factor influences an alternative's ranking with respect to other factors. Paired comparisons can minimise such effects, where alternatives are compared two at a time, and the paired comparisons are then combined.

7.3 Weighted Factor Comparison

In evaluating generator units using a weighted factor comparison, the first step involves selection of criteria to measure the alternatives. The goal of this comparison is to consider each generator unit with respect to a set of factors, reflecting economic, sustainability, social, and practical concerns. I selected fifteen factors against which to evaluate the generator models, based on the most important issues addressed by this project. In order to facilitate the weighting of these factors, I assigned values that sum to 100. Selecting weights was done by first assigning equal weights to each factor, i.e. dividing the total score of 100 by 15, and adjusting the weights to reflect the relative importance of each factor. The list of factors and their weights is as follows:

1. Net present value: This factor indicates the economic feasibility of the generator unit, as capital cost will have a critical impact on selection (14.6).
2. Generator lifetime: A unit with a longer useful life is preferred over one that will require replacement or significant repair sooner (6.6).
3. Generator capacity: The capacity of the generator to make sodium hypochlorite is important for future expansion of the project; a larger capacity will prolong the use of the unit (9.3).
4. Energy usage: Meaningful from both economic and environmental perspectives, a unit requiring less electricity is preferred (9.3).
5. Water and salt usage: Again important for economic and environmental reasons; I wish to use the minimum amount of resources to make the hypochlorite solution (3.9).
6. Supplier experience with similar projects: A supplier having experience with projects in developing countries is beneficial both for project understanding and support (3.9).
7. Generator durability: The unit must be able to stand harsh conditions and inexperienced operators (4.9).
8. Ease of use: As the operators will be local Haitians, the unit must be fairly easy to run, with a minimum of steps in the procedure (14.6).
9. Maintenance needs: Related to durability of the generator, a high-maintenance model is less appropriate than one with less stringent maintenance requirements (8.3).
10. Hypochlorite solution concentration: The higher the concentration, the less filter-owners will need to add to the purifier for disinfection (3.4).
11. Manual and product information: The most simple, diagram-rich manual is preferred, in addition to detailed instructions in case of malfunction (likely to be used by GWI or other volunteers) (5.4).
12. Warranty: This factor reflects the supplier's support of the generator and its confidence in the unit's performance and lifetime (6.1).
13. Size/space requirements: A machine requiring a great deal of space is less practical than a more compact unit, particularly as a building or room will be made especially for the generator (2.9).
14. Portability: For convenience and repair purposes, it is beneficial that the unit be portable (2.9).

15. Supplier support: In case of problems, the ability to contact the unit's supplier by telephone or e-mail directly for support is important (3.9).

7.4 Generator Selection

During the initial search for a sodium hypochlorite generator, I contacted a number of companies about the manufacture of such machines. As the generator unit criteria became more focussed, of the original six suppliers contacted only two remained. Some of these firms were inappropriate due to geographical location, i.e. they are based out of the United Kingdom or Australia, while others do not manufacture generators of a capacity small enough to be suitable for this village-based project. Finally, some generators are simply not geared for use in developing countries, requiring specialised equipment and/or operating skills, and having little durability.

The two companies providing the most suitable units for this project are Exceltec International Corporation and Equipment & Systems Engineering Inc. Each firm manufactures potentially appropriate units for Dumay's needs and a weighted factor comparison was used to make the final generator selection.

7.5 Generator Specifications

The following units are similar with respect to their technology and general requirements. Both Exceltec and Equipment & Systems Engineering make units durable and portable enough to be used in Dumay, and both of the following generators can use AC or DC electricity.

Exceltec's SANILEC 6 unit is designed for water disinfection in remote locations, and has been used in countries such as Burkina Faso and Guatemala under conditions similar to those in Dumay. A SANILEC 2 is also available, but as it can produce a maximum of 1 kg per day of available chlorine, its capacity is insufficient. Although the SANILEC 6's maximum production of 3 kg/day is not needed at this time, the unit can be run intermittently, and the procurement of a large unit will facilitate project expansion.

Equipment & Systems Engineering manufactures a suitable unit for Dumay, the AC100D. It is very similar to the SANILEC 6 unit, although this unit generates hypochlorite solution of 0.6% strength as opposed to SANILEC 6's 0.8% chlorine concentration. This unit can produce up to 2.4 kg of available chlorine per day. The similar but smaller unit, the AC50D has a maximum capacity of 1.2 kg of available chlorine per day, and would not be appropriate for the long term.

The specifications of the SANILEC 6 and AC100D units are displayed in Table 1:

	SANILEC 6	**AC100D**
amount/hr of available chlorine	113 g	100 g
equivalent chlorine concentration	0.8 %	0.6 %
water consumption per 24h cycle	455 L	400 L
salt consumption per 24h cycle	13.6 kg	12 kg
electricity consumption per kg chlorine	5.5 kW	8.3 kW
generator weight	4.1 kg	7.7 kg
generator dimensions	17.8 cm diameter 102.6 cm length	112 cm length
Warranty	2 years	1 year
electrode lifetime (vendor description)	"depends on maintenance"	"several years"
Cost	$2000	$2450

Table 1: Generator Specifications

7.6 Generator Weighted Factor Comparison

Based on the above criteria and unit specifications, I rated both units individually in order to establish total scores for each one. The score is simply the weight of the factor multiplied by the unit's rate out of 1.0 with respect to said factor, and the total score is their sum. Using the generator specifications, each factor was evaluated: some factors were easier to evaluate than others (e.g. generator lifetime versus supplier support) and in some cases both units received poor ratings. The "Ease of use" factor, for example, rated low for both units, simply because generator operation will not be easy for the Haitian operators. Again, I acknowledge the subjective nature of this method but careful consideration was given to each factor and the rates allotted. I believe that this procedure effectively contrasts the two units. Table 2 presents the results of this comparison:

	Factor	**Weight**	**Sanilec-6**		**AC100**	
			Rate	**Score**	**Rate**	**Score**
1	NPV / initial machine cost	14.6	0.8	11.7	0.6	8.8
2	Generator lifetime	6.6	0.7	4.6	0.7	4.6
3	Generator capacity	9.3	0.9	8.4	0.8	7.4
4	Energy usage	9.3	0.9	8.4	0.5	4.7
5	Water, salt usage	3.9	0.7	2.7	0.7	2.7
6	Supplier experience with developing countries	3.9	0.9	3.5	0.9	3.5
7	Generator durability	4.9	0.8	3.9	0.7	3.4
8	Ease of use	14.6	0.5	7.3	0.5	7.3
9	Maintenance needs	8.3	0.6	5.0	0.6	5.0
10	Chlorine concentration of solution	3.4	0.9	3.1	0.7	2.4
11	Manual & product information	5.4	0.6	3.2	0.8	4.3
12	Warranty	6.1	0.8	4.9	0.6	4.3
13	Size, space requirements	2.9	0.8	2.3	0.5	1.5
14	Portability	2.9	0.9	2.6	0.8	2.3
15	Supplier support	3.9	0.7	2.7	0.9	3.5
	sum	**100.0**		**74.3**		**65.1**

Table 2: Generator Weighted Factor Comparison

The above comparison indicates that the SANILEC-6 model is clearly the most appropriate for this project (Figure 5). Its cost, particularly for a generator of this capacity, is an important factor in this selection, as is the experience of its manufacturer, Exceltec International Corporation, having completed similar projects in Burkina Faso and Guatemala. This model clearly scores better using the weighted factor comparison, and as this method incorporates all key issues in generator selection, I recommend the SANILEC-6 for Dumay.

Figure 5: SANILEC 6 Generator

8.0 Project Implementation

As the household water disinfection program is already in place in Dumay, implementing this aspect of the project, sodium hypochlorite generation, should be fairly readily achieved. The most significant challenges will be establishing the generator in Dumay and training its operators. The key objectives of the implementation phase of this project are:

- to run the generator safely and properly, with no accidents or errors in chlorine concentration;
- to reach the same (or better) levels of water disinfection using the new hypochlorite solution as achieved with chlorine bleach;
- to achieve, by the households using the new solution, the capability of using it, and comfort with the change;
- to gain acceptance of the generated chlorine solution and any price changes necessary, by the community at large.

I have separated the implementation into two parts, one involving GWI and the project administrators in Dumay as well as the technicians and generator operators, and the other involving the greater community, i.e. those families who are selected as test cases for the new hypochlorite solution.

8.1 Generator and Operator Requirements

First and foremost, the generator must be procured. As Exceltec International Corp., is located in the US and has experience with projects in developing countries, GWI should have little trouble with this arrangement. Whether the initial costs are to be borne by GWI or a combination of it and Dumay's benefactors will be decided by GWI. The basic needs of the generator are the following (Centres for Disease Control and Prevention, 2001):

- a room for the equipment, with a cement floor at least 2 x 2m, opposite windows for ventilation and circulation of the hydrogen gas by-products and a locking door;
- an electrical source, 110-220 V, 20 amps (here to be provided with PV power)**;**
- salt, best stored in covered plastic containers;
- close proximity to a water source (pump or fountain), and water storage containers;
- a measuring device for the chlorine concentration; and
- 100 to 200 L barrels to store the hypochlorite solution, with covers and spigots for distribution.

Detailed instructions from the manufacturer are needed, as well as a simpler set for every-day use by the operators. Exceltec has executed a very similar project in Burkina Faso, a French-speaking country, thus appropriate instructions are available. Three operators must be trained, by GWI, to run the generator, bottle the solution, and handle any problems that arise. I recommend that technicians or community members already involved with chlorine distribution become the generator operators, as they are familiar with the program and GWI. The ability to read and write in French is also required in order to understand the manual, although even with these skills, GWI must train the operators and monitor their work during the initial period. The operators must be comfortable with the machinery and fully understand their jobs in running it. Most importantly, the concentration of the new solution must be carefully monitored and maintained at 0.8%. During the initial runs of the generator, the chlorine concentration may be too low. This is generally solved by one of the following actions (Centres for Disease Control and Prevention, 2001):

- increase the operation time by 1 hour increments, until the 0.8% chlorine concentration is reached;
- increase the salt concentration in the generator by 10%; or
- check the amperage produced by the machine. If this is the problem, operators may need to contact the manufacturer (this would be handled by GWI).

GWI project leaders must monitor the quality and quantity of sodium hypochlorite production, the capability and dedication of generator operators, and the community's adjustment to this new solution. Nathan Dieudonné should oversee the implementation of the generator, and conduct regular progress meetings with operators and technicians. Operators should be instructed to keep detailed records on the concentration and amount of hypochlorite produced, as well as the amounts of salt, water, and electricity needed for each batch. They should record their maintenance schedules, and any irregularities in production. This may not be a feasible expectation if operators are unaccustomed to record keeping, but it should be attempted.

The most efficient and cost-effective means of procuring a photovoltaic power system for Dumay is to obtain one from Port-au-Prince, guided by recommendations by community leaders from Fonds Verets and Ferrier, as these communities have experience in this area. The source must provide either 110V or 220V single phase power, AC or DC. In the case that solar panels are no longer available in Port-au-Prince, Sunwize Technologies, Inc. was recommended by Equipment & Systems Engineering, Inc.

8.2 Community and Technician Requirements

The initial step in introducing sodium hypochlorite solution to Dumay is to select a group of families for the pilot project. The purpose of this miniature pilot project is to determine the best procedures and product, through trial and error, before expanding to the entire community. In this case, the test population will have a range of experience with the system, be motivated to try the new solution, and have a good understanding of the necessity of adding chlorine to the filter water for disinfection. A range of familiarity is desired, from households who have had filters since 1995 to those who are relatively new to the project, to gauge how people with different levels of experience react to the generated solution. In order to explore the acceptance and efficacy of the new solution, test families will be divided between Dumay's eleven technicians. As this project will eventually include approximately 5000 filters, the miniature pilot project's size must be representative but manageable. Increased technician visits will be necessary to guide correct usage of the generated hypochlorite.

As a potential health concern exists due to the reduction of the filters’ chlorine concentration, I am recommending an initial study case of 60 filters, handled by one technician. These households will be strictly monitored in order to assess the efficacy of both the generated hypochlorite, and the change to a 5 mg/L chlorine concentration. Two months should be sufficient to determine the success of both factors.

Shortly after this test, presuming that it is successful, I propose a miniature pilot project involving 660 filters, 60 per each technician in Dumay.   This number is a small fraction of the total filters projected for this area, however I believe that it is necessary in order to give these households sufficient attention and to quickly identify common problems and solutions**.** Using the same calculation as performed in assessing Dumay's chlorine demand, 660 filters will need a maximum of 150 g/d of available chlorine. The SANILEC-6 may be run intermittently to provide this lower amount. Pilot projects of this nature generally last from 12 weeks to one year (Centres for Disease Control and Prevention, 2001), and as this sample is small, I suggest a maximum time frame of 4 months to obtain a sense of the feasibility of project expansion.

As well as frequent technician visits to involved households, large community meetings will be useful in introducing the new hypochlorite solution, and making all of Dumay aware of the changes to come. The launch of the generator should be an event involving all filter-owners, to create excitement and awareness of the generated solution and its benefits for the community (job creation, long-term cost savings, reduced transport needs, etc.). Special meetings should be held on a monthly basis for the participants in the miniature pilot project, to address concerns and issues regarding the new solution. The change in filter chlorine concentration, to 5 mg/L by the addition of 2 capfuls of the generated solution, should be regularly monitored by technicians, and the bacterial content of the treated water measured by GWI. An indication on the bottle itself that 2 capfuls instead of 1 are now needed may be useful, even a simple reminder written in marker. My major concern is that filter-owners will continue to add the same amount of hypochlorite solution as the stronger chlorine bleach. According to CDC recommendations, however, the chlorine concentration corresponding to adding 1 capful, approximately 2.5 mg/L is still adequate (Centres for Disease Control and Prevention, 2001), although Dumay’s raw water chlorine demand may be problematic at this low concentration. Further, as the transition in practice is relatively simple, I hope that new habits will be readily and quickly formed.

8.3 Cost Recovery

One of GWI's goals for sodium hypochlorite generation is to reduce the costs of disinfectant for the filters, putting these savings back into the program to lead it towards self-sufficiency. At this stage, only a partial cost recovery is possible in Dumay, especially because the capital costs of the generator are very high. Setting a price for the new hypochlorite solution, or leaving it unchanged, requires a number of considerations including the cost of production (salt, electricity, etc.), the current cost of a 250 ml squeeze bottle of chlorine bleach (3 gourdes or $0.12), and the ability/willingness of Haitians to pay. For example, in Zambia, the cost of producing one bottle of disinfectant is $0.20. Project leaders decided on a 25% retail mark-up and charge $0.25 per bottle (Centres for Disease Control and Prevention, 2001). GWI's plan to use profits to contribute to technicians' salaries is another factor to consider in setting the price. Profits are best controlled by M. Dieudonné, as he is trusted and educated, and in close contact with GWI in Florida.

Costs associated with local generation of sodium hypochlorite involve the generator itself, power, and salt. For simplicity and continuity, all expenses are calculated in US dollars. The SANILEC-6 unit, at $2000, is clearly the most significant capital cost. According to solar panel owners in Ferrier, the approximate price of a series of panels is $800 to $1000, obtained through a Catholic priest in Port-au-Prince. As before, assuming 5000 filters will be in use, based on Dumay's projected chlorine demand and the SANILEC-6's salt requirements per kilogram of chlorine, 4 kg/d are needed, accounting for 10% surplus salt used to compensate for impurities. At a cost of \$0.20 per kilogram of salt, the monthly cost is \$24.

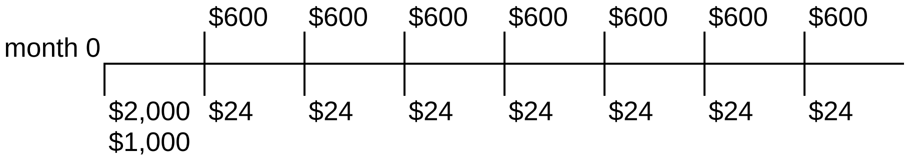
At the January 2001 commercial bleach price of approximately \$0.45 per litre, the monthly cost of bleach for 5000 filters is \$570:

- monthly bleach cost = (5000 filters)(0.25 L/month)(\$0.457/L)
  ≅ \$570

With the use of a generated solution, these costs will be eliminated.

Community bleach sellers bring in \$0.12 (3 gourdes) per squeeze bottle of bleach, totalling \$600 per month for the future 5000 filters. If sodium hypochlorite is sold to the community for the half of the amount per bottle as bleach, 1.5 gourdes, but 2 times more solution is needed per use, bottles will be filled twice per month and monthly income will remain at \$600. These figures assume that 5 mg/L will be a sufficient filter chlorine concentration. I suggest keeping the same monthly disinfectant cost because I do not want to discourage Dumay's filter owners from buying generated solution, and because monetary resources are scarce in the community.

The series of cash flows is as follows (provided that 5000 filters are in use, the generator is run properly; and maintenance costs are minimal yet may vary thus are not included in this series):



In order to determine the time at which the generator's capital costs will be recovered, a time value of money calculation was performed, using the following relationship for a uniform series of cash flows (White et al., 1998):

$$P = (A)[(1+i)^n - 1] / [(i)(1+i)^n]$$

where P = present value
A = individual cash flow
n = number of cash flows
i = interest rate

The number of months required for cost recovery is calculated as follows:

- present costs	= \$3000
- net monthly cash flow	= \$576
- monthly interest rate	≅ i/12 = 7.3% / 12 ≅ 0.61%

Based on tabulated uniform series present worth values (White et al., 1998), the costs of the generator will be recovered in slightly less than 6 months. This analysis is optimistic in that it does not take into account any problems with the transition to the generated solution, and it applies to the larger scale case of the entire Dumay community, numbering 5000 filters, using sodium hypochlorite solution.

As the available information regarding Haiti's interest rate is very uncertain, I also performed these calculations presuming that the consulate provided me with Haiti's combined interest rate as opposed to its market interest rate. In this case, using the same procedure as above, the time required to recover the generator's costs is again just under 6 months. Assuming that because monetary values are in American dollars, a typical American discount rate of 5.5% would be more appropriate (Federal Reserve, 2001), a maximum of 6 months is needed.

8.4 Sensitivity Analysis

I have performed a sensitivity analysis on the above calculations because of the significant uncertainty surrounding the Haitian interest rate, and its effects on the project's cost recovery. The results above indicate that the time frame required to recover initial costs is fairly insensitive to changes in the interest rate. A more rigorous analysis, however, provides a clearer correlation between changes in interest rate and changes in the cost recovery period. Due to the Haitian interest rate's great uncertainty, I contained its possible values within a range from -80% to +80% of the initial 7.3% estimate. I held that the other parameters, initial investment and monthly revenue, were correct.

In a 6 month time frame, the net present value of \$576 monthly payments is (White et al., 1998):

Present worth = 576(P|A (7.3%/12)(1+x), 6 months)

where x = the percent error in estimating the interest rate

Based on the formula for a uniform series of cash flows,

x = 0% Present worth = \$3384

x = - 80% Present worth = $3441
x = +80% Present worth = $3326

Therefore the present value of monthly investments over a 6 month period is relatively insensitive to changes in the interest rate, and cost recovery is affected to a very small extent by such changes. The investment in a generator can be encouraged despite the lack of certainty regarding Haiti's discount rate.

9.0 Conclusions and Recommendations

The purpose of this project was to provide an alternative to the current GWI practice of chlorinating raw water with imported commercial bleach in its Haitian water filtration programs. Based on the current social and political instability in Haiti, as well as the positive response to GWI's efforts thus far, the continued small-scale approach to water purification will be most effective in aiding the Haitian people. This new element, sodium hypochlorite generation, will provide economic benefit as well as the beginnings of self-sufficiency. Dumay, the site of the longest-running and largest GWI program, is well suited to host the pilot project. From Dumay's chlorine demand and plans for future expansion, in the near future I estimate the number of filters to be 5000. Exceltec's SANILEC-6 hypochlorite generator is the most appropriate unit for Dumay's conditions, based on a weighted factor comparison, and I recommend its procurement. The capital cost of this machine plus photovoltaic power units, $US 3000, is perhaps more than what GWI had anticipated, yet when the current costs of buying imported bleach are considered, as well as the revenue to be gained from selling bleach to 5000 filter owners, these costs are fairly readily recovered. Further, disinfection problems associated with bleach degradation will be alleviated due to the low chlorine concentration and short time between manufacture and use of the generated solution.

I do recommend further studies, however, to determine the exact relationship between the raw water's chlorine demand and the minimum amount of chlorine required for adequate disinfection. My suggestion of 5 mg/L as the chlorine dose for the generated hypochlorite, although significantly higher than the CDC's recommended 2 mg/L, may not be sufficient if raw water chlorine demand in Dumay continues to affect disinfection capabilities of the bleach solution.

I sincerely hope that GWI undertakes sodium hypochlorite generation in Dumay, and moves toward the replacement of the entire country's practice of purchasing imported bleach. This change would greatly aid the Haitian people, in terms of health and economics, as well as their self-reliance.

References

American Society for Testing and Materials. (2001). Test Method 534-98 Standard Test Methods for Chemical Analysis of Sodium Chloride. West Conshohocken, Pennsylvania: American Society for Testing and Materials.

American Society for Testing Materials (2001). Test Method D2022-89 Standard Test Methods of Sampling and Chemical Analysis of Chlorine-Containing Bleaches. West Conshohocken, Pennsylvania: American Society for Testing and Materials.

Adeoti, O., Ilori, M. O., Oyebisi, L. O. & Adekoya, L. O. Engineering design and economic evaluation of a family-sized biogas project in Nigeria. Technovation, 20.2, 103-108.

Brent, R. J. (1998). Cost-Benefit Analysis for Developing Countries. Cheltenham, U.K.: Edward Elgar Publishing Ltd.

Cabral, A., Cosgrove-Davies, M. & Schaeffer, L. (1996). Best Practices for Photovoltaic Household Electrification Programs. World Bank Technical Paper, 34, Asia Technical Department Series. Washington D.C.: World Bank.

Centres for Disease Control and Prevention, Department of Health & Human Services. (2001). Safe Water Systems for the Developing World: A Handbook for Implementing Household-Based Water Treatment and Safe Storage Projects. Atlanta: CARE/CDC Health Initiative.

Chlorine Chemistry Council. Chlorine Knowledge Centre. <http://www.c3.org> (cited 1 Nov. 2000).

Country Report: Dominican Republic, Haiti, Puerto Rico. (1999). London: The Economist Intelligence Unit.

Davidson, E. (2000). You Can't Eat GNP - Economics as if Ecology Mattered. Cambridge, Massachusetts: Perseus Publishing.

de Oliveira Jr, A.& Tavares Pinho, J. (1993). An Alternative Water Disinfecting System for Amazon Rural Communities. Waterfront, 3, 14-15.

Doggett, S. & Gordon, L. (1999). Lonely Planet: Dominican Republic and Haiti. Hawthorn, U.K.: Lonely Planet Publications Pty Ltd.

Encyclopaedia Britannica. Salt. <http://www.britannica.com/eb/article.html> (cited 7 Feb. 2001).

Equipment & Systems Engineering, Inc. Aquachlor.
<http://www.quakepro.com/aqua/indes.htm> (cited 13 Feb. 2001).

Exceltec International Corporation. SANILEC On-Site Generators.
<http://www.sanilec.com/products/sanilec/index.html> (cited 1 Nov. 2000).

Faust, S. D. & Aly, O. M. (1998). Chemistry of Water Treatment, 2nd Edition. Chelsea, Michigan: Sleeping Bear Press.

Federal Reserve (2001, January). Federal Reserve Board Press Release.
<http://www.federalreserve.gov/boarddocs/press/general/2001/20010103/default.htm> (cited 1 May 2001).

Gift of Water, Inc. (1999). Water Purifier Assembly Instructions Satellite Beach, Florida: Gift of Water, Inc.

Green, Martin A. (2000). Power to the People: Sunlight to Electricity Using Solar Cells. Sydney: University of New South Wales Press Ltd.

Haitian Consulate of Boston. Telephone interview. 5 April 2001.

Ionics, Incorporated. The Cloromat System.
<http://www.ionics.com/products/consumer/elite/cloromat.html> (cited 1 Nov. 2000).

Kreider, J. F., Hoogendoorn, C. J. & Kreith, F. (1989). Solar Design: Components, Systems, Economics. New York: Hemisphere Publishing Corporation.

Lawrence, C. A. & Block, S. S. (1968). Disinfection, Sterilization, and Preservation. Philadelphia: Lea & Febiger.

Letterman, Raymond D. (1999). Water Quality and Treatment, 5th ed. New York: McGraw Hill Handbooks.

Marciniak, A. J., Imes, P. V., & Marcy, V. M. (1960). Analytical Methods. In D.W. Kaufman (Ed.) Sodium Chloride (pp. 318-359). New York: Reinhold Publishing Corporation.

McGinnes, R. (2001, Apr. 1). NASA Surface meteorology and Solar Energy Data Set.
<http://eosweb.larc.nasa.gov> (cited 1 Apr. 2001).

Munasinghe, M. (1993). Environmental Issues and Economic Decisions in Developing Countries. World Development, 21.11, (1729-1748).

Neville, R. C. (1995). Solar Energy Conversion: The Solar Cell. 2nd ed. Amsterdam: Elsevier Science B.V.

Octave, F. (2000, April). MediaNET Bulletin: Haiti - Water management and difficulties of supply. <http://www.panosinst.org/island/IB29e.html> (cited 15 Feb 2001).

Pires, C. (1998). Sustainability and Cost-Benefit Analysis. Environment and Planning A, 30.12, 2181-2194.

Ramsdell, L. S. (1960). Mineralogy of Salt. In D.W. Kaufman (Ed.) Sodium Chloride (pp.13-22). New York: Reinhold Publishing Corporation.

The Salt Institute. (2001, Feb). What you always wanted to know about salt. <http://saltinstitute.org/4.html> (cited 7 Feb. 2001).

Sconce, J.S. (1962). Chlorine, its manufacture, properties and uses. New York: Reinhold Publishing Corporation.

See, D. (1960). Solar Salt. In D.W. Kaufman (Ed.) Sodium Chloride (pp.96-109). New York: Reinhold Publishing Corporation.

Solar Energy Industries Association. Powerful Solutions with Photovoltaics. <http://seia.org/OldWeb.pvapps.htm> (cited 13 Feb. 2001).

Tiwari, D. N. (2000). Sustainability criteria and cost-benefit analysis: an analytical framework for environmental-economic decision making at the project level. Environment and Development Economics, 5.3, 259-288.

United States Environmental Protection Agency. Drinking Water. <http://www.epa.gov/ebtpages/wdrinkingwater.html> (cited 20 Oct. 2000).

USAID. (2001, January). Haiti Overview. <http://www.usaid.gov/country/lac/ht/index.html> (cited 1 May 2001).

Vil, P. (1999, August). MediaNET Bulletin: Suzanne - or the ordeal of a deported family. <http://www.panosinst.org/island/IB11e.html> (cited 15 Feb 2001).

White, J. A., Case, K. E., Pratt, D. B. & Agee, M. H. (1998). Principles of Engineering Economic Analysis. 4th ed. New York: John Wiley & Sons, Inc.

World Bank. Haiti Data Profile. <http://worldbank.org/data/countrydata/countrydata.html> (cited 15 Feb. 2001).

World Health Organisation. Global Water Supply and Sanitation Assessment 2000 Report. <http://www.who.int/water_sanitation_health/Globassessment/Global8-2.htm> (cited 1 Apr. 2001).