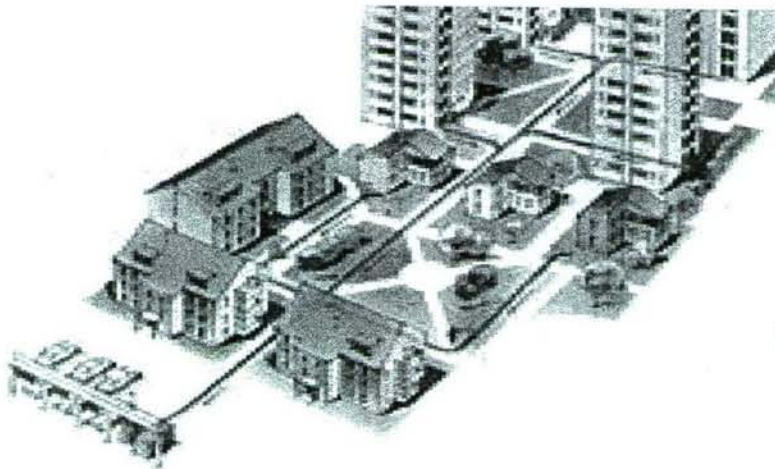


Independent Research Project:

**An In-depth Report on the Development, Advancement, and Implementation of
Pneumatic Waste Collection Systems
and
A Proposed Program for the Practical Evaluation of such a System in terms of Waste
Disposal Parameters, Engineering Design, and Economic Costs**



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Stephen B. Jackson



**Independent Research Project
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Introduction:

At the turn of the nineteenth century the collection and removal of most urban household waste materials was accomplished via local refuse disposal wagons. These refuse vehicles, sometimes referred to as “honey wagons” (I was not able to ascertain exactly why they were called honey wagons although it probably had something to do with the refuse carts similar attraction of flies), would pick-up both a residence’s solid and liquid waste, typically on either a weekly or monthly schedule. This practice continued, especially in Europe, until around the early 1920s when it became more and more common for urbanized areas to design and construct basic waste water collection systems. These sewage systems, using water as both the medium and mechanism for the waste transport, replaced the function of the refuse wagon, at least as far as liquid waste removal was concerned (Hedden et al).

The collection, transport, and disposal of residential solid waste, however, has changed very little. It is still the common practice for households and residential buildings to collect and store their refuse until the appointed time when it is picked up and transported away by the local waste collection agency. And, although the means for this collection has improved considerably with the evolution of more efficient and higher capacity garbage trucks, the method of collection still remains the same. The accumulated refuse is routinely deposited in a common and accessible area, the collection vehicle arrives, the waste is collected (either manually or mechanically), and the waste is then carted away.

Many within the field of solid waste engineering have recognized this method of collection and transport as being less than ideal. As Robert Hedden points out, “Not only does this multiple pick-up technique contribute to poor environmental conditions with its

noise, traffic congestion, odors, and litter, but the labor intensiveness of this method is readily apparent" (p. 768). In fact, according to many reports, the collection of refuse is by far the largest cost item in solid waste disposal, accounting for an average of 80% of the total budget. (Hedden et al, p. 767; Dellaire, p. 83) Why then, is it still common practice for many urban areas to continue this inefficient and often times environmentally destructive practice? The answer boils down to both technological limitations and economic constraints.

Although many different methods have been employed in an attempt to reduce waste collection costs, most have ultimately proven unsuccessful. The majority of these techniques have focused on reducing refuse collection costs by reducing refuse volume. Techniques such as on-site incineration, compaction, shredding, and pulping and baling have been implemented and do result in varying degrees of waste volume reduction. However, even though the waste volume has been reduced, the required number of pick-up points still remains the same. Therefore, although waste volume reduction can result in a decrease in the required periodicity of trash pickup (slightly lower operating costs), this decrease was found to be of little significance when compared to the need to retain the same number of pickup points. (Hedden et al, p. 768)

Furthermore, the manual collection of trash is the favored approach by many developers and urban planners because it requires the least amount of initial capital and provides the greatest flexibility. The cost of purchasing or leasing a fleet of waste transport vehicles is relatively small, often on the order of only three to five percent of a municipality's overall annual budget. In addition, once the vehicles are acquired, they can be sent to practically any location in order to pick-up and haul away the trash. Overtime, should a community's

commercial or residential centers shift, no worries; the local garbage trucks can easily be sent to the new locations in place of the old. Therefore, as one engineer points out, “The *only* advantage of manual trash collection is its low initial capital cost. Operating costs for manual collection, however, are high” (Dallaire, p. 83). Thus, since most developers, as well as politicians, are mainly concerned with the short-term, vice the long-term, costs or gains of a project, they predominantly choose to consider only the manual method for the collection and transport of solid waste.

And just what are the other alternatives to the aforementioned manual collection method. Several ideas and possibilities have been suggested including the conveyance of solid waste via hydraulics (similar to waste water), air-cushion and rubber-tired trolleys, as well as the use of underground conduits with magnetically transported gondolas (Tchobanoglous et al, p. 351). However, the one alternative that has shown the most promise and has actually been implemented at various sites throughout both Europe and the United States is the pneumatic waste transport system.

The pneumatic waste transport system employs air pressure, either positive or negative, as the mechanism for conveying the solid waste from its source to a disposal location. In addition, the waste is transported through a network of metal or composite tubing, either above or below ground, to a common collection area typically located within a distance of one to two kilometers. As one might expect, the advantages of using such a system are many and will be covered at length later on in this report. The one glaring disadvantage to this system, however, is its extremely high initial investment cost. Not only is it necessary to fund for the excavation and construction of the actual pipe network, but it is also necessary to provide the capital for the design and construction of the vacuum/blower plant

as well as the refuse collection facility. As one engineer points out, "The principal limitation of this system is the high capital outlay. The rule of thumb is that the pneumatic transport system costs approximately one percent of the total construction cost of the project. Annual operation and maintenance costs for such a facility amounts to roughly two percent of its capital cost" (Singh, p. 55). Thus, considering that many urban, large-scale, commercial and residential development projects can run into the multi-million dollar price range, the costs for including such a pneumatic waste disposal system can quickly become quite prohibitive.

In light of the current predicament within the field of solid waste engineering, it is my intention to provide comment and, hopefully, illumination into the following areas:

Research Purpose:

- 1) Provide an in-depth report on the historical development, basic components and principles, advantages/disadvantages, and implementation of various pneumatic waste collection systems.

- 2) Propose a standard method for the design and analysis of a pneumatic waste collection system based on general cost information, satisfying waste disposal requirements, and maintaining system performance within a set of specified operational parameters.

Historical Development:

The practice of conveying materials from one point to another via pneumatic pressure is not a recent development. Although I was not able to discover any actual dates, the use of

air pressure to convey materials through a pipe network has been in practice for at least the last one hundred and twenty years, and perhaps even longer. Used to transport all sorts of materials ranging from dry goods to crushed ice to messages and letters, pneumatic conveyance systems have undoubtedly undergone numerous design configurations and operational improvements (Hedden et al, p. 769).

The first patent issued in the United States for any sort of pneumatic conveyance system was granted to Mr. William Boon in 1944. An engineer involved in the laundry business, Mr. Boon's system used vacuum pressure to convey soiled clothing and linen between various laundry processing plants in an attempt to reduce the overall amount of manual handling. Subsequently, Mr. Boon went on to establish his own company, Eastern Cyclone Industries (ECI), which specialized in the manufacturing of pneumatic conveyance systems (Hedden et al, p. 769).

At the same time Mr. Boon was working on the pneumatic transport of soiled linen in the U.S., various Swedish engineers were also utilizing similar techniques in the handling and transporting of solid refuse. Their work, however, was on a much larger and grander scale than Boons, in which they envisioned the incorporation of such a system into the utility network of an entire metropolitan or commercial area. Backed by the generous support of the Swedish government, these engineers were able to make considerable strides in the development, design, and implementation of a large-scale, practical pneumatic waste collection system. In fact, within the relatively short time frame of a decade, the Swedes had designed and constructed the first automated refuse collection system at the Solleftea Hospital in 1961 and the first residential waste handling system at the Sundyberg municipal development in 1966 (Al-Ghamdi et al, p. 475; Hedden et al, p. 770).

Combining their skills and knowledge, these Swedish engineers, along with several business partners, formed the first truly international pneumatic waste collection systems company with the creation of Centralsug (now known as Envac) in 1961. This company has certainly been the benchmark leader within the field of pneumatic engineering over the past forty years. Involved with numerous projects across the globe ranging from amusement parks in the United States (Disney World) to historic city centers in Europe (Leon, Spain) to commercial/residential complexes in the Far East (Seoul, South Korea), Envac has definitely been at the forefront of the pneumatic waste collection industry.

But why was it Sweden, and not the United States, that led the way, especially given that pneumatic technology first appeared in the U.S.? The answer seems to be that many U.S. business leaders were apprehensive and simply not willing to take the financial risk of backing an unproven pneumatic waste collection technology in any large-scale projects. The required initial capital and investment costs were just too high, and thus the risk of failure too great, for any U.S. entrepreneur to take the plunge. Instead, as Robert Hedden points out, "Although pneumatic conveying equipment suitable for transport of refuse in residential complexes was also available in this country at the time, the United States instead chose to watch the Swedish projects before proceeding. This attitude was predominantly due to the high initial capital cost of such a pneumatic system" (p. 770).

However, after the successful implementation of various large-scale projects throughout Sweden, several U.S. businesses and some city governments decided to partner with Envac on various projects. These include Nabisco's incorporation of a system into its Atlanta cookie and cracker plant to transport its reject packaging materials to a central compactor. Phillip Morris's decision to implement a system into its North Carolina plants to

pneumatically dispose of its unusable cigarette paper. And, the New York City government's decision to incorporate a vacuum assisted waste collection system at its Roosevelt Island residential housing project (Anon, p. 31).

Basic Components and Principles:

Although every system is somewhat different in that it must be custom-engineered for its particular site and given refuse characteristics, all pneumatic systems share certain standard components. As depicted in Exhibit 1, these include air intake stations, depository stations, pipeline, waste/air separator, waste discharge collector, suction/blower generator, and air exhaust ports.

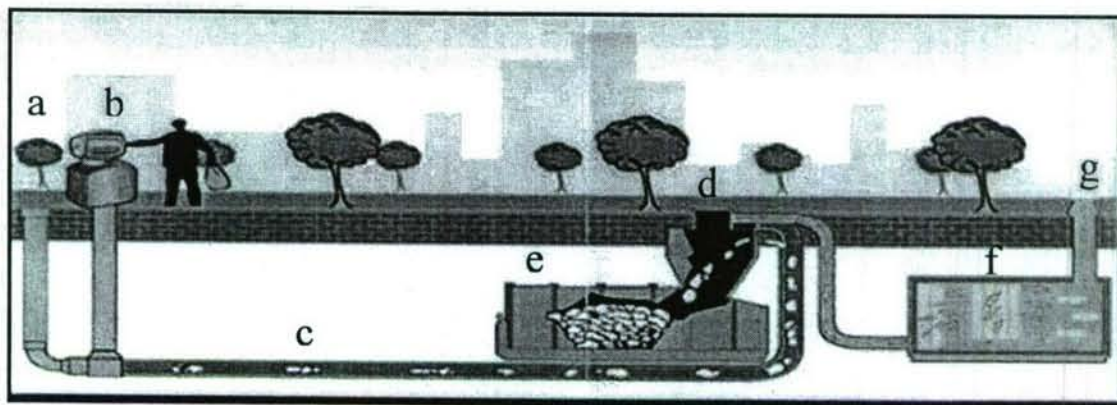


Exhibit 1, Typical Pneumatic Waste Transport System
Air Intake Station (a), Depository Station (b), Pipeline (c), Waste/Air Separator or Cyclone (d), Waste Discharge Collector (e), Suction/Blower Generator (f), and Air Exhaust (g).

The major distinguishing feature between any two pneumatic transport systems is its means of conveyance. All pneumatic waste collection systems will either utilize a positive pressure (push) or a negative pressure (pull) method for refuse conveyance. As one might expect, each type of system has its own particular advantages and disadvantages. The major advantage for a vacuum (pull) type system is that it is more efficient in conveying

materials from several points of collection to a single destination. Conversely, the positive pressure system is superior in moving materials from a single point to a single destination. Therefore, in general, vacuum collection systems are preferred in most municipal and commercial solid waste transport systems (Al-Ghamdi et al, p. 476).

The typical size range for the transport pipe diameter is between 20 to 50 cm. The specific pipe size required is a function of the particle size distribution of the refuse and the quantity of the solid waste to be transported. However, smaller pipe diameters can be used if the waste is pre-shredded or if the discharge periodicity is increased. Additionally, in order to keep the refuse in suspension during transport, the recommended range of air velocity is between 15 m/sec to 30 m/sec (Al-Ghamdi et al, p. 476). The actual speed of the waste travelling throughout the pipe network will be approximately half that of the air velocity. Thus, the higher the air velocity the greater the refuse removal efficiency. However, this increased removal efficiency comes at a price. Not only will it cost more money to generate the increased air flow velocity, but the higher speeds will also increase the rate of deterioration of the piping network. Since trash is typically composed of various abrasive materials, such as metal and broken glass, the movement of this waste at a higher velocity will in turn accelerate the rate of wear and tear on the pipe's interior surface (Dallaire, p. 82). Thus, a balance must be struck between removal efficiency and pipe deterioration. For, just as the initial construction cost is the dominant cost factor; Similarly, any future repairs will require a significant amount of money in order to complete. And finally, the recommended vacuum pressure in the pipe network should be maintained between 20 to 30 kPa (Al-Ghamdi et al, p. 476).

Advantages/Disadvantages of a Pneumatic Waste Collection System:

Environmental

With the implementation of a pneumatic waste collection system, the periodic services of the garbage truck will no longer be required. Thus, traffic problems associated with the collection vehicles such as noise, accidents, exhaust gas, and traffic congestion will be reduced. Further, since the refuse will no longer accumulate within individual residences or be allowed to pile up in outside containers, overall hygiene will undoubtedly improve. The garbage will no longer contribute to the creation of foul odors and it will no longer serve as a breeding ground for various insect pests or vermin.

Safety

Since the pneumatic waste transport system can discharge its refuse directly into any sort of collection container (compactor, incinerator, shredder, baler, or haul-away container), the need for any secondary or tertiary handling of the waste is eliminated. The hazardous work involved in the handling and loading of residential or commercial waste into a collection vehicle will no longer be necessary. Thus, the number of accidents and injuries suffered by waste collection operators will be reduced. Additionally, since combustion cannot be maintained due to the high velocity air-flow within the pneumatic pipe system, the risk of fire, especially within highly concentrated residential and commercial complexes, is reduced (Hedden et al, p. 778). Furthermore, since the waste is no longer transported openly through occupied areas and since the high-velocity movement of the waste within the pipe network acts as a self cleaning mechanism, the pneumatic transport of waste is generally more sanitary (Dallaire, p. 83).

Convenience

The use of a pneumatic waste collection system greatly simplifies the chore of trash disposal for both residents and business owners. All trash materials can be handled loosely without the need for any pretreatment or bagging. Additionally, users can dispose of their garbage whenever they wish. They no longer have to ensure that their garbage cans get pushed out to the curb prior to the weekly arrival of the garbage truck. And finally, the collection of refuse is no longer impacted by adverse weather conditions such as rain, snow, or high winds.

The only inconvenience created will be that caused by the actual construction of the piping system. Unfortunately, as depicted in Exhibit 2, certain services will be disrupted



Exhibit 2, Construction Phase

and traffic delays will most likely occur. Thus, certain inhabitants and businesses within the collection network will undoubtedly suffer inconveniences during the construction phase. However, these inconveniences are only temporary and, upon completion, the overall conditions within the area will improve significantly.

Aesthetics

Since the refuse will be removed immediately, there will no longer be any unsightly and odorous accumulation of waste along residential or commercial thoroughfares. Trash will never again have a chance to overflow and spill out of containers, creating both a public eyesore and a possible vector for disease and pests. Instead, as depicted by Exhibit 3, residential and commercial areas will reflect a neat and orderly appearance, creating a conducive environment for both trade and recreation.



Exhibit 3, Waste Depository Station

Financial

The installation of a pneumatic waste collection system offers both advantages and disadvantages in terms of its financial return. On the one hand, as previously mentioned, it is an unattractive option because of the substantially large initial investment that is required. On the other hand, since it eliminates the double or even triple handling of waste, it provides an advantage in that its annual operating costs are significantly lower than that of a conventional collection system. Therefore, a developer will typically select the type of

collection system based on the system's payback period and on the length of time they intend to remain involved with a project. As Gene Dallaire explains, "All apartment house purchasers of the system have been builders who intend to continue to own and operate the complexes for many years. By contrast, it is difficult to interest those developers who plan to sell the complex once construction is completed. They are not interested in laying out added initial capital to reduce somebody else's operating costs" (p. 83).

Implementation of various Pneumatic Waste Collection Systems (Case Studies):

The decision to install a pneumatic, vice conventional, waste collection system is made dependent upon several key parameters. These parameters include the current and projected waste volume, composition, and source concentration, the current and projected transportation and utility system infrastructure, the distance from source(s) to collection facility, and the level of public concern for various environmental, aesthetic, health, and financial issues.

In the case of certain regions and localities, the decision has been made to continue with the traditional practice of conventional refuse collection and disposal via garbage trucks. However, in other cases, the decision has been made to abandon the conventional approach, and instead adopt the more modern method of pneumatic waste collection and removal. Using the following case studies, I will outline and discuss the various locations, conditions, and parameters which favored the implementation of a pneumatic, rather than a conventional, waste transportation system. These case studies include the historic city center of Leon in Spain, the residential housing development on Roosevelt Island in New York, and the Disney World amusement park in Orlando, Florida.

1) Historical Business District – Leon, Spain

Leon is a medium-sized city located in the northwest corner of Spain with a population of approximately 150,000 inhabitants. An extremely historic city, Leon can trace its roots back to its creation as a Roman legion outpost during the second and third century AD. As shown in Exhibit 4, its picturesque city center contains numerous prestigious buildings and monuments, including its eleventh century walls and the thirteenth century cathedral, the Saint Maria.



Exhibit 4, Saint Maria Cathedral in Leon, Spain

Although the city has worked hard to maintain its unique historical character, during the twentieth century Leon experienced various periods of rapid population growth and expansion. Unfortunately, as a result, its city center suffered from a plethora of social and economic problems including vehicular inaccessibility, inadequate and deteriorating housing, an out-migration of young people, and an increasingly elderly population.

In response, the Spanish government, working closely with the European Union's Regional Development Committee, developed a plan designed to stem the continued abandonment and deterioration of the city's unique historic center. Financed by the

European Union as an Urban Pilot Project, the goals of the project were to improve the urban environment, refurbish historic buildings, and stimulate local economic activity. As such, the project's premier action was the construction and implementation of a pneumatic refuse collection system.

The system was designed to encompass a total area of 37,328 m² and was to service roughly 4,000 inhabitants and approximately 150 bars and restaurants. The system is comprised of a central waste collection facility, 51 maintenance shafts, 71 collection boxes, and a suctioning plant including extraction tubes, waste separation centrifuge (cyclone), waste compactor, and an air purification filter. The maximum transport distance within the system is approximately 1.3 km and the current service rate is almost 10,000 kg/day of organic waste and rubbish.

The pneumatic system utilizes two types of collection boxes. Green boxes for organic wastes and yellow boxes for paper and cardboard. Glass and metals cannot be collected and are therefore disposed of or recycled in traditional containers to be picked-up later. Additionally, collection boxes are also differentiated according to source as being either residential or commercial in origin.

The total cost of the project was 5.2 million Euros or approximately 6.4 million dollars. And the annual maintenance and operating costs are estimated to be approximately 100,000 Euros or \$123,000.

According to Spanish officials, the greatest lesson learned from this project was that close coordination and communication with both local residents and business owners was crucial prior to the actual operation of the system. All users had to be willing to operate the system properly and had to understand what could and could not be disposed off. During

the indoctrination period, local authorities ran several information campaigns, broadcast numerous advertisements, and conducted a great many neighborhood meetings in order to ensure that as many people as possible were educated on the new pneumatic system. In addition, a transition period of three months was also included in which both systems were operated simultaneously. Afterward, the pneumatic system was operated exclusively.

As a result of the success of the Leon project, the Spanish government has since commissioned the construction and implementation of several other pneumatic waste collection systems into the historic city centers of Palma de Mallorca, Vitoria, and Sevilla (Fernandez, p. 1-2).

2) Residential Housing Development – Roosevelt Island, New York

Located just off Manhattan in the middle of the East River, Roosevelt Island is unique because its inhabitants enjoy the services of the only residential pneumatic waste collection system in operation in the United States. Designed in the late nineteen sixties by the aforementioned Swedish company Envac, Roosevelt Island's housing development was to serve as a sort of experiment in social housing. The rationale was that the community would be enhanced because there no longer would be any accumulation of trash or transiting of garbage trucks along any of its residential streets. Additionally, this plan was also developed out of necessity as it was deemed that Main Street was too narrow a corridor for the continued operation of conventional refuse collection vehicles (Laux-Bachand, p. 2).

Designed to use negative pressure as its means of conveyance, the Roosevelt Island pneumatic garbage system was placed into operation in 1975. With an average pipe

diameter of 50 cm, the system operates with an air flow velocity of approximately 27 m/sec, and typically “pulls” between 75,000 and 90,000 kg of garbage a day. This average flow rate of 500,000 to 600,000 kg of refuse per week would equate to the need for approximately 30 to 35 garbage trucks, a potentially significant addition to the island’s already congested traffic situation. Furthermore, the current system services the eastern side of the island via one pipe, filling a 35 m³ compacted container every five days, and the western side of the island via a second pipe, filling a similar container every two days (Laux-Bachand, p. 1). This collection arrangement is depicted in Exhibit 5.

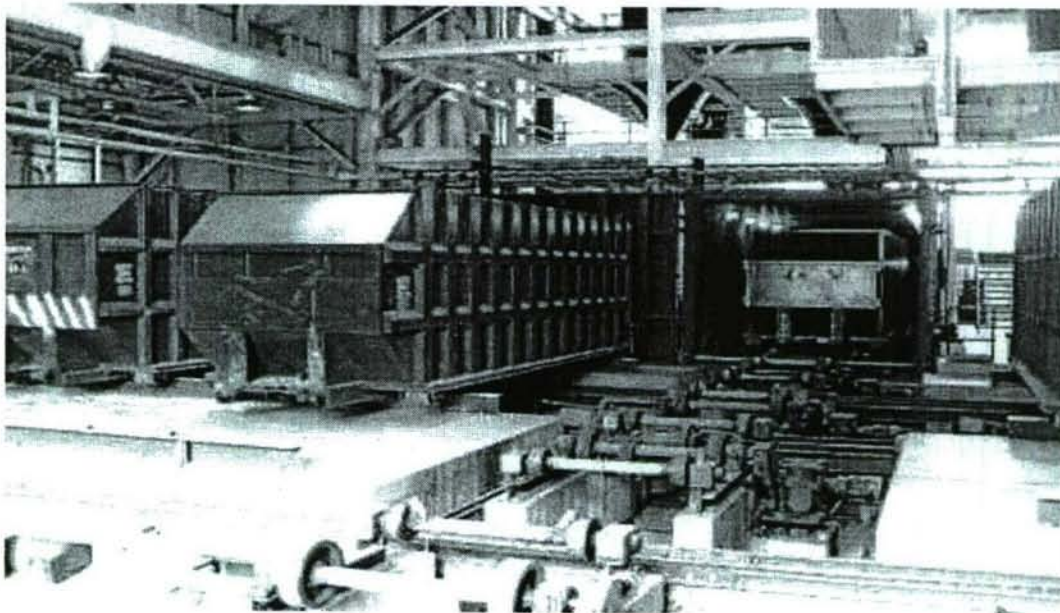


Exhibit 5, Roosevelt Island’s Pneumatic Waste Collection Facility

Beginning in 2002, construction was initiated on an additional two thousand new housing units located on the island’s southern end. In order to extend waste collection services to these new units, Roosevelt Island has once again contracted with Envac to manage the design and construction for the additional network. Although it will take some time before the system is completed, the various issues and costs associated with expanding a network to support new construction are considerably less than those related to expanding

a system to support existing facilities. The expansion of the current pneumatic waste collection system can simply be done in conjunction with the expansion of the other required utilities such as water and sewage piping. As one engineer explains, "Systems can be expanded as the building project expands. The extension of pneumatic conveying tubes is analogous to that of sewer hookups" (Hedden et al, p. 778). Thus, the total cost for the system will be less and the pay back period shorter as a result of the decision to expand the current pneumatic waste collection system rather than implement a more conventional vehicular collection approach.

3) Commercial Complex – Disney World Theme Park; Orlando, Florida

Designed to be a show case city of the future, Walt Disney wanted his Disney World theme park to incorporate all the gadgetry and conveniences that one might possibly imagine being available in the future. As a result, Disney World, which opened in 1971, included a monorail transportation system, its own high efficiency gas and electric distribution system, and the very first fully automated pneumatic waste collection system in the United States (Bravo, p. 893).

Completed in just over two years, the Automatic Vacuum Collection (AVAC) system at Disney World was, at the time, the largest such system in the world. Designed to handle between 22,500 and 50,000 kg of refuse per day, the system can be operated either manually or through a central computer which is programmed to cycle the system periodically throughout the course of a day. Requiring 20 minutes per cycle, Disney World's pneumatic waste collection system operates with an airflow velocity of

approximately 27 m/sec. As depicted by Exhibit 6, the system is comprised of 16 collection stations strategically located throughout the park and nearby hotel facility.

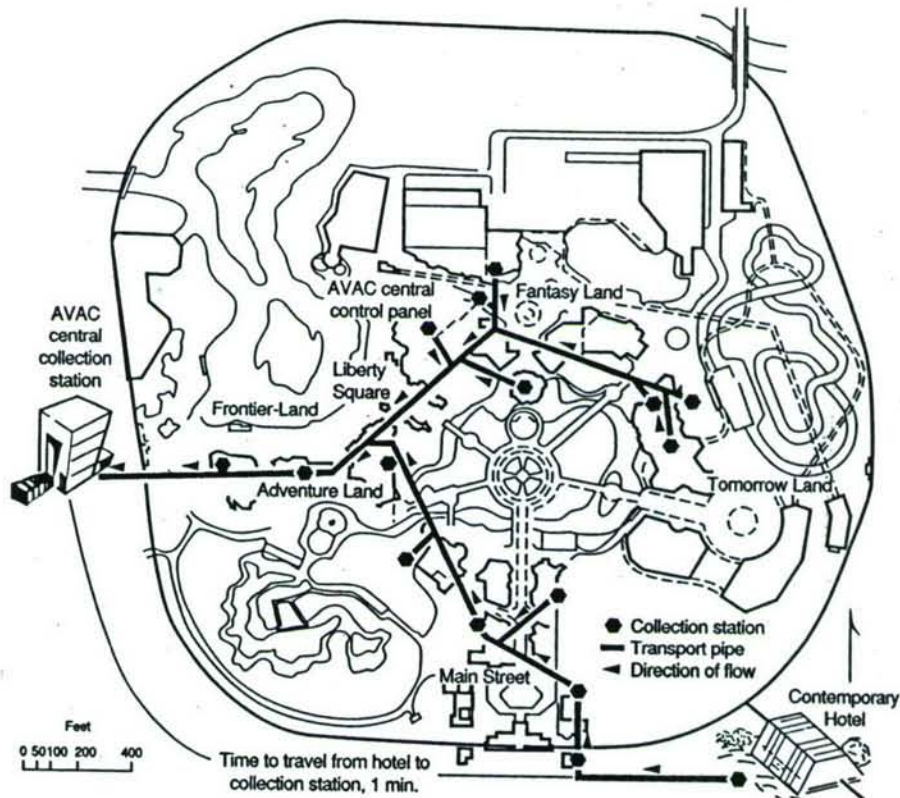


Exhibit 6, Pneumatic Solid Waste Collection System for Walt Disney World

The conveyance network is made up of 50-cm diameter pipes that stretch approximately 2,440 m between the various collection stations and the central collection station. Housed within the collection station are three, two primary and one standby, heavy duty exhausters which can produce the required 280 cubic meters per minute airflow rate used to transport the park's refuse material. Once collected, this waste is then compacted into roll-on containers for eventual transport to the park's incineration plant. And, as the final step, the

transport air is filtered to $2\ \mu$ by an automatically recleanable bag type filter prior to its discharge into the atmosphere (Bravo, p. 894).

Although I was unable to ascertain any data detailing the annual operating and maintenance costs associated with the pneumatic waste collection system, I did find out that the cost for construction and installation of the system in 1971 was approximately 1 million dollars (Singh, p. 55). Therefore, conservatively speaking, in terms of convenience, aesthetics, and labor intensity, I think that it is fairly safe to assume that Disney's decision to incorporate a pneumatic rather than manual system for the collection and removal of waste within its theme park has certainly paid off.

Proposed Standard Method for the Design of a Pneumatic Waste Collection System:

Using Excel, I have developed a program which will estimate the amount of waste generated (mass and volume), calculate the required system parameters (i.e. mass flow rate, minimum pipeline diameter, power requirements, etc.), and perform a cost analysis between a pneumatic system and a comparable conventional waste collection system. The program provides sections for the input of data should the user know the variables specific value, such as the exact cost for construction or materials. Otherwise, the program provides default values based on information garnered from various textbooks, standardized manuals, or generally accepted engineering practices. Additionally, in the following sections I've outlined the exact methodology, listed the specific physical and engineering computational equations, and discussed the various assumptions made in the development of my program. And finally, I've included a sample problem in order to demonstrate the capabilities and potential of this program.

1) Physical Parameters for the Pneumatic Conveyance of Solid Waste

As described by Dr. Tara Singh, "The physical constraints of a pneumatic transport system include a number of parameters. Pertinent among them are total volume of solids, composition of trash, number of charging stations required, type and size of pipe used, and layout of the buildings to be serviced" (p. 55).

In determining the volume and specific composition of the generated waste stream, I relied upon information gathered from several tables within the Integrated Solid Waste Management textbook by Tchobanoglous, Theisen, and Vigil. These included tables 3-6, 3-8, 4-1, and 6-3, which I condensed into two separate tables in order to describe the composition of waste likely to be found within an urban environment. These condensed tables are provided as Tables 1 and 2 respectively.

Table 1, Urban Residential Solid Waste

<u>COMPONENT</u>	(lb/yd ³) <u>UNCOMPACTED SPECIFIC WEIGHT</u>	(lb/yd ³) <u>COMPACTED SPECIFIC WEIGHT</u>	(%) <u>AS GENERATED</u>
Organic			
Food Wastes	490	810	11.0%
Paper	150	220	41.7%
Cardboard	85	135	7.4%
Plastics	110	220	8.6%
Textiles	110	170	2.4%
Rubber	220	340	0.6%
Leather	270	440	0.6%
Wood	400	540	2.5%
Inorganic			
Glass	330	810	9.8%
Tin cans	150	270	7.4%
Aluminum	270	405	0.6%
Other Metal	540	1940	3.7%
Dirt/Ash	810	1685	3.7%
Total:			100.0%

Composite Specific Weight (lb/yd ³):		
	Uncompacted:	242.8
	Compacted:	467.9

Table 2, Urban Commercial Solid Waste

COMPONENT	(lb/yd ³) UNCOMPACTED SPECIFIC WEIGHT	(lb/yd ³) COMPACTED SPECIFIC WEIGHT	AS GENERATED (%)		
			Restaurants & Bars	Retail Businesses	Professional Offices
Organic					
Food Wastes	490	810	20.0%	2%	2%
Paper	150	220	60.0%	50%	60%
Cardboard	85	135	2.5%	5%	5%
Plastics	110	220	5.0%	1%	2%
Textiles	110	170		40%	1%
Rubber	220	340			1%
Leather	270	440			
Wood	400	540	2.5%	1%	10%
Inorganic					
Glass	330	810	5.0%		2%
Tin cans	150	270	2.0%		2%
Aluminum	270	405	2.0%		2%
Other Metal	540	1940		1%	10%
Dirt/Ash	810	1685	1.0%		3%
Total:			100.0%	100.0%	100.0%

Composite Specific Weight (lb/yd ³):		
	Uncompacted:	238.6
	Compacted:	392.7

Both Tables provide the Composite Specific Weight of the expected solid waste in terms of its uncompacted form (Pneumatic transport) and compacted form (Conventional transport). Additionally, in developing Table 2, I considered only three possible commercial sources: Restaurants & Bars, Retail Businesses, and Professional Offices. I considered just these three sources because I believe they encompass the majority of typical

businesses which would most likely be located within an urban center and would have potential access to a pneumatic system.

In determining the type and minimum size of pipe required, I used the basic flow equation:

$$Q = A * v \longrightarrow A = Q / v \longrightarrow A = (\pi/4) * d^2 \quad \& \quad Q = V / (F * t) \longrightarrow$$

$$\text{Therefore,} \quad d_{\min} = \{(4 * V) / (\pi * F * t * v)\}^{1/2}$$

Where Q is the volumetric flow rate (m³/sec), A is the pipe area (m²), v is the flow velocity (m/sec), V is the volume of waste generated per day (m³/day), F is the number of cycles per day, t is the length of a cycle, and d is the minimum pipe diameter (cm). Of course, if the calculated minimum pipe diameter does not accommodate the particle size distribution of the generated waste, the user is free to select a size that will be adequate. Additionally, although the number of cycles per day (F) is selected by the user, the necessary length of the cycle is determined by the program. The cycle length is calculated such that waste deposited at the farthest reaches of the system will have sufficient time to travel through the network to the collection area. Therefore, given that the waste moves at approximately half the speed of the air (Dallaire, p. 82), the required cycle length (t) is calculated as follows:

$$v_{\text{solid waste}} = 1/2 * v = L / t \longrightarrow t = (2 * L) / v$$

Where L is the pipe length (m).

As for the type of pipe, I assumed standard steel because of the need to use a material that is both sturdy and durable.

Similarly, in determining the number of garbage trucks required for a comparable conventional waste transportation system, I used the following equation:

$$T = (V * 7) / (C * n * 5)$$

Where T is the number of required trucks, V is the volume of waste generated per day (m^3/day), 7 is the number of days waste is generated per week, C is the volumetric capacity per vehicle (m^3), n is the number of vehicle runs (fill up, drop off waste at landfill, and return empty) per day, and 5 is the number of days the waste truck is in service per week.

And finally, since each system will need to be configured according to the requirements and characteristics of the specific area in question, the number of charging stations and the exact system layout will need to be determined by the program user. These input parameters, however, can be entered into the system through the variables of system length and cycle periodicity.

2) Engineering Parameters for the Pneumatic Conveyance of Solid Waste

The engineering parameters calculated within my proposed program include the power lost due to the flow of air, the power lost due to the flow of solid waste, and the resulting, approximate power required in order to keep the entire system in operation. The following equations and relationships, as per Al-Ghamdi et al, are provided as follows:

$$P = P_a + P_s$$

Where P is the total power required, P_a is the power loss due to airflow, and P_s is the power loss due to the flow of solids

In addition, the airflow loss can be divided into two parts. The loss due to friction and the minor loss due to air inlets, separation at bends, and filtration. The friction power loss can be calculated as:

$$P_{af} = \pi f / (8R) (PLDv^3/T)$$

Where P_{af} is the power loss due to air friction (watts), f is the air friction coefficient, R is the gas constant ($8314 \text{ Pa}\cdot\text{m}^3/\text{Kgmol}\cdot\text{K}$), P is the pressure (Pa), D is the pipe diameter (m),

v is the air velocity (m/sec), L is the pipe length (m), and T is the air temperature ($^{\circ}\text{K}$). The minor power loss, which depends upon the number of bends, the number of inlets, and the type of filter used, is typically quite small when compared to the friction loss and can usually be neglected in the analysis. (Al-Ghamdi et al, p. 477)

The power loss due to the motion of the solid waste can be determined based on the sum of four separate power losses:

$$P_s = P_{s1} + P_{s2} + P_{s3} + P_{s4}$$

Where P_{s1} is the power required to propel the solids initially at rest, P_{s2} is the power required to overcome any elevation difference, P_{s3} is the power required to sustain horizontal motion, and P_{s4} is the minor power loss caused by bends in the pipes. The first three losses can be calculated using the following equations:

$$P_{s1} = Mv^2/2$$

$$P_{s2} = MgH$$

$$P_{s3} = \lambda MgL$$

Where M is the mass flow rate of solids (kg/sec), g is acceleration due to gravity (9.8 m/sec^2), H is the elevation difference (m), and λ is a factor related to the friction coefficient between the material being conveyed and the material of the pipe. The term λ is specifically defined as the tangent of the angle of slide, in which the angle of slide is the angle with the horizontal of an inclined plane at which slope a quantity begins to slope downward over the surface. The minor loss due to bends in the pipe, P_{s4} , is relatively quite small and can typically be ignored. (Al-Ghamdi et al, p. 478)

3) General Cost Information

The cost information utilized within my program include those required for the material and construction of the pneumatic system, the equipment needed for a comparable conventional system, the annual operation and maintenance of both systems, and the salaries of the required personnel. If known, the exact dollar amount for each of these various expenses can be inputted directly by the user. However, if it is a preliminary analysis or the exact amounts are unknown, than the user can simply use the default values provided within the program. The default figures, as detailed within the program, are based upon average values as provided by various manuals (construction/material), journal articles (operating/maintenance costs), as well as various Internet websites (equipment).

In addition, the program incorporates a Break-Even Analysis graph, in which the Net Present Values for each system, pneumatic and conventional, are plotted over a twenty year time period. Using this graph, one can determine the precise length of time it will take for the cumulative costs of the pneumatic system to equal the cumulative costs of the conventional system, and to therefore determine which system provides the greatest economic return and should be chosen. The equation for this calculation is as follows:

$$NPV = IC + \sum_{n=1}^{20} AC * (1 + e)^n * (1 + i)^{-n}$$

Where NPV is the Net Present Value, IC is the Initial Cost, AC is the Annual operational and maintenance Costs, e is the annual rate of inflation, i is the effective annual interest rate, and n is the number of years to be considered.

Sample Problem:

The following data was used in order to provide a sample run for my proposed
Pneumatic Waste Collection Analysis program:

1) Waste Generation

DATA INPUT:	(000's) POPULATION	(lb/day) WASTE GENERATION
Residential:	10,000	3.82
Commercial:		
Restaurants/Bars:	100	400
Retail Businesses:	125	500
Professional Offices:	75	500

DATA OUTPUT:	(lb/day) WASTE WEIGHT	(ft ³ /day) UNCOMPACTED WASTE VOLUME	(ft ³ /day) COMPACTED WASTE VOLUME
Residential:	38,200	4,248.12	2,204.20
Commercial:			
Restaurants/Bars:	40,000	4,525.93	2,750.02
Retail Businesses:	62,500	11,755.49	7,402.94
Professional Offices:	37,500	4,169.24	2,055.00
TOTAL:	178,200	24,699	14,412

2) Pneumatic System Parameters

DATA INPUT:	
Velocity, V (m/sec):	20
Pipe Length, L (m):	2,000
Cycle Periodicity, F (Cycles/day):	6
Elevation Difference, H (m):	0
Air Flow Friction Coefficient, f_a :	0.05
Waste Coefficient of Static Friction, f_s :	0.3
Air Temperature, T (K):	286
System Pressure, P (kPa):	25

DATA OUTPUT:	
Mass Flow Rate, M (kg/sec):	67.36
Cycle Length, t (min):	3.33
Minimum Pipe Diameter, $D_{\min}$ (cm):	20.0
Airflow Power Required, P_{af} (kW-hrs/day):	0.2
Solid Waste Power Required, P_s (kW-hrs/day):	136.5
TOTAL Power Required, P_T (kW-hrs/day):	136.7

3) Conventional System Parameters

DATA INPUT:	
Vehicle Capacity (m^3):	15
Personnel per Vehicle:	1
Average Route Distance (km):	10
Vehicle Runs per Day:	3

DATA OUTPUT:	
Required Number of Vehicles:	13
Distance Driven per Day (km):	127.0

4) Pneumatic Costs

DATA INPUT:	
Cost Excavation & Fill (\$/LF):	2.37
Cost of Pneumatic Tube System (\$/LF):	220
Cost of Collection Facility (000's \$):	500
Electricity Costs (\$/KW-hr):	0.10

DATA OUTPUT:	
Total Capital Cost for Project (000's \$):	1958.7
Annual Maintenance Costs (000's \$):	19.6
Annual Operation Costs (000's \$):	5.0

5) Conventional Costs

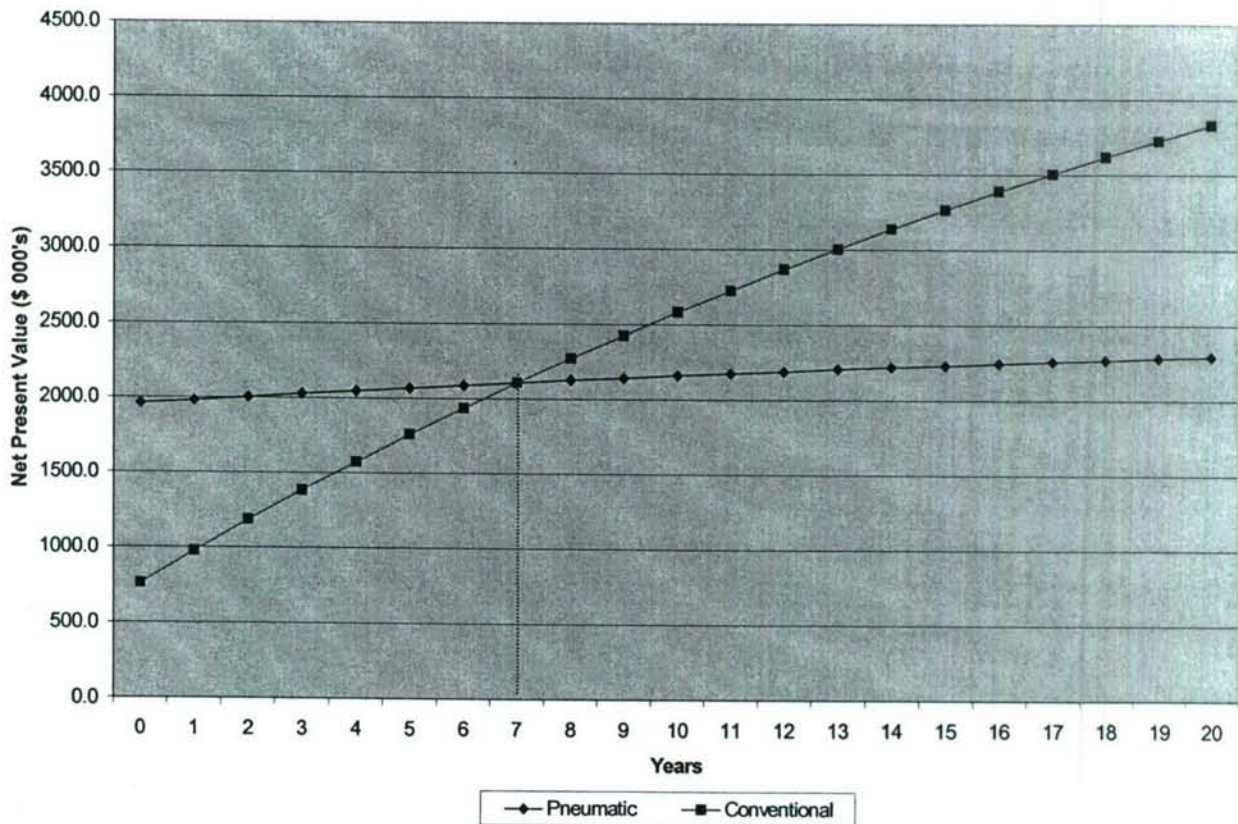
DATA INPUT:	
Cost per Trash Collection Vehicle (\$):	60,000
Annual Salary of Vehicle Operator (\$):	15,000
Average Fuel Consumption per Vehicle (Miles/Gallon):	5
Cost of Vehicle Fuel (\$/Gallon):	2.00

DATA OUTPUT:

Total Capital Cost for Vehicles (000's \$):	761.9
Annual Operating Costs (000's)	215.1
Annual Maintenance Costs (000's \$):	7.6

6) Cost Analysis**DATA INPUT:**

Rate of Return, R (%):	8%
Rate of Inflation, I (%):	4%

Break-Even Analysis

Thus, given the input data, the Break-Even point occurs at approximately the seven-year mark. Interestingly, these results correspond to those reported by Envac in which they

found that the typical Break-Even point was usually reached in six to eight years. (Dallaire, p. 85)

Conclusions and Recommendations:

As a result of my research and study into the subject of pneumatic waste collection systems, I have reached the following conclusions and propose the following recommendations:

Conclusions

- 1) Urban pneumatic waste collection systems are generally superior to conventional (vehicular/manual) waste collection systems in terms of their reduced environmental impacts, improved safety record, increased amount of convenience, enhanced level of aesthetics, improved degree of hygiene, and decreased long-term economic costs.

- 2) The key logistical parameters that must be considered when evaluating the possible implementation of a pneumatic waste collection system include the current and projected waste volume and composition, the current and projected waste source concentration, the current and projected transportation and utility system infrastructure, the distance from source(s) to the collection facility, and the level of public concern and support for various environmental, aesthetic, health, and financial issues.

- 3) Potential application for pneumatic waste collection systems include historic city centers, high density metropolitan residential and commercial centers, office building complexes, amusement parks, and sports complexes.
- 4) As an initial step, an engineering and economic analysis should be performed in order to determine the necessary scope and feasibility of any proposed pneumatic waste collection system.

Recommendations

- 1) Continued research into the development of low-cost, wear-resistant composite pipe materials. As reported in the NKK Technical Review, "NKK has already developed a wear-resistant, high-silicon steel pipe that is approximately equal in workability and weldability to the JIS SS material, is low in cost, and has twice the wear resistance of SS400 material. This pipe was actually used as the refuse transportation pipe at Yebisu Garden Place in Tokyo Japan" (Nogita et al, p. 57). As improvements are achieved in the durability, workability, and manufacturing of various pipe materials, further reductions will in turn be realized in both the initial construction and long-term maintenance costs for pneumatic waste collection systems; Thus making them less cost prohibitive and more attractive.
- 2) Initiation of an informational campaign designed to educate the public on the advantages and potential of pneumatic, vice conventional, waste collection systems. This campaign can be run in conjunction with similar Recycling and Waste Reduction

campaigns, and the message can easily be implemented into our school systems as well as incorporated into government-funded television and radio advertisements. I believe that once more people become aware and understand that pneumatic systems are a viable and, often times, superior method for the collection and removal of urban refuse, than there will be a corresponding increase in the level of public support for the initiation and funding of various public pneumatic waste collection system projects.

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