The Promise of All-Electric Injection Molding Machines: A Promise Kept?

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ABSTRACT

All-electric plastic injection molding machines were developed to use electromechanical actuators to eliminate fluid power (hydraulic pumps, control valves, and actuators) from the machine. This new technology holds the promise to reduce energy consumption, improve control, and increase productivity over the conventional hydraulic technology. These benefits have been widely touted by all-electric machine manufacturers based on generic mold testing and client testimonials.

This paper further investigates the potential of the all-electric technology and reports on the experience of one Vermont manufacturer. It includes a case study of side-by-side performance of an existing hydraulic and a new all-electric machine producing similar parts. Energy consumption of each machine was monitored over a one week period. Cycle time and shot size information was used to calculate the specific energy consumption of each machine. The hydraulic machine was found to require 0.278 kWh per pound of plastic processed compared to 0.073 kWh per pound for the all-electric machine. Using the purchase of a new hydraulic machine as a baseline, a financial analysis revealed a 31% internal rate of return for the customer based on energy savings alone.

Background

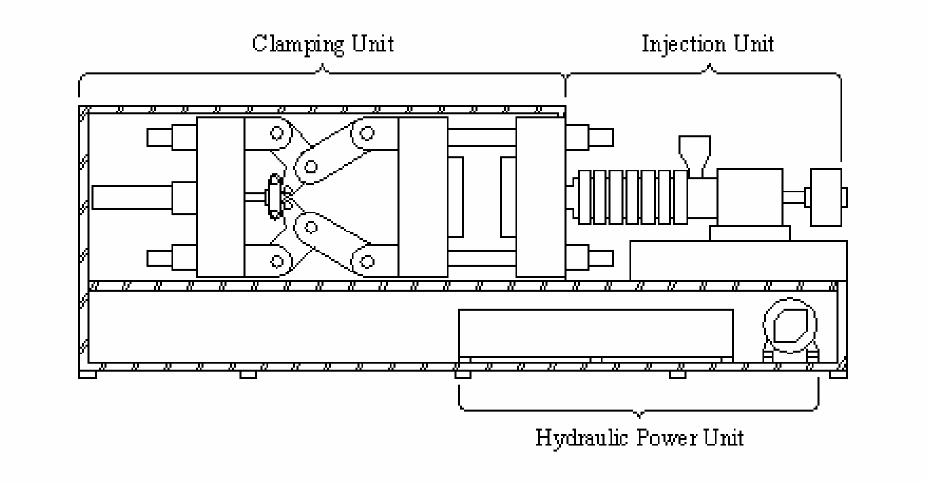
Plastic Injection Molding

Injection molding is the forming of raw plastic material into a part of specified shape and configuration. The size, complexity, and geometry of the parts produced are limited only by the properties of the plastic, the capabilities of the molding machine, and the skill of the part and mold designers. Plastic injection molding is used to produce everything from CDs to cell phones, car bumpers to lawn furniture, toys to Tupperware. In fact, the American plastic injection molding industry generated $310 billion in shipments in 2002 as reported by the Society of the Plastics Industry, and accounts for approximately 32% (by weight) of all plastic products produced (Rosato & Rosato 1986).

Hydraulic and All-Electric Injection Molding Machines

The plastic injection molding machine is a tool that performs the processes required to convert raw plastic material into a finished (or nearly finished) part. The functions performed by the machine are divided between the injection unit and the clamping unit. The injection unit plasticizes the material, the two units combine to mold the part, and the clamping unit ejects the completed part. The principal difference between a hydraulic and an all-electric machine is the actuation method used for screw rotation, injection, and clamp motion. The basic molding process is identical between the two machines. A typical hydraulic toggle injection molding machine is illustrated in Figure 1.

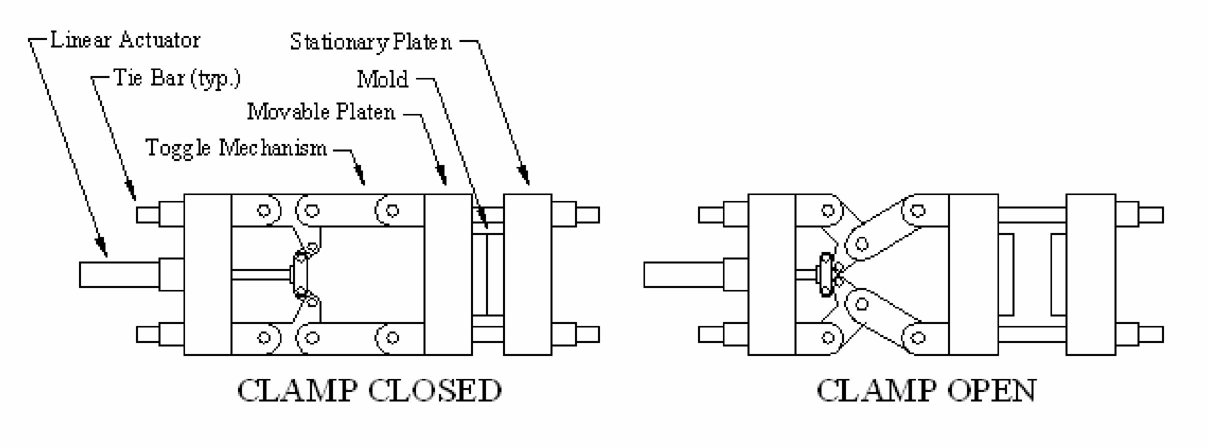
Figure 1. Hydraulic Toggle Injection Molding Machine



The clamping unit. The clamping unit is responsible for opening and closing the mold, maintaining closure while the plastic is injected, and ejecting the completed part from the mold. The clamping unit uses a mated pair of plates, or platens, and operates in a manner similar to a vice. The movable platen is forced open or closed to allow mold insertion, part removal, and to generate the required clamping force. The platens are mounted to a set of tie bars that act as guides for the movable platen and supply the balancing tension required to oppose the clamping force.

The movable platen can be moved by a direct-coupled hydraulic cylinder or by a linear actuator connected to a toggle mechanism. The full hydraulic clamp by definition requires hydraulic actuation, whereas the toggle clamp may be either hydraulic or all-electric. The toggle clamp uses a complex mechanical linkage attached to the movable platen and a linear motion device, either a hydraulic cylinder (in the case of a hydraulic toggle machine) or an electromechanical actuator (in the case of an all-electric machine). The actuator uses the majority of its stroke to close the mold. A much shorter portion of the stroke is used to force the toggle mechanism over-center, generating a mechanical advantage that results in a high clamping force. A toggle clamp is diagramed in Figure 2.

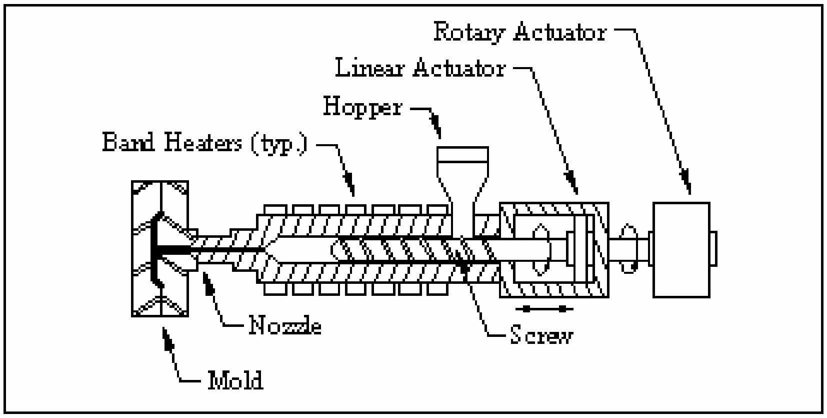
Figure 2. Toggle Clamping Unit



The injection unit. The injection unit is responsible for preparing and delivering the shot to the mold. The modern injection molding machine uses a reciprocating screw to both plasticize and inject the material. A rotational actuator (a hydraulic motor for a hydraulic machine or an electric motor for the all-electric) rotates a screw inside an enclosed chamber, or barrel. The motion of the screw draws material from the hopper and applies shear forces to the solid material as moves through the barrel. This shearing action, combined with heat input from electric band heaters located along the entire length of the barrel combine to melt and homogenize the material.

The motion of the screw moves the material to the tip of the injection barrel, causing the screw to retract until a full shot size is achieved. The result is molten plastic at the tip of the screw that is ready for injection into the mold. Injection requires a linear actuator to push the screw forward, forcing the material to exit the injection nozzle and enter the mold. The actuator is either a hydraulic cylinder in a hydraulic machine or an electromechanical actuator for an all-electric machine. Figure 3 illustrates a reciprocating screw type injection unit.

Figure 3. Reciprocating Screw Injection Unit



Sources of All-Electric IMM Energy Savings

One of the prominent drivers for all-electric machine development is an interest in reducing energy costs. The all-electric machine saves energy by eliminating the losses inherent in a hydraulic system. These losses are due to idle operation of the power unit, leakage within components, and frictional losses within the components and fluid distribution lines. Through these processes, wasted energy is converted to heat which then must be removed through cooling.

1) Reduced energy consumption during idle operation. The energy consumed by a hydraulic machine is determined by how efficiently the hydraulic power unit can provide the various actuators with hydraulic fluid at the proper flow and pressure. A hydraulic power unit consists of a fluid reservoir, pumps, control valves, and the hydraulic tubing, hoses, and fittings required to transfer the fluid to the actuators located throughout the machine. In the most common case, an electric motor is directly coupled to a pump and operates at constant speed. The pump is typically a fixed volume, positive displacement unit. This means that the pump provides essentially the same amount of flow over all operating conditions. Fluid flow that is not required by the machine is circulated back to the reservoir through an unloading circuit. While this circuit is designed to minimize pressure drop and therefore motor load, electric motor and hydraulic pump inefficiencies continue to consume energy even during this “unloaded” state. In a typical injection molding cycle, these idle periods may approach 40% to 50% of the entire cycle time. Considering a 75 hp / 1200 rpm electric motor driving a 50 gpm fixed displacement vane pump system as an example, the unloaded pump/motor system will consume approximately 2.0 kW (Parker Hannifin 2004). A typical efficiency of 83% can be used for hydraulic pumping systems (Vickers 1996).

A contributing factor to the idle losses described is related to hydraulic pump sizing. The hydraulic pump must be sized to provide the maximum flow and the maximum pressure required by the machine at any point within the cycle. Interestingly, these two requirements do not occur simultaneously. The maximum flow requirement occurs when the relatively large clamping cylinder is in motion. At this time, the pressure requirement is determined by the force required to overcome friction of the movable platen and is relatively low. The maximum pressure requirement occurs when full clamp tonnage is achieved. At this time, the flow requirement is minimal as the cylinder is already full of nearly incompressible fluid and additional flow is not required. The result is that the pump and electric motor are oversized for most portions of the cycle, and oversizing leads to reduced efficiency under low load conditions. Some hydraulic systems use variable volume pumps (output flow rate is varied during the cycle), pressure compensated pumps (flow is reduced to the minimum required to maintain a desired pressure in the system), or variable frequency drives (motor speed is reduced during idle periods) to reduce standby losses and the effect of oversizing, but losses are still significant and equipment costs are higher. Pacific Gas and Electric indicates average savings of 40% for both variable volume and variable speed hydraulic machines compared to 78% for all-electric versions (PG&E 2002).

An all-electric machine uses electromechanical actuators rather than fluid power devices to achieve the same results. The hydraulic motor is replaced by an electric motor coupled to the screw through a drive mechanism. The injection and clamping actuators convert the rotary motion of a servo motor into linear motion using a ball screw. The servo motor is coupled to the ball screw indirectly through a timing belt and gears. The screw or clamping unit is coupled to a ball nut that rides on the ball screw. As the ball screw rotates, the ball nut is forced along the length of its stroke resulting in linear motion of the nut and the attached clamp or injection mechanism. This results in very little energy consumption while the machine is idle, as the servo motors are not in motion unless the machine is in motion. While some heat is generated by the electronic components, this is very small when compared to the losses within the hydraulic power unit.

A reduction in energy consumption during idle portions of the molding cycle accounts for the majority of the energy benefits of the all-electric machine. When motion is required, the overall efficiency of the electric motor-pump-control valve-distribution system-actuator-mechanism is not significantly lower than the servo motor-timing belt-ball screw-ball nut-mechanism of the all-electric machine (Zulas 2004).

2) Elimination of internal leakage losses within hydraulic components. Internal leakage is an additional drawback of a hydraulic system. Control valves can be of the spool, cartridge, or check valve variety and all have internal moving parts which require clearances. Although tolerances are tightly controlled, there is an inherent loss of useful energy as high pressure fluid passes through the clearance and returns to the low pressure reservoir.

3) Elimination of frictional losses within hydraulic lines. An additional drawback of a hydraulic system is pressure drop during fluid distribution. Pumping fluid through the hydraulic system (including fittings, hoses, tubing, manifolds, valves, filters, and heat exchangers) and back to the reservoir converts useful fluid energy to heat through friction. Eliminating the hydraulic distribution lines eliminates leakage and distribution losses entirely.

4) Reduced cooling requirements. The need for cooling is a direct result of inefficiencies within an injection molding system. Losses within a hydraulic system are converted to heat, and this heat is dissipated to the air or raises the temperature of the hydraulic fluid. Cooling equipment must operate to maintain a comfortable working environment and to prevent overheating of the hydraulic fluid which could result in damage to hydraulic seals or hoses. In a climate controlled shop, removing heat is accomplished with an air conditioning system. In the case of year-round cooling requirements, the air conditioning system may consume energy equivalent to about 40% of the energy rejected to the ambient air. For example, an additional 400 kWh is required to operate air conditioning equipment in order to reject 3.4 million Btu (or 1,000 kWh) of waste heat. While both hydraulic and all-electric machines reject some heat to the air, these losses are much lower for the all-electric machine.

A similar case is made for cooling the hydraulic fluid. A tube-and-shell heat exchanger is often employed to cool the fluid as it returns to the reservoir. The fluid passes through the shell and water is circulated through the tubes resulting in heat exchange. In order to reduce water consumption, a closed water loop is often used. In this system, a cooling tower and/or chiller are employed to ensure a low enough water temperature to ensure proper hydraulic fluid temperature. If all of the injection molding machines in a facility are all-electric, this system may be eliminated entirely.

Given the factors described above, there can be little debate that all-electric machinery will reduce overall energy consumption and energy costs compared to hydraulic equipment. Further, with utility-based and other energy efficiency programs striving to reduce electricity demand in order to plan supply and to control costs, it would seem obvious that these programs would support the purchase of all-electric machinery. This is indeed the case in Vermont. Efficiency Vermont, a rate-payer funded organization striving to reduce the overall costs of electric energy use statewide, has supported the installation of 7 all-electric injection molding machines ranging in size from 85 tons to 390 tons of clamping capacity in the last two years. Efficiency Vermont provides financial incentives and technical support to manufacturers considering all-electric machinery. Our efforts focus on quantifying the financial benefits of purchasing efficient machinery and overcoming first-cost barriers.

Non-Energy Benefits of the All-Electric IMM

The focus of this paper is on the easily quantifiable energy cost benefits of the all-electric machine. However, the all-electric machine offers additional benefits that must be considered when making a comparison. These benefits are qualitatively summarized below.

1) Improved control. All-electric machines use an encoder attached to each servo motor. The encoder provides position information to the machine controller and is used to constantly monitor and control the process. One manufacturer reports that the encoder provides up to

16,384 pulses per motor revolution and encoder scan and machine response times on the order of 1 millisecond (Zulas 2004). For comparison, a typical hydraulic machine has a typical response time on the order of 50 ms due to the nature of spring-positioned control valves (Vickers 1998). Hydraulic machine controllers have scan times on the order of 20 ms as faster scan times would not result in improved control. The level of control exhibited by all-electric machines results in very tight tolerances on acceleration (and therefore velocity and position) as well as hold and injection times. In fact, the same manufacturer claims position control to within 0.001 inches and injection time control to within 0.001 seconds.

2) Improved consistency. The superior feedback and control of all-electric machines results in consistency over all operating conditions. Encoder-based control allows the all-electric machine to provide very accurate and repeatable molding conditions. This may reduce scrap (and possibly associated inspection costs) and reduce raw material costs. Another benefit is the ability to use identical machine setup parameters on multiple machines or at different times which may improve flexibility and reduce setup and changeover time. Due to the control delays inherent in hydraulic control systems, accuracy and repeatability may be affected by oil temperature changes or component wear. Further, each individual machine may exhibit different operating characteristics and require fine tuning of the control parameters.

3) Reduced cycle time. Cycle time may be reduced due to the ability to closely match desired acceleration and velocity profiles. This allows maximum use of the machines capabilities. Another benefit is the independent nature of the servo motors controlling the all-electric machine functions. This allows multiple functions to occur simultaneously, such as screw rotation and “eject-on-the-fly” during clamp open, which reduces overall cycle time. Hydraulic machine control algorithms tend to be sequential because the same power unit must serve each actuator and simultaneous operation may introduce pressure or flow control conflicts.

4) Elimination of hydraulic fluid. By eliminating fluid power from the machine, the costs associated with the purchase, disposal, and filtration of the fluid is also eliminated. Site regulation associated with the storage of petroleum-based fluids may also be eliminated. Maintenance benefits include a reduction in the cost and down time associated with repairing leaks, replacing seals, and preventative maintenance of hydraulic components.

5) Improved working environment. Machine operators may also benefit from the installation of all-electric machinery. Safety concerns related to slippery floors and housekeeping duties may be reduced. Further, all-electric machinery may reduce noise levels by reducing motor noise and run time.

A Case Study

Efficiency Vermont routinely conducts measurement and evaluation testing of supported measures to assist in program design. These tests provide feedback on the accuracy of our savings estimates and assist us in evaluating future opportunities. Based on our limited experience with all-electric injection molding and the large potential savings, Efficiency Vermont undertook a case study to collect data and improve our savings evaluation techniques.

Description of the Study

A customer installed a new 390-ton all-electric injection molding machine in November 2004. This was the second all-electric machine purchased by the customer. The new all-electric machine replaced one of their 13 remaining hydraulic machines that had been purchased on the secondary equipment market and was now deemed beyond its useful life. A sister hydraulic machine dating to 1971 was still in operation and was considered representative of the displaced machine. The molded parts produced on each machine were very similar. Each machine produced (10) parts per cycle with a total shot weight of 1.10 pounds. During the study, both machines had a total cycle time of 30 seconds although the customer reported cycle time reductions of 10% with some tooling.

Measurements

The power required by each machine was monitored using a poly phase power meter manufactured by Dent Instruments (ElitePro model). The hydraulic and all-electric machines were monitored simultaneously over one week (approximately 120 run-hours). The recording interval was 1 minute. The resulting data set included read date, read time, and true RMS power in kilowatts at each interval. The data set included approximately 10,000 individual data points for each machine.

Energy Analysis

Representative data samples for the all-electric and hydraulic machine are shown in Figure 4. The data sample shown represents a continuous 6 hour period that includes a post-weekend startup. This is illustrated by the spike in power required to heat up the injection barrel before machine actuation can begin. The average power for each machine was calculated over all operating hours during the sample week. The results are shown in Table 1. As shown, the all-electric machine consumed only 26% as much energy per pound of plastic processed compared to the existing hydraulic machine.

The annual energy savings for the all-electric machine is calculated using the specific energy values shown in Table 1 and the production forecast provided by the customer. The customer anticipates processing approximately 650,000 pounds of plastic on the new machine in 2005. The estimated machine energy savings is calculated using Equation 1.

Equation 1:

$$\text{Machine Energy Savings [kWh]} = \left(\text{SE}_{\text{hyd}} - \text{SE}_{\text{elec}}\right)\left(\text{APT}\right)$$

where SE_n = Specific energy of plastic processing, kWh/lb. (from Table 1)
APT = Annual Plastic Throughput, 650,000 lb.

The resulting annual machine energy savings is 133,250 kWh. As described above, a secondary benefit of the all-electric machine is a reduction in machine cooling requirements. The manufacturing floor is not air-conditioned, therefore only a reduction in chilled water requirements was considered. A new hydraulic machine of equivalent size is equipped with a 75 hp electric motor. Given the typical efficiency of hydraulic systems, up to 17% of the input energy may be converted to heat. To account for heat loss to the air and to exclude energy input to the band heaters, it is assumed that 10% of the electrical energy input to the hydraulic machine would be converted to heat in the fluid. This heat would in turn be removed by the installed chilled water system (a 100-ton water-cooled chiller with an evaporative cooling tower for condenser heat rejection) with a coefficient of performance of approximately 4.57 (EER 15.6 or 0.77 kW/ton). The annual cooling energy savings is calculated with Equation 2.

Equation 2:

$$\text{Annual Cooling Energy Savings [kWh]} = \left[\frac{(SE_{hyd})(APT)(\%HT)}{COP}\right]$$

where %HT = Portion of electric energy input resulting in fluid heating, 10%
COP = Estimated coefficient of performance of heat rejection system, 4.57

The estimated annual cooling energy savings is therefore 3,950 kWh. The estimated total energy savings resulting from the purchase of the all-electric machine compared to the hydraulic machine is the combination of machine and cooling savings, or 137,200 kWh. The annual energy consumption and savings is calculated and shown in Table 2. Potential material, maintenance, or scrap reduction benefits were not included in the analysis.

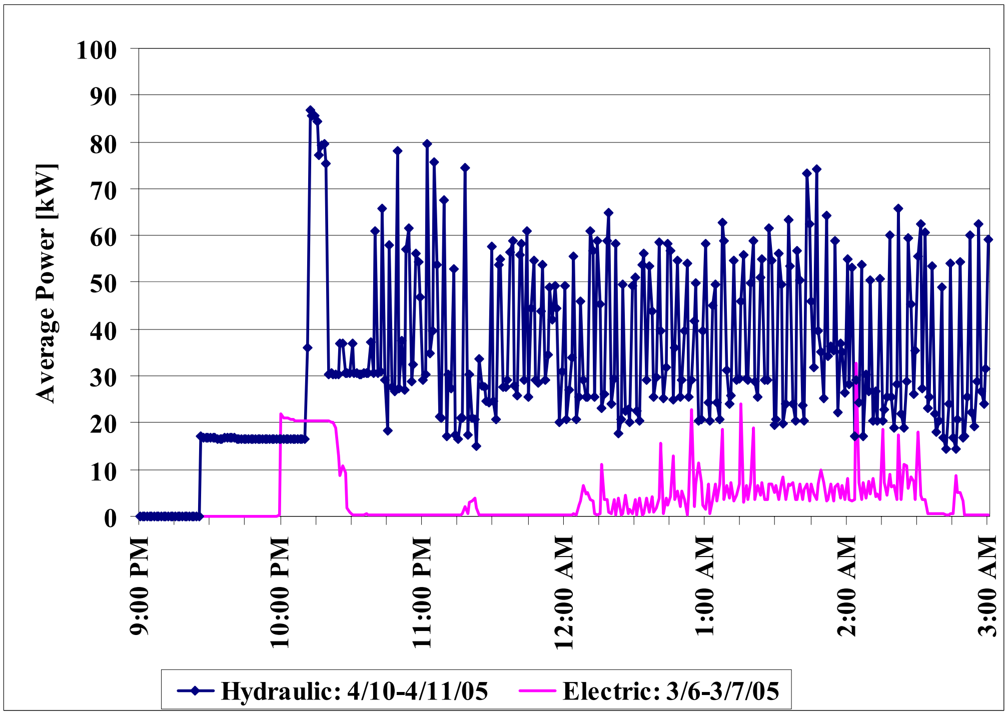
Table 1. All-Electric and Hydraulic Machine Data Summary

	Units	All-Electric	Hydraulic
Average Power	**kW**	9.70	36.72
Total Energy	**kWh**	1,027	4,284
Cycle Time	**s**	30.0	30.0
Shot Size	**lb.**	1.10	1.10
Plastic Processed	**lb.**	13,974	15,400
Specific Energy	**kWh/lb.**	0.073	0.278

Table 2. All-Electric and Hydraulic Machine Annual Energy Comparison

	Units	All-Electric	Hydraulic
Annual Machine Energy	**kWh**	47,450	180,700
Annual Cooling Energy	**kWh**	0	3,950
Total Annual Energy	**kWh**	47,450	184,650
Annual Energy Savings	**kWh**	137,200	-

Figure 4. Average Power Values using 1-Minute Intervals (6-Hour Sample)



Financial Analysis

The customer has leased the all-electric machine with a 5-year term and a $1 buyout. The incremental cost of the all-electric over a new hydraulic machine, as provided by the machine vendor, was approximately $48,000. A summary of the financial analysis is shown in Table 3. Note that the table does not reflect the value of the incentive provided by Efficiency Vermont.

Table 3. Financial Analysis

	Units	Value
Electricity Savings	kWh	137,200
Blended Electricity Charge	$/kWh	$0.110
Annual Energy Savings	$	$15,092
Incremental Equipment Cost	$	$48,000
Simple Payback	years	3.2
Internal Rate of Return	%	31%
Incremental Monthly Lease Payment	$	$946
Monthly Energy Savings	$	$1,258
Time to Net Positive Cash Flow	months	Immediate

As illustrated in Table 3, the simple payback period based on energy savings alone is over 3 years. If this were the sole criteria for choosing the all-electric machine, this payback period may have been deemed too long. A more rigorous cash flow analysis provides information that may make the project more attractive. For example, the project has an internal rate of return of 31%. Further, the monthly energy savings are greater than the incremental monthly lease payments, so the purchase of an all-electric machine is found to be immediately cash positive. For this application, the all-electric machine is the logical choice regardless of financial incentives. However, incentives can play a major role in the decision-making process in situations with less favorable economics or where other barriers are present, and completing this type of financial analysis for the customer will help them make an informed decision.

Limitations of the Case Study

The case study considers only the energy benefits of the all-electric machine. There are many factors effecting the injection molding process that are beyond the scope of this initial study. These additional factors may affect the suitability of a machine for a given application. Some of the factors identified through this case study are briefly discussed below.

1) The existing hydraulic machine is near the end-of-life. The annual energy savings calculations compare the existing hydraulic machine with a new all-electric machine whereas the financial analysis assumes a new hydraulic machine would be purchased as the baseline. Presumably, a new hydraulic machine would use less energy than the existing hydraulic machine and reduce the potential energy savings. A comparison of a newer hydraulic machine and an all-electric machine would offer a better comparison for the financial analysis. Future work will include this type of analysis.

2) The customer produces simple, low cost parts. Scrap rates are very low, with setup and testing being the primary source of bad parts. For this particular customer, the advantages of reducing scrap and material costs were not significant. The relative simplicity of the parts produced allowed for wide tolerances on machine setup resulting in the ability of an old machine with limited control and repeatability to produce good parts. In the event that a manufacturer is producing high end parts with very tight tolerances or expensive materials, the improved precision and repeatability of the all-electric machine may contribute to improved economics.

3) The customer has very long production runs. Parts are produced in very large quantities and tool changeover is minimal. For the most part, tooling is dedicated to a given machine and product orders determine the machine operating hours for each machine. This situation results in a minimal impact on machine up-time. For a more flexible manufacturing operation with frequent tool changes, the ability to rapidly change over and set up the all-electric machine may increase the available production time within a given shift.

4) The customer has a moderate cycle time. Increasing part size appears to improve the economics of the all-electric machine. This is due to longer idle periods within the cycle for part cooling and the advantages of an idle servo motor consuming little energy compared to an "idle" hydraulic power unit that must continuously circulate hydraulic fluid. A shorter cycle time with fewer idle periods will decrease the savings associated with the all-electric machine.

5) The customer must operate and maintain both hydraulic and all-electric equipment. All-electric machinery introduces new operating and maintenance procedures to a manufacturer with an existing investment in hydraulic equipment. The case study manufacturer mitigated the cost associated with these issues by negotiating technical support services, processing training classes, and maintenance training classes into the supplier proposal. Operating both machine types also means the customer will not fully realize some of the benefits of eliminating hydraulic fluid, such as reduced purchase cost, disposal cost, filtration cost, regulation cost, replacement parts inventory cost, noise reduction, and safety improvement until all machines have been replaced. These benefits may be very important for a new facility considering both technologies.

A single case study cannot be representative of all injection molding applications. The significant energy savings identified, however, should certainly be intriguing to a manufacturer in the equipment market. Additional testing, research, and discussion will improve our ability to accurately predict the energy cost benefits and identify the best opportunities to apply the all-electric technology.

Conclusion

The findings of the case study indicate that the potential savings of an all-electric machine can indeed be significant and that purchasing an all-electric machine can be a very attractive investment. It appears that all-electric injection molding machinery does indeed have the potential to revolutionize plastics manufacturing.

The all-electric technology is maturing rapidly, and is quickly displacing hydraulic technology as the machine of choice with most Vermont molders in the new equipment market. As illustrated above, the energy benefits (and possibly non-energy benefits) can result in a very short payback on the incremental cost of an all-electric machine over a hydraulic unit even without utility incentives. While the all-electric machine cannot yet be considered the “baseline” technology, the market appears to be moving quickly in this direction. In fact, one observer predicts 2007 will be the first year that all-electric machines outsell hydraulic machines (Klaus 2005). The question for energy efficiency programs is how much should be invested in this type of marketplace, now and in the future.

Vermont manufacturers will continue to consider both the all-electric and hydraulic technology when making equipment-purchasing decisions in the near term. Efficiency Vermont will continue to promote the all-electric machine and conduct pre- and post-installation monitoring to better quantify the true energy cost benefits across the application spectrum. This information, provided by a reputable third party, will allow Vermont’s plastic injection molding manufacturers to decide whether the all-electric injection molding machine will keep its promise to them.

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