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WHITE PAPER
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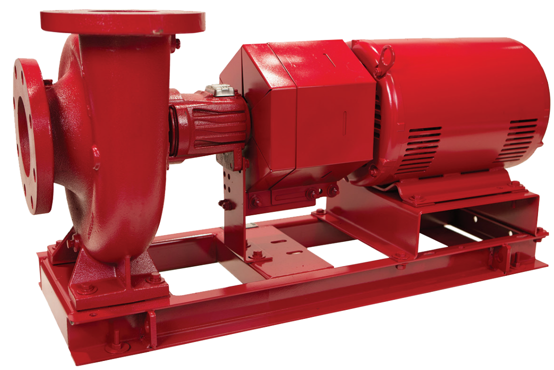
Efficiency Island Technical Review

Presented by: Xylem Applied Water Systems

Efficiency Islands
What are they? How do they result in operating benefits?

Pump system efficiency is interlocked along with other system components within HVAC systems. Evidenced by movements in ASHRAE Standard 90.1[1], system efficiency has moved to the forefront when designing HVAC systems. As part of this movement, the design of end suction centrifugal pump products has advanced to enable improved system efficiencies. This design approach yields significant benefits to the designers and operators of HVAC systems for buildings and facilities. Primary among these enhancements are improved efficiency ranges offered by the newest designs. These efficiency improvements are best described as enhanced *Efficiency Islands*. This paper describes the *Efficiency Islands* and how, from a system perspective, these enhancements can address new system efficiencies or lead to the retrofit and improvement of existing systems.

Let's begin by describing what is meant by the term *Efficiency Island*. **Figure 1** shows the *Island* (shaded red) with boundaries of the maximum impeller diameter performance, the minimum diameter performance and the iso-efficiency lines (81 percent and above in the illustration). This envelope looks like and is thus called an *Efficiency Island*. As seen in **Figure 1**, there are many *Efficiency Islands* that make up the performance curve for a centrifugal pump. For the best operating performance, it is desired to have these *Islands* be as wide and as deep as possible. **Figure 2** demonstrates what is meant by width (in terms of flow rate) and depth (in reduced impeller diameter) of these *Islands*. **Figure 1** also shows the ANSI/Hydraulic Institute Standards[2] Preferred Operating Range (POR) which is defined as the flow range from 70 to 120 percent of Best Efficiency Point (BEP). This is the optimal range for centrifugal pump operation.



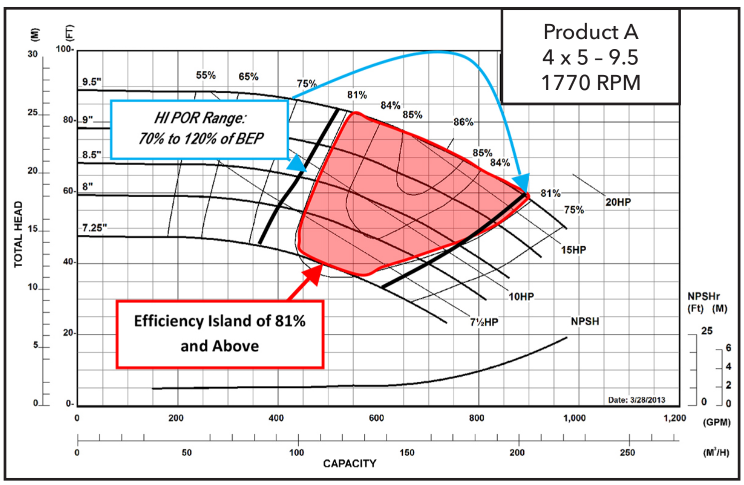


Figure 1

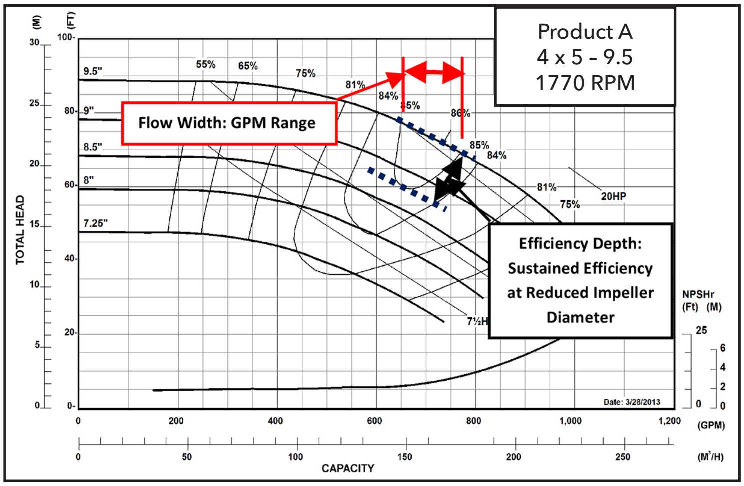


Figure 2

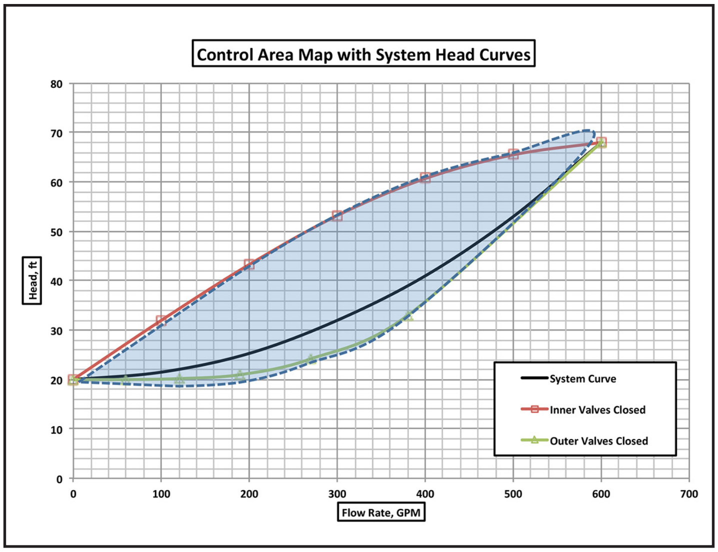


Figure 3

HVAC systems have substantial load variations (flow rates) depending on the load profile. Coupled with the load variations are the head variations, which are dependent on the physical size of the system and components within the system. One system head curve does not represent the true system resistance against which the pump must operate. Previous work has identified both lower and upper system head curves as applicable in heating and cooling systems.[3-4] An example of the upper and lower system head curves and the control area is shown in **Figure 3**. The area between the upper and lower system head curves is known as the control area (blue region). Pump operation can occur within this zone, not just at the upper and lower boundaries or on a single system curve within the boundary.

As **Figure 3** illustrates, operation in a narrow band of flow and pressure requirements simply doesn't happen in the majority of these systems. So to provide efficient systems the *Efficiency Islands* need to be wide, deep and with high efficiency levels. Narrow flow width for iso-efficiencies and rapid drop in efficiency as the impeller diameter is reduced, are not desirable to achieve the most efficient system operation.

When considering operation with a constant speed drive to meet the variations of a typical load profile, one can readily see that control valve throttling moves the pump on its curve and dissipates significant energy – wasted energy and added operational cost. To handle normal load profiles, a variable speed drive is preferred to enable load variations to be achieved with overall improved system efficiency. Newer designs employing enhanced *Efficiency Islands* enable the engineer or operator to improve the system efficiency using either fixed or variable speed pump operation.

Modern HVAC Centrifugal Pump Design Objectives:

Modern designs should utilize the most sophisticated and cutting edge computational fluid dynamics design tools available to achieve improvement of efficiency in three aspects:

- Higher efficiency levels
- Wider efficiency ranges (from a flow rate perspective) at constant diameters
- Sustain higher efficiency levels as impeller diameters are reduced.

Comparative Results:

To examine how a modern HVAC centrifugal pump design improves efficient operation, flow and efficiency can be viewed from a slightly different perspective; that of efficiency versus flow rate as a percentage of BEP with particular emphasis on the Hydraulic Institute (HI) POR.

The following illustrations will compare the results of a modern design effort to several current end suction products in the HVAC market. The majority of the new product sizes follow this example. The illustrations compare **Product A** (4 x 5 – 9.5) performance to **Product B** (4 x 5 - 9.5) and **Product C** (4 x 5 – 9.25) at 4 pole 60 Hz speed (1800 RPM). More conventional efficiency comparisons are also provided, as well as operating cost analyses for several heating load profiles and design conditions.

Maximum Diameter Efficiency Comparisons:

This comparison of maximum diameter efficiencies is done using a percentage of BEP flow. The HI recommends a POR of 70 to 120 percent of BEP flow rate. This ensures a consistent comparison is made among pumps with somewhat differing BEP flow rates. A comparison of the actual HI POR flow rates for each competitor at maximum and reduced diameter is also provided. **Figure 4** illustrates the efficiency advantage for Product A in the HI POR band

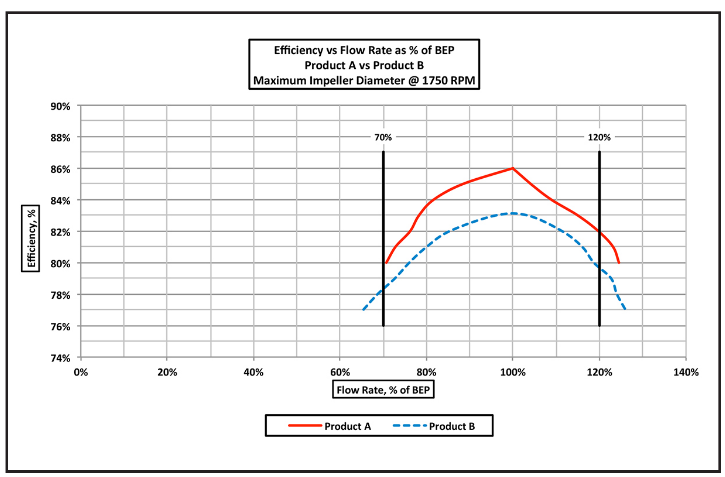


Figure 4

compared to Product B. At the same percentage of BEP flow, Product A has higher efficiency. At the same efficiency level, Product A offers a wider flow rate range.

Figure 5 compares the maximum diameter efficiency of Products A and C. At the same efficiency, the range of BEP flow is greater for Product A than Product C. For example, the flow range of Product C at 83 percent efficiency is from 90 percent of BEP to 113 percent of BEP. The flow range for Product A at 83 percent is from 78 to 115 percent of BEP.

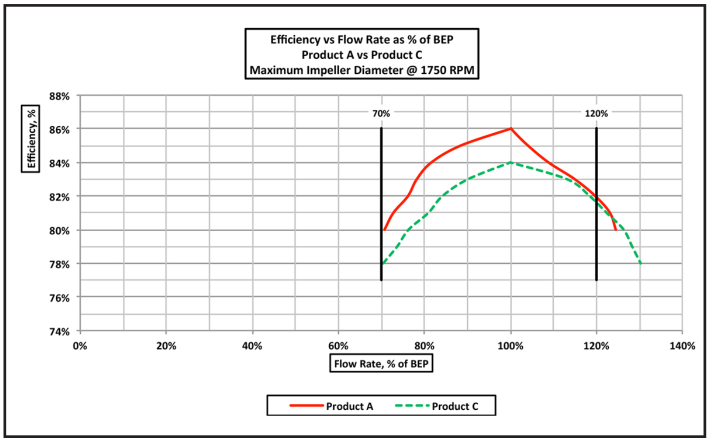


Figure 5

Reduced Diameter Efficiency Comparisons:

Figures 6 and **7** compare efficiency at maximum and reduced diameter impellers for Products A and B. In **Figures 6** and **7** the maximum diameter efficiency is shown as the solid line for the two products and the reduced diameter in the dotted line of the same color. A historical specification requirement limiting the impeller diameter to 90 percent of the maximum impeller diameter is used for this illustration. Note the efficiency of the reduced impeller diameter **(Figure 6)** for Product A exceeds even the maximum impeller diameter efficiency of Product B, a clear illustration of improved efficiency at cut down impeller diameters and enhanced *Efficiency Islands*.

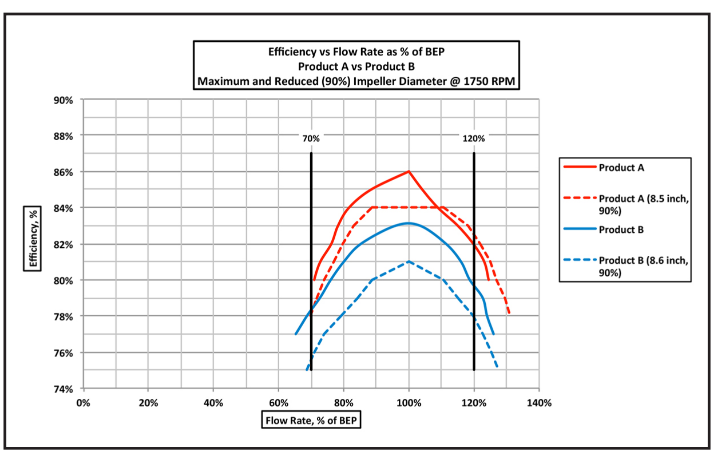


Figure 6

Figure 7 shows a similar example. Again, Product A efficiency at the cut down diameter is better than the maximum impeller diameter efficiency of Product C.

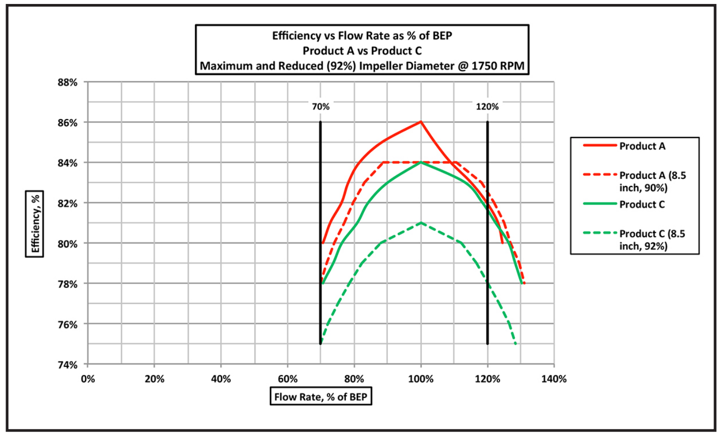


Figure 7

A comparison of the ANSI/HI POR (70 percent to 120 percent of BEP) for each of the pump sizes just examined is provided in **Figure 8**. The maximum impeller flow range is shown along with the reduced impeller diameter flow range. Each line indicates data points for the 70 percent flow, the BEP flow and the 120 percent flow rate.

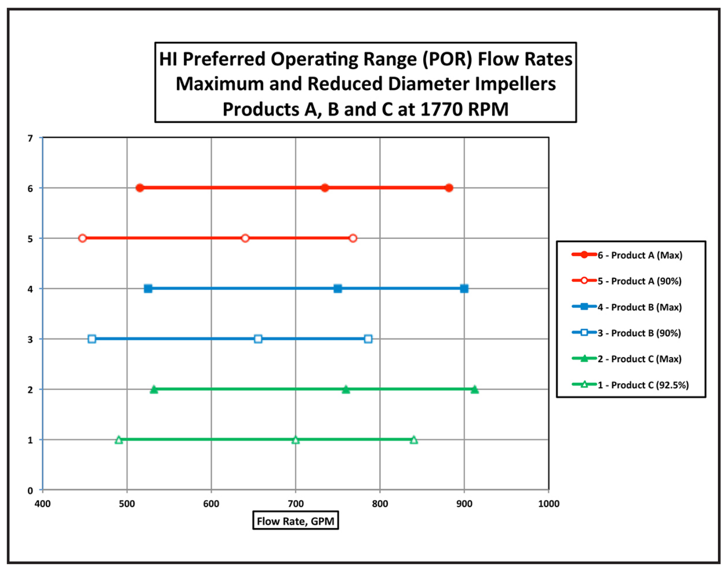


Figure 8

A more traditional view of flow versus TDH with efficiency is also provided in the next illustrations. **Figure 9** shows Product A (in red) compared to Product B (in blue). There is very little difference in TDH versus flow rate for each unit. There is a sizable advantage to Product A when efficiency is compared at BEP and, more importantly, as one operates to the left or right of BEP.

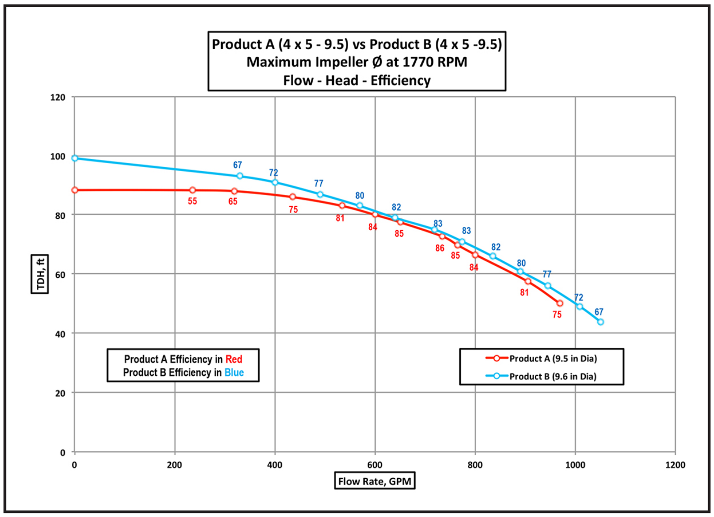


Figure 9

Figure 10 shows Product A (in red) compared to Product C (in green). There is some difference in TDH capabilities versus flow rate for each unit. Again, there is a sizable advantage to Product A when efficiency is compared at BEP and as one operates to the left of BEP. The different shape of the head capacity curve and the slightly different BEP design point are aspects of pump comparison which make it difficult to have a completely uniform comparison of products.

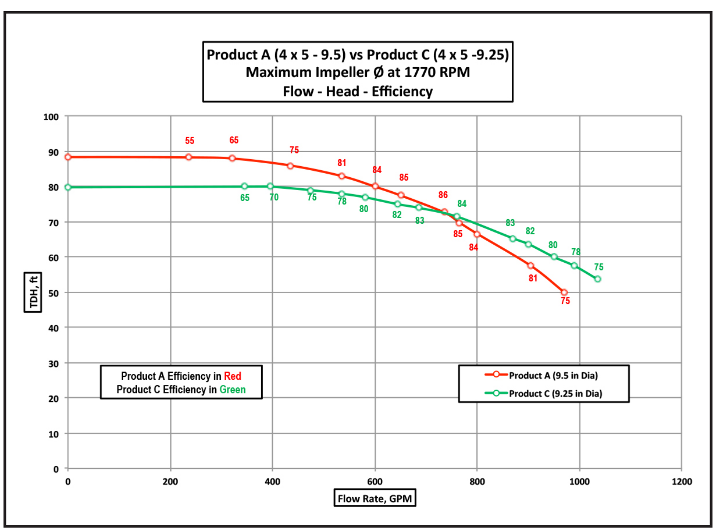


Figure 10

Figure 11 shows Product A (in red) compared to Product B (in blue) for a reduced diameter impeller (90 percent). The TDH variation is nominal versus flow rate for each unit. There is a substantial advantage to Product A when efficiency is compared at BEP and more importantly as one operates to the left or right of BEP.

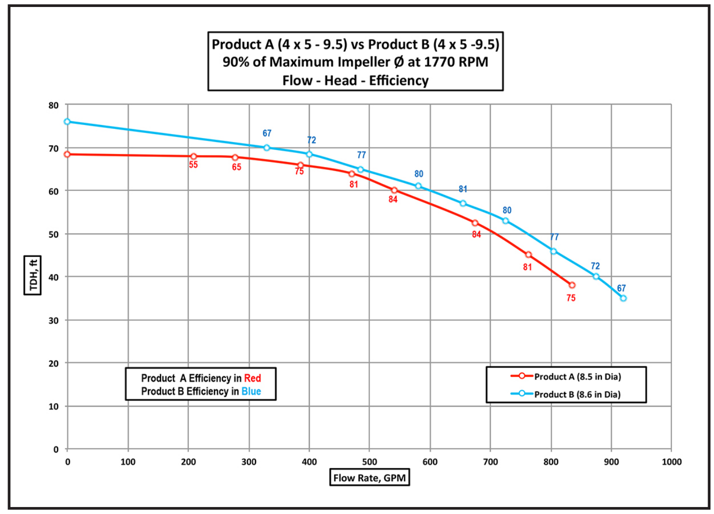


Figure 11

Figure 12 compares Product A (in red) to Product C (in green). The H-Q differences reflect different design approaches. The efficiency clearly reflects the advantage of Product A. Retaining high efficiency levels as the impeller diameter is reduced provides several advantages in addition to energy cost savings. With the higher efficiency levels it is sometimes possible to use smaller motors for non-overloading motor size requirements for either the constant speed or variable speed drive situations. Noise levels and mechanical loads are also reduced as the impeller diameter is reduced.

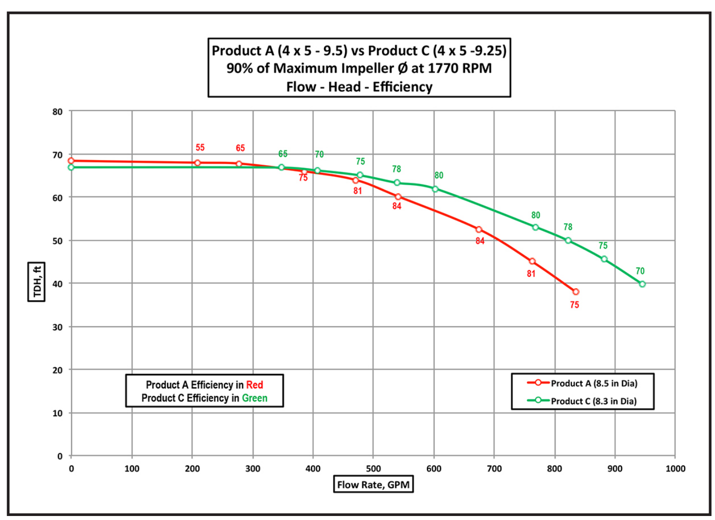


Figure 12

From another viewpoint, the following comparisons are examples of the wider *Efficiency Islands* (with respect to flow rate) and deeper *Efficiency Islands* (with respect to sustained efficiency at reduced impeller diameters). Refer to **Figure 2**.

Max Impeller Ø Efficiency Island				
Product	**Impeller Ø**	**E, %**	**Flow Width (GPM Range)**	**Impeller Depth (Cut Ø)**
Product A	9.5" (max)	85%	120 GPM (650 - 770 GPM)	8.75" (¾" cut, 92% of max Ø)
Product B	9.6" (max)	83%	60 GPM (715 – 775 GPM)	9.54" (1⁄16" cut, very shallow)
Product C	9.25" (max)	83%	180 GPM (690 – 870 GPM)	9.125" (⅛" cut, 98.5% of max Ø)

Deep Efficiency Islands			
Product	**Impeller Ø (max Ø to 90% Ø)**	**E, % (max Ø to 90% Ø)**	**Flow Width (GPM Range)**
Product A	9.5" (max) → 8.5"	85% → 84%	135 GPM (540 – 675 GPM)
Product B	9.6" (max) → 8.6"	83% → 80%	155 GPM (575 – 730 GPM)
Product C	9.25" (max) → 8.25"	84/83% → 80%	120 GPM (620 – 740 GPM

Efficiency at Max Ø and Min Ø				
Product	**Max Impeller Ø**	**Min Impeller Ø**	**Peak Efficiency Island, % (at Max Ø)**	**Peak Efficiency Island, % (at Min Ø)**
Product A	9.5"	7.25"	85%	81%
Product B	9.6"	7"	83%	67%
Product C	9.25"	7.5"	83%	78%

CONTROL CURVES AND VARIABLE SPEED OPERATION

Previously, the aspect of the control area has been reviewed (see **Figure 3**). This indicates the variations at which pumps in HVAC systems must operate. When the aspect of *Efficiency Islands* is paired with the control area, it becomes evident the best, most efficient operation will result from variable speed operation. The width and depth of the *Efficiency Islands* of Product A address the type of systems encountered in the HVAC industry; however, even with a variable speed drive, pump selection relative to BEP can impact the overall system efficiency. Examples of two selections – one to the left of BEP and one to the right of BEP – illustrate this consideration.

Figure 13 illustrates the historical, traditional pump selection with the design point to the left of BEP. While it offers meaningful operating cost savings through variable speed operation, there are opportunities for improvement. As operation occurs at many load conditions from the design point down to very low loads, the pump efficiency will always decrease.

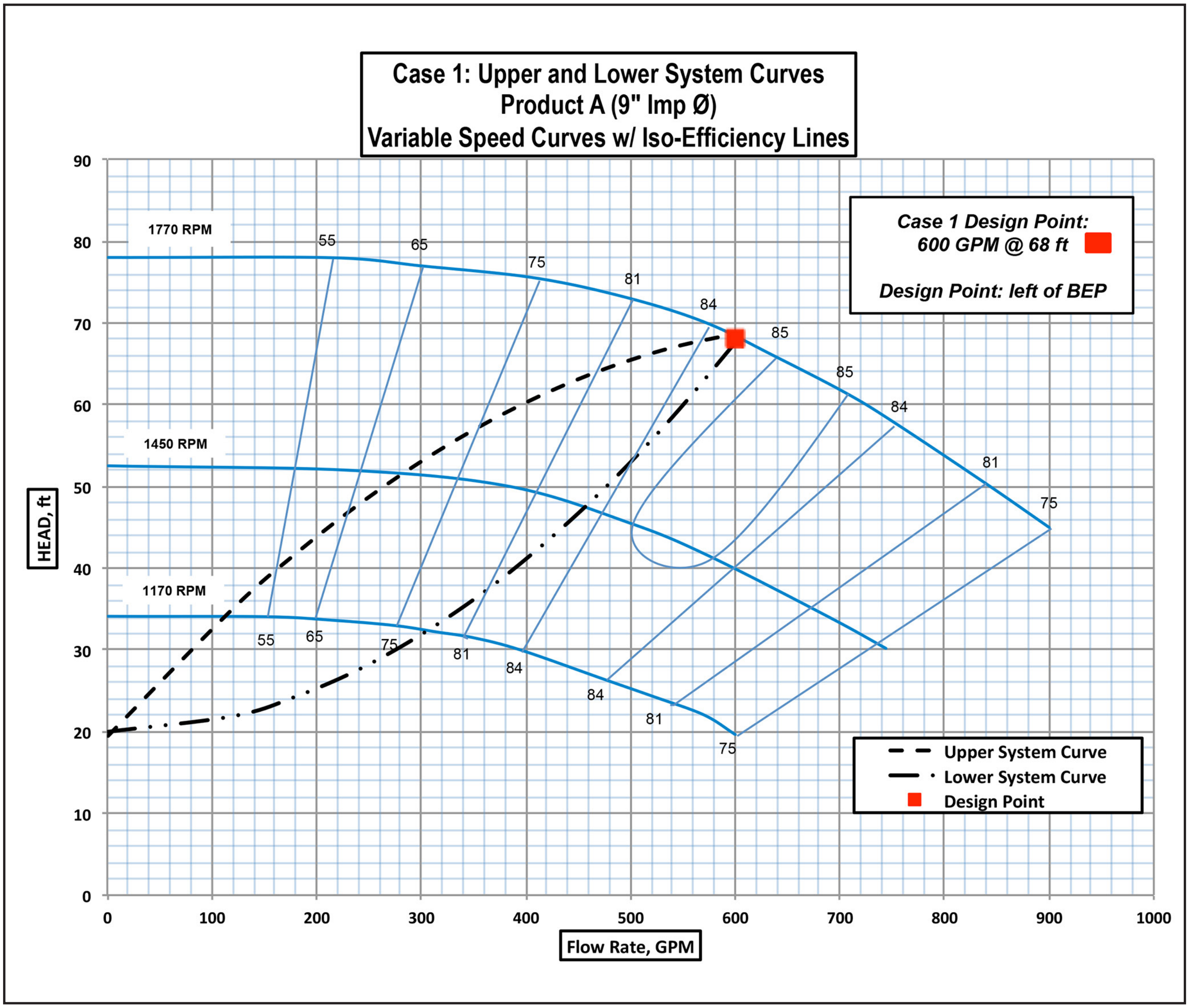


Figure 13

The next example in **Figure 14** shows a pump selected with the design point to the right of BEP. As can be noted when the pump operates at load conditions below design, the pump moves back through the higher *Efficiency Islands*. This yields a more economical operating system throughout the load profile.

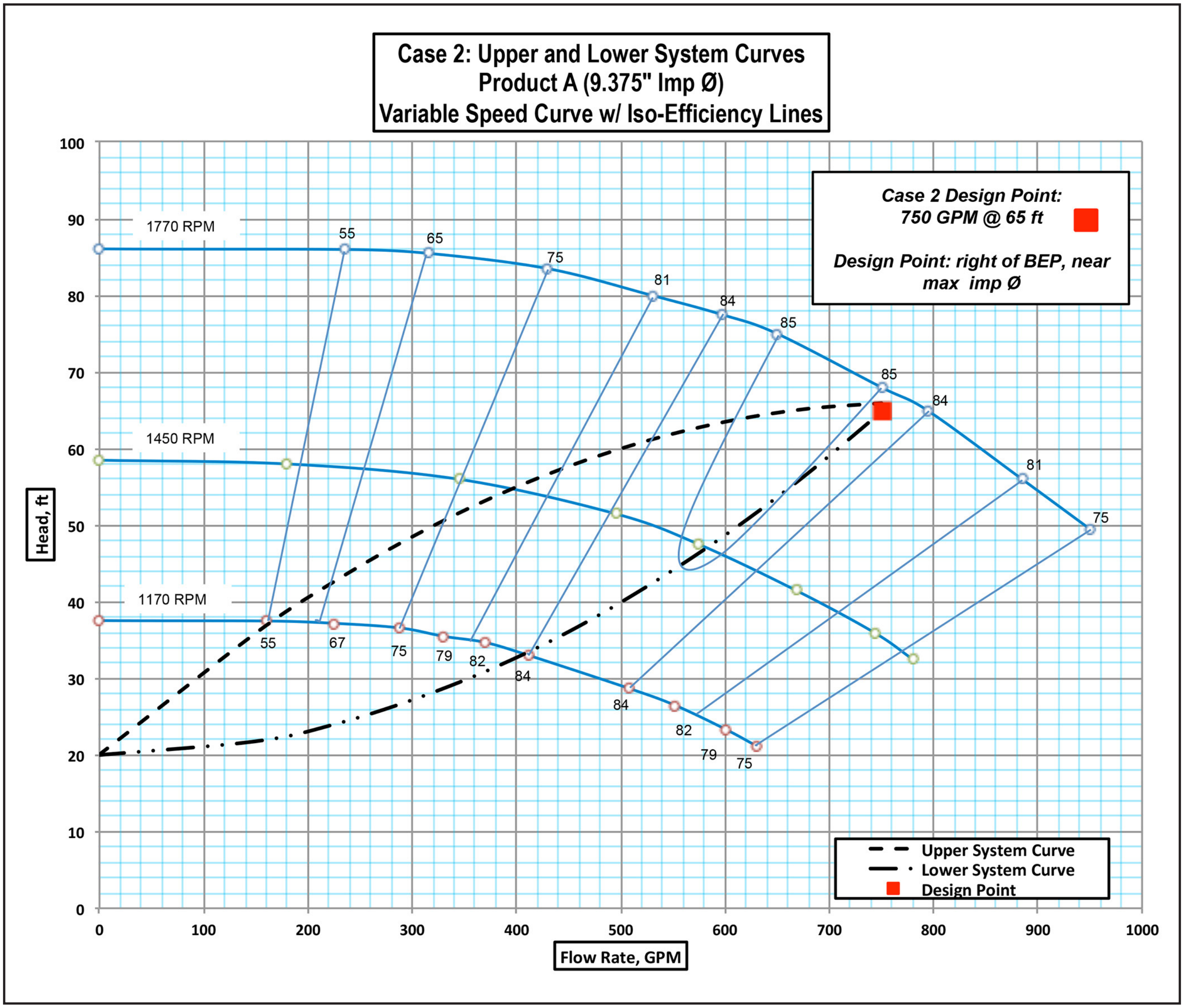


Figure 14

Operating Cost Comparisons:

Some examples follow that illustrate the results one can see using modern design enhancements with the resulting advantages of the *Efficiency Islands*. Three cases are illustrated with operating costs tabulated for Products A, B and C.

	Case 1	*Case 2*	*Case 3*	
Design Flow Rate =	**600**	**750**	**650**	**[GPM]**
Design Head =	**68**	**65**	**50**	**[ft]**
Control Head =	**20**	**20**	**15**	**[ft]**

Notes and Assumptions:

1] AOC = Annual Operating Cost

2] Operating cost analyses for both constant speed and variable speed drives are illustrated.

3] Motor efficiency was set to be equal to the lower system motor efficiency for each product evaluated within each case.

4] Energy cost is assumed to be $0.10/kW-hr.

5] Operating hours for the School/University load profile is 8,760 hrs/yr.

6] Operating hours for the Hospital load profile is 7,884 hrs/yr.

7] Annual Savings are compared to Product A based on the design condition above and the system curve indicated in the table.

8] Positive Annual Savings are favorable to Product A and negative savings **($)** indicate Product A to be higher.

9] Case 1 represents a pump selection with the design rating to the left of BEP.

10] Case 2 represents a pump selection with the design rating near maximum diameter to the right of BEP.

11] Case 3 represents a pump selection with the design rating at a reduced diameter to the right of BEP.

School/University Heating Load Profile:

Table A										
Constant Speed Operation		**Case 1 (Lower System Curve)**			**Case 2 (Lower System Curve)**			**Case 3 (Lower System Curve)**		
School/Univ	**Heating**	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C
	Total kW-hrs	65,100	78,952	71,785	81,171	87,506	80,620	54,602	63,515	65,953
	AOC	$6,510	$7,895	$7,179	$8,117	$8,751	$8,062	$5,460	$6,352	$6,595
	Annual Savings using Product A		$1,385	$669		$634	($55)		$892	$1,135

Table B										
Constant Speed Operation		**Case 1 (Upper System Curve)**			**Case 2 (Upper System Curve)**			**Case 3 (Upper System Curve)**		
School/Univ	**Heating**	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C
	Total kW-hrs	Same as Lower System Curve since pump operates on its H-Q curve at constant speed with a control valve dissipating excess head.								
	AOC									
	Annual Savings using Product A									

Table C										
Variable Speed Operation		**Case 1 (Lower System Curve)**			**Case 2 (Lower System Curve)**			**Case 3 (Lower System Curve)**		
School/Univ	**Heating**	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C
	Total kW-hrs	32,080	32,825	33,810	37,179	38,216	38,589	25,244	26,344	26,564
	AOC	$3,208	$3,282	$3,381	$3,718	$3,822	$3,859	$2,524	$2,634	$2,656
	Annual Savings using Product A		$74	$173		$104	$141		$110	$132

Table D										
Variable Speed Operation		**Case 1 (Upper System Curve)**			**Case 2 (Upper System Curve)**			**Case 3 (Upper System Curve)**		
School/Univ	**Heating**	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C
	Total kW-hrs	48,606	50,415	52,695	57,245	58,404	60,454	40,326	41,307	45,270
	AOC	$4,861	$5,041	$5,270	$5,725	$5,840	$6,045	$4,033	$4,131	$4,527
	Annual Savings using Product A		$180	$409		$115	$320		$98	$494

Hospital Heating Load Profile:

Table E										
Constant Speed Operation		**Case 1 (Lower System Curve)**			**Case 2 (Lower System Curve)**			**Case 3 (Lower System Curve)**		
Hospital	**Heating**	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C
	Total kW-hrs	63,097	77,712	71,071	78,797	85,754	79,815	52,945	61,289	64,562
	AOC	$6,310	$7,771	$7,107	$7,880	$8,575	$7,982	$5,295	$6,129	$6,446
	Annual Savings using Product A		$1,461	$797		$695	$102		$835	$1,152

Table F										
Constant Speed Operation		**Case 1 (Upper System Curve)**			**Case 2 (Upper System Curve)**			**Case 3 (Upper System Curve)**		
Hospital	**Heating**	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C
	Total kW-hrs	Same as Lower System Curve since pump operates on its H-Q curve at constant speed with a control valve dissipating excess head.								
	AOC									
	Annual Savings using Product A									

Table G										
Variable Speed Operation		**Case 1 (Lower System Curve)**			**Case 2 (Lower System Curve)**			**Case 3 (Lower System Curve)**		
Hospital	**Heating**	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C
	Total kW-hrs	37,850	38,508	39,330	44,112	45,292	45,232	29,908	31,191	31,245
	AOC	$3,785	$3,851	$3,933	$4,411	$4,529	$4,523	$2,991	$3,119	$3,124
	Annual Savings using Product A		$66	$148		$118	$112		$128	$133

Table H										
Variable Speed Operation		**Case 1 (Upper System Curve)**			**Case 2 (Upper System Curve)**			**Case 3 (Upper System Curve)**		
Hospital	**Heating**	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C	Prod A	Prod B	Prod C
	Total kW-hrs	52,236	54,609	56,353	59,613	61,353	59,504	43,263	42,971	47,755
	AOC	$5,224	$5,461	$5,635	$5,961	$6,135	$5,950	$4,326	$4,297	$4,775
Annual Savings using Product A			$237	$412		$174	($11)		($29)	$449

An example of the cost analysis for **Table H** above is provided in **Table I** below. This provides the data for Products A, B and C for variable speed operation for the Hospital Heating profile for Case 1 (Upper System Curve) in **Table H**.

Hospital	Heating	Product A		Upper System		9" Ø				
Load		Flow	Head	RPM	Pump	BHP	Drive/Motor	kW-hr	Cost/day	Wire/Water
Profile	Hrs/day	GPM	ft		Eff		Eff			Eff
40%	3.6	240	47.8		67.00%	4.32	86.46%	13.43	$1.34	57.93%
50%	6.0	300	53.1		73.00%	5.51	86.36%	28.56	$2.86	63.04%
60%	2.4	360	57.6		74.50%	7.03	86.05%	14.62	$1.46	64.11%
70%	2.4	420	61.5		79.00%	8.26	85.72%	17.25	$1.72	67.72%
80%	2.4	480	64.6		82.00%	9.55	85.38%	20.02	$2.00	70.01%
90%	2.4	540	67.0		83.00%	11.01	85.03%	23.18	$2.32	70.57%
100%	2.4	600	68.7		84.50%	12.32	84.67%	26.05	$2.60	71.55%
			days/yr =	365			kW-hr/day =	143.11	$14.31	
							Total kW-hrs =	52,235.71		
							Cost per kW-hr =	$0.10		
							Total Hours per year =	8760		
							Annual Operating Cost (AOC) =	$5,223.57		

Hospital	Heating	Product B			Upper System		8.95" Ø			
Load		Flow	Head	RPM	Pump	BHP	Drive/Motor	kW-hr	Cost/day	Wire/Water
Profile	Hrs/day	GPM	ft		Eff		Eff			Eff
40%	3.6	240	47.8	1309	64.26%	4.51	86.46%	14.00	$1.40	55.56%
50%	6	300	53.1	1404	69.22%	5.81	86.36%	30.12	$3.01	59.78%
60%	2.4	360	57.6	1490	72.92%	7.18	86.05%	14.94	$1.49	62.75%
70%	2.4	420	61.5	1569	75.71%	8.62	85.72%	17.99	$1.80	64.90%
80%	2.4	480	64.6	1641	77.87%	10.06	85.38%	21.09	$2.11	66.49%
90%	2.4	540	67.0	1709	79.50%	11.49	85.03%	24.20	$2.42	67.60%
100%	2.4	600	68.7	1771	80.72%	12.90	84.67%	27.27	$2.73	68.35%
			days/yr =	365			kW-hr/day =	149.61	$14.96	
							Total kW-hrs =	54,608.53		
							Cost per kW-hr =	$0.10		
							Total Hours per year =	8760		
							Annual Operating Cost (AOC) =	$5,460.85		

Hospital	Heating	Product C			Upper System		8.71" Ø			
Load		Flow	Head	RPM	Pump	BHP	Drive/Motor	kW-hr	Cost/day	Wire/Water
Profile	Hrs/day	GPM	ft		Eff		Eff			Eff
40%	3.6	240	47.8		60.00%	4.83	86.46%	15.00	$1.50	51.88%
50%	6	300	53.1		65.50%	6.14	86.36%	31.83	$3.18	56.57%
60%	2.4	360	57.6		70.50%	7.43	86.05%	15.45	$1.55	60.67%
70%	2.4	420	61.5		74.00%	8.81	85.72%	18.41	$1.84	63.43%
80%	2.4	480	64.6		76.30%	10.26	85.38%	21.52	$2.15	65.14%
90%	2.4	540	67.0		78.00%	11.71	85.03%	24.66	$2.47	66.32%
100%	2.4	600	68.7		80.00%	13.01	84.67%	27.51	$2.75	67.74%
			days/yr =	365			kW-hr/day =	154.39	$15.44	
							Total kW-hrs =	56,352.59		
							Cost per kW-hr =	$0.10		
							Total Hours per year =	8760		
							Annual Operating Cost (AOC) =	$5,635.26		

Table 1

Operating Cost Analyses Summary

Constant Speed Operation:
In virtually all cases for the system loads evaluated, there are prominent annual cost savings using Product A versus Products B and C. Power savings realized with Product A are typically in the 10 to 20 percent range when operating at constant speed.

Variable Speed Operation:
There are annual savings accrued utilizing Product A in virtually all situations compared to the competition with variable speed operation. The savings attributed to the gain in pump efficiency are much lower in magnitude compared to constant speed operation. This can be explained, in part, by the fact that variable speed operation reduces the power needed to much lower values than constant speed operation. At the lower power requirements for variable speed operation, the differences in power savings do not generate as much dollar cost savings although the changes are meaningful from a percentage basis. Savings are typically in the 3 to 6 percent range when comparing variable speed operation. Also caution must be used since variable speed operation can occur within the control zone region bounded by the upper and lower system curves. It is not good practice from an evaluation standpoint to assume all operation will occur on the traditional, lower system head curve.

When variable speed drives are considered, the most advantageous operating efficiency will be obtained when the design point is selected to the right of BEP. Product A also provides for situations when reduced impeller diameters can be selected to satisfy a driver non-overload requirement with VFD situations.

Summary Analysis:
Design enhancements that yield enhanced *Efficiency Islands* provide multiple advantages for engineers and users. Recognizing the wide variation in flow and pressure demands of HVAC systems, one should place additional emphasis on the capability of pump units to meet these varying conditions while sustaining efficient operation. The large majority of the Product A sizes will yield results similar to those presented in this comparison. Knowledge of heating, cooling and water supply systems by the centrifugal pump supplier organization and sales network, enables combined system and pump expertise to come to the forefront. This ensures practical design solutions for systems and pumps providing long term, cost effective operation.

Let's review results from this effort. Whenever possible there has been focus on the HI POR for pump selection. Coupling this with variable speed operation provides many benefits, including:

- Higher operating efficiencies
- Lower mechanical loads on the shaft and bearings
- Longer mechanical seal life
- Lower vibration levels
- Lower noise levels.

Comparison of Product A efficiency performance to Products B and C from several perspectives illustrates the meaning and results obtained from the improved *Efficiency Islands* of Product A.

How do the improved characteristics of Product A that result in larger *Efficiency Islands* translate to advantages for the customer?

1. When comparing constant speed operating units, lower operating costs will predominantly result.
2. When pump and driver sizes are compared, there will be occasions when smaller pumps and/or smaller drive sizes can be used.
3. Sustaining efficiency levels at reduced impeller diameters can allow non-overloading motor sizes to be limited with variable speed drives when at maximum speed.
4. While not directly compared in this discussion, variable speed units offer significant annual operating cost savings when compared to fixed speed units for the same service conditions. Additional benefits relating to maintenance and operational flexibility result when comparing a variable speed drive versus a fixed speed unit.
5. When variable speed units are compared, operating cost savings will not be as dramatic as comparing fixed speed units, but when savings are indicated it leads to an overall, more efficient pump operation. This yields the best balance of operating cost and flexibility from energy, operational and maintenance perspectives.
6. Especially with variable speed drives, consider selecting pumps with the design point to the right of BEP. This allows operation at reduced loads to move back through the most efficient pump range rather than continue to move away from the most efficient range when a pump is selected to the left of BEP.

[1] ASHRAE 90.1 – 2010 Energy Standard for Buildings

[2] ANSI/Hydraulic Institute Standard 9.6.3 – 2012, Guideline for Allowable Operating Region

[3] Simplified Analysis of Flow in Closed Loop Hydronic Systems, Bell & Gossett Technical Brochure TEH-802P, August 2001

[4] Variable Primary Flow Systems, Bell & Gossett Technical Brochure TEH-910, 2010