A Common Sense Method for Autoclave Design

by Kermit A. Buntrock
Buntrock Industries, Inc.

During our years of supplying autoclave systems to the industry, we have learned a number of ways to improve system performance while economizing system design. Probably the most dramatic improvement is the use of the wet accumulator. For a properly designed system, its use can frequently cut initial investment by over 30%, produce continuing savings through energy conservation, while offering better, more consistent results and fewer cracked shell molds. The logic of its use is couched in the principle of energy storage.

As an example, consider a typical small town's need for water. As residents arise in the morning and bathe, etc., water consumption goes up dramatically. As industry begins another day of production, water demand may rise even higher. In the evening after the residents retire, water demand is at a minimum. In order to smooth out these fluctuations and minimize pumping and delivery costs, most communities install water towers. Now a large reservoir of water can be stored for use during peak demand hours and pumping costs minimized by utilizing smaller pumps during off hours as well as high demand times.

Autoclave dewaxing has remarkable similarities to our water tower example. A large energy input is called for during the surge cycle for rapid pressurization (Typical: 0-90 PSI within 10 seconds). Once pressurized, much less steam is required per unit of time for the remaining 12-15 minute cycle time. Although additional energy is required after surge to heat shell, melt wax, and some lost to surroundings, we know the most critical design criteria in autoclaving is the initial surge pressure. Once the surface skin of the wax is melted, and expansive forces are no longer pushing outward against shell walls, remaining wax can be melted out at lower temperatures and pressures. (Low energy ovens have been used successfully in microwave units after surface pressures have been relieved.) Thus our main concern is providing sufficient surge energy, and this can be done by providing sufficient energy storage for immediate use rather than oversizing a boiler for 10 seconds of important work and 12 minutes of "loaf" time.

Energy Storage

In designing our autoclave system, we must first determine how much energy is required for our initial surge. Table 1 shows volume capacities and surge energy required for various sized autoclaves. You will note we are using fairly standard sizes and pressures (90 PSI for autoclave operation). For example, a 48" diameter x 60" long autoclave requires 16.14 pounds of steam

TABLE 1
Standard Autoclave Sizes & Steam Capacities

Dimensions Diameter	Length	Straight Vessell Volume f3	Volume of STD ASTM Domes f3	Total Volume f3	Lbs. Steam @90 PSI Lbs	BTU's @90 PSI
24	36	9.4	2	11.4	2.43	2880
30	36	14.7	4	18.7	3.81	4516
36	36	21.4	7	28.4	5.78	6850
36	48	31.4	7	38.4	7.81	9255
42	48	38.5	11.5	50.0	10.18	12065
48	48	50.3	16.5	66.8	13.59	16107
48	60	62.8	16.5	79.3	16.14	19125
48	66	69.1	16.5	85.6	17.42	20646
48	72	75.4	16.5	91.9	18.70	22163
54	72	95.4	24	119.4	24.30	28800
60	60	98.2	32	130.2	26.50	31408
60	72	117.8	32	149.8	30.48	36125
72	72	169.6	56	225.6	52.10	61749

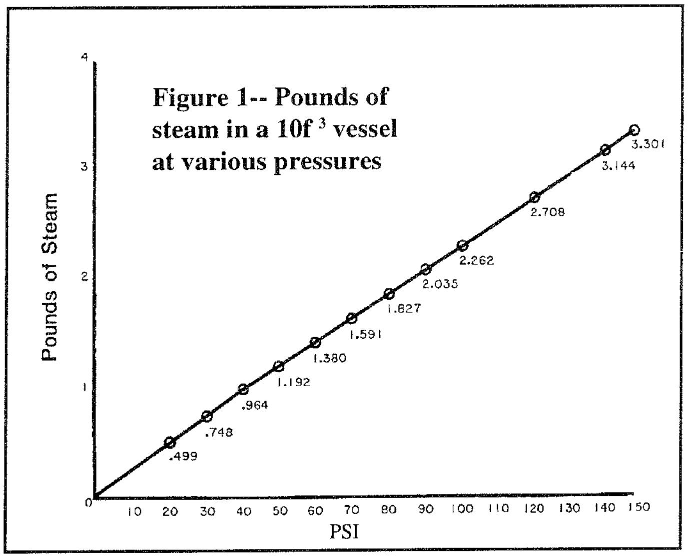


Figure 1-- Pounds of steam in a 10f^3 vessel at various pressures

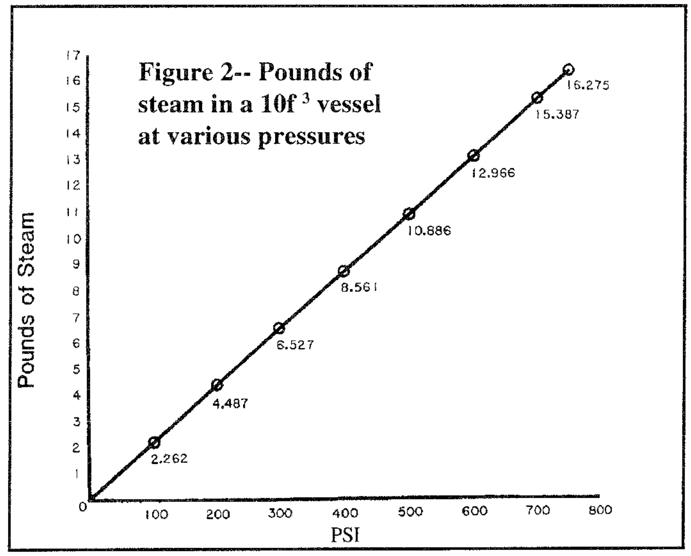


Figure 2-- Pounds of steam in a 10f^3 vessel at various pressures

containing 19,125 BTUs (British Thermal Units), to fill the 79.3 cubic feet (f^3) vessel to a pressure of 90 pounds per square inch (PSI).

For our simple model, it is easiest to think in terms of BTUs. Our boiler is the BTU factory, the accumulator is our "water tower" reservoir for BTU storage, and the autoclave is an empty vessel to be filled with BTUs. Since we know how many BTUs are required for our surge (Table 1), we can now concentrate on accumulator design.

Our energy can be stored in an accumulator as either dry steam, superheated water, or a combination. For simplicity when an accumulator stores mostly steam, we call it "dry", whereas if it stores superheated water, we call it "wet".

We know that a pound of steam at a given temperature contains more energy than a pound of water at the same temperature. We also know that a pound of water (at our operating pressures) is much more dense than a pound of steam. Our goal is to determine the minimum sized (minimum cost) accumulator which will release the required BTUs and whether it should be wet or dry.

Figures 1 and 2 show the pounds of steam which can be stored in a 10f^3 accumulator at various pressures. Figure 3 shows the pounds of water which can be stored in the same vessel at various pressures. If we have a 150 PSI boiler and desire to operate our accumulator at 140 PSI, we have our choice of storing 554 pounds of superheated water or 3.14 pounds of steam in our 10f^3 accumulator.

Figure 4 shows a comparison of the energy content of our 10f^3 accumulator when operated wet or dry at pressures from zero to 150 PSI. From the figure we can see our accumulator will store 180,700 BTUs if wet and only 3,750 BTUs if dry. Our choice is obvious, we will operate the accumulator wet.

We must next determine if our accumulator will release sufficient BTUs to meet our surge energy requirement. For our 48" x 60" autoclave, we need 19,125 BTUs of surge energy. After the autoclave door has been shut and secured, the pressur-

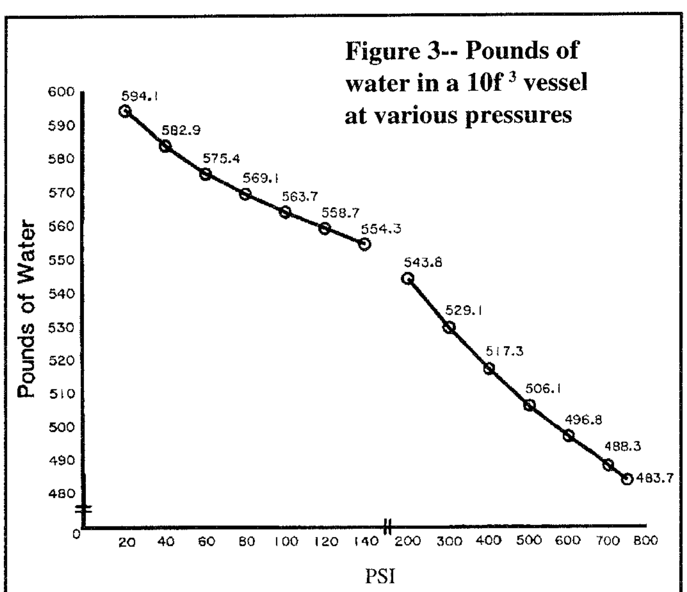


Figure 3-- Pounds of water in a 10f^3 vessel at various pressures

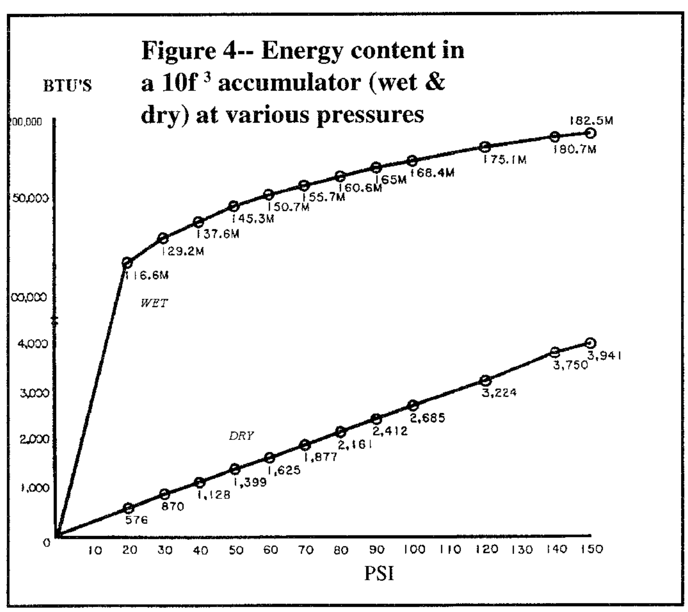


Figure 4-- Energy content in a 10f^3 accumulator (wet & dry) at various pressures

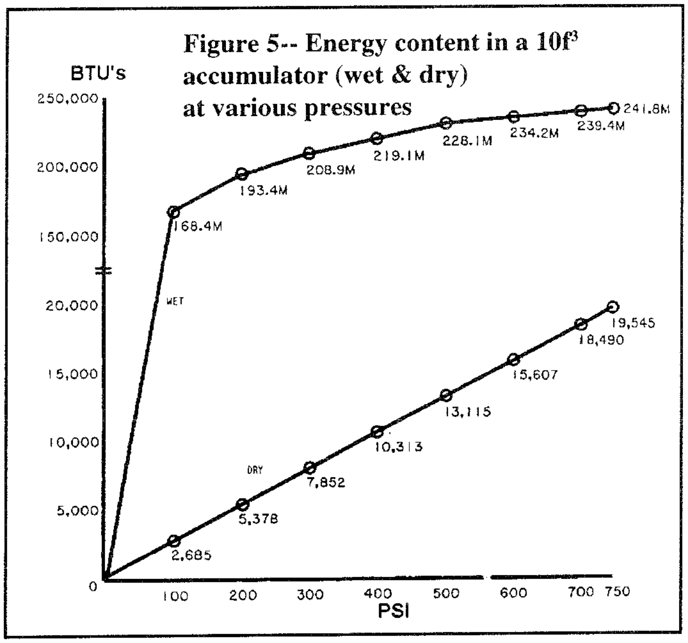


Figure 5-- Energy content in a $10f^3$ accumulator (wet & dry) at various pressures

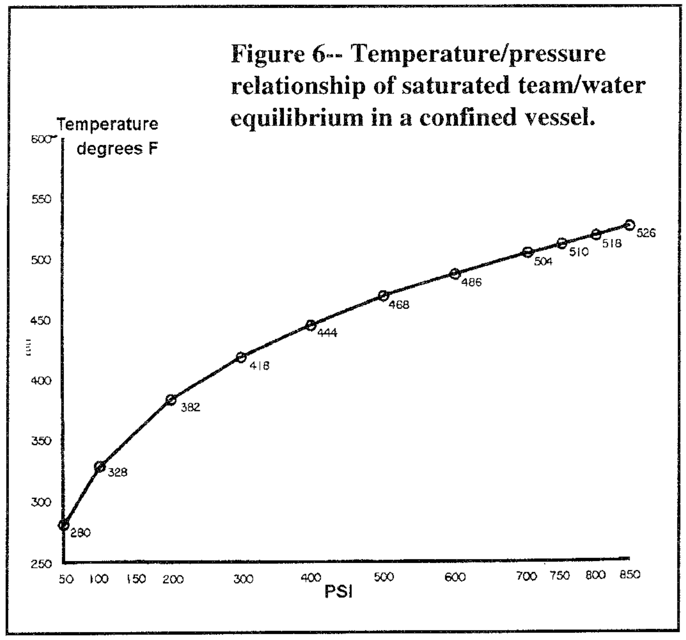


Figure 6-- Temperature/pressure relationship of saturated team/water equilibrium in a confined vessel.

ization fill valve is opened and superheated water flashes to steam and surges into the empty vessel. As this happens, pressure in the accumulator will fall as pressure in the autoclave rises. Since we want to reach 90 PSI in the autoclave, for full pressurization we must be certain that our accumulator pressure stays at least 90 PSI or higher. We can use Figure 4 to approximate our pressure head fall and BTUs released. For a pressure head fall of 40 PSI (from 140 to 100 PSI, we can release 12,300 BTUs (180.7M - 168.4M). Even if we operate the accumulator at its full 150 PSI and allow pressure drop to 90 PSI, we still generate only 17,500 BTUs. Our $10f^3$ accumulator is simply too small to fully pressurize our 48"x60" autoclave.

We can calculate the proper sizing as follows:

$$\frac{\text{BTUs required}}{\text{BTUs generated per volume}} = \text{Volume Required}$$

$$\frac{\text{19,125 BTU's (required)}}{\text{12,300 BTUs (generated for each } 10f^3)} \bullet 10f^3 = 15.55$$

Thus, our accumulator should have a capacity to hold at least $15.55f^3$ of superheated water. From Table 1, we note that a 30" diameter x 36" long domed pressure vessel has a volume of $18.7f^3$. If we fill it with $15.6f^3$ of superheated water and $3.1f^3$ of dry steam freeboard, our accumulator can be expected to function properly, falling from 140 PSI to 100 PSI each time surge energy is required.

Boiler Sizing

Our boiler must be capable of "pumping up" our accumulator from 100 to 140 PSI after each surge. If we allow 15 minutes between cycles, the boiler must produce (at least) the 19,175 BTUs during this period.

Boilers are rated in horsepower, which is a measure of the boiler's ability to produce steam at a certain rate. A 1 HP boiler will produce 34.5 lbs of steam per hour, or 33,500 BTUs per hour.

To recharge the accumulator for its surge energy, our boiler must produce 19,175 BTUs each 15 minutes. Thus its required horsepower is:

$$\frac{\text{19,175 BTUs} \bullet \text{4 cycles/hour}}{\text{33.500 BTUs for each HP}} = 2.3\text{HP}$$

We know from experience that this figure is preposterously low, as most large autoclave systems have boilers for 40 HP and up. The "old rule of thumb" of sizing a boiler (without an accumulator) equal to 1.25 times the cubic feet of the autoclave would require a 100 HP boiler and common sense dictates that is an overkill, just as our 2.3HP boiler seems incredibly small.

To properly size the boiler we must also consider the load and the work being done. Thus far our model has utilized an empty autoclave. Obviously some energy is expended in heating shells and trays, melting wax, and some lost to surrounds. According to boiler manufacturers, heat loss to surroundings can be cut to as little as 5-10% for a closed and well insulated system. Our next step is to determine the energy required to heat shells, trays, and melt wax.

Of course, this energy will vary according to load size. I was given the following information by a customer using a 36" x 48" autoclave.

Light load weight: 300-400 lbs.
Heavy load weight: 700-800 lbs.
For the heavy load: Steel basket weight = 50 lbs.
Melted out wax = 80 lbs.
Total weight of dewaxed shells = 670 lbs.
Upsizing these for our 48" x 60" autoclave: (1.67x)
Steel basket weight = 83.5 lbs.
Melted out wax = 133.6 lbs.
Total weight dewaxed shells = 1119 lbs.

To calculate energy we can use the following mathematical model. Let:

Wax Weight = W_w = 133.6 Ibs * (1)
Specific heat of wax (solid) = $C_p^w(S)$ = 0.5 (2)
Metal Basket weight = W_m = 83.5 Ibs. (1)
Specific heat of steel = C_p^s = 0.11 (3)
Total weight of dewaxed shells (refractory) = W_r = 1119 lbs. (1)
Specific heat of refractory = C_p^r = 0.2 (3)
Latent heat of wax = C_w = 103 BTUs/lb (2)
Specific heat of wax (liquid) = $C_p^w(1)$ (2)
T_1 = room temperature in °F = 72° (4)
T_2 = melting point of wax in °F = 150° (5)
T_3 = final autoclave temperature in °F = 320°F (6)

$$\text{BTUs consumed} = W_w \bullet C_p^{w(s)}(T_2 - T_1) + W_w \bullet C_w + W_w C_p^w(1)\ (T_3 - T_2) + W_m \bullet C_p^{si}(T_3 - T_1) + W_r \bullet C_p^r(T_3 - T_1)$$

Using numerical values:

BTUs consumed = 133.6 • 0.5 (150-72) +133.6 • 103
+ 133.6 • 0.5 (320-150) + 83.5 • 0.11 (320-72)
+ 1119 • 0.2 (320-72)
=5210.4 + 13,760.8 +11,356 +2,277.9 +55,502.4
=88,107.5 BTUs consumed

We have calculated that 88,107 BTUs are consumed by our work load. We remember that 19,175 BTUs were consumed in the surge pressurization, so 107,282 BTUs are consumed during each autoclave cycle (no heat loss). Allowing 10% heat loss to surroundings:

$\frac{107,282}{.90}$ = 119,202 BTUs consumed during each 15 minute cycle. Proper boiler sizing is now given as:

$\frac{119,202}{33,500}$ x 4 = 14.2 HP or 15 HP

Resizing the Accumulator for Full Loads

Using the energy requirements for the fully loaded autoclave implies that we now re-examine our logic on accumulator sizing. A very small percent of wax will melt when we have heated the refractory shell weight above the wax melting point. Since our goal is to instantaneously melt the wax skin to eliminate shell cracking, we can recalculate these additional BTUs our accumulator must release as follows:

Small quantity of wax to be melted ≅ 10 Ibs.
Refractory (shell) temperature required ≅ 170°F
Using these values:
Instantaneous BTU Work Demand =
10 • 0.5 (78) + 10 • 103 + 0 + 83.5 • 0.11 • (98) + 1119 • 0.2 • (98)
390 + 1030 + 900 + 21,932 = 24,252
Instantaneous BTU Work Demand = 24,252

Thus our accumulator should produce 19,175 BTUs for surge and an additional 24,252 BTUs to ensure instantaneous wax melt out. This is 43,427 BTUs or slightly more than double our original accumulator size.

Combining our total model, our "optimum" 48 x 60 autoclave system should have

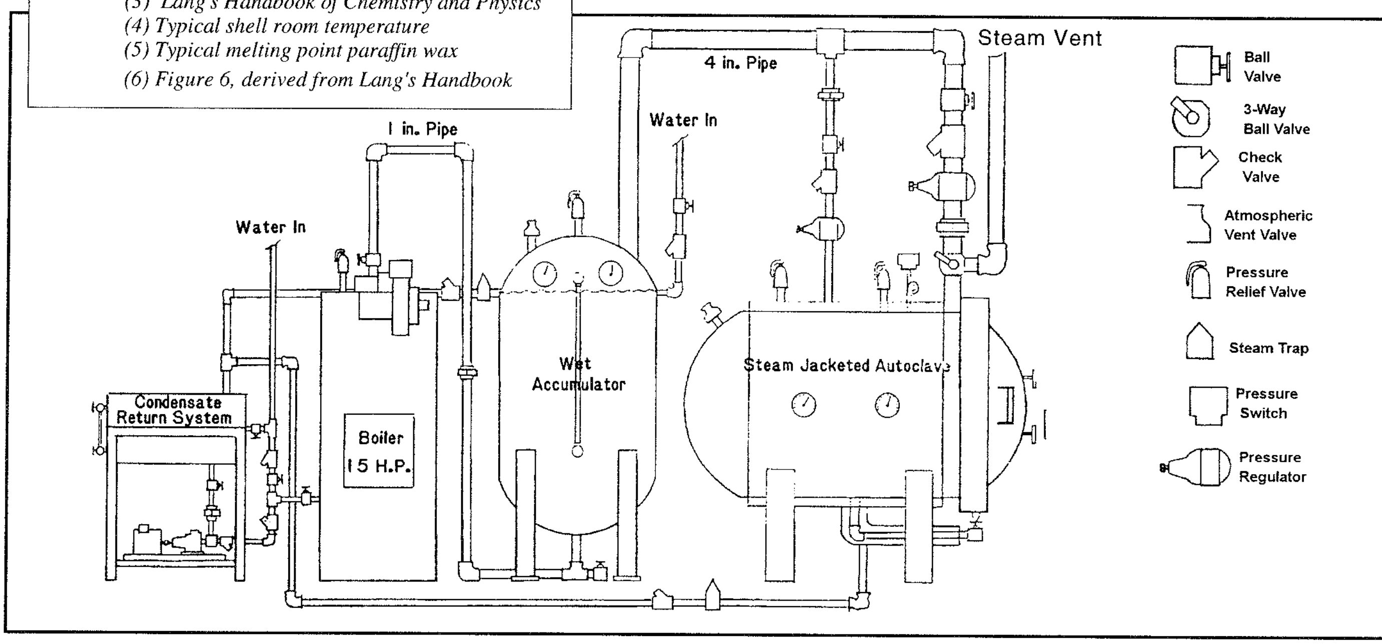
$\frac{43,427}{12,300}$ · 10 = 35.3 f^3 of superheated water

We could use a 36" x 48" (double domed) "wet" (Table 1) accumulator containing 35.3f^3 of superheated water and 3.1f^3 of dry steam freeboard, operated at 140 PSI prior to each surge. A 15 HP boiler is sufficient for 4 autoclave cycles per hour. We could just as easily use a 10 HP boiler but then only run 3 loads per hour.

Pressurizable Jacket

You will note in the above discussion we have used a 10% heat loss to surroundings for energy consumption during the entire

** Footnotes for mathematical model:*
(1) Calculated from customer data
(2) Data from National Wax Lab (for paraffin)
(3) Lang's Handbook of Chemistry and Physics
(4) Typical shell room temperature
(5) Typical melting point paraffin wax
(6) Figure 6, derived from Lang's Handbook



cycle. For our "instantaneous BTU work demand" we have again applied equation two, but then allowed no such energy loss. This is probably acceptable due to the instantaneous nature of our surge pressurization, but it also presumes the use of preheated and pressurizable jacket surrounding the autoclave. With sufficiently preheated vessel sidewalls, their BTU energy absorption during pressurization can be considered nil.

Some older systems in the industry employ insulated, but non-jacketed autoclave vessels. This design is undesirable from the point that substantial surge pressure BTUs will be absorbed in heating vessel sidewalls. You will note from equation two that the metal basket weight was presumed to be 83.5 lbs. and heating slightly above wax melting temperatures required only 900 BTUs. However, if we add an additional 800-1,000 lbs. of cold steel (estimated weight of vessel sidewalls) to term 4 in equation 2, up to an additional 10,780 BTUs would be consumed in heating these massive sidewalls. Such a change could easily result in additional cracked shell molds. Companies which have these systems are well advised to run one or two empty cycles first in order to preheat vessel sidewalls. Even so, valuable surge pressurization BTUs will still be lost with this system design.

Piping the Autoclave System

Figure 7 shows a simplified schematic of the piping of our "optimum" 48" x 60" autoclave system. You will note boiler steam is percolated through a bottom port in our accumulator. This ensures full pressurization of accumulator and minimizes any heat stratification. Our accumulator water level is maintained just above the beginning of the top dome. We have placed a condensate return line back to the boiler, using the outlet port just at the upper dome in the accumulator to maintain our water level. We have used all schedule 80 pipe with a 1-inch line from the boiler to the accumulator, as we are not concerned with rapid pressurization of the accumulator. We have used a special 4-inch line with a 2-foot riser from the accumulator to the autoclave. This permits rapid pressurization of the autoclave and prevents siphoning of water into the vessel. A 1-inch line is used to connect the autoclave jacket to the accumulator; a pressure regulator is set at 100 PSI on this line to assure jacket pressure is maintained higher than vessel pressure to minimize condensation. A bottom port from the jacket is steam trapped and feeds back to the condensate return system. The vessel drain port is also steam trapped but feeds to our blowdown separator. Wax is caught in a special stainless steel tray with its own drain line, which allows the option of pumping directly to an "in-house" reclaim system without energy loss in cooling. The system has been design engineered and optimized for efficiency.

The same logic and model presented in this paper can be used to design and optimize any autoclave dewaxing system.

New Work in System Design

After our units ship to customer sites, our company is involved in follow-up after the sale to assure that the autoclave systems are performing as intended. One of the refinements which has resulted from this field follow-up is the use of a special bypass line for regulating vessel pressure. Virtually all valves, pipe elbows, strainers, etc. serve to restrict steam flow as well as to do their intended function. Particularly troublesome is the pressure regulator. One customer removed the pressure regulator on the incoming vessel steam line. This enabled him to cut surge pressurization time from 14 seconds to 6 seconds. By providing a less restricted, more open flow line, he was able to improve results dramatically. In order to continue utilizing pressure regulation for the vessel, we now use a special bypass line for the regulator, thus leaving the main fill line unrestricted. This has resulted in a substantial improvement in system performance.

Another refinement now offered is a fast closure door. Most doors are manually closed and then lock via a hydraulically moving ring. This sequence usually takes 6-8 seconds (or longer), but has been cut to 1.2 seconds in the new design. We recently supplied a system using this design along with high pressure boiler and a rapid opening, automatic fill value. When installed, this system offered door closure and pressurization up to 120 PSI in less than 3 seconds, a sequence time believed impossible only a few years ago.

Special Design Systems

A number of investment casters have expressed interest in autoclave systems capable of melting plastic patterns or a combination of plastic and wax assemblies. Two approaches to this problem are possible.

The first uses a high-pressure/high-temperature autoclave system with the steam/water accumulator operating at equilibrium. As in the standard dewaxing system the vessel temperature can be directly determined by operating pressures. This relationship is given in steam tables and is presented pictorially in Figure 6. Since most plastics used for investment casting patterns melt between 450°F and 500+°F, extra-high pressures are required.

Our company designed and installed one such system which used a special boiler rated at 550 PSI. The autoclave was mounted vertically to maximize load capacity while minimizing the autoclave volume to be pressurized. With the correct sizing and use of a wet accumulator, the system comes to a surge pressure of 450 PSI in 4 seconds using only a 10 HP boiler. Cost for this system would have been prohibitive and design nearly impossible without the use of a wet accumulator and the principles presented here.

Operating pressures above 800 PSI and temperatures above 500°F are possible with the use of a special coil type boiler (ASME rated at 900 PSI), and a high pressure wet accumulator. However, as pressures escalate to these levels, so do system costs. Figure 6 clearly shows diminishing returns at ultra high pressures for the steam/water (pressure determine temperature) equilibrium type design.

As a result, we have been exploring a new design technique. A special afterburner is used in place of the standard accumulator. After steam is produced by the boiler, it is piped to extra burners where it is superheated. This design makes possible operating temperatures above 550°F but with pressures under 200 PSI. Such a system would be capable of melting out assemblies made of a combination of plastic and wax. We know of no such system in operation in the investment casting industry today, but as technology marches on we may see a number of such sophisticated systems.

Sexual Harrassment is one of several topics to be discussed in a session on Labor and Employment Law as a part of the Investment Casting Institute's Spring Management Meeting April 26-27 in Washington D.C.. For further informatin, see pp. 6-7)

Now that the Supreme Court Has Spoken, Companies Must Revamp Sexual Harassment Policies

Each employer should reexamine its policy on sexual harassment in light of the U.S. Supreme Court's October ruling in the case of Harris v. Forklift Systems. The decision changes the balance between employer and employee in such cases, making it much tougher for the company to win in situations which are, as the trial judge described the Harris case, "a close case."

The key holding by the high court follows the recommendation of the Equal Employment Opportunity Commission that a worker claiming to be the victim of sexual harassment does not have to show that she suffered serious psychological injury before she can collect damages. Previously, of the four circuit courts of appeals that had ruled on that question, only one had taken that position. The majority said that harassment cannot be said to have made a workplace environment abusive if the women who were the object of the abuse took it in their stride. The effect of the decision is compounded by the recent change in the civil rights act allowing plaintiffs to demand a jury trial in sexual harassment cases. That makes winning on a motion for summary judgment all the more important.

At worst, juries will react more emotionally to charges than a judge; at best, juries still require longer and more expensive trials. Doug McDowell, who defends companies in harassment cases, warns that after the Harris decision, juries have "a lot of leeway" to find illegal harassment in cloudy situations. Though the judges changed the test for what is considered abusive, what is more important is their subtext and the way they handled the case. The high court went out of its way to send lower courts a strong message: Take sexual harassment charges very seriously. That's why it's imperative to have a spirited program to prevent such incidents. Even if the program isn't 100%, mere existence will provide a strong defense for an accused company. The fact that the Supreme Court decision was unanimous tells trial judges that this is an area that can no longer be subject to overmeticulous distinctions. And the speed with which the justices rushed out the decision--a mere 27 days from the oral arguments, astonishing speed for a case generating this much attention--is a not-very-subtle signal that they consider the issue an extremely important one.

The Wobbly Line

The Harris case is not about overt discrimination such as refusing to promote a woman to supervise male workers, say, or offering a job or promotion in return for sex. Those situations are clear violations of Title VII of the 1964 Civil Rights Act, and relatively easy problems for executives to stomp out. The trickier issue is the kind of workplace banter, joshing or even overt insulting which can be little more than the give-and-take of a normal workplace. The woman who brought the case to the Supreme Court, a manager in an equipment rental firm, withstood her boss's remarks for more than two years before lodging any complaint. She quit six weeks later when, after apologizing and promising to clean up his act, he began the mocking again. The court record in the case listed such comments as "We need a man as the rental agent" and offers to "go to the Holiday Inn" to negotiate a raise. When that kind of treatment crosses a line, it becomes unlawful because the target of the attacks is deemed subject to different working conditions than other employees. If that difference is based on sex (or, although it was not the issue in the Harris case, race, religion or national origin), it's illegal discrimination.

The conundrum for management is that no one knows just where the line is. It was clear in oral arguments on the Harris case that Justice Antonin Scalia was particularly troubled by the fuzzy definitions of what is allowed and what is forbidden, but he eventually concluded that there is no way to come up with a precise definition. The only test the high court will use is whether a "reasonable person" would find the conduct abusive. The examples need not be "especially egregious" and there need not be evidence that the target of the abuse turned in a poorer performance because of the jibing. (The courts will assume the victim had to work harder to do as good a job as those who were not harassed.)

Some older decisions drew a distinction between "mere words" and touching and other physical acts. But companies can no longer rely on that difference. The defense that the complained-about behavior was "only talk" is now a sure loser.

What Matters

If the dispute gets into court, judges trying to decide if the charges merit a jury trial are now told to weigh: the frequency of the incidents; their severity; whether they were humiliating; whether there was a physical threat, open or implicit; and whether the behavior "unreasonably interfered with an employee's work performance."

The judge is given no guidance on how much importance to give to each factor. In fact, Justice Sandra Day O'Connor wrote that "this is not, and by its nature cannot be, a mathematically precise test." But the key is that even if there is no evidence at all that the conduct affected a person's work, the employer can still be found liable for damages for harassment.

In making it tougher for a company to beat back charges of sexual harassment, the Harris decision actually makes it easier for bosses to get tough with subordinates about treating women and minorities with dignity. There's a risk that if a company

Reprinted with permission, "You and the Law", National Institute of Business Management, Inc., PO Box 25348, Alexandria, VA 22313-5348. Phone 1-800-543-2055.