Whole Milk Reverse Osmosis Retentates for Cheddar Cheese Manufacture: Cheese Composition and Yield

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ABSTRACT
The impact of concentrating whole milk by reverse osmosis prior to Cheddar cheese making was studied. Heat treated, standardized, whole milk was reduced in volume by 0, 5, 10, 15, and 20% prior to Cheddar cheese manufacture. Milk solids at various milk volume reductions were 11.98, 12.88, 13.27, 14.17, and 15.05%, respectively. Permeates contained only traces of organic matter and would not create a significant by-product handling problem for a cheese plant. Solids content of the whey from cheese making increased with increasing milk concentration. Proximate compositions of reverse osmosis cheeses were comparable to control cheeses. Fat losses decreased, and fat retained in the cheese increased with increasing milk solids concentration. Improved fat recovery in the cheese was related to the amount of mechanical homogenization of milk fat during the concentration process. Actual, composition adjusted, and theoretical cheese yields were determined. Increased retention of whey solids and improved fat recovery gave cheese yield increases of 2 to 3% above expected theoretical yields at 20% milk volume reduction. Water removal from whole milk prior to Cheddar cheese manufacture gave increased productivity and cheese yield without requiring different cheese-making equipment or manufacturing procedures.

INTRODUCTION
The cheese manufacturing industry has considerable interest in concentrating whole milk prior to Cheddar cheese manufacture. Several Cheddar cheese manufacturers in the United States currently are using conventional evaporation methods to concentrate whole or skim milk prior to cheese manufacture (30). Removal of 5 to 20% of the water from whole milk by reverse osmosis (RO) or conventional evaporation may offer many advantages of production efficiency to a cheese manufacturer.

Most research on membrane filtration of milk for cheese manufacture has focused on ultrafiltration (9, 11, 14, 16, 21, 33). Some research has been with reverse osmosis concentration of skim milk (1, 31) prior to yogurt manufacture (13). Other research (24) has evaluated the influence of concentration of whole milk by conventional evaporation on cheese making. Reverse osmosis has been used to concentrate whole milk before Cheddar cheese manufacture, but the cheese had variable texture and unacceptably high coliform counts (2). The authors (2) indicated that membranes in their RO system were in poor sanitary condition before the start of their study, and bacteriological quality of their milk concentrates and cheese may not be typical of good commercial cheese making conditions. Barbano and Malik (6) made Cheddar cheese from RO skim milk concentrate that was recombined with cream. The cheese was of acceptable quality during early aging but had slower protein breakdown than normal commercial Cheddar cheese.

Membrane fouling reduces operating efficiency of a membrane filtration system. Fouling of RO membranes by various milk constituents has limited use of RO for concentration of milk. Multistage recycle design of RO units (26) has improved flux rates, and considerable information has been published on methods to decrease membrane fouling problems (15, 18, 29, 32).

Our objective was to evaluate the impact of RO concentration of whole milk on Cheddar cheese manufacture.
cheese yield and composition. Milk volume reductions of 5, 10, 15, and 20% were selected so that it would be possible to use conventional cheese making equipment, ingredients, and traditional Cheddar cheese manufacturing procedures. Milk concentration and cheese making were in a Cheddar cheese plant so that the procedures and conditions would be typical of those in commercial cheese manufacture.

This study evaluated a range of milk concentrations (part 1) and then focused on a more detailed evaluation of the 15% milk volume reduction by an RO system with a different method of pressure regulation (part 2).

MATERIALS AND METHODS

Milk Processing and Cheese Manufacturing

All milk processing and cheese manufacturing was in a commercial Cheddar cheese plant. Experimental cheese making was under pilot scale conditions that were designed to be the same as milk handling and cheese making procedures for normal commercial Cheddar cheese manufacture. Raw whole milk (4°C) was pumped from milk storage silos to a conventional high-temperature short-time (HTST) heat exchanger at 22,955 kg/h. Milk was heat treated at 65°C for 21 s and cooled to 30°C. This is the normal subpasteurization heat treatment of milk used for production of New York State aged Cheddar cheese. Whole milk was standardized to approximately a .7 ratio of casein to fat by addition of heat treated skim milk before concentration.

Milk flow (Figure 1) from the HTST unit was split and about 1,360 kg/h of milk was diverted to the RO unit. The RO unit was a Paterson Candy International multistage recirculation system with six B1 modules (26). The membranes were T2/15W cellulose acetate with an operating upper temperature limit of approximately 35°C. The balance of the unconcentrated milk flow (Figure 1) went to enclosed 16,360-kg capacity cheese vats. The experimental cheese vat was a 3,640-kg capacity conventional cheese vat. Approximately 1,135 liters of RO milk concentrate was produced in

Figure 1. Milk flow within the cheese plant.
75 min and delivered directly into the 3,640-kg capacity cheese vat at 30°C. This was only about 30 min longer than it normally took to fill a 16,360-kg cheese vat during the normal production schedule in this cheese plant. Therefore, the milk was not handled long before cheese making.

The experimental cheese vat was calibrated by added known weights of water (30°C) and a stainless steel calibration stick marked for subsequent measurement of milk volume at 30°C. Weight of water at 30°C was converted to corresponding volumes by calculation. The volume of milk or milk concentrate was measured (3,640-kg capacity vat was always filled to the 1,135-liter mark). Next, the weight of 1,135 liters milk or milk concentrate at 30°C was calculated based on its milk fat and solids-not-fat content as recommended in the milk market administrators' report (3) on weight-volume conversion factors for milks of various composition and temperature.

Starter culture was added to the RO milk concentrate while the vat was being filled. By the time the 3,640-kg experimental cheese vat was filled, the starter culture ripening period was complete, and rennet was added. The 3,640-kg capacity cheese vat was always filled to the same 1,135-liter mark no matter what milk concentration factor was used. Addition of starter culture was adjusted to give a normal total cheese making time and rate of pH change. Starter culture used with RO concentrates was the normal bulk starter used at the same time in the 16,360-kg capacity cheese vats on that day of production.

The same commercial calf rennet that normally was used for Cheddar cheese production in this plant was used for all experimental lots of cheese. Research (6, 14) indicated that rate of proteolysis during cheese aging was retarded if a normal amount of milk coagulant was not retained in the cheese. Therefore, the amount of rennet added to milk concentrates was based on the original unconcentrated milk volume.

The coagulum was cut 25 to 30 min after rennet addition. Milk concentrates gave much firmer coagulation than unconcentrated milk, but the time from rennet addition to cut was kept the same for all treatments. The coagulum was cut with conventional 8.3-mm cheese knives, allowed to heal for 5 min, then slowly agitated for 10 min (30°C). The temperature was increased from 30 to 33°C during the first 15 min of cooking followed by a temperature increase from 33 to 38°C in the subsequent 15 min. Next, curd and whey were stirred at 38°C for an additional 30 min. Whey was drained from curd, and a normal cheddaring procedure was used. Cheese curd was milled, salted, hooped, and pressed by normal commercial procedures. Individual blocks of experimental cheese were weighed to the nearest .05 kg immediately after pressing. Theoretical and composition adjusted cheese yields were calculated as in (8).

Levels of Milk Concentration Evaluated

In part 1, we evaluated the impact of milk volume reductions (5, 10, 15, and 20%) by a PCI RO unit equipped with a high pressure throttle valve. The control vats of cheese (zero milk volume reduction) were made from unconcentrated, standardized, whole milk in the 3,640-kg capacity conventional cheese vat under the same processing conditions as all the RO cheese except that the milk was not passed through the RO unit. These cheeses will be called the 3,640-kg vat controls. All of the cheese made in the 3,640-kg capacity experimental vat during this study was made by an experienced cheese maker from the cheese plant. At the same time that every experimental vat of cheese was made in the 3,640-kg capacity vat (whether it was from unconcentrated or RO concentrated milk), a comparison vat of cheese was always made with the same starter culture in a 16,360-kg capacity vat. These vats of cheese will be called the 16,360-kg vat controls. Cheese from 16,360-kg vats was more useful for evaluations of cheese quality and composition than for cheese yield because the 16,360-kg vats were not calibrated accurately for milk weight determination.

In part 2, we selected 15% milk volume reduction (milk concentration that would have significant economic advantages) and did a more complete evaluation of the impact of this RO concentration of whole milk on cheese composition and yield. The PCI RO unit was modified with an exit pipe reduce diameter instead of high pressure throttle valve for regulation of operating pressure. Our objective was to determine if we could adequately
control the cheese making process to obtain a cheese of comparable composition and quality to that normally produced in this plant.

Sampling and Analyses

Samples of milk plus starter taken prior to rennet addition, whey immediately before draw, and cheese at 7 days of age were taken for each 3,640-kg experimental and control vat of cheese. Permeate samples were collected each time the RO unit was operated. Samples of milk plus starter were preserved immediately with potassium dichromate (.5 grain per 35 ml) and quickly frozen at -55°C to prevent sample deterioration. Whey samples were not preserved chemically but were frozen under the same conditions as milk samples. Cheese samples were analyzed fresh except for protein analysis in part 2, which was on frozen and thawed samples.

Individual milk and whey samples were thawed in a conventional microwave oven and analyzed immediately. A frozen milk or whey sample can be thawed quickly (1 or 2 min with a microwave oven) to avoid long delays that can result in unwanted bacterial or enzymatic deterioration of samples during thawing. Conditions of microwave oven operation (time and power) can be adjusted easily so that a sample thaws and does not increase above normal refrigeration temperatures. This method of thawing works best when samples are removed from a freezer, sample container caps loosened, and then placed directly in the oven for thawing. If a sample is thawed partially when placed in the microwave oven, the liquid portion of the sample will become hot before the frozen portion of the sample melts.

Milk samples were analyzed for milk fat with a Milko Scan 104 infrared analyzer calibrated by the Babcock test (19). Total protein (total nitrogen x 6.38) and nonprotein nitrogen [nitrogen soluble in 12% trichloroacetic acid (TCA)] in milk and whey were determined by Kjeldahl analysis (8, 19). Casein content of milk samples was determined by a modification (19) of the International Dairy Federation method (20). Total solids in milk and whey samples was determined by a modified Babcock method (25).

Total solids in cheese was measured by atmospheric forced air oven drying of 2 g of cheese at 100°C for 24 h (25), fat was by the Babcock method (25), protein by the macro-Kjeldahl method (19), and salt by the Volhard method (25). The galactose and lactose-monohydrate in cheese were determined by an enzymatic method (5). Titratable acidity of cheese was determined as described in AOAC methods (19) with a modification of the ratio of cheese to water used in sample preparation (10 g of cheese in 95 ml of 60°C water instead of 10 g in 105 ml) so that the same sample filtrate could be used for the titratable acidity, lactose, and galactose determinations.

RESULTS AND DISCUSSION

Cheese Production and Composition

Cheddar cheese was made from unconcentrated standardized whole milk (ratio of casein to fat approximately .7) and standardized whole milk that was RO concentrated by 5, 10, 15, and 20% reduction of volume. Composition of milk (Table 1) for control cheese was typical of standardized milk composition normally used for Cheddar cheese manufacture in this factory. The fat and casein content of the 15% reduced-volume milk in part 2 was higher than in part 1 because the initial unconcentrated milk had higher fat and casein content in part 2. The RO system in part 2 was designed to remove 15% of the milk volume regardless of the initial composition of the unconcentrated milk. In a commercial application of this technology, it would be better to concentrate the milk to the same casein and fat (throughout the year) to obtain consistent raw material composition for cheese making. The percent nonprotein nitrogen in milk retentates did not increase with increasing concentration in part 1 (Table 1), because a portion of the original milk nonprotein nitrogen (mainly urea) passes through the cellulose acetate RO membranes in the permeate.

Permeate contained no measurable milk fat, lactose, or protein, as determined by conventional analysis methods. The permeate did contain nitrogen, but all of it was soluble in...
TABLE 1. Composition of control milk and reverse osmosis milk concentrates.

<table>
<thead>
<tr>
<th>Milk volume reduction (%)</th>
<th>Number of vats</th>
<th>Fat</th>
<th>Casein</th>
<th>NPN</th>
<th>Lactose</th>
<th>Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>9</td>
<td>3.44</td>
<td>2.45</td>
<td>.15</td>
<td>4.57</td>
<td>11.98</td>
</tr>
<tr>
<td>Part 1</td>
<td>5</td>
<td>3.62</td>
<td>2.55</td>
<td>.17</td>
<td>4.72</td>
<td>12.88</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3.66</td>
<td>2.74</td>
<td>.17</td>
<td>4.93</td>
<td>13.27</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>3.91</td>
<td>2.80</td>
<td>.15</td>
<td>5.23</td>
<td>14.17</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4.21</td>
<td>3.04</td>
<td>.15</td>
<td>5.58</td>
<td>15.05</td>
</tr>
<tr>
<td>Part 2</td>
<td>15</td>
<td>4.11</td>
<td>2.93</td>
<td>.17</td>
<td>5.20</td>
<td>14.20</td>
</tr>
</tbody>
</table>

1 All cheese made in the 3,640-kg capacity vat.

2 Nonprotein nitrogen expressed as 12% TCA (trichloroacetic acid) soluble nitrogen multiplied by 6.38.

12% TCA. Most of this nitrogen was measurable as urea nitrogen. Urea content of the permeate was similar to that in the milk (milk 13.1 mg/100 ml, permeate 12.7 mg/100 ml). Urea is one of the major constituents of the native nonprotein nitrogen fraction of milk (35). Urea was determined by an enzymatic assay procedure (4) used for determining urea in blood.

Total solids and lactose in whey (Table 2) increased with increasing reduction of milk volume. Thus, with a 20% reduction of milk volume the whey at draw was about 2% higher in solids than normal Cheddar cheese whey. Even though the fat content of the milk concentrates was higher than the uncentrated control milks (Table 1), fat in the whey did not increase proportionately (Table 2). The nonprotein nitrogen in whey was higher than in the original milk because of the 12% TCA soluble glycomacropeptide released during proteolysis of κ-casein by chymosin.

Moisture, fat, protein, and salt content of cheese made in the 3,640-kg vat were similar to the composition of cheese made in 16,360-kg capacity production vats (Table 3). When the first experimental vats of cheese were made from milk at 5% volume reduction, starter culture activity was enhanced. Improved starter culture activity was not anticipated. Acidity of the RO cheese at 5% volume reduction (Table 3) was excessive and resulted in lower cheese grade at 10 days. As percent reduction of milk

TABLE 2. Composition of unseparated whey at draw.

<table>
<thead>
<tr>
<th>Milk volume reduction (%)</th>
<th>Number of vats</th>
<th>Fat</th>
<th>Protein</th>
<th>NPN²</th>
<th>Lactose</th>
<th>Solids</th>
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<tbody>
<tr>
<td>Control</td>
<td>9</td>
<td>.31</td>
<td>.92</td>
<td>.19</td>
<td>4.70</td>
<td>6.76</td>
</tr>
<tr>
<td>Part 1</td>
<td>5</td>
<td>.30</td>
<td>.96</td>
<td>.23</td>
<td>4.87</td>
<td>7.16</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>.27</td>
<td>1.00</td>
<td>.23</td>
<td>5.08</td>
<td>7.38</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>.29</td>
<td>1.08</td>
<td>.20</td>
<td>5.37</td>
<td>8.15</td>
</tr>
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<td></td>
<td>20</td>
<td>.28</td>
<td>1.14</td>
<td>.21</td>
<td>5.76</td>
<td>8.82</td>
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<tr>
<td>Part 2</td>
<td>15</td>
<td>.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 All vats of cheese produced in the 3,640 kg capacity vat.

2 Nonprotein nitrogen expressed as 12% TCA (trichloroacetic acid) soluble nitrogen multiplied by 6.38.
TABLE 3. Composition of control cheeses and cheeses made from whole milk rennetates at 10 days.

<table>
<thead>
<tr>
<th>Milk volume reduction</th>
<th>Vat size</th>
<th>Number of vats</th>
<th>Moisture</th>
<th>Fat</th>
<th>Protein</th>
<th>Salt</th>
<th>Lactose</th>
<th>Galactose</th>
<th>Titratable acidity</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control 3,640</td>
<td>9</td>
<td></td>
<td>37.3</td>
<td>32.6</td>
<td>24.8</td>
<td>1.52</td>
<td>.07^1</td>
<td>.02^2</td>
<td>.98</td>
<td>5.10</td>
</tr>
<tr>
<td>Control 16,360</td>
<td>9</td>
<td></td>
<td>36.8</td>
<td>32.6</td>
<td></td>
<td>1.37</td>
<td>.08^1</td>
<td>.03^2</td>
<td>.93</td>
<td>5.13</td>
</tr>
<tr>
<td>Part 1 5% 3,640</td>
<td>4</td>
<td></td>
<td>37.1</td>
<td>32.6</td>
<td>25.0</td>
<td>1.37</td>
<td>.20^2</td>
<td>.03^2</td>
<td>1.13^2</td>
<td>5.02</td>
</tr>
<tr>
<td>Control 16,360</td>
<td>4</td>
<td></td>
<td>36.3</td>
<td>33.0</td>
<td>25.1</td>
<td>1.45</td>
<td>.30^2</td>
<td>.03^2</td>
<td>.92^2</td>
<td>5.15</td>
</tr>
<tr>
<td>Part 1 10% 3,640</td>
<td>2</td>
<td></td>
<td>36.8</td>
<td>32.2</td>
<td>25.4</td>
<td>1.34</td>
<td>.14</td>
<td>.02</td>
<td>1.03</td>
<td>5.08</td>
</tr>
<tr>
<td>Control 16,360</td>
<td>2</td>
<td></td>
<td>36.9</td>
<td>32.7</td>
<td>25.4</td>
<td>1.32</td>
<td>.16</td>
<td>.02</td>
<td>.89</td>
<td>5.14</td>
</tr>
<tr>
<td>Part 1 15% 3,640</td>
<td>4</td>
<td></td>
<td>37.0</td>
<td>32.2</td>
<td>25.0</td>
<td>1.40</td>
<td>.24</td>
<td>.04</td>
<td>1.03</td>
<td>5.08</td>
</tr>
<tr>
<td>Control 16,360</td>
<td>4</td>
<td></td>
<td>36.5</td>
<td>33.0</td>
<td>25.3</td>
<td>1.46</td>
<td>.14</td>
<td>.02</td>
<td>.96</td>
<td>5.18</td>
</tr>
<tr>
<td>Part 1 20% 3,640</td>
<td>3</td>
<td></td>
<td>36.8</td>
<td>33.2</td>
<td>24.7</td>
<td>1.45</td>
<td>.40</td>
<td>.02</td>
<td>1.02</td>
<td>5.05</td>
</tr>
<tr>
<td>Control 16,360</td>
<td>3</td>
<td></td>
<td>36.1</td>
<td>33.1</td>
<td>25.3</td>
<td>1.47</td>
<td>.18</td>
<td>.02</td>
<td>.97</td>
<td>5.08</td>
</tr>
<tr>
<td>Part 2 15% 3,640</td>
<td>14</td>
<td></td>
<td>35.8</td>
<td>32.9</td>
<td>25.4</td>
<td>1.61</td>
<td>.43</td>
<td>.03</td>
<td>.87</td>
<td>5.20</td>
</tr>
<tr>
<td>Control 16,360</td>
<td>14</td>
<td></td>
<td>36.6</td>
<td>32.6</td>
<td>25.4</td>
<td>1.46</td>
<td>.33</td>
<td>.03</td>
<td>.86</td>
<td>5.21</td>
</tr>
</tbody>
</table>

1^Number of vats equal 7.
2^Number of vats equal 3.

Volume increased, starter culture inoculum had to be decreased and milk ripening time shortened in part 1. These modifications were determined by comparison with performance of the same bulk starter culture in the same unconcentrated milk used simultaneously in a 16,360-kg capacity vat. At 15% reduction of milk volume (part 1) the first vat of RO cheese was too acid, but after we determined how much to reduce the starter and ripening time for specific starter culture strains, the cheese acidity was normal. As we continued increasing the milk volume reduction in part 1, we gained experience in controlling cheese acidity. At 20% reduction of milk volume our ability to control cheese acidity was better than at lower reductions of milk volume in part 1. In Part 2, 14 vats of RO cheese at 15% reduction of volume had pH and acidities similar to those in normal production (Table 3). In general, it was necessary to decrease the amount of starter culture by 20 to 30% and decrease the ripening time at 30°C by 10 to 20% to obtain a normal rate of pH change during cheese making from RO milk concentrates.

Any modification of the Cheddar cheese making process must produce consistently a finished cheese with the desired moisture content. Less water will be removed from the cheese curd when the water content of milk has been reduced prior to cheese making. Moisture control in the finished product was not a significant problem with milk concentrated to these extents (up to 20% reduction of milk volume). Normal cheese making procedures (i.e., cut size, cook temperature, etc.) were used to control cheese moisture. We increased the cut size from 5.5 to 8.3 mm and decreased the final cook temperature by 1 or 2°C to maintain moisture of finished product in the range of 36.5% to 37%. All cheese made in the 3,640-kg capacity vat in parts 1 and 2 used the 8.3-mm cut size. These minor modifications of manufacturing procedure gave adequate control over moisture in the cheese if starter culture performance was controlled.

Control of pH and acidity of finished product is a function of controlling both starter culture activity during manufacture and salt content of the cheese. When Cheddar cheese is made from milk concentrates, control of salt content of the finished product is even more important than in normal Cheddar cheese production (22, 23). If the salt concentration in the aqueous phase of the cheese is too low, the starter will continue to produce acid from residual lactose in the cheese. Cheddar cheese made from milk concentrates had slightly
higher residual lactose than Cheddar cheese made from unconcentrated milk (Table 3). Composition of the moisture phase of the cheese curd at draw is similar to that of whey that surrounds cheese curd at that time. The increased lactose in cheese made from milk concentrates reflects increased solids and lactose content of the whey at draw (Table 2). Both lactose content and titratable acidity of Cheddar cheese made from unconcentrated milk under normal manufacturing conditions can vary considerably.

Extensive bacteriological testing of RO milk concentrates and finished cheese was throughout the study (10). Standard plate counts and staphylococcus and coliform counts of RO milk concentrates were similar to those of the unconcentrated milk. Slight increases were well within expected increases due to concentration. Staphylococcus and coliform counts of cheese made from RO milk concentrates were similar to those in cheese made on the same day from the same unconcentrated milk and starter culture. We had no bacteriological or cleaning problems with the RO system used for concentrating whole milk over about 1 yr with the same set of RO membranes.

Mineral content of milk, milk concentrates, permeate, whey, and cheese were determined and are reported in (10). There were no nutritionally significant differences in mineral content of Cheddar cheese made from RO milk concentrates and normal commercial Cheddar cheese. In general permeates contained less than 1.3% of the original total milk minerals for each of the nine minerals quantitated.

Cheese Yield

Cheese yield is one of the most economically important aspects of cheese manufacturing. The casein and fat content of a milk or milk concentrate will determine its theoretical cheese yield. VanSlyke and Price (34) proposed a formula for calculating the theoretical cheese yield of milk based on its casein and fat content and the desired final moisture in the cheese. They reported that Cheddar cheese yield = 1.93 (% milk fat) + (% milk casein − .1) 1.09/1 − (% moisture in the cheese/100). Milk casein and fat make up more than 90% of the solids content of Cheddar cheese. High efficiency of recovery of milk fat and casein is important for good cheese plant performance. The VanSlyke cheese yield formula indicates that the target percent fat recovery in the cheese, with milk that has a ratio of casein to fat of .7, should be 93%. Recovery of casein is not given a fixed target percent recovery but instead is incorporated into the cheese yield formula as the percent casein minus .1%. At a milk casein content of 2.40%, the expected casein recovery would be about 95.8%. Research on commercial Cheddar cheese yield performance (8) has indicated that low fat recovery (83 to 88%) in cheese can be a problem.

Theoretical cheese yield and observed composition-adjusted yields at various reductions of milk volume are in Table 4. As expected, total cheese yield increased significantly (α=.01) as milk was concentrated by RO. However, composition-adjusted cheese yield expressed as percent of theoretical cheese yield at 10, 15, and 20% reduction of milk volume in part 1 was greater (α=.05) than control (Table 4). Recovery of milk fat and casein increased with increasing reduction of milk volume in part 1 (Table 5). The amount of milk fat lost into the whey at draw indicated that more of the original milk fat was retained in the cheese. Increased fat and casein recovery was responsible for part of the increased cheese yield. Another contribution to increased cheese yield was from additional whey solids, primarily lactose, retained in the cheese. At 15% reduction of milk volume with the modified RO unit (part 2), the cheese yield efficiency (composition-adjusted yield divided by theoretical yield; Table 4) and fat recovery (Table 5) were not significantly different from control.

Why was there increased fat recovery in the cheese in part 1 but not part 2? In part 1 a high pressure throttle valve was used to regulate back pressure on the RO unit. This valve caused enough mechanical damage to the milk fat globules that large increases of free fatty acid content of heat treated milk were observed (7). Milk passage through the partially open high pressure throttle valve was similar to a low pressure homogenization process. Investigations (27, 28) indicated that conventional homogenization increases fat recovery in Cheddar cheese. In addition, Mabbitt and Cheeseman (24) observed similar increases of retention of milk fat in cheese curd when whole milk was
TABLE 4. Theoretical and composition adjusted Cheddar cheese yields.

<table>
<thead>
<tr>
<th>Milk volume reduction (%)</th>
<th>Number of vats</th>
<th>Theoretical yield (kg/100 kg)</th>
<th>Adjusted yield (%)</th>
<th>Percent of theoretical*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>9</td>
<td>9.59</td>
<td>9.48</td>
<td>98.9</td>
</tr>
<tr>
<td>Part 1</td>
<td>5</td>
<td>10.07*</td>
<td>9.96*</td>
<td>98.9</td>
</tr>
<tr>
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<td>10</td>
<td>10.46*</td>
<td>10.40*</td>
<td>99.5***</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>10.97*</td>
<td>11.05*</td>
<td>100.7**</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>11.86*</td>
<td>12.06*</td>
<td>101.7**</td>
</tr>
<tr>
<td>Part 2</td>
<td>15</td>
<td>11.51*</td>
<td>11.32*</td>
<td>98.4</td>
</tr>
</tbody>
</table>

1 All cheese made in the 3,640-kg capacity vat.
2 Based on the VanSlyke cheese yield formula, 93% fat recovery and 37% moisture.
3 Adjusted to 37.0% moisture and 1.70% salt.
4 Composition adjusted yield as a percentage of theoretical yield.

*Analysis of variance and least significant difference test indicate treatments that are significantly different (α=0.01) from the control.

**Analysis of variance and least significant difference test indicate treatments that are significantly different (α=0.05) from the control.

TABLE 5. Fat and casein recovery in the cheese and fat loss in whey at draw.

<table>
<thead>
<tr>
<th>Milk volume reduction (%)</th>
<th>Number of vats</th>
<th>Fat recovery in cheese (%)</th>
<th>Fat loss in whey at draw (%)</th>
<th>Casein recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>9</td>
<td>90.5</td>
<td>8.1</td>
<td>96.6</td>
</tr>
<tr>
<td>Part 1</td>
<td>5</td>
<td>90.3</td>
<td>7.4</td>
<td>97.1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>91.4</td>
<td>6.7*</td>
<td>96.4</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>91.0</td>
<td>6.6*</td>
<td>97.5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>94.5*</td>
<td>5.8*</td>
<td>97.6</td>
</tr>
<tr>
<td>Part 2</td>
<td>15</td>
<td>88.9</td>
<td>7.1*</td>
<td>96.6</td>
</tr>
</tbody>
</table>

1 All cheese made in the 3,640-kg capacity vat.
2 Fat recovery equals weight of fat in the cheese divided by weight fat in the milk or milk concentrate.
3 Fat loss in the whey at draw equals the weight of fat in the whey at draw divided by the weight of fat in the milk or milk concentrate.
4 Casein recovery in the cheese equals the weight of protein the cheese (about 1% of the protein in cheese is not casein) divided by the weight of casein in the milk.

*Analysis of variance and least significant difference test indicate that treatments are significantly different (α=0.01) from the control.

Journal of Dairy Science Vol. 67, No. 12, 1984
concentrated by evaporation prior to curd formation. They speculated that casein micelles were interacting with the milk fat globule membrane. This could have been caused by mild milk fat homogenization that occurs in evaporators. Thus, in part 1 of this study, partial homogenization of the milk fat in the RO unit appeared to be responsible for the significant decrease of amount of fat lost into whey at draw for 10, 15, and 20% reduction of milk volume and for increased fat recovery in the cheese (Table 5). In part 2 another method of back pressure regulation in the RO unit was by an exit pipe of reduced diameter, which replaced the throttle valve, and reduced the amount of mechanical disruption of milk fat globules (22). Fat recovery in the cheese made from 15% reduced volume of milk in part 2 was not significantly different from control. Fat loss from the whey at 15% reduction of milk volume in part 2 (Table 5) was lower than control but was not as low as the 15% reduction of milk volume in part 1. More mechanical shearing of fat globules occurred in part 1 than in part 2. Fat globule shearing was responsible for decreased fat losses from the whey and improved retention of fat in cheese.

Green et al. (17) evaluated the influence of homogenization that occurs during ultrafiltration (UF) of milk on the structure and properties of rennet curds. They compared the amount of homogenization and casein micelles bound to milk fat globules in whole milks given the following treatments: a) pasteurized only, b) pasteurized and conventionally homogenized, c) pasteurized and fractionated in a spiral wind membrane system, and d) pasteurized and fractionated in a PCI open tubular UF system. Ultrafiltration of whole milk in the spiral wound membrane system resulted in little homogenization of milk fat. Thus, there was little difference in the degree of homogenization between treatment a and c. Fat globule size in milks from treatments b and d showed evidence of significant homogenization. There were also differences in amount of casein micelles associated with milk fat globule membrane in milks from the four treatments. Whole milk treated in the PCI open tubular UF system d had more than twice as many casein micelles per unit area of fat globule membrane surface than any of the other treatments. Even though there was significant homogenization in the PCI UF unit, the mechanism of fat globule homogenization in a membrane system must be sufficiently different from normal two stage homogenization to give rise to differences in interactions of casein with milk fat globule (17).

Mechanics and design of the PCI UF unit used by Green et al. (17) were similar to the PCI RO unit used in part 1 of this study. If a higher proportion of casein micelles are deposited on milk fat globule membrane surfaces during milk concentration in the PCI RO or UF system, then the casein micelles attached to these globules could become bound to the casein matrix during rennet coagulation of milk. This is consistent with observations of Cheeseman and Mabbitt (12). Binding of milk fat globules to the casein matrix during milk coagulation by rennet may explain the improvement of fat recovery during Cheddar cheese making from milk concentrates produced in a PCI RO system that used a high pressure throttle valve.

Green et al. (17) also observed that homogenization of milk fat in the PCI UF system resulted in reduction of fat loss during cheese making. This finding is consistent with our observations of improved fat recovery in cheese from a PCI RO system for milk concentration in part 1. The spiral would UF system, used by Green et al. (17), caused less homogenization of milk fat. Rennet coagulation of these UF retentates resulted in high fat losses. Bush et al. (8) observed a 40% greater fat loss when UF fractionated skim milk was standardized with cream and made into Cheddar cheese. In this case, the milk fat globules did not undergo any shearing during membrane concentration. When we removed the throttle valve from our RO system (part 2), milk fat homogenization decreased and fat recovery in the cheese decreased. Increased fat recovery in cheese is of significant economic value to the cheese industry because milk fat is worth more as Cheddar cheese than as whey cream. A process that gives a mild but controlled shearing to milk fat globules and results in increased retention of milk fat in Cheddar cheese would be of significant economic value to the cheese industry if texture and flavor characteristics of the cheese are acceptable. Additional studies on physical and chemical
interactions of casein micelles and milk fat globule membranes during various shearing treatments are needed.

Mechanical damage to milk fat globules at low temperatures (30°C) in subpasteurized whole milk may result in elevated free fatty acid content of cheese and undesirable off-flavors. However, in fully pasteurized good quality milk there should be little or no increase (7) of free fatty acids. Yield improvement that can be gained by controlled shearing of milk fat globules should be investigated more thoroughly. Cheddar cheese of acceptable commercial composition and yield can be made at total solids and ratio of casein to fat would allow procedures to become more consistent. This may offer a method for reducing vat-to-vat and seasonal variation of cheese composition and quality.

ACKNOWLEDGMENTS

The authors express their appreciation for support from the New York State Cheese Manufacturers Association, Cuba Cheese, Inc., and the Damrow Company. We thank Earl Dean, Albert Green, Maureen Chapman, Joni Ruller, and Mary DellaValle for their technical assistance.

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