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THE EFFECTS OF CAPPER ROTATIONAL SPEED AND MAGNETIC CLUTCH TYPE ON THE IMMEDIATE REMOVAL TORQUE OF CT CLOSURES

presented by

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of the requirements for

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THE EFFECTS OF CAPPER ROTATIONAL SPEED AND MAGNETIC CLUTCH TYPE ON THE IMMEDIATE REMOVAL TORQUE OF CT CLOSURES

By

Bruce J. Natzel II

A THESIS

Submitted to
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ABSTRACT

THE EFFECTS OF CAPPER ROTATIONAL SPEED AND MAGNETIC CLUTCH TYPE ON THE IMMEDIATE REMOVAL TORQUE OF CT CLOSURES

By

Bruce J. Natzel II

The loss of torque after application of a closure to a container is common. Many factors influence the torque retention of closures including temperature, vibration, and component dimensions. This study identified additional variables that affect torque retention of closures. The variables studied include capper rotation speed, clutch type, dwell time, liner type, and pigment.

28mm continuous thread (CT) with both black and white pigments and 38mm CT closures with white pigment were used in this study. Varying liner systems were also used. Magnetic Ratcheting and Magnetic Hysteresis clutches were used to study differences in immediate removal torque values with these closures.

Capper rotation speed, clutch type, and liner type exhibited large effects on immediate removal torque. As rotation speeds were changed, the Hysteresis clutch was much more consistent in torque than the Ratcheting clutch as measured by immediate removal torque.

ACKNOWLEDGMENTS

I wish to thank my family and friends for the support and encouragement they have given me throughout all of my years of study. Thanks especially to my wife for her love and understanding.

I also wish to thank my committee members, Drs. Lockhart, Burgess, and Gilliland for their guidance throughout the process of writing this thesis. Special appreciation goes to Dr. Lockhart for all of the help and support that he has graciously given me during my Graduate studies.

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LIST OF SYMBOLS AND ABBREVIATIONS

CT	Continuous Thread
IRT	Immediate Removal Torque
RPM	Revolutions Per Minute
TIP	Torque Inch Pounds

INTRODUCTION

The issue of torque retention of a threaded closure is very important in many industries. Inadequate torque in pharmaceuticals, for example, can lead to loss of efficacy of the active ingredient, leakage of the product, loss of confidence in the product by consumers, and recalls. It is equally important to avoid removal torque values that are excessively high. If the closure cannot be removed with a reasonable amount of force, the system will be considered a failure. Immediate removal torque values are therefore expected to fall within a range of acceptable values depending on the size and type of closure.

The application of the closure-liner system has many variables involved. It is widely known that component dimensions, vibration, and temperature have a large impact on the resulting torque retention. It is the goal of this research to identify additional variables that may lead to the loss of torque in the closure system. The bulk of this study looks at the effects of capper rotation speed and type of magnetic capping clutch on torque retention. Other areas of this study focus on the effects of varying liner systems, pigment in the closure body, and dwell time of the capping clutch.

The studies were performed using a Zalkin, single spindle, semi-automatic capper (Figure 1). 28mm closures utilizing three different liner systems with either black or white pigment in the closure body and 38mm closures utilizing one liner system and white pigment were used. Two capping clutches, Magnetic Ratcheting and Magnetic Hysteresis, were used to study differences in immediate removal torque values with these closure systems (Figures 2, 3). For clarification, the clutch is considered the magnetic mechanism of the capping head, while the chuck is the portion of the capping head that contains the jaws used to hold the closure in place during the capping process.

This research is a continuation of the work performed by Xiaole Fan (1999) at Michigan State University. Her studies looked at the effects of rotation speed and liners on immediate removal torque. Two major differences exist between the studies. First, only the Magnetic Ratcheting clutch was available for study at the time of her research. Secondly, the capping machine was not previously capable of having the capper speed and rotational speed set independently, so the dwell time of the clutch could not be controlled.

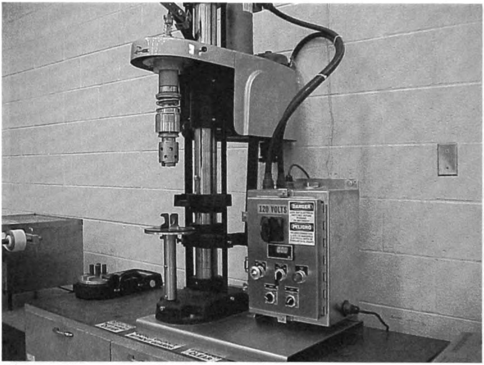


Figure 1 Zalkin Capper

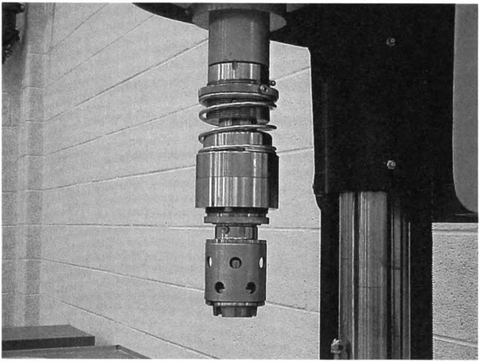


Figure 2 Zalkin Capper shown with Ratcheting Chuck.

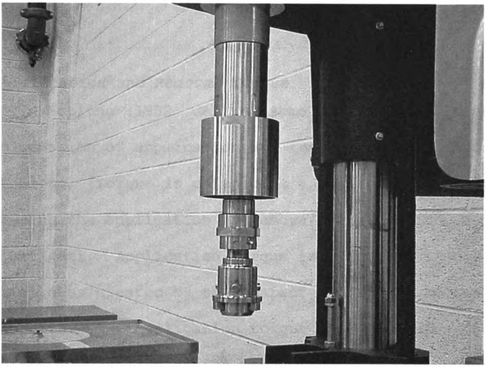


Figure 3   Zalkin Capper shown with Hysteresis Chuck.

LITERATURE REVIEW

Application and Removal Torque:

Leblong (1982) defined some useful terms in the discussion of application and removal torque. According to Leblong, "Torque is defined as a resistance occurring during the application or removal of a cap from a container. Application torque is a measure of cap tightness created by the contact between a cap and a container." Application torque is not a value that is directly measured on the production line. Although it can be measured using a manual or automatic torque tester, most production cappers do not register an application torque. Therefore, it is necessary to control the application torque with settings on the machine and observe the effects on the removal torque. "Removal torque is the maximum amount of force required to loosen a cap while attempting to open it."

Many factors other than the package itself can affect the removal torque values. According to Leblong (1982), "The product contained can affect removal torque especially if it is a liquid or if it develops internal pressure. Temperature and humidity, their fluctuations, and their extremes in storage and transportation, can affect removal torque". Anon (1990) described instances where hot-filled products can lead to the closure backing off and thus reducing the removal torque. To overcome this, Anon stated that "some packagers employ a secondary tightening operation (called retorquing) after the cooling process". Due to this effect, it is important to keep the temperature constant during torque studies.

Greenway (1993) concluded in a study on application and removal torque that a "large part of cap torque decay occurs immediately after being torqued". For this reason, the method of measuring Immediate Removal Torque (IRT) values was used in this study. This process, measuring the removal torque values at fifteen minutes after the application of the closure, accomplishes three goals. First, it allows us to measure the removal torque values at a specific amount of time after application in order to standardize the test. Secondly, it allows time for much of the initial stress relaxation to occur in order to measure the effect of this phenomenon. Lastly, this method allows the timely measurement of samples while limiting the introduction of other factors such as temperature and humidity changes over time. The goal here is to measure the removal torque after much of the stress relaxation has occurred, but to limit other effects that may vary slightly from one testing time to another.

Jenkins, Shabushnig, and Cianciullo (1988) discussed the issue of closure tightness. According to the article, the most important reasons to assure adequate application and removal torques are customer perception, stability of the product, and containment of the product. "In today's competitive market a consumer would avoid buying a product if there is evidence of product leakage, tampering or something as simple as a cap which is difficult to remove". The authors went on to talk about how the stability of products from liquids to solids can be affected by the closure and seal area. Evaporation or the addition of moisture may expose a moisture sensitive product to excessive moisture, loss of moisture, or change in concentration of a liquid. Ensuring that the closure is applied according to a specified range of torque values can easily prevent these problems, according to this article. By developing a history of removal torque values based upon the application torque, materials, and machine settings, one can attempt to predict the success of future applications. This article showed a linear relationship between the application and removal torque values. This is helpful in determining the appropriate application torque in order to achieve the desired removal torque. Time, temperature, and other environmental considerations, however, must be taken into account to ensure an accurate prediction of removal torque.

According to Thompson (1999), vibration, storage, and handling can result in torque decay of a closure system. He also mentions the difficulty in determining the application torque to use when working with a recommended range of immediate removal torque values. Thompson concluded, "it cannot be assumed that applying the maximum recommended application torque will solve retention problems". He also determined that the type of resin used could influence the torque retention. In his particular study, for example, it was found that PVC bottles exhibited higher torque retention than HDPE bottles.

Supachai Pisuchpen (2000) discussed the importance of the coefficients of friction of the closure and bottle threads, as well as the liner, on immediate removal torque. Using this information, he developed a model in an attempt to predict the torque retention of a closure. Various aspects of the closure were considered, including the use of glue to adhere the liner to the closure body and the method used to manufacture the closure body. The effects that these variables had on IRT were discussed.

Kilbridge (2000) developed a mechanical bottle utilizing strain gauges in an attempt to measure the application torque. This differs from the usual way of determining application torque, which involves the measurement of removal torque. The next stage in this research will include the introduction of wireless technology to the bottle. When this is available, it may allow one to measure the forces applied to a closure in real time. This will enable constant monitoring of the capping machine in order to identify the need for maintenance.

Greenway et al (1994) studied the effects of pigments and their impact on immediate removal torque. "There are significant differences in removal torque between white and red caps, but not between blue and black". Therefore, it is important to realize that not all pigments relate to changes in removal torque values, but some pigments can have an effect. It was also found that "removal torque values decreased when drop heights increased". This is important when considering the effects of packaging machinery and distribution on torque retention.

Capper Speed and Dwell Time:

Greenway, Danville, and Lazzara (1973) studied the effects of capper machine dwell time and closure application speed on removal torque values. The study showed that "with constant application torque, increases in cap application speed and dwell time increase removal torque." It was found, though, that these increases in removal torque level off at higher capper speeds and higher dwell times. This behavior suggests that capper settings can have an impact on the eventual removal torque values. Care must be taken, therefore, in the setup of the machine in order to provide predictable torque values.

Xiaole Fan (1999) performed research on the effects of capper rotational speed on immediate removal torque. Her findings showed that IRT values increased as rotation speed increased. The foam liner used in the study exhibited large increases in IRT values above the rotation speed of 300 rpm. This was attributed to the physical properties of the foam liner. At the time of this study, the capping machine was incapable of having the capper speed and rotation speed set independently. Therefore, the dwell time of the clutch was not held constant.

Effect of Liners and Materials:

Leblong (1982) mentions the importance of considering liner materials when evaluating the removal torque values during a torque study. "Two identical cap/containers with a simple difference in cap liner composition may have very different removal torque characteristics". When performing a study of torque retention, it is important to use exactly the same liners, materials, and treatments as the actual packaging system to be used with the product. Otherwise, variations may exist due to the liners themselves. Differences such as wax coating on a liner, flame treatment on a bottle finish, or thread pitch can make a study meaningless.

Evaluation of Data:

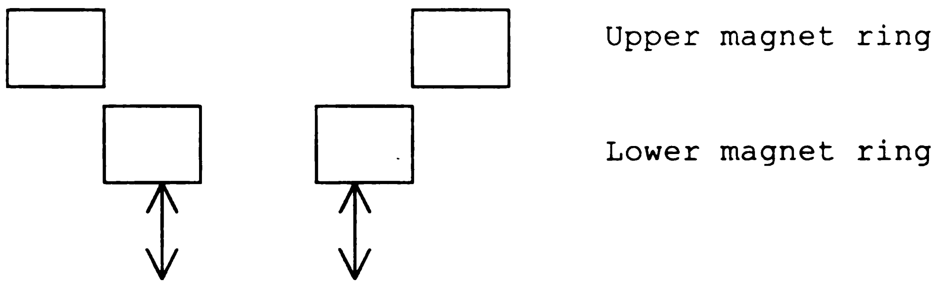
In analyzing the data obtained during a torque study, it is necessary to consider the fact that capping machines do not apply at a specific application torque. They are capable, however, of being set to yield immediate removal torque values that are within a certain acceptable range. Therefore, according to Leblong, the use of standard deviation can be employed to compare the consistency of the performance of one closure to that of another. On some occasions, the range of acceptable values of removal torque may be greater than would seem appropriate. However, Leblong states that "removal torque values down near zero are sometimes still good enough to maintain product integrity. On the other extreme, large caps are easily openable at surprisingly high removal torque values". To establish the proper range of acceptable removal torque values, a permeation or bubble test can be performed to establish the lower limit. The upper limit can be determined by testing the openability by test subjects. A package system may exhibit a large range of removal torque values, which may or may not be an issue depending on the acceptable range of these values.

METHODS, MATERIALS, AND EQUIPMENT

Methods:

Seven different closure systems were studied; six 28mm closures utilizing three different liner systems with either black or white pigment in the closure body, and one 38mm closure system with white pigment. The capping heads contain two different non-mechanical, frictionless magnetic clutches, Magnetic Ratcheting and Magnetic Hysteresis. Varying the distance between the two concentric magnetic rings performs the adjustment of the torque. The Ratcheting clutch contains multiple magnets in each of two rings. The Hysteresis clutch, which also functions to control the application torque, utilizes a solid magnet between two similar magnetic rings (Figure 4).

Ratcheting Clutch



Hysteresis Clutch

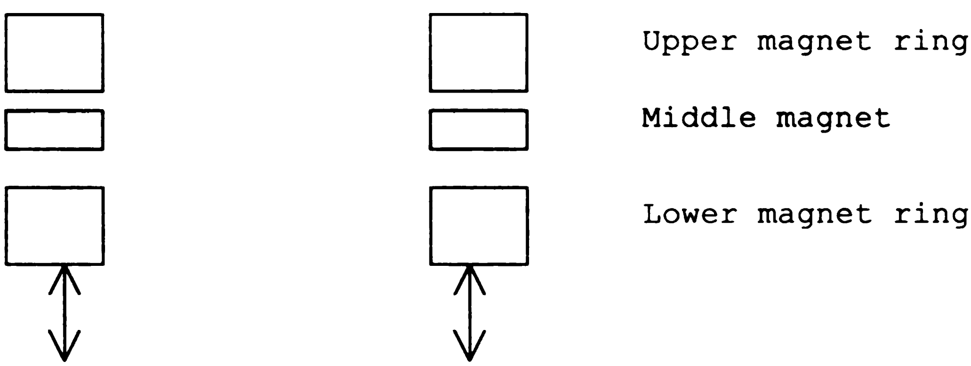


Figure 4 Illustration of Magnet Arrangement in Ratcheting and Hysteresis Clutches. (Cross-section)

Arrows represent movement of the lower magnet ring to facilitate torque changes.

A static torque of 15 torque inch pounds (TIP) was used for all tests. The setting was determined by removing the capping head from the capper and placing the jaw end into a manual torque tester. As the capper head was rotated, the digital reading on the torque tester indicated the static torque. To adjust the static torque, the torque control set screw was loosened, the body rotated to change the torque setting, and the set screw re-tightened. This process was repeated by trial and error until the 15 TIP target was reached. As the body that houses the magnet mechanism is rotated, the magnet rings are either moved closer together or further away from one another. This dictates the amount of resistance that will be used to control the torque. When the housing is turned clockwise, the magnet rings move closer together thus increasing the static torque. Conversely, turning it counter-clockwise will move the magnet rings farther away from one another and therefore will decrease the static torque.

The dwell time of the machine can be defined as the length of time that the clutch is activated during the application of a closure. As recommended by the manufacturer, the dwell times for both clutches were set at 1.5 seconds for all testing except where low and high unacceptable dwell times were desired. Through trial and error, the dwell time was adjusted to 1.5 seconds by changing the capper speed. The capper speed is the speed at which the machine moves through a cycle by moving down to apply the closure, applying the closure, and moving back up to complete the cycle.

Low dwell time, for purposes of this experiment, was considered 0.5 seconds, while high dwell time was tested at 3.5 seconds. These dwell times were set in a similar fashion as stated previously for the acceptable 1.5 second dwell time. Tests for dwell time studies were performed at 150, 200, and 250 rotations per minute (rpm) using the white 0.035″ P/VTLF pulp liner system. Low and high dwell time immediate removal torque values were then compared to each other and to the acceptable dwell time IRT results.

Rotation speeds of 50 to 350 rpm at 50 rpm increments were tested for all closure systems. Testing was not done beyond the 350 rpm point due to manufacturer recommendations that past this point, the effect of inertia may be so great that it influences the amount of torque experienced. Rotation speeds of less than 50 rpm were not tested because the capping machine was not capable of maintaining a constant speed below this point. For all tests performed, the rotational speeds of the machine were set and verified using a digital non-contacting tachometer.

A bottle was then placed on the capping machine and a closure placed in the jaws. Thirty bottles were capped for each rotational speed setting and closure system variation. Fifteen minutes after application, the closures were removed using the manual digital torque tester using a consistent technique.

Statistical conclusions were drawn from the data about the effects of liner materials, pigment, capper rotation speed, type of magnetic clutch used, and dwell times using Minitab software, Version 12.22. For each type of clutch, three-way ANOVA's were performed to determine the statistical significance of the rotation speed, liner, and pigment. A two-way ANOVA was used to study the effects of dwell time with the Ratcheting clutch. Due to an imbalance in sample sizes, a general linear model was used to analyze dwell time with the Hysteresis clutch. With each analysis, residuals were investigated for normality and for outliers indicating possible data entry errors.

Materials and Equipment:

- 28-400, 60 ml HDPE square bottles.
- Owens-Illinois 28-400, non-child resistant continuous thread polypropylene closures (white and black) with 0.035″ P/SF pulp liners attached with center dot of glue. Liner: 0.035″ pulpboard bonded with adhesive to 0.004″ white sulfite paper and 0.00075″ saran film.
- Owens-Illinois 28-400, non-child resistant continuous thread polypropylene closures (white and black) with 0.035″ P/VTLF pulp liners attached with center dot of glue. Liner: 0.035″ pulpboard bonded with adhesive to 0.003″ bleached Kraft paper coated with 0.001″ HDPE, 0.004″ vinyl chloride acetate, and a wax treatment.
- Owens-Illinois 28-400, non-child resistant continuous thread polypropylene closures (white and black) with 0.040″ PL-4025 OB seal polyethylene foam liners attached with center dot of glue.
- Owens-Illinois 38-400, non-child resistant continuous thread polypropylene closures (white and black) with 0.035″ P/VTLF pulp liners attached with center dot of glue. Liner: 0.035″ pulpboard bonded with adhesive to 0.003″ bleached Kraft paper coated with 0.001″ HDPE, 0.004″ vinyl chloride acetate, and a wax coating.

- Zalkin TM-3 semi-automatic single spindle capper, Magnetic Ratcheting and Hysteresis heads.
- Secure Pak Torque Tester - Electronic, digital display.
- Pocket-Tach 20: Non-contact tachometer, Swiss Precision Instruments.
- Minitab Statistical Software, Version 12.22, Minitab Inc., 3081 Enterprise Drive, State College, PA 16801-3008

RESULTS AND DISCUSSION

Results:

Effect of Rotation Speed on Immediate Removal Torque:

Much variation in immediate removal torque values was seen as capper rotational speeds were changed, especially when the Ratcheting clutch was used. Tests performed using 28mm closures resulted in a similar trend for all liner and pigment combinations as can be seen in Table 1 and Figure 5.

Table 1 Average IRT Values, Ratcheting Clutch, 28mm Closure. (n=30 for each combination)

	0.035 P/SF White	**0.035 P/SF Black**	**0.035 P/VTLF White**	**0.035 P/VTLF Black**	**0.040 PL-4025 OB Seal White**	**0.040 PL-4025 OB Seal Black**
50 RPM	8.5	8.5	10.5	10.3	5.0	6.2
100 RPM	8.5	8.8	9.7	10.6	6.6	7.1
150 RPM	17.7	17.9	19.1	17.9	7.9	9.3
200 RPM	21.9	21.0	23.8	24.3	10.2	11.7
250 RPM	16.5	15.1	18.1	17.5	6.5	6.9
300 RPM	15.7	14.9	19.7	18.9	7.4	8.0
350 RPM	17.0	16.7	21.8	21.9	8.7	9.5

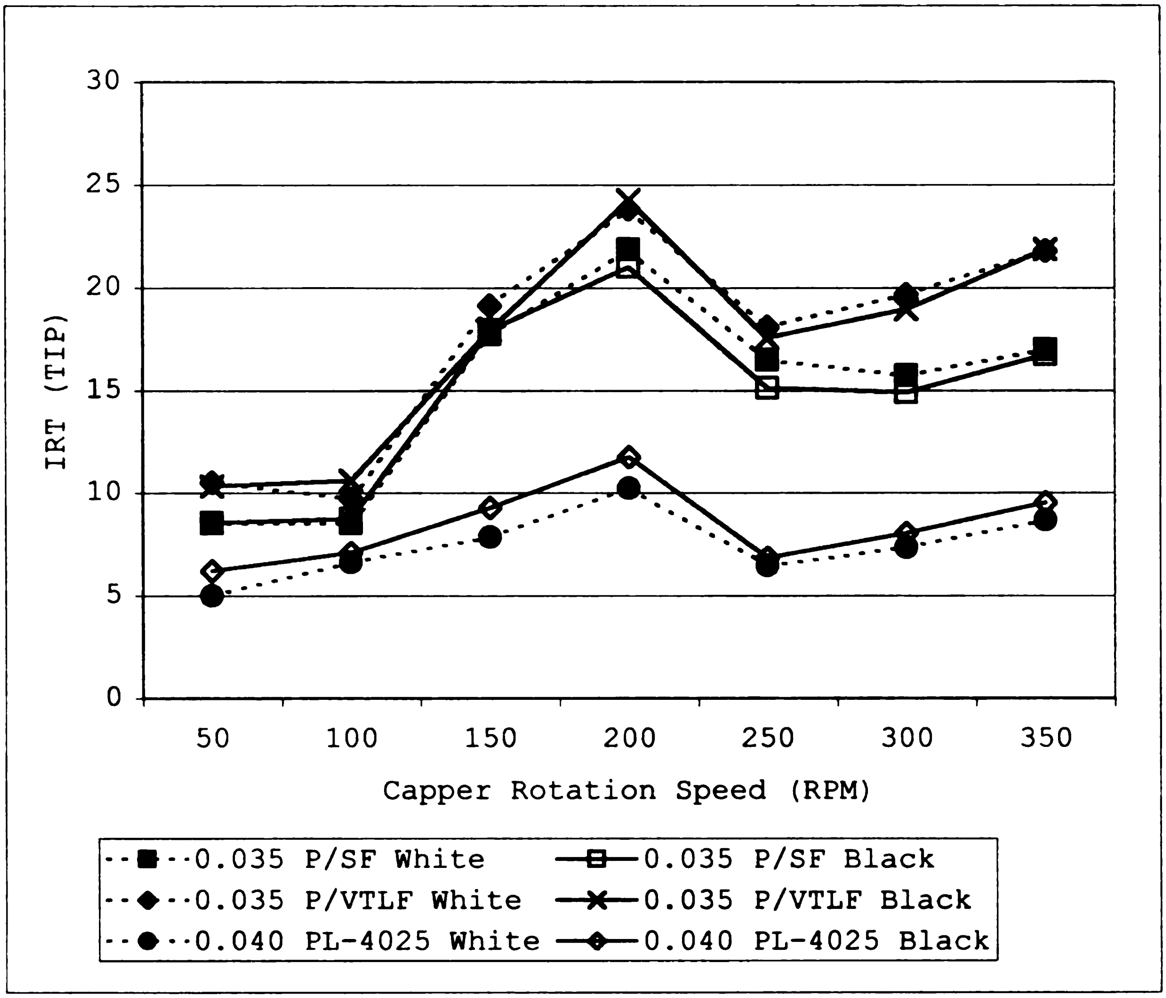


Figure 5 Average IRT Values, Ratcheting Clutch, 28mm Closure

With each 28mm closure type, the immediate removal torque peaked around 200 rpm. The immediate removal torque values then began a decline and either leveled off or increased again around 250 rpm. Although the foam liners, 0.040 PL-4025 OB Seal white and black, did not exhibit as large a variation along these rotation speeds, they did show a similar trend and peaked at about the same rotation speed.

The results of the ANOVA (Appendix Analysis 1) showed highly significant effect of rotation speed on immediate removal torque. The P-values are 0.000 for main effects of rotation speed and liner and their interaction. The sum of squares for the 20 degrees of freedom associated with rotation speed, liner, and the interaction of rotation speed and liner accounts for 99.5% of that for the 41 degrees of freedom in the regression. Visually, this can be seen in the pattern of the figures previously discussed.

Testing was duplicated for one pulp-lined closure and one foam-lined closure for rotation speeds between 100 rpm and 250 rpm to see if the pattern was repeatable. White closures with 0.035 P/SF and 0.040 PL-4025 OB seal were chosen for four verification tests. Table 2 and Figure 6 show the results of these tests. Indeed, these tests showed the same trend as the previous tests.

Table 2 Average IRT Values-Verification of Select Rotation Speeds-Ratcheting Clutch, 28mm Closure. (n=15 for each verification combination)

	0.035 P/SF White	**0.035 P/SF White Ver.**	**0.040 PL-4025 White**	**0.040 PL-4025 White Ver.**
50 RPM	8.5	--	5.0	--
100 RPM	8.5	9.2	6.6	6.6
150 RPM	17.7	17.5	7.9	8.0
200 RPM	21.9	23.4	10.2	9.8
250 RPM	16.5	16.6	6.5	6.3
300 RPM	15.7	--	7.4	--
350 RPM	17.0	--	8.7	--

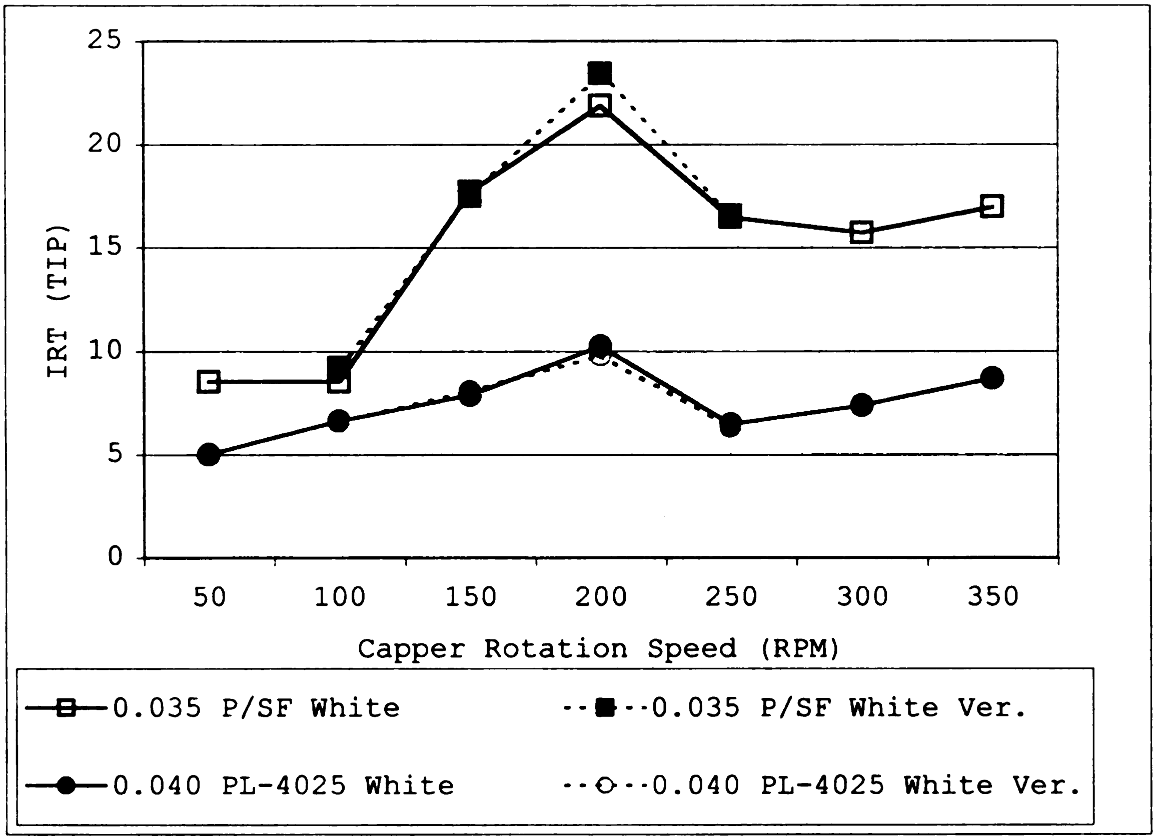


Figure 6 Average IRT Values-Verification of Select Rotation Speeds-Ratcheting Clutch, 28mm Closure.

Testing was performed at 10 rpm increments between 150 rpm and 250 rpm to determine the specific trend of the immediate removal torque values within this range. Figure 7 shows the results of tests performed on the white closures lined with 0.035 P/VTLF. As seen in the figure, the maximum is at 210 rpm for this closure system and the response is fairly flat for rotation speeds in the range of 190 to 220 rpm. The values in Figure 7 are consistent with values reported within the range of 150 to 250 rpm in Figure 5 on page 21.

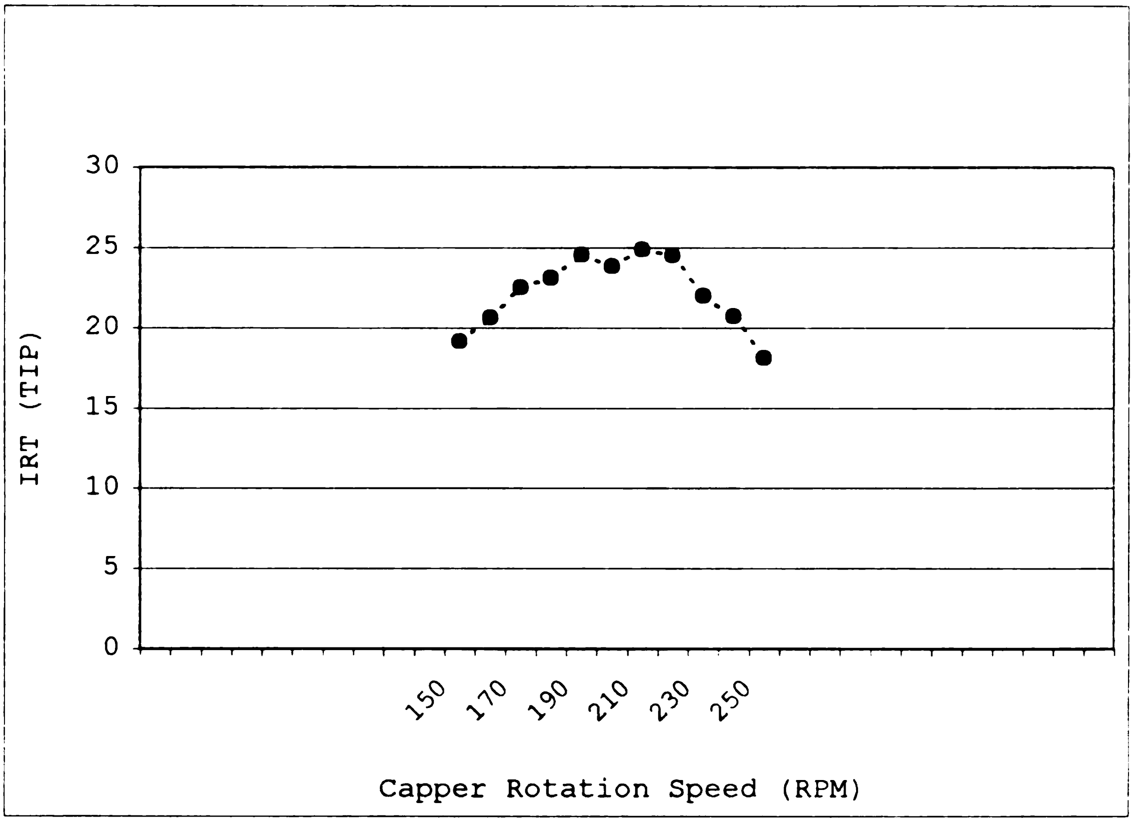


Figure 7 Average IRT Values for 150-250rpm in 10rpm Increments, Ratcheting Clutch, 0.035 P/VTLF White 28mm Closure. (n=15 for each rotation speed)

Where the 0.035 P/VTLF lined white closures were tested in the 38mm size, they exhibited a similar trend to that of the 28mm closures as seen in Table 3 below and Figure 8 on page 29.

Table 3 Average IRT Values, Ratcheting Clutch, 38mm Closure. (n=30 for each rotation speed)

	0.035 P/VTLF White
50 RPM	6.8
100 RPM	7.3
150 RPM	16.7
200 RPM	19.8
250 RPM	11.7
300 RPM	11.8
350 RPM	12.9

The immediate removal torque values were lower at all rotation speeds than those of the 28mm closure system using the same liner, as can be seen in Figure 9 on page 29. Differences in immediate removal torque values are expected simply due to the mechanical advantage of the larger closure. Also, two different capping chucks were used to apply these different sized closures.

As observed previously, a large effect from rotational speed on immediate removal torque was realized using the Ratcheting clutch. The large change of IRT values in the interval of 150 to 250 rpm can cause many problems with either inadequate or excessive application torque. If the rotation speed of the capper is set at a point where drastic differences in immediate removal torque occur with small changes in rotation speed, large variations in torque may result. Knowledge of the machine behavior is, therefore, very important.

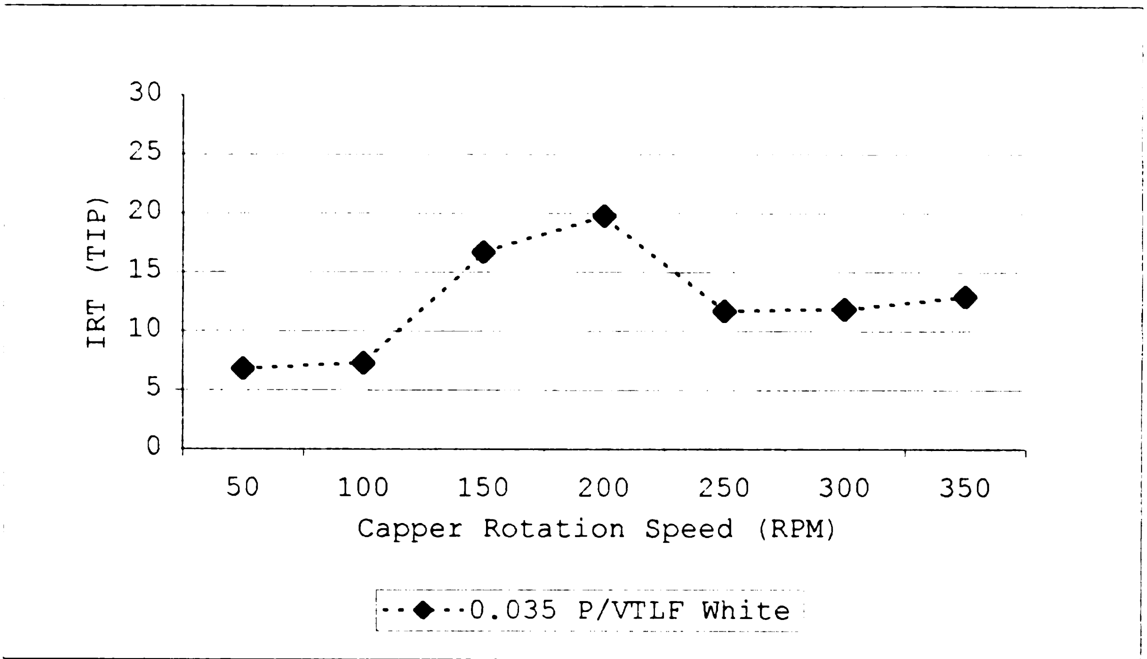


Figure 8 Average IRT Values, Ratcheting Clutch, 38mm Closure

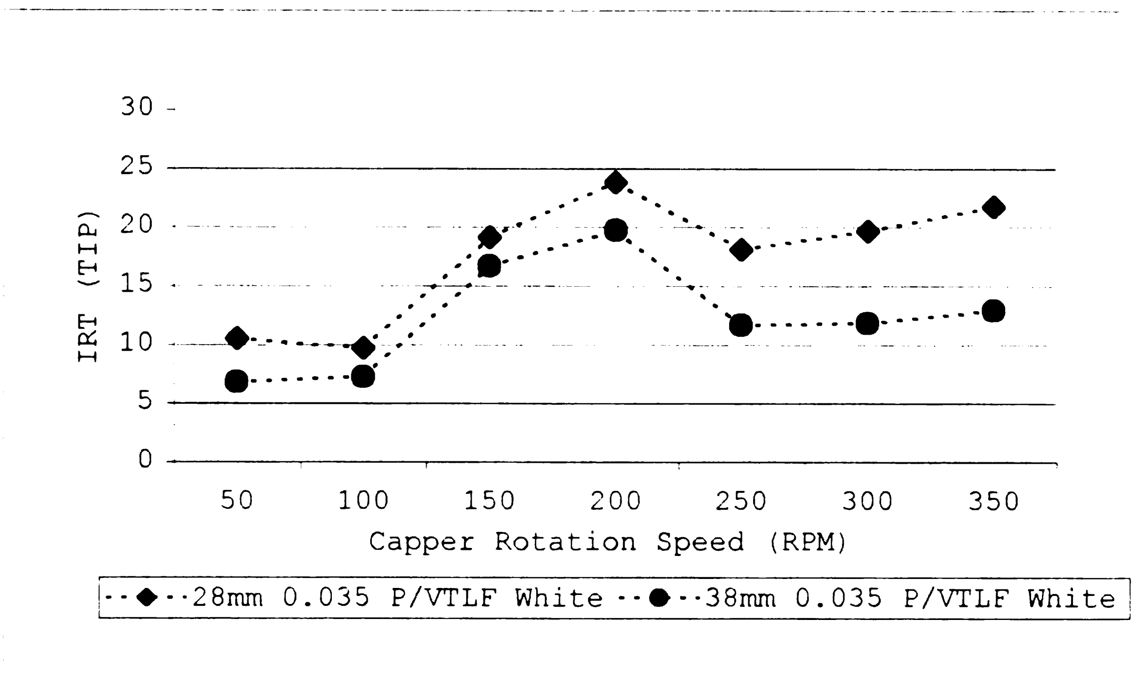


Figure 9 Comparison of 28mm and 38mm Closures, Ratcheting Clutch.

Using the Hysteresis clutch, the changes in immediate removal torque did not vary much as the rotation speed was changed (Table 4, Figure 10). However, the effect was still statistically significant, resulting in a P-value of 0.000 (Appendix Analysis 2). It is clear from Figure 10 and the ANOVA that rotation speed, although statistically significant, accounts for much less of the variation than does liner. The trends across rotation speeds are relatively flat across the range of rotation speeds tested.

Table 4 Average IRT Values Hysteresis Clutch, 28mm Closure. (n=30 for each combination)

	0.035 P/SF White	**0.035 P/SF Black**	**0.035 P/VTLF White**	**0.035 P/VTLF Black**	**0.040 PL-4025 OB Seal White**	**0.040 PL-4025 OB Seal Black**
50 RPM	11.0	11.3	15.3	15.3	5.7	6.0
100 RPM	12.1	12.2	15.7	15.7	6.3	6.7
150 RPM	12.2	11.9	16.4	16.7	6.3	6.9
200 RPM	11.9	11.7	17.3	16.1	7.1	6.7
250 RPM	12.5	12.3	16.8	17.2	7.1	7.1
300 RPM	12.5	12.1	17.3	17.1	6.6	7.6
350 RPM	12.2	11.5	16.9	16.3	6.5	7.4

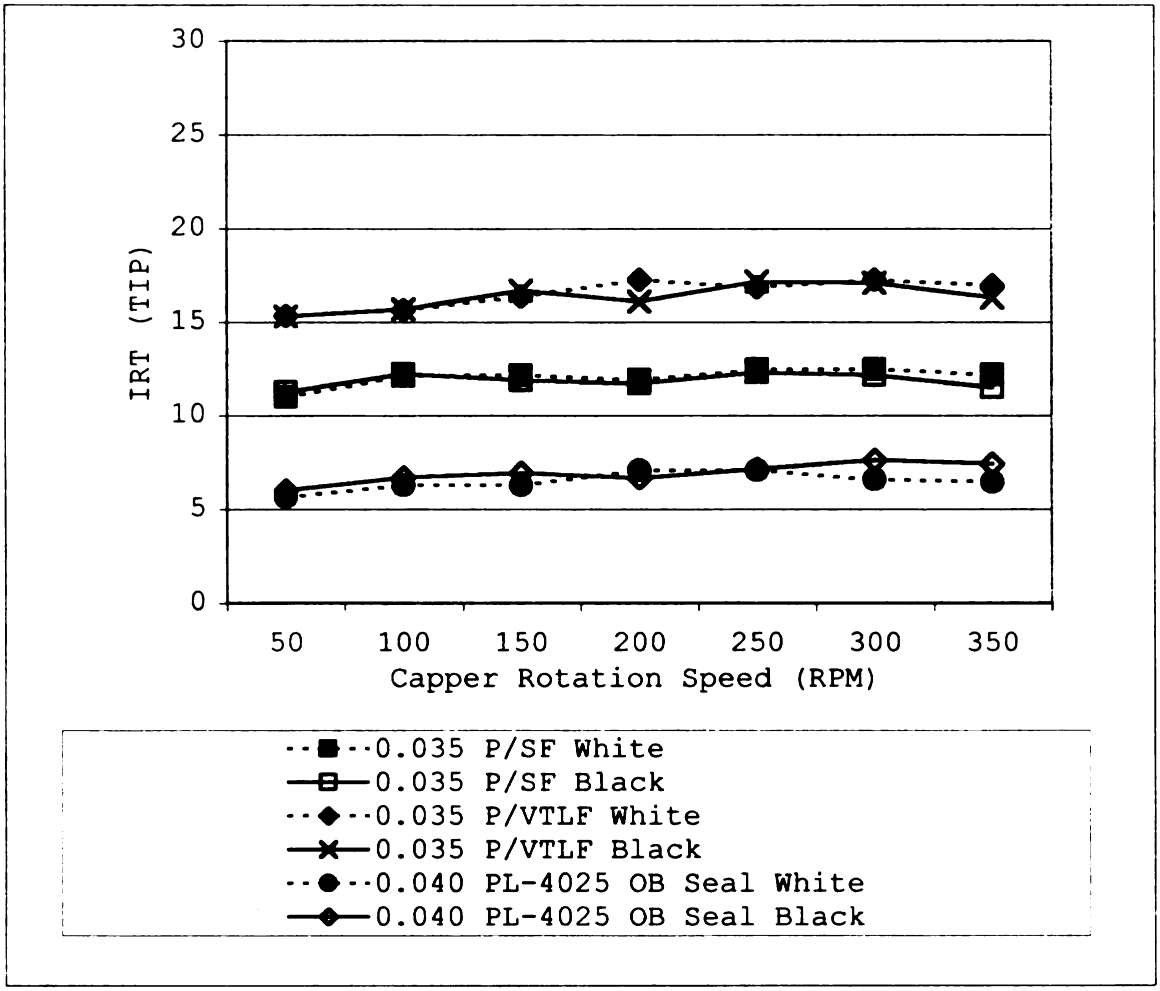


Figure 10 Average IRT Values Hysteresis Clutch, 28mm Closure

Effect of Magnetic Clutch Type on Immediate Removal Torque:

When studying the effect of rotation speed on immediate removal torque, it is necessary to consider the type of magnetic clutch that is being used. Major differences in the trend of immediate removal torque values were seen between the Ratcheting and Hysteresis clutches. Comparisons of immediate removal torque results between the Ratcheting and Hysteresis clutches for each 28mm white closure system are shown in Figures 11-13.

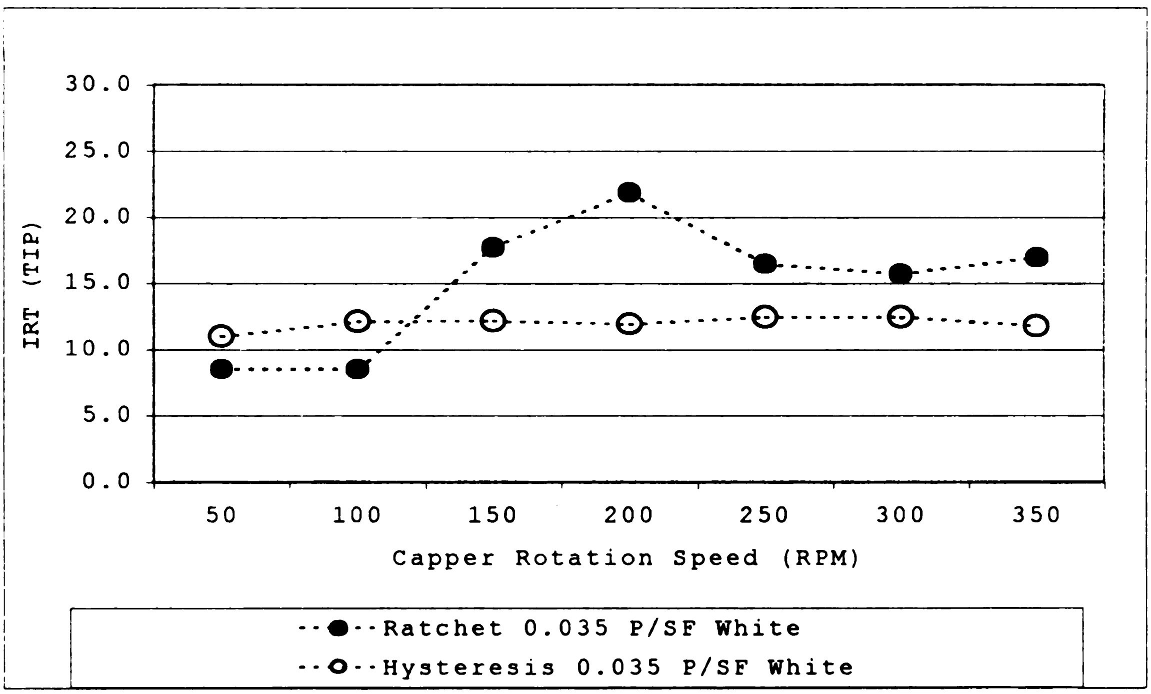


Figure 11 Comparison of Hysteresis and Ratcheting Clutches, 0.035 P/SF White, 28mm Closure.

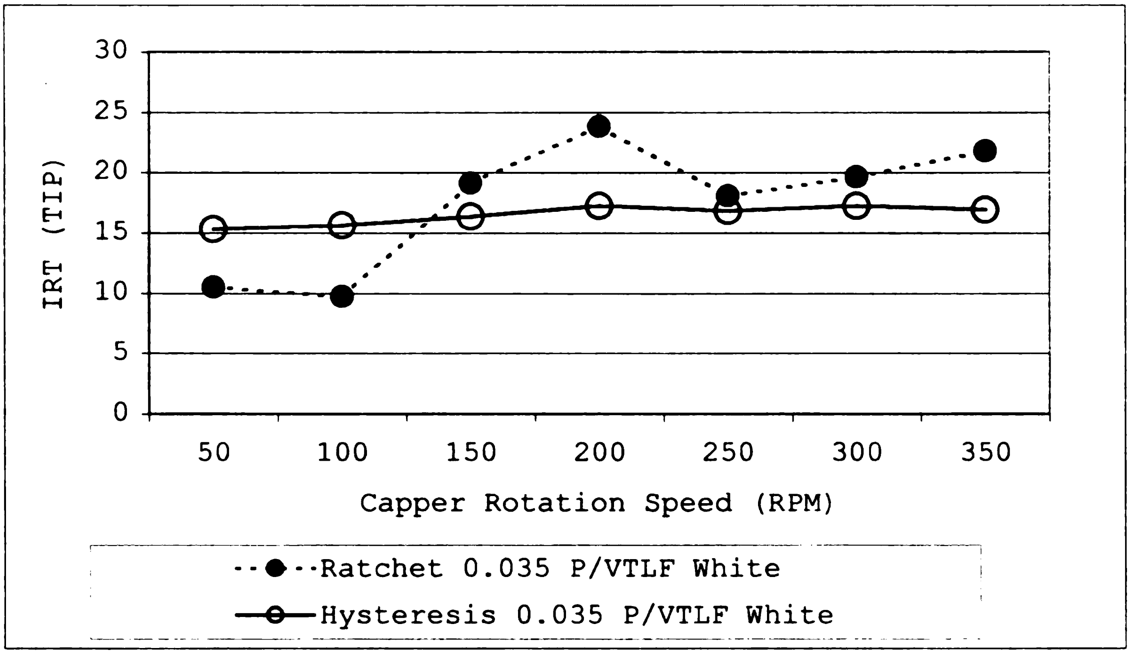


Figure 12 Comparison of Hysteresis and Ratcheting Clutches, 0.035 P/VTLF White, 28mm Closure.

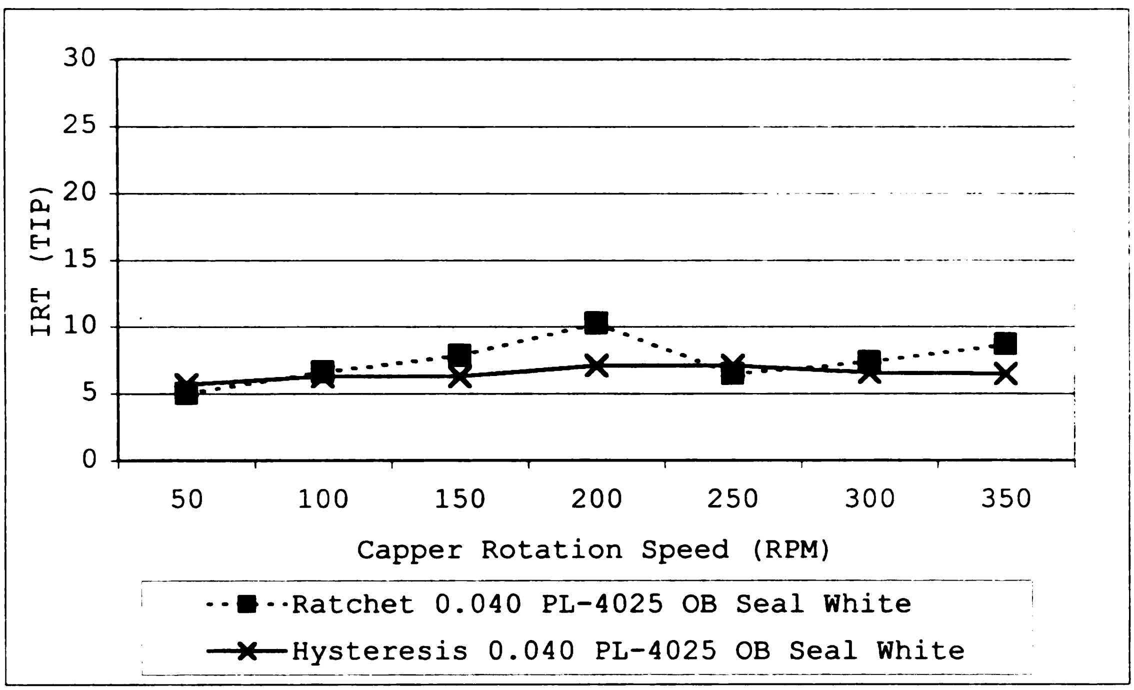


Figure 13 Comparison of Hysteresis and Ratcheting Clutches, 0.040 PL-4025 White, 28mm Closure.

The immediate removal torque values of the closures applied with the Hysteresis clutch show much less variation as the rotational speeds change. This pattern was consistent with the 38mm closure tested. As seen in Table 5 and Figure 14, the immediate removal torque values with the 38mm closures are more consistent along the range of rotation speeds tested. Again, the immediate removal torque values were lower at all rotation speeds than those of the 28mm closure system as can be seen in Figure 15.

Table 5 Average IRT Values Hysteresis Clutch, 38mm Closure. (n=30 for each rotation speed)

	0.035 P/VTLF White
50 RPM	9.4
100 RPM	10.2
150 RPM	10.6
200 RPM	10.0
250 RPM	9.8
300 RPM	9.8
350 RPM	10.0

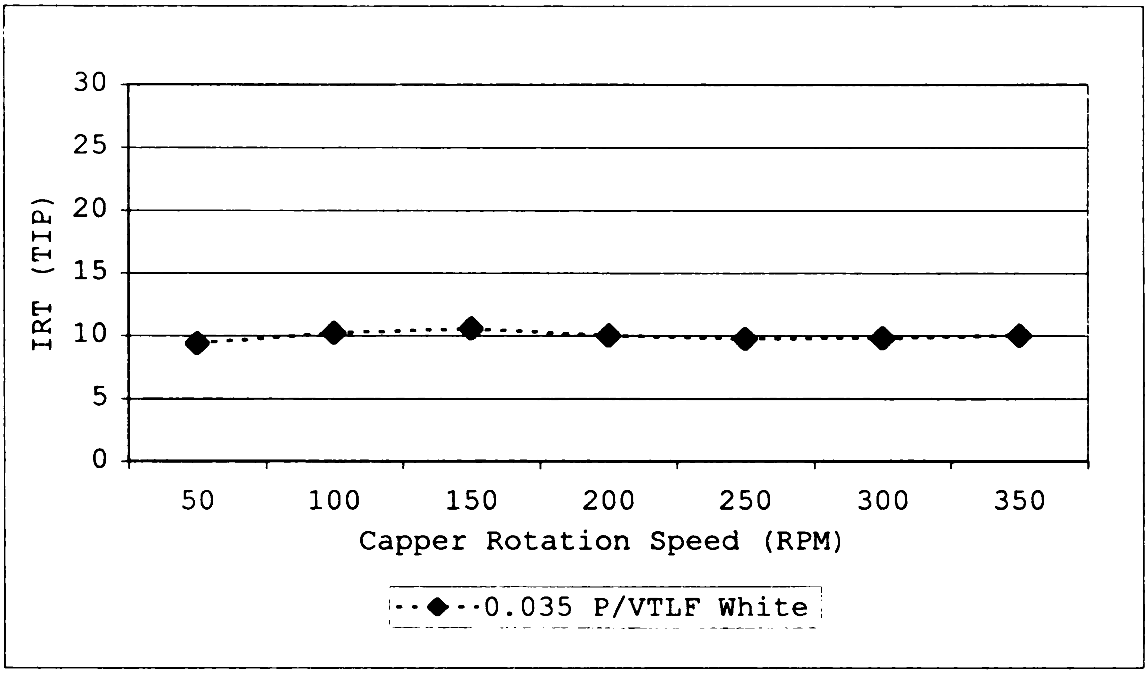


Figure 14 Average IRT Values Hysteresis Clutch, 38 mm Closure.

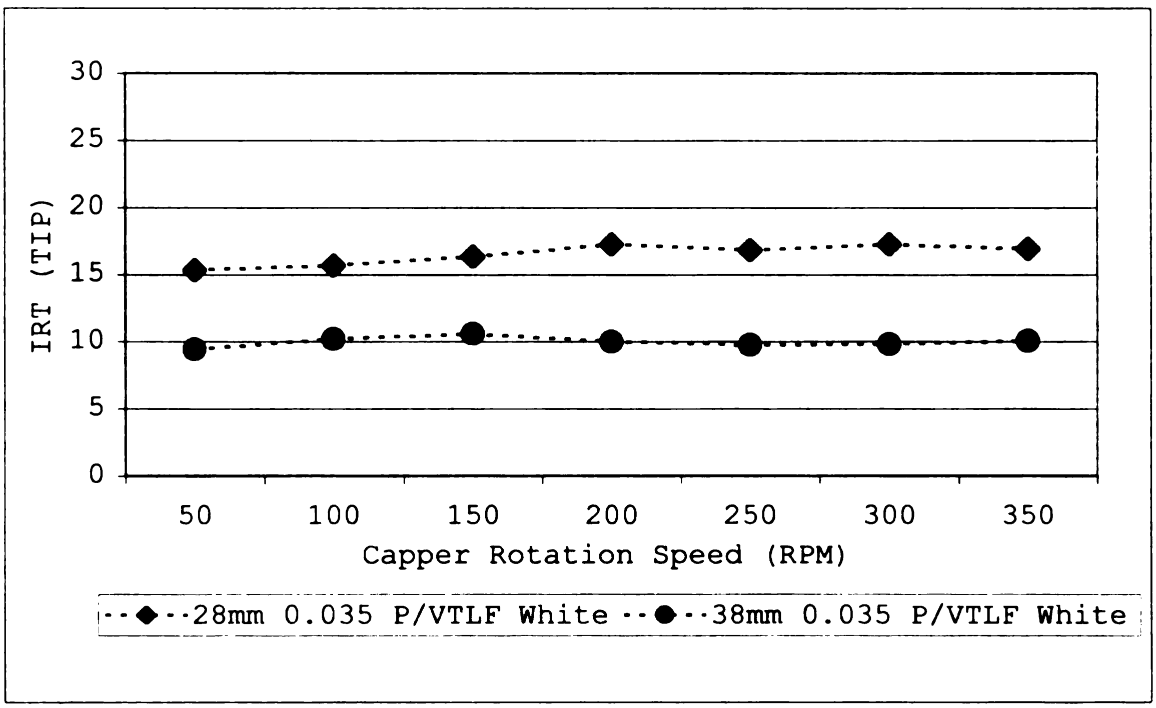


Figure 15 Comparison of 28mm and 38mm, White 0.035 P/VTLF Closure, Hysteresis Clutch.

The effects on immediate removal torque from the type of magnetic clutch used are clear. The Ratcheting clutch resulted in much more variation at varying rotation speeds than the Hysteresis clutch. The Hysteresis clutch results show much more consistent removal torques. The effective use of a capping clutch such as the Ratcheting type must be based on a much more careful analysis of the torque behavior throughout varying speeds.

Effect of Liner Systems on IRT Values:

Two different 28mm pulp-lined closure systems and one 28mm foam-lined closure system were tested on both the Ratcheting and Hysteresis clutches. Large differences in immediate removal torque values were found between closures with pulp and foam liners. The foam-lined closures showed much lower immediate removal torque values than the pulp-lined closures, as shown in Figure 5 on page 21 and Figure 10 on page 31. This was true for both the Ratcheting and the Hysteresis clutches.

The statistical analyses of the effects of liners on immediate removal torque also showed highly significant differences as noted earlier (See Appendix, Analyses 1 and 2). Differences were seen among all three liner types in both the Ratcheting and Hysteresis clutches. A distinct relationship among them is best illustrated in Figure 10 on page 31 where the additional effect of the rotation speed is not pronounced. In this figure it is obvious that there are contributions from the liner systems.

The choice of liner system used in a closure can have a large effect on the torque behavior of the closure system, so careful analysis of the properties of the liner must be considered. Failure to do so can give torque values that are either greater or less than expected.

Effect of Dwell Time on IRT Values:

Dwell time exerted some effect on the immediate removal torque values. Tests for torque at unacceptable dwell times were performed at rotational speeds of 150, 200, and 250 rpm for both the Ratcheting and Hysteresis clutches. The effects were greatest with the Ratcheting clutch at speeds of 150 and 200 rpm (Table 6, Figure 16). The low dwell times resulted in the lowest immediate removal torque values and the high dwell times resulted in the highest IRT values. At 250 rpm, though, the high and low dwell times yielded results approximately the same, both being higher than the acceptable dwell time values. The ANOVA and some confidence interval estimates for the Ratcheting clutch are reported in Appendix Analysis 3. The

P-values are 0.000 for the main effects of dwell time and rotation speed and their interaction.

Table 6 Unacceptable and Acceptable Dwell Time IRT Averages, Ratcheting Clutch. (n=30 for each setting)

	150 RPM	200 RPM	250 RPM
Low Dwell Time	16.5	21.4	20.0
Acceptable Dwell Time	19.1	23.8	18.1
High Dwell Time	21.8	25.8	19.6

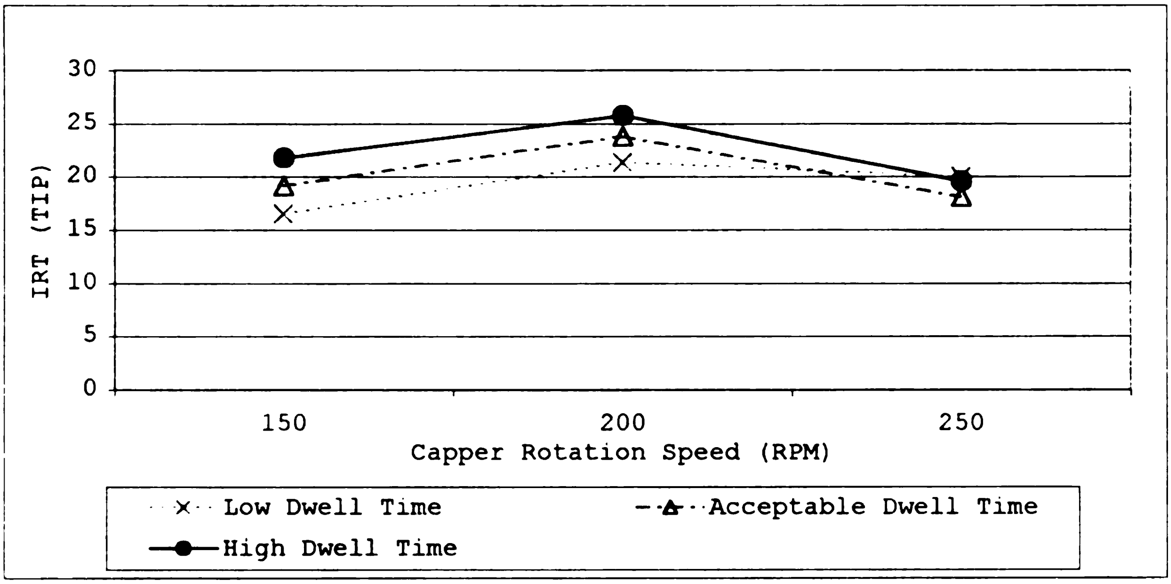


Figure 16 Unacceptable and Acceptable Dwell Time IRT Averages, Ratcheting Clutch.

The Hysteresis clutch also showed effects of dwell time on immediate removal torque (Table 7, Figure 17). However, the effect was much smaller than that of the Ratcheting clutch. The differences in IRT values decreased as the rotational speed increased from 150 rpm to 250 rpm.

The statistical analysis performed here used the General Linear Model approach because the sample sizes are not all equal. The results on the analysis are reported in Appendix Analysis 4. The P-values are 0.000 for the main effects of rotation speed and dwell time. Comparing Figures 16 and 17, the Ratcheting clutch showed greater differences of average IRT due to dwell time than did the Hysteresis clutch.

Dwell time, therefore, can influence the application torque of a closure even at a consistent static torque setting. This is explained by the fact that, at higher dwell times, the force from the magnets is being applied for a longer period of time.

Table 7 Unacceptable and Acceptable Dwell Time IRT Averages, Hysteresis Clutch. (n=15 for each low and high dwell time setting, n=30 for each acceptable dwell time setting)

	150 RPM	200 RPM	250 RPM
Low Dwell Time	15.4	16.9	16.8
Acceptable Dwell Time	16.4	17.3	16.8
High Dwell Time	17.9	18.1	17.8

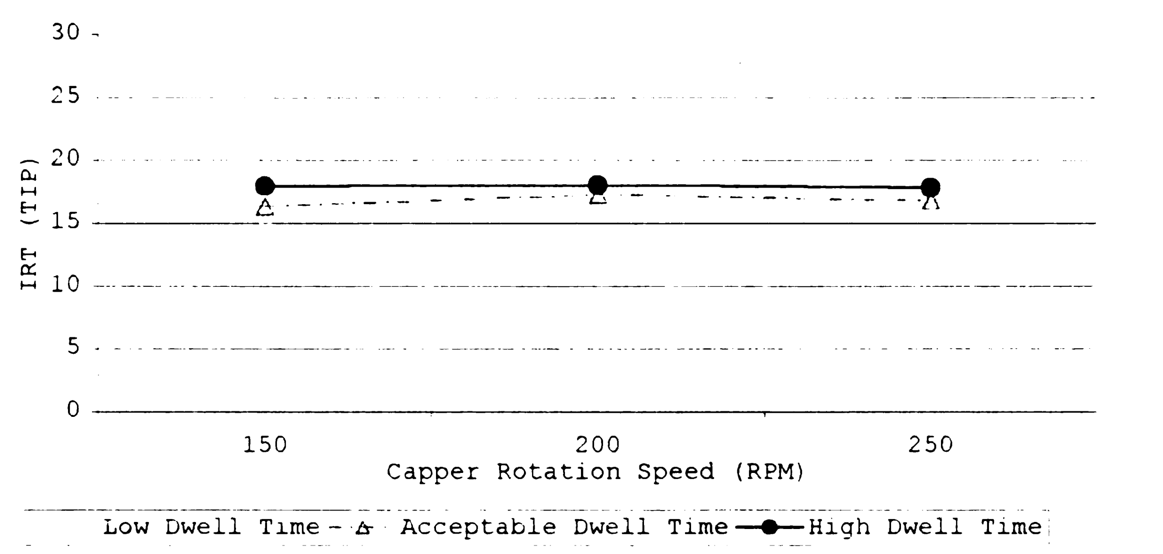


Figure 17 Unacceptable and Acceptable Dwell Time IRT Averages, Hysteresis Clutch.

The Effect of Pigment on IRT Values:

For each 28mm closure-liner system studied, both white and black pigments were used. The results show some very small differences in immediate removal torque values with many of the closure systems.

The statistical analyses showed the effect of the pigments on immediate removal torque to be insignificant. The P-value from the pigment using the Ratcheting clutch is 0.157, and 0.673 for the Hysteresis clutch (Appendix Analyses 1 and 2). In fact, the differences in pigment in some cases resulted in higher immediate removal torque values while at other times resulted in lower IRT values. There were, however, statistically significant interactions between pigment and rotation speed, pigment and liner type, and pigment, rotation speed, and liner type. These interactions were seen in both the Ratcheting and Hysteresis clutches.

Discussion:

Of the variables studied, rotation speed, liner type, and clutch type had the most influence on immediate removal torque values. Dwell time, although to a lesser extent, also proved to have some effect on IRT.

The type of clutch used was found to contribute to differences in immediate removal torque values. The two types of magnetic clutches used in this study, Magnetic Ratcheting and Magnetic Hysteresis, differ in the magnetic components within the housing. The impacts supplied by the magnets of the Ratcheting clutch cause the immediate removal torque values to differ at varying rotation speeds. The IRT values in this study peaked consistently around 210 rpm. This behavior suggests that the clutch has reached a point of resonance and is responsible for this increase in torque. The Hysteresis clutch does not produce these large impacts as the clutch is activated and, therefore, had less influence on IRT. The extra magnet that is located between the two rings of magnets in the Hysteresis clutch functions to reduce the effects of the impacts and thus decrease the variation in IRT values.

Since the IRT values can be influenced by rotational speed, it is helpful to look at how this speed can vary. Closure systems are exposed to varying rotational speeds on a packaging line in a variety of ways. For example, to accommodate an increase or decrease in the line speed, the capper speed must be changed. In order to accomplish this, the rotation speed and cycle speed must be changed. The rotation speed and cycle speed must both be changed because they are dependent on each other for producing the appropriate dwell time. If the cycle time is increased while the rotation speed is maintained, the closure may not be rotated the number of times needed to be applied completely.

The rotational speed can also vary during startup and shutdown cycles. These events occur when the capper is turned on or off in the middle of a run. In the case of powering the capper up, the machine will ramp up to the speed to which the capper is set. During this ramp-up time, however, bottles on the line may be capped at rotation speeds lower than the set speed of the capper. A similar scenario may occur on a line that is designed so that the capper ceases its rotation if there is a significant gap between containers on the line. In this case, the capper may ramp down and back up when it senses another container is approaching the capper. Again, the rotational speed of the capper may still be in the process of reaching the set speed and, depending on the clutch being utilized, may receive varying amounts of application torque.

As dwell time of the clutch is changed, the amount of time that the closure-container system experiences the effects of the magnets also changes. Some, albeit limited, effect from dwell time on IRT was established. It is important to control the dwell time of a capper in order to achieve consistent application torque.

Variations in liner material must be considered when solutions to problems with immediate removal torque values are needed. Liner materials can have an effect because of differences in stress relaxation characteristics, temperature stability, and surface coatings. Some liners are coated to provide advantages such as water or chemical resistance. Coatings often have different coefficients of friction, which result in different removal torque values. Low torque values may lead to loss of barrier or leakage. High torque values may lead to difficulty in opening the container and customer dissatisfaction.

Differences between the pulp and foam liner systems may be explained by the inherent physical property variations. The amount of, and resistance to, deformation differ between the liner materials. This difference can lead to variations in the torque behavior of the closure-liner system.

The two pulp liners were different from each other in immediate removal torque values, especially in the Hysteresis clutch studies. Clearly, the differences in surface coatings contributed to these variations. The 0.035 P/VTLF lined closures resulted in the higher removal torque averages. At the very beginning of the rotation to remove these closures, it was noted that this liner showed signs of "sticking" to the finish area of the bottle. This behavior was not noted with the other pulp liner system. The wax coating that this liner utilizes may be contributing additional friction during removal of the closure. When peak removal torque values occur at the beginning of the removal process, it suggests the importance of the static coefficient of friction in the removal of closures.

Pigments in the closure body have been reported to be a cause of low removal torque values as they may cause changes in the polymer properties. These properties may include stress relaxation characteristics or differences in the dimensions of the closure due to shrinkage variations after forming. However, in this study, black and white pigments were not found to make a significant difference in immediate removal torque. However, other pigments should be studied to determine their effects on IRT.

Analyses were performed in this study to determine the statistical significance of the various data. Small residual variances were realized in fitting the models to the torque data. The residual mean squares are 2.07, 0.98, 1.40, and 1.10 in Analyses 1-4 of the Appendix. With the large sample sizes that were used, small differences can be highly statistically significant. For example, in using the Ratcheting clutch, the interactions involving color are statistically significant in Analysis 1 but are relatively small when compared to the effects of rotation speed and liner. The same can be said for the Hysteresis clutch in Analysis 2.

SUMMARY AND CONCLUSIONS

Multiple factors contribute to the issue of torque retention. Variations in liner materials and closure body materials are directions to look when problems with torque retention arise. Suppliers must use the same materials as requested with properties that meet specifications. Incoming materials and components must be inspected to guarantee that they meet these qualifications in order to avoid problems with significant variation of materials and/or dimensions. Variables that are not commonly associated with torque retention issues involve the capping machine itself.

Capper rotational speed, the type of clutch utilized, and dwell time are all variables that can potentially affect torque retention. Unfortunately, it is difficult to know how much effect is a result of variables such as time and relaxation and how much is a result of the capping machine itself. For example, if a closure is applied at 15 TIP and is removed after 15 minutes at an IRT of 20 TIP, it is difficult to determine what the actual application torque was. The machine effects may have caused the closure to be applied at 30 TIP, then the closure system relaxed to the point of 20 TIP immediate removal torque.

On the other hand, the machine effects could be slight and the closure may actually be applied to 21 TIP with the relaxation only reducing the IRT by 1 TIP. In order to measure the amount of contribution from only machine factors, the various effects would need to be separated out.

It is important to look at the effect of liner type on the immediate removal torque values. Choices in liners are often influenced by product compatibility, barrier, or tamper evidence capabilities. The effect on the torque behavior, however, is often not considered. If changes are made to liner systems, testing should be performed to ensure proper torque retention is possible using the new closure-liner system.

Dwell time should be maintained at an acceptable level in order to keep immediate removal torque values predictable. When the dwell time exceeds the recommended amount of time, the closure may receive a higher level of application torque. These effects may vary, like many variables studied, with the clutch utilized.

The 28mm and 38mm closures exhibited differences in the immediate removal torque values, demonstrating that a specific immediate removal torque value cannot be assumed appropriate for all closure systems. A closure that has a mechanical advantage due to its larger diameter does not necessarily require higher application torque to prevent failure of the closure system. This is because protection from leakage is provided by the contact of the threads of the closure to the threads of the bottle and the finish area of the bottle to the liner. Just because the closure can be removed at a lower torque should not imply that the contact of the above mentioned areas are not comparable or adequate.

Depending on the type of clutch used, the rotational speed can have an effect on the immediate removal torque. The Ratcheting clutch produced a wide range of removal torque average values along the rotational speeds tested. The Hysteresis clutch, on the other hand, produced immediate removal torque values that exhibited less variation among the varying rotational speeds.

Some differences in the results between this study and that of Xiaole Fan are evident. Although the same capping machine was used in both studies, some changes were made to it between the times of the two studies. The machine was modified to allow capper speed and rotational speed to be set independently. This change made it possible to control the dwell time. In Xiaole Fan's research, the dwell time could not be controlled. This is a very important difference. Machines in production may be set up in either of the two ways tested. Different results from the same capping machine may be noticed depending on the capabilities of setting the various speeds.

Xiaole Fan's research produced results using the Ratcheting clutch that differed from this study. There were, however, similarities. Her results did not show the large increase in immediate removal torque values near the 200 rpm point. In her study, the IRT values increased steadily after rotation speeds of 350 rpm. Although this study did not test past 350 rpm, similar results would be expected due to the effects of inertia.

The consistency of the Hysteresis clutch offers advantages to the capping process. During setup of the capping machine, it is much easier to determine the appropriate torque setting if the torque does not vary markedly along the rotation speeds. If a capping machine is used that varies in torque as the rotation speeds change, then whenever line speeds change torque may change. In this case, the static torque settings may need to be changed whenever the line speed is changed. This can often get overlooked. Additionally, even if the torque control is adjusted when appropriate, changes in the rotational speed throughout the normal cycle may still occur.

Consequently, when the capper slows down or speeds up due to capper shutdowns, ramp-ups or ramp-downs, the rotational speed will change. During this progression through the process, bottles will experience varying levels of rotation speeds. If using the Ratcheting clutch, these variations can cause large differences in immediate removal torque values. In this situation, however, according to the results obtained in this study, the Hysteresis clutch would still produce closures that have consistent IRT values. This behavior lends itself to the conclusion that the impacts of the Ratcheting clutch magnets have an effect on the capping process.

Additional research is recommended for other areas of the torque retention issue. The disc capper enjoys widespread use in many capping applications. Therefore, it would be beneficial to conduct the research similar to that performed in this study using a disc capper. It would be the goal of that study to determine whether a similar relationship exists between speeds of the capper and immediate removal torque values. It would also be useful to research the cause of the differences between the Ratcheting and Hysteresis clutches. Although it can be speculated that the magnetic components have an effect on this behavior, it would be helpful to know more details behind this issue.

The Hysteresis and Ratcheting clutches should also be tested at rotational speeds above 350 rpm. It is believed that inertia will play an increasing role beyond this point. It would be helpful to determine the extent of this effect for both clutch types. Lastly, additional research should be performed using other pigments, closure body materials, bottle materials, and liner systems.

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BIBLIOGRAPHY

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APPENDIX

APPENDIX

Minitab Analyses:

ANALYSIS 1: ANOVA, RATCHETING CLUTCH:

(Balanced Design)

Factor	Type	Levels	Values						
RPM	fixed	7	50	100	150	200	250	300	350
LINER	fixed	3	1	2	3				
COLOR	fixed	2	1	2					

Analysis of Variance for IRT (Ratcheting)

Source	DF	SS	MS	F	P
RPM	6	16110.73	2685.12	1294.47	0.000
LINER	2	20425.72	10212.86	4923.53	0.000
COLOR	1	4.16	4.16	2.01	0.157
RPM*LINER	12	3409.33	284.11	136.97	0.000
RPM*COLOR	6	38.63	6.44	3.10	0.005
LINER*COLOR	2	107.77	53.88	25.98	0.000
RPM*LINER*COLOR	12	59.91	4.99	2.41	0.004
Error	1218	2526.50	2.07		
Total	1259	42682.74			

ANALYSIS 2: ANOVA, HYSTERESIS CLUTCH:

(Balanced Design)

Factor	Type	Levels	Values						
RPM	fixed	7	50	100	150	200	250	300	350
LINER	fixed	3	1	2	3				
COLOR	fixed	2	1	2					

Analysis of Variance for IRT (Hysteresis)

Source	DF	SS	MS	F	P
RPM	6	258.74	43.12	44.21	0.000
LINER	2	19873.66	9936.83	1.0E+04	0.000
COLOR	1	0.17	0.17	0.18	0.673
RPM*LINER	12	49.63	4.14	4.24	0.000
RPM*COLOR	6	24.32	4.05	4.16	0.000
LINER*COLOR	2	27.59	13.79	14.14	0.000
RPM*LINER*COLOR	12	33.62	2.80	2.87	0.001
Error	1218	1187.98	0.98		
Total	1259	21455.72			

ANALYSIS 3: TWO-WAY ANOVA DWELL TIME, RATCHETING CLUTCH:

Analysis of Variance for IRT

Source	DF	SS	MS	F	P
RPM	2	1201.00	600.50	428.68	0.000
Dwell	2	445.81	222.91	159.13	0.000
Interaction	4	322.43	80.61	57.54	0.000
Error	261	365.61	1.40		
Total	269	2334.85			

```
                         Individual 95% CI
RPM         Mean    ---+---------+---------+---------+--------
150         19.15    (-*-)
200         23.67
250         19.24    (-*-)
                    ---+---------+---------+---------+--------
                      19.20     20.40     21.60     22.80
```

```
                         Individual 95% CI
Dwell       Mean    ----------+---------+---------+---------+-
0.5 s       19.30     (-*-)
1.5 s       20.36               (--*-)
3.5 s       22.40                                    (-*-)
                    ----------+---------+---------+---------+-
                            20.00     21.00     22.00     23.00
```

ANALYSIS 4: GENERAL LINEAR MODEL, DWELL TIME, HYSTERESIS CLUTCH:

Factor	Type	Levels	Values
Dwell	fixed	3	1 2 3
RPM	fixed	3	150 200 250

Analysis of Variance for IRT, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Dwell	2	61.446	61.446	30.723	27.93	0.000
RPM	2	22.994	20.610	10.305	9.37	0.000
Dwell*RPM	4	11.238	11.238	2.809	2.55	0.041
Error	171	188.125	188.125	1.100		
Total	179	283.802				