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# Y2K Options and the Liquidity Premium in Treasury Bond Markets

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## Abstract

Financial institutions around the world expected the millennium date change (Y2K) to cause an aggregate liquidity shortage. Responding to concerns about this liquidity shortage, the Federal Reserve Bank of New York auctioned Y2K options to primary dealers. The options gave the dealers the right to borrow from the Fed at a predetermined interest rate. The implied volatilities of Y2K options and the aggressiveness of demand for these instruments reveal that the Fed's action eased the fears of bond dealers, contributing to a drop in the liquidity premium of Treasury securities. Our analysis shows the link between the microstructure of government debt prices and the central bank's provision of liquidity. The use of Y2K options and their effect on the liquidity premium broadly conform to the economic theory and practice of the public provision of private liquidity.



Key words: Y2K options, liquidity, Treasury bonds


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# 1 Introduction

The Millennium Date Change (usually referred to as Y2K or sometimes Century Date Change) was viewed, ex-ante, as a period of potential aggregate liquidity shortage. Liquidity or "ready access to funds" is paramount to the survival of firms and financial intermediaries such as government bond dealers. Liquidity is especially paramount when an aggregate shock (or aggregate uncertainty) threatens the overall economy. The liquidity premium and the supply-demand of liquidity ahead of Y2K is the focus of our enquiry.

Responding to the concern of liquidity shortage around Y2K, the Federal Reserve Bank of New York auctioned options that gave the bond dealers the right to borrow from the Fed at a pre-determined rate. By selling these Y2K options, the central bank committed a large amount of liquidity to the Treasury bond markets. Our goal here is to use this unique event to gain insights into the premium on aggregate liquidity shocks and the liquidity premium in the Treasury bond markets.

Through the event of Y2K and Y2K options, we see the link between the liquidity premium of government debt and the central bank's provision of liquidity. The implied volatilities of Y2K options and the demand aggressiveness reveal that the Fed's action eased the fears of Treasury bond dealers. It contributed to a drop in the liquidity premium of Treasury securities. Y2K options and their effects on liquidity premium broadly conform to the economic theory and practice on public provision of private liquidity.

Our paper proceeds as follows. In Section 2, we discuss the nature of the Y2K problem and describe the Fed's issuance of Y2K options to deal with the problem.[1] In Section 3, we analyze the implied volatilities of Y2K options and the aggressiveness of demand for the central bank's provision of liquidity. This analysis allows us to get an assessment of market's view of potential liquidity shocks in the period *before* the Y2K date and to document how the view changed from October through December in 1999. In Section 4, we link Y2K options to the liquidity premium in the Treasury markets. Finally in Section 6, we interpret the Fed's use of Y2K options in the context of received economic theory on public provision of private liquidity. We also discuss other actions taken by the Fed, as well as actions taken by other central banks. In Section 6 we provide concluding remarks.

[1] A more complete description of Y2K options and the intent of the Fed in issuing them is available in Drossos and Hilton (2000).

# 2 Background

## 2.1 The Potential Liquidity Shortage around Y2K

On the Y2K date, financial institutions faced the technological risk that their own systems would fail and cause operational problems. Toward the end of the 20th century, these institutions began to rely heavily, if not exclusively, on computers to transact business, keep records, and maintain security. Nearly every financial transaction involves numerous computer functions. The Y2K problem originated from a belief that most computer software, using only the last two digits to identify the year, could misinterpret a transaction date in 2000 as one in 1900. With such misinterpretation, interest could be miscalculated, stock trades could vanish, and customers could have difficulty accessing their accounts or using their credit and debit cards. This high level of technological dependence made financial institutions particularly vulnerable to the Y2K problem.

Beyond this technological vulnerability and perhaps more importantly, financial institutions also faced the risk that their counterparties would fail on the Y2K date. Financial institutions are known for their interconnectedness and dependence on counterparties for safe operations. For example, a bank depends on its borrowers to repay loans in order to avoid losses. Financial institutions rely on funding vehicles provided by other institutions to maintain adequate liquidity. Because of this reliance on counterparties, financial institutions faced the risk that counterparties, borrowers, and clients would succumb to Y2K problems, fail to meet their obligations, and cause losses.

The counterparty risk could in turn cause liquidity shortage around Y2K. Due to concerns of the counterparty risk, banks wanted to shift settlements of forward transactions away from Y2K. The potential withdrawal by a number of institutions during this period may have discouraged trading, issuance and investment during the Y2K transition.

A signal for the shift of transactions away from Y2K was visible in June 1999 when the term spread between the six month-LIBOR and the three-month LIBOR more than doubled from a level of 13.63 basis points on June 28 to 28.25 basis points on June 30 (see Panel A in Figure 1). The implication is clear: lenders in the inter-bank market wanted a premium to lend cash when the loan was due near Y2K. The term spread continued to widen to a level as high as 42.75 basis points as of September 28, 1999. Then, the spread dropped precipitously by 54.75 basis points to −12.00 basis points[2] the next day, due to the ballooning of the three-month LIBOR. This drop reflects the fact that the three-month LIBOR rate as of

[2]When comparing the jumps in terms of borrowing costs in dollars, we should control for the differences in the time to maturity of underlying deposits.

September 29, 1999 applied to loans that matured very close to the Y2K date. We also see that the term spread reverted to "normal" levels after Y2K.

The shift of transactions also caused other LIBOR term spreads to jump. In Panel B, the term spread between three-month LIBOR and one-month LIBOR stood at 12.88 basis points on September 28, 1999 and then more than quadrupled to 67.88 basis points on September 29, 1999. The term spread then reached a level of 49.88 basis points on November 26, 1999 only to drop to a level of −36.63 basis points on November 29, 1999. Similar patterns occur in the spread between the one-month and one-week LIBOR rates (see Panel C). The spread jumped up one month before Y2K and dropped one week before Y2K.

Jumps related to the year-end date happened only in 1999 but not in other years. In panels D, E and F of Figure 1, we plot the spread between the six-month and three-month LIBOR during 1998, 1997 and 1996. It is clear that the changes of the spread at the end of September in 1998, 1997 and 1996 were only small fractions of the change at the end of September in 1999. These graphs suggest that the concern of the Y2K problem caused the large jumps in the LIBOR term spread. The most likely interpretation for the jumps is that banks were reluctant to make loans that matured at the end of 1999.

The reluctance to make loans matured on and right after Y2K pushed up the commercial paper rate. From June to November of 1999, the spread between one-month commercial paper and Treasury Bills rates fluctuated between 20 and 74 basis points for non-financial and financial companies. However, beginning on December 1, 1999, the spread for non-financial companies increased dramatically and reached a peak level of 116 basis points on December 27. This is an increase of 84 basis points from a spread of 32 basis points on November 30. The spread for financial companies also increased dramatically in the last month of 1999. It escalated from 31 basis points on November 30 to 114 basis points on December 23. Clearly, the lack of liquidity made short-term borrowing costs higher than usual for loans that matured right after Y2K.

The rise in borrowing cost was also visible in Eurodollar time deposits. The spread between the rates on one-month Eurodollar time deposits and Treasury bills fluctuated between 20 and 77 basis points during June – November of 1999, like the spreads of commercial paper over the T-Bills. The spread then began to widen quickly on December 1 and reached a peak of 131 basis points by December 8, 1999. The spreads remained at a high level until December 28, 1999 and then declined significantly thereafter. Clearly, due to counterparty risk, the cost of obtaining liquidity from money markets in the private sector became prohibitively expensive during the period immediately before Y2K.

Counterparty risk posed a major concern of the U.S. central bank. Peter Fisher, then executive vice president of the Federal Reserve Bank of New York, described this concern clearly: "It seemed quite reasonable for customers and bankers to agree to shift settlements of forward transactions away from the first few days of January. However, we became more troubled by the escalating efforts, of a number of market participants, to discourage normal trading, issuance and investment activities during the Y2K transition. The destruction of market liquidity implied by these efforts presented the risk of a self-fulfilling prophecy, whereby extreme risk aversion would create expectations—and the reality—of exceptionally thin market conditions, making it more likely that markets could be jarred by even a modest external shock—Y2K related or otherwise."[3]

In August of 1999, the U.S. central bank concluded that Y2K was likely to precipitate to a liquidity shortage if no actions were taken to prevent it. The central bank was aware of the possibility that customers and bankers might agree to shift settlements of forward transactions away from the Y2K period. It concluded that the market might need potentially large year-end reserves. If dealers and financial intermediaries were to withdraw from important markets such as repurchase agreements during this critical period, it would be challenging for the Fed to meet the need for liquidity in a highly illiquid financing market at year-end.

## 2.2 Options Issued by the U.S. Central Bank

The U.S. central bank responded with several policy initiatives to meet the potential aggregate liquidity shortage, but the most important and innovative initiatives were the issuance of options. The U.S. central bank sold state-contingent bond contracts, contracts with terms explicitly specified to be contingent on the economic state around Y2K. It was possible because Y2K represented one of the few foreseeable states of potential aggregate liquidity shortage.[4] These contracts were options that allowed institutional buyers to exercise in the presence of aggregate liquidity shock around Y2K, clearly targeted to meet the potential shortage of liquidity for banks and players in the Treasury bond market.

The first initiative that issues option contracts was the Special Liquidity Facility (SLF). The Federal Open Market Committee (FOMC) approved the initiative on July 20, 1999, more than five months ahead of Y2K. Under SLF, the depository institutions were allowed to borrow from the Federal Reserve discount window at an interest rate that was 150 basis points above the prevailing federal funds target rate from October 1, 1999 to April 7, 2000. In SLF, depository institutions were given call options for credit on July 20, 1999. The strike

[3]Source: "Money Market and the Century Date Change," speech by Executive Vice President Peter R. Fisher before the Money Marketeers of New York University on December 01, 1999.

[4]Year-ends, and major holidays are other states whose timing are known ahead. Seasonal agricultural needs for liquidity are also relatively foreseeable.

of the option was set at 150 basis points above the prevailing federal funds target rate, and it could be exercised during the period from October 1, 1999 to April 7, 2000.

The second initiative was the Standby Financing Facility (SFF), in which the Fed conducted a series of auctions to sell options contracts. These options gave the holders the right, but not the obligation, to execute overnight repo transactions with the New York Fed at a pre-set strike price, which was a financing rate that was 150 basis points above the prevailing federal funds target rate. The unit of the option contract was \$50 million. These options could be exercised during some specified periods around Y2K. Under SFF, demanders of future liquidity were invited to bid for the options at periodic intervals before Y2K. The Fed's purpose in issuing these options was to insure that the bond markets operated smoothly around Y2K so that the Fed could conduct its monetary policy operations without running into difficulties. In its August 24 meeting, the FOMC made the necessary rulings to permit the auction of these options.[5]

In SFF, options were sold in uniform-price auctions, which is the current form of auctions for all Treasury debt securities. The supply in each auction is the total amount accepted in the auction. This amount is announced before each auction. However, the result of an auction probably affected the amount the Fed planned to accept in the next auction. According to Drossos and Hilton (2000), the Fed increased the quantities in the second and the third auctions because the demand in the first round surpassed the Fed's expectations. The price determined by the supply and demand in an auction is referred to as the stop-out rate.[6] The stop-out rate contains useful information about the liquidity demand since the bidders bid after the supply is announced by the central bank. For a fixed supply, the higher stop-out rate the bidder is willing to pay for buying the option on liquidity, the greater the demand for the public provision of private liquidity.

The Federal Reserve Bank of New York conducted seven auctions in SFF, selling three types of options with varying maturity dates in each auction. The auctions were on the following seven dates in 1999: October 20, October 27, November 3, November 10, November 17, November 23, and December 1. The first type of the options allowed the holder to exercise during the period of December 30, 1999 – January 5, 2000, which covered the Millennium Date Change. This option is referred to as "the December 30 strip" by the Federal Reserve Bank. The second allowed the holder to exercise during the period of December 23, 1999 – December 29, 1999. The third allowed the holder to exercise during the period of January 6, 2000 – January 12, 2000. The last two options are referred to as "the December 23 strip"

[5] Source: *Press Release* by the Federal Reserve Bank of New York on September 8, 1999.

[6] Stop-out rates are quoted in basis points. Ten basis points for an option on \$50 million overnight loan are equivalent to \$138.89, which is calculated from $\$50,000,000 \times (10/360) \times (1/100) \times (1/100)$.

and "the January 6 strip" respectively.

Through the option contracts in SFF and SLF, the central bank assured the availability of a large amount of liquidity around Y2K. Using SFF, the Fed sold a large quantity of liquidity insurance to Treasury bond dealers. Table 1 presents a summary of the options issued in SFF. The total repo contracts sold in the options of the December 30 strip were worth $223 billion. The total repo contracts sold in the options of January 6 and December 23 strips were worth $144 billion and $114 billion, respectively. Using SLF, the Fed committed itself to providing depository institutions with an alternative source of liquidity for handling potentially large withdrawals (demand for liquidity) of deposits or currencies. This commitment shaped the expectations about the availability of year-end liquidity.[7]

The options issued in SFF are distinct from those in SLF in several ways. First, the holders of options operated in different markets; the option holders in SLF were depository institutions while the option holders in SFF were bond dealers. According to Drossos and Hilton (2000), one reason for SFF is that the Fed did not think the benefits of SLF would be sufficiently transmitted to the bond dealer market. Second, options in SLF were issued free of cost while options in SFF were sold for a price. The prices and demand curves of the options in SFF allow us to examine the market view of the liquidity shortage prior to Y2K, while such an examination is not possible with the free options in SLF. In the rest of this paper, we refer to the options in SFF as Y2K options.

# 3 Prices and Demand Functions of Y2K Options

## 3.1 Repo as the Underlying

In order to understand the payoff and value of Y2K options, we first examine the behavior of repo rate (or the general collateral rate). Repo rate is the underlying rate of Y2K options because dealers must collateralize their overnight borrowing from the Fed. In panel A of Table 2, we present the summary statistics of repo rates during May 21, 1991 – October 19, 1999. The beginning date is the first date of our data,[8] and the last date is the day before the first auction of Y2K options. Since the strike prices of Y2K options are quoted as spread

[7] The Fed reported that there were 14 instances in which depositary institutions borrowed from the Special Liquidity Facility for more than ten consecutive days, and another 42 instances of borrowing for two to ten consecutive days. This evidence is consistent with the view that some financial institutions did not have inexpensive access to market sources of funds. (Source: *Revisions to Discount Window Programs*, Board of Governors of the Federal Reserve System, October 24, 2002.)

[8] We obtained the repo and Fed funds rates from Bloomberg. The earliest date of these data available from Bloomberg is May 21, 1991.

over the prevailing Fed funds target rate, in panel A of Table 2 we also provide the statistics for the spread between the repo rate and the target rate during the same period.

The repo rate tends to spike at quarter-ends (including year-ends). In Figure 2, we plot the repo rates over the period 1991 through 1999. Along with the repo rates, we plot the Fed funds target rates after adding 150 basis points. As one might expect, on most days the repo rate is very close to (in fact, slightly below) the Fed funds target rate. Nevertheless, repo rate often spikes, and the spikes tend to occur one or two days before the quarter-ends and year-ends. Understanding these spikes is essential for the valuation of Y2K options because maturity of the December 30 strip of Y2K options spanned over a year-end but the maturity dates of the other two strips did not.

The literature has documented that short-term interest rates tend to rise near quarter-ends or year-ends. For example, using one-month LIBOR and related derivatives, Griffiths and Winters (2005) and Neely and Winters (2005) have shown that short-term interest rates tend to rise at year-ends. Such rise is attributed to increases in risk or preference for liquidity around quarter-ends or year-ends. Musto (1997) notes that commercial paper tends to sell at a discount if it matures in the next calendar year, and attributes the discount to agency problems. It is well known that financial institutions typically clean up liabilities in their accounts for quarter-end or year-end reporting. This is referred to as window dressing, which reduces liquidity in money markets. Due to window dressing, the volatility of repo rates within a quarter should be different from the volatility around a quarter-end (and year-end).

We can estimate and test the difference between the repo rate's behavior around a quarter-end and its behavior within a quarter. We examine the sub-sample of the repo-target spreads that are on quarter-end dates and two business days around. For convenience, we refer to this sub-sample as the "quarter-end" sample. All the spreads that are more than two days away from quarter-end dates constitute another sample, which is referred to as the "within-quarter" sample. To test for the difference between the two sub-samples, we use the maximum likelihood method to estimate the following specification:

$$r_t = a + bI_t + \epsilon_t \qquad \epsilon \sim N(0, \exp(d + cI_t)) \ , \tag{1}$$

where $r_t$ is the repo-target spread, and $I_t$ is the dummy variable that equals 1 when $t$ is in the quarter-end sample and 0 otherwise.

The mean and volatility of repo rate around a quarter-end are significantly different from those within a quarter. We can see the difference by examining the estimates of the parameters $a$, $b$, $c$ and $d$, which are reported in panel B of Table 2. All these estimates are significantly different from zero. The mean and standard deviation of the sub-samples implied by these parameters are reported in panel C. Parameter $a = -1.61$ is the average repo-target spread of the within-quarter sample. Parameter $b = 16.80$ is the difference between the means of the two sub-samples, indicating that the quarter-end sample has much higher mean than the within-quarter sample. Parameter $d = 5.47$ implies that the standard deviation of the within-quarter sample is $e^{d/2} = 15.38$. Parameter $c = 1.42$ indicates that the ratio of the quarter-end standard deviation to the within-quarter standard deviation is $e^{c/2} = 2.03$. The significance of $b$ and $c$ in our model for repo rate is consistent with the empirical evidence of window dressing reported in the literature.

Since repo contracts are collateralized loans while Fed funds are not collateralized, repo rates should normally be lower than Fed funds rates but not around quarter-ends. In the within-quarter sample, the repo rates are on average lower than the target rates by 1.61 bps and statistically significant (panel C of Table 2). This number is consistent with the intuition that the interest rate on a loan should be higher if it is not collateralized. However, this intuition does not hold for quarter-end sample. Interestingly, this intuition does not hold in the complete sample either (panel A of Table 2); the mean of the spread between repo and target rates is far smaller than one basis point (0.25 bps), and the $t$-statistic is insignificant (only 0.65) for testing whether the mean is zero.

The jump in the repo-target spread around Y2K is not materially different from other jumps around quarter- or year-ends. In Figure 3 we plot the spread between repo rate and Fed funds target rate over the last three months of 1999 and the first month of 2000. The spread has a typical spike as those on other quarter-ends or year-ends. A special feature is the big drop of the repo rate before the New Year's Day. The Federal Reserve Bank of New York used morning repo rates to chart the behavior of repo rates on the days around Y2K;[9] we reprint the chart in Figure 4 for ready reference. The repo rates in Figure 4 fell significantly in the last few days before Y2K. The Fed's annual report suggests that the drop is due to the Fed's provision of liquidity right before Y2K. Notice that Our moving average of repo-target spreads in Figure 3 is consistent with the chart in Figure 4.

## 3.2 Liquidity Premium in Option Prices

An important question was whether the observed prices of Y2K options contained any premium, which reflected a potential jump in repo rates at the end of 1999. It is clear that the price of the December 23 strip should have contained little year-end or Y2K premium because it matured well before the end of 1999. If there was a year-end premium and/or

[9] *Domestic Open Market Operations during 1999*, the Federal Reserve Bank of New York, Markets Group, February 2000.

a Y2K premium, it is most likely to have been reflected in the price of December 30 strip, which could be exercised in the week that covered Y2K. The January 6 strip might also contain some Y2K premium if the market expected the Y2K problem to last beyond the first few days of 2000. From Table 1, we observe that in each auction the stop-out rate of December 30 strip is much higher than the stop-out rates of other two strips.

The high stop-out rate of December 30 strip alone is not sufficient for us to conclude that a Y2K premium existed in the price of Y2K options. First, these options had different maturities. Second, the options were auctioned on different dates and consequently have different levels of underlying repo rates on those dates. Third, and most importantly, given the fact that repo rates usually have higher volatility around a quarter-end (or a year-end) than during a quarter, the December 30 strip of Y2K options was expected to be more expensive than the other two strips, even if there was no concern about the Y2K problem at the end of 1999. We wish to know whether there was an incremental premium due to the effect of Y2K. Unfortunately, there are no repo options around other year-ends for us to compare with Y2K options.

The value of Y2K options should however be very low if the market did not believe that an unusual jump on Y2K is likely. Based on the historical behavior of repo rate up to the last quarter of 1999, Y2K options were unlikely to be in the money if Y2K did not affect the overnight borrowing rate. The payoff of a Y2K option is a linear function of the repo-target spread if the option is in the money (i.e., if the repo rate is above the Fed funds target rate by more than 150 bps), and the payoff is zero otherwise. The value of a Y2K option depends on the likelihood that the repo-target spread is above 150 bps. The statistics in Table 2 show that the maximum repo-target spread in our sample is 145 bps and its date is December 30, 1996, which is a year-end. Therefore, if repo rates are not expected to jump over the historical maximum level of 145 bps, it is very unlikely for a Y2K option to be in the money. Apparently, the Fed set the strike price high enough so that these options are used as insurance for Y2K shocks that are over and above the historical year-end jumps of short-term rates.

To compare prices of Y2K options, we use Black's model of interest rate caps to calculate their implied volatilities. It is important to stress that we do not need to assume that Black's model is the correct pricing model for Y2K options. Following common practice in academia and industry, we simply use Black's model to extract implied volatilities so that we can compare values of options on the same underlying but with different times to maturity and different strike prices. Y2K options are caplets. The underlying interest rate of Y2K options is the repo rate. Strike rate $K$ is 150 basis points above the target rate. The size of the loan, denoted by $L$, in one Y2K option contract can be viewed as \$50 million because it is the increment of the bids. The expiration time of the option is the expiration period of a strip, which is of Bermudan-type and contains a few days. In order to use Black's formula, we treat Y2K options as European options that mature only on a particular day in the expiration period and denote the date by $T$.[10] The timing of the caplet's payoff is a day after the exercise of a Y2K option and is denoted by $T'$. Black's formula for a caplet in an interest rate cap is

$$c = e^{-rT'} L(T' - T)\,[F N(d_1) - K N(d_2)] \tag{2}$$

$$d_1 = \frac{\ln(F/K) + 0.5\sigma^2 T}{\sigma\sqrt{T}} \tag{3}$$

$$d_2 = \frac{\ln(F/K) - 0.5\sigma^2 T}{\sigma\sqrt{T}}\ . \tag{4}$$

where $N(\cdot)$ is the cumulative distribution function of the standard normal distribution. Besides those parameters specified in a cap contract, we need three variables, which are determined by the capital markets. The first is $r$, which is the yield to maturity for zero-coupon bond that matures at $T'$. We can obtain it from the term structure of LIBOR contracts. The second is $F$, which is the forward repo rate for the period from $T$ to $T'$. We can obtain it from the curve of term repo rates. The third is $c$, which is the price of the option. We can calculate it from the stop-out rate. (Please refer to footnote 6). Now, the only thing unobservable in the formula is the volatility, $\sigma$, of the underlying. We can solve for $\sigma$ from equations (2), (3) and (4); the solution is the implied volatility. The implied volatilities of Y2K options are reported in Table 3, and a graphical presentation of the implied volatilities is shown in Figure 5.

The implied volatilities suggest that the dealers felt that large jumps in repo rates might happen during a narrow period surrounding January 1, 2000. Judged by implied volatility, the December 30 strip is considerably more expensive than the December 23 strip. The ratios presented in Table 3 indicate that the implied volatility of December 30 strip is twice as big as the implied volatility of December 23 strip in most auctions. Clearly, the price of December 30 strip contains at least a liquidity premium on the year-end jump of borrowing rate. Given our arguments concerning the choice of the strike price of Y2K options, we suspect that at least part of the option's premium reflected the Y2K concerns over and beyond the usual year-end concerns. Interestingly, the implied volatility of January 6 strip is about the same as (and even slightly smaller than) the implied volatility of December 23 strip, indicating that liquidity was not viewed as a problem a week after New Year's Day.

[10] In fact, changing the choice of the maturity date in the expiration period of Y2K options causes only negligible changes in our results.

A liquidity premium due to a jump beyond the usual year-end effect might exist in December 30 strip of Y2K options. To see this, we compare the implied volatilities with the standard deviation of the repo-target spread. The Y2K options in December 23 strip should be a function of the volatility during a quarter, while the options in December 30 strip should be a function of the volatility at quarter end. For the repo-target spread, the ratio of the standard deviation of quarter-end sample to the standard deviation of within-quarter sample is 2.03 (panel C of Table 2). If Y2K is not an incremental liquidity shock to the usual year-end effect, then the ratio of the implied volatilities for the two strips should be comparable with the ratio of the standard deviations in the two sub-samples of repo-target spreads. In contrast, the ratio of the implied volatility of the December 30 strip to the implied volatility of the December 23 strip is about 2.50 in three auctions and above 2.03 in all except the last two auctions (see Table 3). We view this as an indication, although not solid evidence, of the Y2K premium in the December 30 strip. In the last auction, the ratio of implied volatilities of the two strips is only 1.70. If we take the stand that 2.03 is a normal level for the ratio of quarter-end volatility to within-quarter volatility, the low ratio in the last auction indicates that the market expected a liquidity shock even smaller than the usual year-end, possibly due to the injection of liquidity by the Fed.

The implied volatilities indicate that dealers' expectation of year-end jump changed over the seven auctions. For the purpose of our analysis in later sections, the relevant issue is not whether there is a Y2K premium in addition to the usual year-end premium. Rather, the key issue is whether the Fed actions influenced the funding costs of dealers. In this context, the *variation*, rather than the level, of the implied volatilities over the auctions is important; the variation points to the effect of central bank's injection of liquidity and the change of views by market players. In Table 3, and more visibly in Figure 5, the implied volatility of December 23 strip remains almost constant. This indicates that the dealer's view of the within-quarter repo rates was not changing or influenced by the issuance of Y2K options. The implied volatility of December 30 strip, however, varied over the auctions. Then, the ratio of the implied volatility of December 30 strip to the implied volatility of December 23 strip varied accordingly. In contrast, the implied volatility of January 6 strip did not vary as much over the auctions.

## 3.3 Aggressiveness of Demand

It will be interesting to investigate directly how the demand of Y2K options varied over the seven auctions. The variation of the demand function should reflect the effects of Fed's injection of liquidity on market conditions. The Fed's intention with Y2K options was to ensure that dealers have enough protection against liquidity shocks so that they do not withdraw from the market. After each auction, the Fed adjusted the accepted amount in the next auction to satisfy the demand for liquidity protection. In each auction, the accepted amount (supply) should directly affect the implied volatility of Y2K options in the auction. It might also indirectly affect the implied volatility in the later auctions if it affected the demand functions in later auctions. According to its 1999 report of open market operations, the Fed believed that the demand was satisfied, observing the drop of option price in the last auction.

With the data obtained from the Federal Reserve Bank of New York, we can estimate the demand functions in each auction. We use the standard demand function with constant elasticity. The functional form is

$$Q = e^a P^{-b} \ ,$$

where $Q$ is the quantity of the Y2K options quoted in billions of dollars of repurchase agreements and $P$ is the price of the Y2K options quoted in basis points. We estimate the parameters $a$ and $b$ from the regression:

$$\ln(Q_i) = a - b \ln(P_i) + \epsilon_i \ ,$$

where $Q_i$ is the total quantity bid at prices lower than or equal to price $P_i$. The parameter $a$ is the intercept of the log-linear regression of the demand function. The parameter $b$ is the demand elasticity, which measures the sensitivity of quantity to price changes. The assumption of constant elasticity is motivated not only by simplicity but also by the fact that we had a problem with small sample size. The relatively small number of grids of bidding price and quantity[11] would have rendered the estimation of a more general demand curve difficult.

For the December 30 strip, we plot the estimated demand curves in the seven auctions (Figure 6). The accepted amount (supply) is indicated by the vertical line that meets the demand curve, and a horizontal line indicates the stop-out rate. We present the demand and supply only for the December 30 strip because this strip contains the liquidity premium for year-end and Y2K, as we demonstrate previously.

We want to know how aggressively dealers bid in each auctions. For this purpose, we can compare the quantity demanded in one auction at a price with the quantity demanded in another auction at the same price. Let $a$ and $a'$ are the intercepts in the log-linear regressions of two demand functions. If the two demand functions have the same elasticity, then the

[11] In SFF, the increment in price is 0.5 basis point and the increment in quantity is $50 million.

ratio of the two quantities demanded at any price level is $e^{a-a'}$. In this sense, $e^a$ measures the aggressiveness of the demand because larger $a$ is, higher is the quantity demanded for any given price. If two demand functions have different elasticities, $e^{a-a'}$ is the ratio of the quantities demanded at price $P = 1$. Therefore, $e^a$ is the quantity demanded at unit price. We thus refer to $e^a$ as the *aggressiveness of the demand*. In Table 4, we provide the demand aggressiveness and elasticity for each auction of each strip of Y2K options.

The aggressiveness of demand shows that dealers concerned about a potential liquidity shortage on the Y2K date, but not before or after it. On each auction date, the demand for the December 30 strip is always more aggressive than the demand for the other two strips. It suggests that the year-end or Y2K concerns brought about strong demand for the December 30 strip. In contrast, the aggressiveness of the demand for the January 6 strip is only slightly higher than the December 23 strip. Dealers did not seem to worry about prolonged liquidity shortage after Y2K. To look at the relative aggressiveness, in Table 4 we report the ratio of the aggressiveness for the December 30 strip to the aggressiveness for the December 23 strip. This ratio varied drastically over the seven auctions and has a downward trend.

Indeed, dealers bid aggressively for the insurance of Y2K liquidity shock in early auctions but much less so in later auctions. The aggressiveness of the demand for the December 30 strip was high on October 27 and November 3. It started to diminish in the auction on November 10. The demand curves for the last three auction dates plotted in Figure 6 clearly show a significant drop. In the last auction, the aggressiveness of the demand for the December 30 strip was about the same as the demand for the other strips. The variation of the aggressiveness for January 6 or December 23 strip was much smaller than the variation for December 30 strip. Therefore, the Fed's injection of liquidity exerted a large influence on the demand for December 30 strip but a small influence on the demand for January 6 and December 23 strips.

It is important to point out that the aggressiveness measures the bidding behavior at a single auction independently. It does not treat the bidding behavior as part of a broader bidding strategy that takes into account the knowledge that there are future auctions. Unfortunately, due to confidentiality, the auction data provided by the Fed do not allow us to track individual bidders for strategic bidding behavior. To complicate matters, the Fed was also learning from each auction and dynamically altering the supply.

# 4 Liquidity Premium in Treasury Bond Markets

## 4.1 On/off-the-Run Spread as Liquidity Premium

The liquidity premium in government securities has received extensive attention from an empirical perspective. The papers by Kamara (1994), Duffie (1996), Jordan and Jordan (1997), Krishnamurthy (2002), Longstaff (2001), Buraschi and Menini (2002) represent some of the earlier contributions.

In empirical studies, the proxy for the liquidity premium in government debt is usually the spread between the yield to maturity of a newly auctioned government security and that of a government security auctioned earlier. The newly auctioned government security is referred to as on-the-run or new bond, while the one auctioned earlier is referred to as off-the-run or old bond. With rare exceptions, an on-the-run bond trades at a yield lower than the yield of similar off-the-run bond. The level of the spread depends, inter alia, on the expected auction date and the actual occurrence of the next auction. When the next auction occurs, the current on-the-run bond becomes the next off-the-run bond with lower liquidity, and the current off-the-run bond becomes an even older issue, which has even lower liquidity.[12] The magnitude of the spread between on-the-run and off-the-run debt issues and their relationship to auction dates are reported in Sundaresan (1994).

The on/off-the-run spread has been related to their specialness in the repo markets, which is another proxy for the liquidity premium of government securities.[13] Duffie (1996) constructs a model where a bond attracts a higher price if it trades special in the repo markets. He observes that Treasury bonds have different values in the market for collateral — the new bond is generally more attractive as collateral than the old bond. Hence, a new bond commands higher price (or lower yield) relative to the old bond. The collateral value obviously goes up in periods of liquidity shortage, thereby resulting in higher spread between on-the-run and off-the-run bonds.

There is much empirical research demonstrating that the on/off-the-run spread serves as a reasonable proxy for the liquidity premium. For example, Jordan and Jordan (1997) provide evidence supporting this view. Buraschi and Menini (2002) examine the term repo spread, which is regarded as an indicator of the duration of expected specialness in the repo markets. They show that the violation in the expectations hypothesis may be due to the

[12] In a "reopening" auction, in which the supply of an existing issue is increased via auction, this will not be the case.

[13] A government security is said to trade "special" in the repo market when the owner of that security is able to pledge it as collateral and borrow money on a short-term basis at interest rates that are considerably lower than the prevailing rates on similar loans collateralized by other government securities.

presence of time-varying liquidity premium in government debt securities. Krishnamurthy (2002) gives a liquidity underpinning in his explanation of the level and variations in on/off-the-run spread. He does this by exploring the relationship of on/off-the-run spread to the spread between commercial paper and Treasury Bills. Longstaff (2001) demonstrates that the short-term spread is primarily driven by liquidity related factors.

Because on/off-the-run spread is extensively studied in the literature and is available on high-frequency basis, we will closely examine this measure of liquidity premium in the period around Y2K. An alternative candidate for the measure of the liquidity premium is the difference between general collateral repo rates and special repo rates. Given Duffie's (1996) theoretical arguments and Krishnamurthy's (2002) empirical work, we suspect that the spread between the general collateral rate and the special repo rate as a measure of liquidity premium will generate results that are qualitatively similar to those we presented in this paper. Unfortunately, we do not have access to historical data on the special repo rates.

The on/off-the-run spread examined in our analysis is the average of the spreads on five-year and 10-year Treasury notes. The data are a daily time series provided by Lehman Brothers. The 10-year notes are liquid securities in Treasury markets. Although the 30-year bond was a major benchmark used in many previous studies, the new issues of 30-year bonds ceased to be liquid in 1999 when the Treasury started to reduce the quantity of new issues of 30-year bonds and planned to initiate a buyback program in response to the projected surplus over the next several years.[14] If the data were to include 30-year bonds, it would be hard to tell whether the rise of the liquidity premium is caused by the shrinking supply of 30-year bonds or by Y2K concerns.

Incorporation of five-year notes in the data offers an inclusive measure of the on/off-the-run spread on medium-term notes. Fleming (2003) reminds us that, due to the suspension of 20-year bonds, on/off-the-run spread of 10-year notes is expected to behave differently than the spread of other Treasury securities. The inclusion of five-year notes should alleviate Fleming's concern. (To alleviate the concern even further, we report results separately for on/off-the-run spread of five-year notes.) Note that five-year notes have the same quarterly auction cycle as 10-year notes in 1999. Because they have the same auction cycle, we can examine the average on/off-the-run spread of five-year and 10-year notes. Averaging the spreads reduces the noise driven by the microstructure of the Treasury bond markets.[15]

[14] On August 4, 1999, the Treasury announced the consideration of debt buyback program and launched it on January 13, 2000. The first buyback is on March 9, 2000. This possibility was anticipated by the market, although the announcement that issuance of 30-year bonds was suspended came on October 31, 2001. The 30-year bonds were last auctioned in August of 2001.

[15] In contrast, two-year Treasury notes are auctioned on a monthly basis. The two-year notes cannot be

To look at the behavior of on/off-the-run spread around Y2K, in Figure 8 we plot the spread during January 1, 1999 — January 31, 2000. The figure shows the auction dates as vertical lines. Disregarding the fluctuations related to the auction cycle, the spreads have an upward trend and peaked during the first half of 1999, but then dropped substantially during the second half. More importantly, the spread did not rise sharply toward the end of 1999. To understand what happened to on/off-the-run spread before Y2K, we link the behavior to the provision of liquidity by the Federal Reserve Bank of New York in the last quarter of 1999.

## 4.2 Specifications for Testing the Effects of Y2K Options

Since the on/off-the-run spread is affected by several factors in the markets, we need to control for those factors by using a model for the behavior of the spread when testing for the effects of Y2K options. For this control, we use Krishnamurthy's (2002) model, which accounts for auction cycle, the supply of Treasury securities and the liquidity premium in the general cash markets. The basic variables in Krishnamurthy's model are as follows. On date $t$, let $\mathrm{TLR}_t$ be the relative time to the next auction date of Treasury bond. Specifically, it is defined as

$$\mathrm{TLR}_t = \frac{\text{number of days from date } t \text{ to next auction}}{\text{number of days from last auction to next auction}} \; . \tag{5}$$

Krishnamurthy's model also allows nonlinear effects of the auction cycle and thus includes the square of the cycle, $\mathrm{TSQ}_t \equiv \mathrm{TLR}_t^2$, as a basic variable. Another basic variable is the liquidity risk in the general cash markets, which is measured by the spread, denoted by $\mathrm{CPB}_t$, between one-month commercial paper and three-month T-bills.[16] The liquidity premium of the Treasury market is also closely related to be the supply, denoted by $\mathrm{SUP}_t$, of the on-the-run five-year and 10-year Treasury notes.

The *basic model* for our analysis assumes that the on/off-the-run spread is a function of the auction cycle, commercial paper rate and the supply of new bonds. The regression equation of the model is

$$\begin{aligned} S_t &= \beta_0 + \beta_{\mathrm{TLR}}\mathrm{TLR}_t + \beta_{\mathrm{TSQ}}\mathrm{TSQ}_t + \beta_{\mathrm{CPB}}\mathrm{CPB}_t \\ &\qquad + \beta_{\mathrm{CTL}}\mathrm{CTL}_t + \beta_{\mathrm{CTQ}}\mathrm{CTQ}_t + \beta_{\mathrm{SUP}}\mathrm{SUP}_t + \beta_{\mathrm{STL}}\mathrm{STL}_t + \epsilon_t \; , \end{aligned} \tag{6}$$

included in the average because it is difficult to control for the effects of numerous and non-synchronous auction dates. Moreover, on/off-the-run spread of two-year notes is very small and noisy.

[16]Three-month T-bills are used here because one-month T-bills were not introduced by the Treasury as a benchmark until year 2000.

where $\beta_0$ is a constant and other $\beta$s are coefficients of the variables. In this model, we follow Krishnamurthy (2002) to allow $\text{CPB}_t$ and $\text{SUP}_t$ to interact with the auction cycle, and consequently include the following variables:

$$\text{CTL}_t \equiv \text{CPB}_t \times \text{TLR}_t \tag{7}$$

$$\text{CTQ}_t \equiv \text{CPB}_t \times \text{TSQ}_t \tag{8}$$

$$\text{STL}_t \equiv \text{SUP}_t \times \text{TLR}_t \ . \tag{9}$$

In general, we expect the on/off-the-run spread to correlate positively with commercial paper rate and negatively with the supply of the on-the-run Treasury securities.

Using implied volatility of Y2K options, we can assess the effects of Y2K options on on/off-the-run spread. Given the close link between repo markets and Treasury bond markets, high liquidity premia in options on repo should be associated with high liquidity premia in the Treasury bond markets. The change of Y2K premium in the options over the seven auctions offers insight into the change in the liquidity premium related to the liquidity shortage around Y2K. The implied volatilities of Y2K options show how unusual the market expected the liquidity shortage to be around Y2K. We therefore hypothesize that if the implied volatility of the December 30 strip drops relative to the December 23 strip, the liquidity premium in Treasury bond markets should also drop, ceteris paribus.

We introduce a variable RIV to capture the changes of the year-end and Y2K premium in the price of Y2K options. On date $t$, let $\text{RIV}_t$ be the ratio of the implied volatility of the December 30 strip to the implied volatility of the December 23 strip if $t$ is one of the seven auction dates for Y2K options. For a date $t$ between two auctions of Y2K options, $\text{RIV}_t$ is the linear interpolation of the volatility ratios in the two auctions. If date $t$ is before all auctions of Y2K options, $\text{RIV}_t$ equals the volatility ratio in the first auction. After all auctions of Y2K options, the variable $\text{RIV}_t$ is set to the volatility ratio in the last auction. Obviously, the variable $\text{RIV}_t$ is step-wise linear in time. Although this does not fully capture the day-to-day variation in the Y2K premium (or year-end premium), it provides an approximation of the changes. The approximation is admittedly imprecise but it can still be informative, especially if it is significantly correlated with the on/off-the-run spread after controlling for other factors.

We extend the basic model to include the variable $\text{RIV}_t$ and refer to the extended model as *RIV model*. The model is expressed as

$$\begin{aligned} S_t = \ & \beta_0 + \beta_{\text{TLR}}\text{TLR}_t + \beta_{\text{TSQ}}\text{TSQ}_t + \beta_{\text{CPB}}\text{CPB}_t + \beta_{\text{CTL}}\text{CTL}_t \\ & + \beta_{\text{CTQ}}\text{CTQ}_t + \beta_{\text{SUP}}\text{SUP}_t + \beta_{\text{STL}}\text{STL}_t + \beta_{\text{RIV}}\text{RIV}_t + \epsilon_t \ . \end{aligned} \tag{10}$$

If on/off-the-run spread is affected by Y2K and the issuance of Y2K options, the coefficient

$\beta_{\text{RIV}}$ should be positive because a high Y2K premium in the prices of Y2K options should be associated with a high liquidity premium in the Treasury bond markets.

We can also use the aggressiveness of demand to assess the effects of Y2K options on the on/off-the-run spread. Given the close link between repo markets and Treasury bond markets, high demand for protection of shocks in repo rate should be associated with high liquidity premium in the Treasury bond markets. As we have discussed in Section 3.3, if the Fed successfully satisfied the demand for protections against liquidity shocks, the issuance of Y2K options should have affected the demand of Y2K options in the next auction besides pushing down the price of Y2K options in a current auction. If the Fed's injection of liquidity improved the market conditions and reduced the borrowing cost for dealers, the reduction of demand for Y2K options should have been associated with a decrease in the liquidity premium in Treasury bond markets. If this is true, on/off-the-run spread should have dropped when the aggressiveness of the demand for December 30 strip of Y2K options dropped relative to the December 23 strip.

To capture the changes of the demand for Y2K options, we introduce a variable AGR. On date $t$, let $\text{AGR}_t$ be the ratio of the aggressiveness for the December 30 trip to the aggressiveness for the December 23 strip if $t$ is one of the seven auction dates for Y2K options. For a date $t$ between two auctions of Y2K options, $\text{AGR}_t$ is the linear interpolation of the aggressiveness ratios in the two auctions. If date $t$ is before all auctions of Y2K options, $\text{AGR}_t$ equals the aggressiveness ratio in the first auction. After all auctions of Y2K options, the variable $\text{AGR}_t$ is set to the aggressiveness ratio in the last auction. Like RIV, the variable $\text{AGR}_t$ is step-wise linear in time and thus does not fully capture the day-to-day variation in the year-end and Y2K premium, but it provides a useful approximation of the changes.

To test the effects of changes in demand functions, we extend the basic model for the on/off-the-run spread by including $\text{AGR}_t$. The extended model is referred to as *AGR model*. The model is expressed as

$$\begin{aligned} S_t &= \beta_0 + \beta_{\text{TLR}}\text{TLR}_t + \beta_{\text{TSQ}}\text{TSQ}_t + \beta_{\text{CPB}}\text{CPB}_t + \beta_{\text{CTL}}\text{CTL}_t \\ &\quad + \beta_{\text{CTQ}}\text{CTQ}_t + \beta_{\text{SUP}}\text{SUP}_t + \beta_{\text{STL}}\text{STL}_t + \beta_{\text{AGR}}\text{AGR}_t + \epsilon_t\,. \end{aligned} \tag{11}$$

If on/off-the-run spread is affected by the Fed's injection of liquidity, the coefficient $\beta_{\text{AGR}}$ should be positive because a high demand for liquidity protection should be associated with a high liquidity premium in the Treasury bond markets.

## 4.3 Empirical Results for the Effects of Y2K Options

For the models of the on/off-the-run spread, we report the empirical estimates in Tables 5 and 6. The $t$-statistics and $p$-values in the table are adjusted for heteroscedasticity and serial correlation as formulated by White (1980) and Newey and West (1987). The lag in Newey-West adjustment is 10, representing two weeks of business days. We in fact experimented with lags ranging from 0 to 30 and found the results are qualitatively the same. Both variables RIV and AGR have estimation errors. For simplicity, we assume that the measurement errors are uncorrelated to the errors in our regression specifications. To estimate the specifications, we use data on Treasury notes auctions and data on commercial paper rates and obtain them from the Board of Governors of the Federal Reserve.

The basic model provides a partial, but not satisfactory, description for the behavior of the on/off-the-run spread around Y2K. Panel A of Table 5 (or Table 6) presents the estimates of the basic model based on the daily samples during January 4, 1999 – January 31, 2000, a period displayed in Figure 8 and discussed in Section 4.1. The auction cycle and commercial paper rate (i.e., the coefficients $\beta_{\mathrm{TLR}}$, $\beta_{\mathrm{TSQ}}$, $\beta_{\mathrm{CPB}}$, $\beta_{\mathrm{CTL}}$, and $\beta_{\mathrm{CTQ}}$) are significant. This is consistent with the results reported by Krishnamurthy (2002). However, none of the coefficients related to the supply of Treasury notes (i.e., $\beta_{\mathrm{SUP}}$ and $\beta_{\mathrm{STL}}$) are significant. This is inconsistent with the common intuition that the on/off-the-run spread should be negatively correlated with the supply. The irrelevance of the supply of Treasury notes indicates that the behavior of the on/off-the-run spread in 1999 is unusual. The adjusted R-squared of the basic model is rather small, only 36.63%, showing low explanatory power of the model.

When we include RIV or AGR into the model, its explanatory power improved drastically. The adjusted R-squared of RIV model is 65.75%, and the adjusted R-squared of AGR model is 70.47% (see estimates for the RIV model in panel A of Table 5 and for AGR model in panel A of Table 6). The effect of supply becomes significant. The coefficient $\beta_{\mathrm{STL}}$ is significant. The negative sign of $\beta_{\mathrm{STL}}$ (in conjunction with the insignificance of $\beta_{\mathrm{SUP}}$) is consistent with the intuition that the supply of Treasury notes should negatively affect the on-off-the-run spreads of the Treasury notes.

The empirical results show that Y2K options affected the liquidity premium in the Treasury markets. The estimate of coefficient $\beta_{\mathrm{RIV}}$ in the RIV model is positive and significantly different from zero, as shown in panel A of Table 5. A high implied volatility of the December 30 strip is associated with a high on/off-the-run spread. The positive coefficient of RIV implies that the on/off-the-run spread declined as the Y2K premium in Y2K options dropped. Since the implied volatility of the December 23 strip stayed almost constant, the drop of RIV was mainly related to the drop of the implied volatility of the December 30 strip.

Similarly, the estimate of coefficient $\beta_{\text{AGR}}$ in the AGR model is also positive and significant, as shown in panel A of Table 6. Since Fed's injection of liquidity caused the drop of demand for December 30 strip, the positive coefficient of AGR implies that the Fed's injection caused the on/off-the-run spread to shrink.

The effects of Y2K options are robust to the Treasury bonds we choose for the tests. As noted earlier, the above results are based on the average on/off-the-run spread of five-year and 10-year notes. We repeat the analysis with the data on five-year notes and 10-year notes separately. The results are qualitatively the same. In panel B of Table 5, we report estimates of the RIV model. The coefficient of RIV is 1.87 with a $t$-statistic 4.47 when estimated from the data on five-year notes. This coefficient is 8.18 with a $t$-statistic 9.09 when estimated from the data on 10-year notes. In panel B of Table 6, we report the estimates of the AGR model. The coefficient of AGR is positive and significant regardless whether five-year note data or 10-year note data are used for estimation, indicating robust effects of Y2K options on risk premium in Treasury markets.

The effects of Y2K options are also robust when we extend the sample period around Y2K. The focus on data in 1999 may cause some concern because the on/off-the-run spread climbed sharply after the Russian default on August 17, 1998. It is well known that the rise of on/off-the-run spread was one of the major reasons for the collapse of Long Term Capital Management (LTCM), a hedge fund in Connecticut. After the collapse of LTCM in the fall of 1998, the on/off-the-run spread started dropping. The drop of the on/off-the-run spread from the crisis of Russian default might have coincided with the drop of on/off-the-run spread in 1999. To address this concern, we extend our data back to August 17, 1998. This is the earliest date on which our data is available because the five-year and 10-year notes had different auction cycle before this date.[17] To check the robustness of our results, we also extend the data forward to the end of 2000. The results are reported in panel C of Tables 5 and 6. The coefficients of RIV and AGR remain to be positive and significant.

# 5 A Broad View of Central Bank Actions

## 5.1 State-Contingent Provision of Liquidity

The special role played by government debt in providing liquidity to the private sector has been emphasized in a number of papers. Clearly, papers by Diamond (1965) and Woodford

[17] On the same date, the Treasury conducted an auction of five-year notes and switched the auction cycle from monthly to quarterly so that the five-year and 10-year notes have the same auction cycle. Since then, the five-year notes are typically auctioned one day before the auction of 10-year notes.

(1990) fall in this category. Other papers, such as Holmstrom and Tirole (1998) stress the role of government bonds in alleviating agency, moral hazard and informational problems. These models may not be directly applicable to the Y2K event, in which the actions of the Fed were primarily directed to money markets.

State-contingent provision of liquidity is theorized by Holmstrom and Tirole (1996), who provide a framework for understanding the optimality of options contracts issued by government. Although their model is stylized and it does not exactly correspond to the circumstances of the Y2K problem, a key insight that can be gleaned is clear: if the potential liquidity shortage is aggregate and the date or period of the shortage is known ahead of time, it is desirable for the central bank to provide state-contingent liquidity. We suspect that this insight is robust with respect to the potential liquidity shock around Y2K. From this viewpoint, Y2K options and their effects on liquidity premium conform to the economic theory.

The Y2K options sold by the Fed constitute a clear example of state-contingent liquidity provision: these options were out of the money by 150 basis points from the Fed funds target rate. Experience during 1991-2000 indicates that none of the year-end spikes in repo rates deviated by more than 150 basis points from the Fed funds target rate. In fact, the maximum historical deviation was 146 basis points. Thus, the sale of Y2K options at a strike of 150 basis points above the Fed funds target rate is a classic case of state contingent provision of liquidity that was targeted to potential spikes in funding costs that go beyond the usual year-end effects in the decade covering 1991-2000. The implied volatilities of these options then allowed us to examine the ex-ante beliefs of the dealers about funding costs in the period surrounding Y2K date change.

## 5.2 Other Central Bank Actions Prior to Y2K

Besides Y2K options, several other policy initiatives were activated by the U.S. central bank to meet the potential aggregate liquidity shock in the second half of 1999.[18] The central bank extended the maximum maturity of repo operations to 90 days. The purpose of this modification was to meet the year-end seasonal demands and any unusual demands for liquidity beginning as early as October 1999. In addition, this change in maximum maturity allowed the dealers to fund their inventories through the period of Y2K.

The U.S. central bank also expanded the menu of collateral in repo transactions to include

[18] Descriptions of the actions taken by the Federal Reserve in U.S. in this section are largely drawn from "Money Market and the Millennium Date Change," by Peter Fisher, December 1, 1999, the Federal Reserve Bank of New York.

mortgage-backed securities. This change was motivated by the central bank's desire to expand the pool of assets in its balance sheet. The rationale was to ensure that the potential demanders of liquidity from the central bank are able to deliver securities as collateral in the period of crisis. Restricting the pool of assets that are eligible for collateral in repo transactions would have meant that the central bank might have been unable to add its desired level of reserves to some market segments because players in these segments might have been unable to post collateral. This expansion also reduces the incremental demand on government securities that would putatively trade at a significant liquidity premium during periods of liquidity shortage. These government securities will remain in the market playing a critical role in alleviating the liquidity shortage.

To increase liquidity, the U.S. central bank shifted the normal settlement and custody arrangements for repo transactions to tri-party custodians. The most important aspect of this policy was the fact that the bond dealers and other intermediaries were given greater flexibility to substitute collateral in their repo transactions. This flexibility can be valuable when there is aggregate uncertainty.

One important policy change was that the central bank placed itself as the counterparty. This eliminated counterparty default risk from the perspective of the dealers and banks. In a period of liquidity shortage, default risk is clearly an important consideration for banks and dealers. In the special measures for Y2K, the U.S. central bank was acting as counterparty to the repo transactions as well as to the options transactions.

Central banks in other countries also took special measures during the Y2K period. For example, the Bank of Canada issued Y2K options that were free of charge to Canadian depository institutions in a manner similar to the SLF provided by the U.S. central bank[19]. The Bank of Canada also expanded the range of collateral as the U.S. central bank did. As another example, the Bank of England issued special Treasury bills that matured on December 31, 1999. The Bank of England also expanded the maturity date of repo contract to 90 days and the range of collateral.[20] To our knowledge, however, only the U.S. central bank *sold* options on liquidity in private markets.

# 6 Concluding Remarks

It should be stressed that the effect of Y2K options was mostly on the liquidity premium in the Treasury bond market, but not in broader markets, because Y2K options only injected

[19]Source: Bank of Canada Press Release, September 2, 1999

[20]Source: The Bank of England Quarterly Bulletin, August and November 1999 issues.

liquidity into the primary dealers market. The goal of the Fed was to ensure that banks and dealers in the financial markets would not withdraw from the markets around Y2K. The goal was not necessarily to reduce the cost of access to unsecured credit markets by private sector entities. Indeed, during Y2K we saw an increase in the cost of borrowing for banks because Y2K options did not provide liquidity to the players in unsecured credit markets such as LIBOR.

We have not explored the costs of instituting a program of this nature from the perspective of the Central Bank, which is the liquidity provider. Drossos and Hilton (2000) discuss the cost-benefit aspect of Y2K options and observe the following: "Moreover, it seemed clear that any potential costs of the Desk's actions fall far short of the costs that could be expected to arise from a breakdown in established financing patterns." The importance of formally analyzing the costs and benefits of state contingent liquidity provision is worthy of further research.

Our research focus on liquidity premia in the Treasury markets and Y2K options can be broadened to studies on many related issues. For example, during a liquidity crisis, an important task for the central bank is to reduce the counterparty credit risk. In fact, when the central bank issues Y2K options and expands repo maturity and collateral, the central bank acts as the counterparty to relieve the credit risk. Therefore, it would be interesting to examine margin borrowing, trade credit, and actions by the central bank during a liquidity shock. Such an examination could be a part of future research in this area. In addition, one could explore other foreseeable potential aggregate liquidity events. One such event might be the introduction of Euro currency. Moreover, one could examine year-ends and long holidays for the presence of liquidity premia and the related actions taken by the central bank.

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# B Tables

Table 1: Basic Characteristics of the Auctions of Y2K Options

The total amount of bids and the accepted amounts are reported in billions of dollars. The stop-out rates are quoted in basis points. The ratio of accepted to total is the total amount of bids divided by the accepted amounts.

| | Auctions | | | | | | |
|---|---|---|---|---|---|---|---|
| | Oct 20 | Oct 27 | Nov 03 | Nov 10 | Nov 17 | Nov 23 | Dec 01 |
| | December 30 Strip | | | | | | |
| Total amount of bids | 115.65 | 146.90 | 135.75 | 85.75 | 82.95 | 51.10 | 52.95 |
| Accepted amount | 18.05 | 25.00 | 50.00 | 49.95 | 30.00 | 25.00 | 24.95 |
| Ratio of accepted to total | 0.16 | 0.17 | 0.37 | 0.58 | 0.36 | 0.49 | 0.47 |
| Stop-out rate (basis point) | 10.00 | 15.00 | 16.00 | 8.00 | 8.00 | 4.00 | 2.00 |
| | January 6 Strip | | | | | | |
| Total amount of bids | 66.50 | 86.00 | 107.50 | 65.85 | 64.00 | 36.05 | 43.70 |
| Accepted amount | 12.00 | 12.00 | 25.00 | 40.00 | 20.00 | 20.00 | 15.00 |
| Ratio of accepted to total | 0.18 | 0.14 | 0.23 | 0.61 | 0.31 | 0.55 | 0.34 |
| Stop-out rate (basis point) | 3.00 | 5.00 | 11.50 | 2.50 | 2.50 | 2.50 | 4.00 |
| | December 23 Strip | | | | | | |
| Total amount of bids | 47.75 | 55.90 | 77.35 | 44.00 | 49.25 | 27.45 | 20.20 |
| Accepted amount | 11.95 | 12.00 | 20.00 | 30.00 | 14.90 | 10.00 | 15.00 |
| Ratio of accepted to total | 0.25 | 0.21 | 0.26 | 0.68 | 0.30 | 0.36 | 0.74 |
| Stop-out rate (basis point) | 1.50 | 2.50 | 11.00 | 1.00 | 1.00 | 1.50 | 0.50 |

Table 2: Statistics of the Repo Rates

The general collateral rates (repo rates) for over-night loans are reported in percentage points. The repo-target spread is the difference between the repo rate and the prevailing Fed funds target rate and reported in basis points. The sample covers the period from May 21, 1991 to October 19, 1999 and its simple statistics are reported in panel A. The maximum likelihood estimates of the parameters in equation (1) are reported in panel B. The sample of repo-target spreads is split into two sub-samples — the within-quarter sample and the quarter-end sample. The quarter-end sample consists of the observations on quarter-end date and two business days around it. The rest of the observations belong to the within-quarter sample. Panel C presents the statistics of the sub-samples, including the mean and standard deviation implied by the maximum likelihood estimates in panel B.

A. Simple Statistics of Repo and Repo-Target Spread

| | Repo rate | Repo-Target Spread |
|---|---|---|
| Number of observations | 2,102 | 2,102 |
| Maximum | 6.10 | 145 |
| Minimum | 2.70 | -85 |
| Mean | 4.72 | -0.25 |
| Standard deviation | 0.99 | 17.82 |
| t-statistics | 218.12 | -0.65 |

B. Maximum Likelihood Estimates of Parameters

| Parameter | *a* | *b* | *c* | *d* |
|---|---|---|---|---|
| Estimate | -1.61 | 16.80 | 1.42 | 5.47 |
| Standard error | 0.36 | 2.95 | 0.09 | 0.01 |
| z-value | -4.42 | 5.70 | 16.47 | 382.77 |
| p-value | 0.00 | 0.00 | 0.00 | 0.00 |

C. Statistics of the Sub-Samples of Repo-Target Spreads

| | Within-quarter Sample | Quarter-end Sample |
|---|---|---|
| Number of observations | 1,932 | 170 |
| Maximum | 130 | 145 |
| Minimum | -85 | -80 |
| Mean | -1.61 | 15.18 |
| Standard deviation | 15.38 | 31.27 |
| Ratio of quarter-end stdev to within-quarter stdev | 2.03 | |

Table 3: Implied Volatilities of Y2K Options

Based on the stop-out rates of Y2K options, implied volatilities are calculated from Black's formula of interest rate caps. The volatilities are reported in percentage points. A volatility ratio is the implied volatilities of a strip divided by the implied volatility of December 23 strip.

| | Auctions | | | | | | |
|---|---|---|---|---|---|---|---|
| | Oct 20 | Oct 27 | Nov 03 | Nov 10 | Nov 17 | Nov 23 | Dec 01 |
| | Implied Volatilities | | | | | | |
| Dec 30 Strip | 55.19 | 62.57 | 67.31 | 57.39 | 59.54 | 53.27 | 48.37 |
| Jan 6 Strip | 22.60 | 24.11 | 28.93 | 25.06 | 23.66 | 25.35 | 30.10 |
| Dec 23 Strip | 22.20 | 23.91 | 30.78 | 24.89 | 23.56 | 26.50 | 28.50 |
| | Volatility Ratios | | | | | | |
| Dec 30 / Dec 23 | 2.49 | 2.62 | 2.19 | 2.31 | 2.53 | 2.01 | 1.70 |
| Jan 6 / Dec 23 | 1.02 | 1.01 | 0.94 | 1.01 | 1.00 | 0.96 | 1.06 |

Table 4: Aggressiveness of Demand for Y2K Options

A demand function is estimated by a regression of log quantity on log stop-out rate. The elasticity of demand is the slope coefficient in the regression. The aggressiveness of demand is the value of $e$ to the power of the intercept. An aggressiveness ratio is the aggressiveness for a strip divided by the aggressiveness for December 23 strip.

| | Auctions | | | | | | |
|---|---|---|---|---|---|---|---|
| | Oct 20 | Oct 27 | Nov 03 | Nov 10 | Nov 17 | Nov 23 | Dec 01 |
| December 30 Strip | | | | | | | |
| Elasticity of demand | 1.10 | 0.92 | 0.73 | 0.90 | 0.53 | 0.71 | 1.14 |
| Intercept in regression | 5.31 | 5.85 | 5.82 | 5.50 | 4.43 | 4.11 | 4.03 |
| Aggressiveness | 202.73 | 346.48 | 337.67 | 245.90 | 83.57 | 61.10 | 56.09 |
| January 6 Strip | | | | | | | |
| Elasticity of demand | 1.71 | 0.92 | 0.69 | 0.40 | 0.40 | 0.63 | 0.65 |
| Intercept in regression | 3.90 | 4.26 | 4.84 | 4.41 | 3.64 | 3.42 | 3.71 |
| Aggressiveness | 49.44 | 71.01 | 126.15 | 82.53 | 38.07 | 30.58 | 40.97 |
| December 23 Strip | | | | | | | |
| Elasticity of demand | 1.32 | 0.93 | 0.57 | 0.60 | 1.15 | 0.53 | 1.33 |
| Intercept in regression | 3.00 | 3.27 | 4.01 | 3.44 | 3.16 | 2.79 | 2.53 |
| Aggressiveness | 19.99 | 26.27 | 55.26 | 31.22 | 23.57 | 16.23 | 12.57 |
| Aggressiveness Ratios | | | | | | | |
| Dec 30 strip / Dec 23 strip | 10.14 | 13.19 | 6.11 | 7.88 | 3.55 | 3.76 | 4.46 |
| Jan 6 strip / Dec 23 strip | 2.47 | 2.70 | 2.28 | 2.64 | 1.62 | 1.88 | 3.26 |

Table 5: Effects of the Volatility Implied by Y2K Options

The basic model and the RIV model are estimated using on/off-the-run spreads over various periods that span around Y2K. The average spreads on five-year and 10-year Treasury notes are used for the estimates in panels A and C, while the spread on five-year notes and the spread on 10-year notes are used separately for the estimates in panel B. The standard errors, as well as the $t$-statistics and $p$-values, are adjusted for heteroscedasticity and serial correlation.

A. Using Samples during Jan 4, 1999 – Jan 31, 2000

| | Basic Model | | | | RIV Model | | | |
|---|---|---|---|---|---|---|---|---|
| | R-sqr: | 38.28% | Adj-R: | 36.63% | R-sqr: | 66.76% | Adj-R: | 65.75% |
| Variables | coeff | stderr | t-stat | p-val | coeff | stderr | t-stat | p-val |
| Const | -7.80 | 6.80 | -1.15 | 0.25 | -14.76 | 7.22 | -2.04 | 0.04 |
| TLR | 55.14 | 14.23 | 3.87 | 0.00 | 54.01 | 12.01 | 4.50 | 0.00 |
| TSQ | -30.77 | 7.97 | -3.86 | 0.00 | -28.28 | 6.04 | -4.68 | 0.00 |
| CPB | 25.20 | 4.37 | 5.76 | 0.00 | 13.58 | 4.42 | 3.07 | 0.00 |
| CTL | -81.49 | 14.73 | -5.53 | 0.00 | -50.25 | 15.63 | -3.22 | 0.00 |
| CTQ | 56.33 | 14.39 | 3.91 | 0.00 | 42.73 | 14.02 | 3.05 | 0.00 |
| SUP | 0.21 | 0.43 | 0.48 | 0.63 | 0.19 | 0.49 | 0.39 | 0.70 |
| STL | -1.00 | 0.75 | -1.33 | 0.18 | -1.50 | 0.76 | -1.97 | 0.05 |
| RIV | | | | | 4.71 | 0.58 | 8.12 | 0.00 |

B. Using Samples of Separate Spreads

| | Five-Year On/off-the-un Spread | | | | 10-Year On/off-the-run Spread | | | |
|---|---|---|---|---|---|---|---|---|
| | R-sqr: | 51.89% | Adj-R: | 50.42% | R-sqr: | 66.62% | Adj-R: | 65.60% |
| Variables | coeff | stderr | t-stat | p-val | coeff | stderr | t-stat | p-val |
| Const | -8.56 | 3.64 | -2.35 | 0.02 | -14.59 | 5.89 | -2.48 | 0.01 |
| TLR | 37.59 | 6.79 | 5.54 | 0.00 | 44.52 | 12.73 | 3.50 | 0.00 |
| TSQ | -28.63 | 4.69 | -6.11 | 0.00 | -31.03 | 9.80 | -3.17 | 0.00 |
| CPB | 12.42 | 4.41 | 2.82 | 0.01 | 15.48 | 4.46 | 3.47 | 0.00 |
| CTL | -46.89 | 14.14 | -3.32 | 0.00 | -59.42 | 18.12 | -3.28 | 0.00 |
| CTQ | 43.85 | 11.67 | 3.76 | 0.00 | 50.21 | 20.22 | 2.48 | 0.01 |
| SUP | 0.19 | 0.31 | 0.62 | 0.53 | -0.35 | 0.42 | -0.82 | 0.41 |
| STL | -0.67 | 0.43 | -1.55 | 0.12 | -0.80 | 0.71 | -1.13 | 0.26 |
| RIV | 1.87 | 0.42 | 4.47 | 0.00 | 8.18 | 0.90 | 9.09 | 0.00 |

C. Using Samples during Extented Periods

| | Aug 17, 1998 - Jan 31, 2000 | | | | Aug 17, 1998 - Dec 29, 2000 | | | |
|---|---|---|---|---|---|---|---|---|
| | R-sqr: | 47.82% | Adj-R: | 46.64% | R-sqr: | 47.52% | Adj-R: | 46.80% |
| Variables | coeff | stderr | t-stat | p-val | coeff | stderr | t-stat | p-val |
| Const | -15.56 | 7.78 | -2.00 | 0.05 | 7.29 | 3.50 | 2.08 | 0.04 |
| TLR | 51.99 | 12.95 | 4.01 | 0.00 | 34.44 | 7.67 | 4.49 | 0.00 |
| TSQ | -21.74 | 7.33 | -2.97 | 0.00 | -18.86 | 5.30 | -3.56 | 0.00 |
| CPB | 1.04 | 3.78 | 0.28 | 0.78 | 2.54 | 3.54 | 0.72 | 0.47 |
| CTL | -15.98 | 15.85 | -1.01 | 0.31 | -17.18 | 13.30 | -1.29 | 0.20 |
| CTQ | 18.72 | 14.57 | 1.28 | 0.20 | 18.24 | 11.46 | 1.59 | 0.11 |
| SUP | 0.46 | 0.52 | 0.87 | 0.38 | -0.76 | 0.27 | -2.82 | 0.00 |
| STL | -2.02 | 0.85 | -2.38 | 0.02 | -1.07 | 0.35 | -3.06 | 0.00 |
| RIV | 4.98 | 0.66 | 7.59 | 0.00 | 3.55 | 0.86 | 4.15 | 0.00 |

Table 6: Effects of the Aggressiveness of Demand for Y2K Options

The basic model and the AGR model are estimated using on/off-the-run spreads over various periods that span around Y2K. The average spreads on five-year and 10-year Treasury notes are used for the estimates in panels A and C, while the spread on five-year notes and the spread on 10-year notes are used separately for the estimates in panel B. The standard errors, as well as the $t$-statistics and $p$-values, are adjusted for heteroscedasticity and serial correlation.

A. Using Samples during Jan 4, 1999 – Jan 31, 2000

| | Basic Model | | | | AGR Model | | | |
|---|---|---|---|---|---|---|---|---|
| | R-sqr: | 38.28% | Adj-R: | 36.63% | R-sqr: | 71.35% | Adj-R: | 70.47% |
| Variables | coeff | stderr | t-stat | p-val | coeff | stderr | t-stat | p-val |
| Const | -7.80 | 6.80 | -1.15 | 0.25 | -10.89 | 6.70 | -1.63 | 0.11 |
| TLR | 55.14 | 14.23 | 3.87 | 0.00 | 53.52 | 10.28 | 5.21 | 0.00 |
| TSQ | -30.77 | 7.97 | -3.86 | 0.00 | -21.31 | 4.32 | -4.93 | 0.00 |
| CPB | 25.20 | 4.37 | 5.76 | 0.00 | 12.01 | 4.57 | 2.63 | 0.01 |
| CTL | -81.49 | 14.73 | -5.53 | 0.00 | -40.34 | 14.97 | -2.69 | 0.01 |
| CTQ | 56.33 | 14.39 | 3.91 | 0.00 | 30.85 | 12.35 | 2.50 | 0.01 |
| SUP | 0.21 | 0.43 | 0.48 | 0.63 | 0.34 | 0.46 | 0.75 | 0.45 |
| STL | -1.00 | 0.75 | -1.33 | 0.18 | -1.83 | 0.71 | -2.59 | 0.01 |
| AGR | | | | | 0.61 | 0.07 | 8.60 | 0.00 |

B. Using Samples of Separate Spreads

| | Five-Year On/off-the-un Spread | | | | 10-Year On/off-the-run Spread | | | |
|---|---|---|---|---|---|---|---|---|
| | R-sqr: | 50.51% | Adj-R: | 49.00% | R-sqr: | 76.18% | Adj-R: | 75.45% |
| Variables | coeff | stderr | t-stat | p-val | coeff | stderr | t-stat | p-val |
| Const | -6.62 | 3.53 | -1.87 | 0.06 | -6.45 | 5.81 | -1.11 | 0.27 |
| TLR | 37.26 | 6.74 | 5.53 | 0.00 | 40.38 | 11.07 | 3.65 | 0.00 |
| TSQ | -26.62 | 5.01 | -5.32 | 0.00 | -18.94 | 5.63 | -3.36 | 0.00 |
| CPB | 12.76 | 4.55 | 2.80 | 0.01 | 12.23 | 4.93 | 2.48 | 0.01 |
| CTL | -46.04 | 14.56 | -3.16 | 0.00 | -41.13 | 16.11 | -2.55 | 0.01 |
| CTQ | 41.12 | 12.21 | 3.37 | 0.00 | 29.67 | 14.80 | 2.01 | 0.05 |
| SUP | 0.24 | 0.30 | 0.81 | 0.42 | -0.15 | 0.41 | -0.37 | 0.71 |
| STL | -0.73 | 0.44 | -1.65 | 0.10 | -1.27 | 0.61 | -2.09 | 0.04 |
| AGR | 0.20 | 0.06 | 3.50 | 0.00 | 1.10 | 0.11 | 10.10 | 0.00 |

C. Using Samples during Extented Periods

| | Aug 17, 1998 - Jan 31, 2000 | | | | Aug 17, 1998 - Dec 29, 2000 | | | |
|---|---|---|---|---|---|---|---|---|
| | R-sqr: | 51.26% | Adj-R: | 50.17% | R-sqr: | 50.49% | Adj-R: | 49.81% |
| Variables | coeff | stderr | t-stat | p-val | coeff | stderr | t-stat | p-val |
| Const | -11.67 | 7.26 | -1.61 | 0.11 | 11.82 | 3.84 | 3.07 | 0.00 |
| TLR | 52.99 | 12.09 | 4.38 | 0.00 | 31.42 | 7.14 | 4.40 | 0.00 |
| TSQ | -16.09 | 5.69 | -2.83 | 0.00 | -16.34 | 4.80 | -3.40 | 0.00 |
| CPB | -0.11 | 3.56 | -0.03 | 0.97 | 1.85 | 3.43 | 0.54 | 0.59 |
| CTL | -8.88 | 14.60 | -0.61 | 0.54 | -13.57 | 12.84 | -1.06 | 0.29 |
| CTQ | 10.36 | 13.05 | 0.79 | 0.43 | 14.30 | 10.93 | 1.31 | 0.19 |
| SUP | 0.62 | 0.48 | 1.29 | 0.20 | -0.78 | 0.26 | -3.06 | 0.00 |
| STL | -2.38 | 0.76 | -3.11 | 0.00 | -1.02 | 0.33 | -3.10 | 0.00 |
| AGR | 0.65 | 0.08 | 8.38 | 0.00 | 0.50 | 0.11 | 4.77 | 0.00 |

# C Figures

Figure 1: Term Spreads in Interbank Markets in 1999

Panels A, B, and C plot the term spreads among six-month, three-month, one-month and one-week LIBOR in 1999. Panels D, E, and F plot the term spread between six-month and three-month LIBOR in 1998, 1997, and 1996.

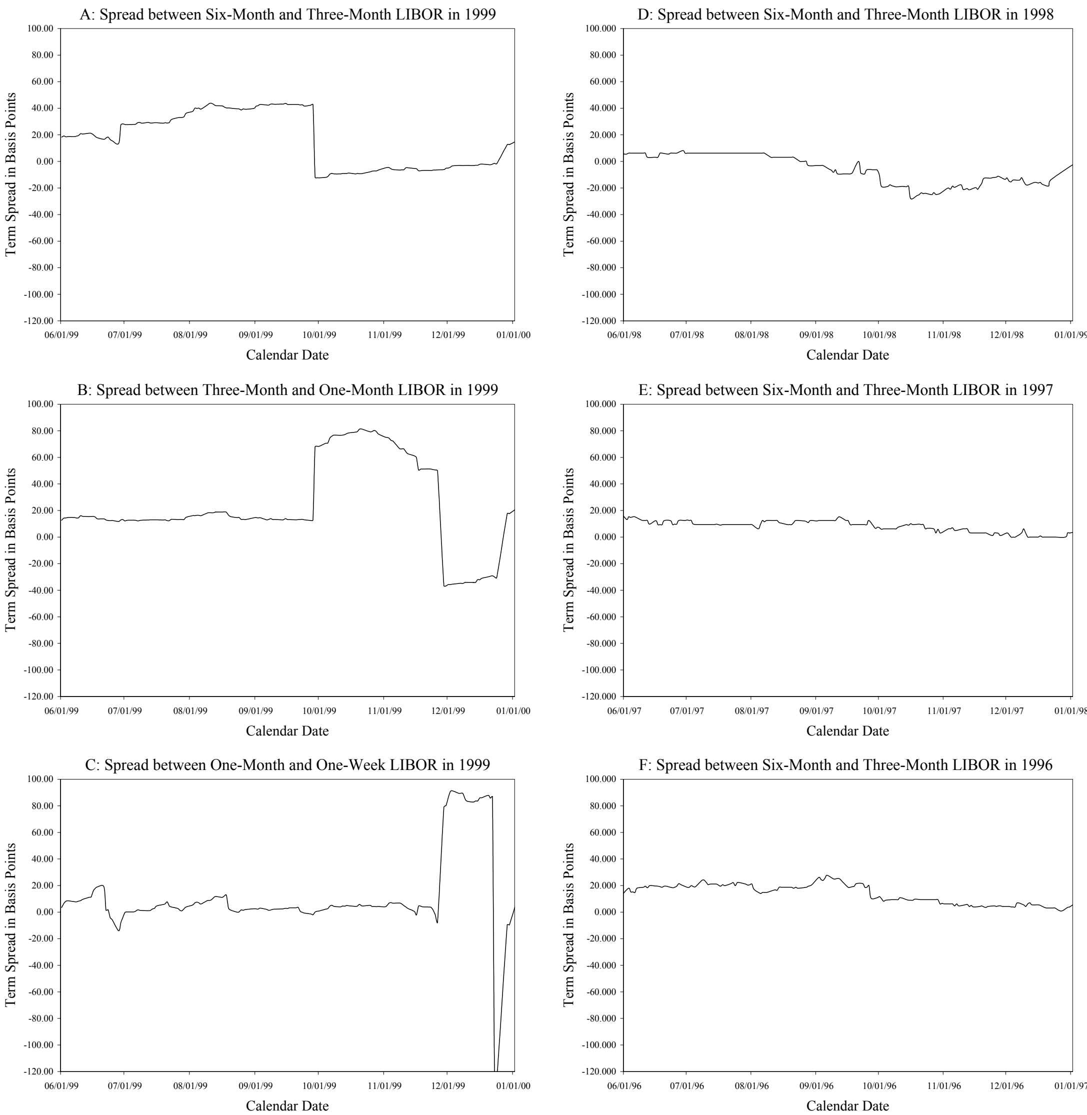

Figure 2: Behavior of Repo Rates

For the period from May 21, 1991 to Jan 31, 2000, the general collateral rates (repo rates) for over-night loans are plotted along with the Fed funds target rates raised by 150 basis points. A dotted vertical line indicates the first day of a quarter. A solid vertical line indicates the first day of a year.

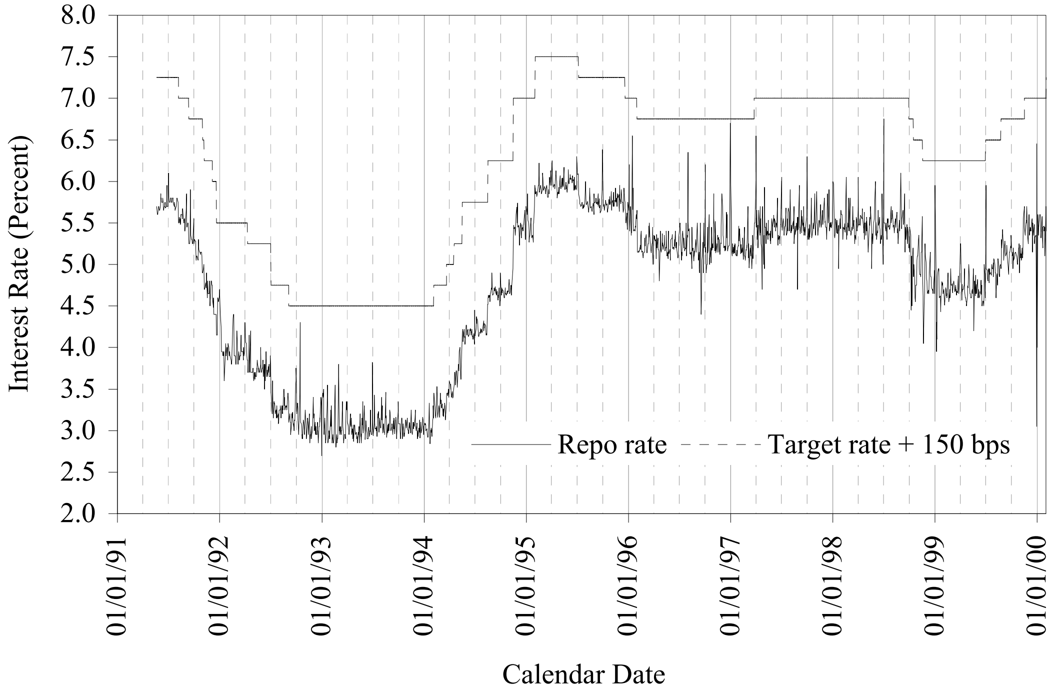

Figure 3: Spread between Repo Rates and Fed Funds Target Rates

For four months around Y2K, the spread between repo rates and Fed funds target rates are plotted along with its three-day moving average. A dotted vertical line indicates the first day of a quarter.

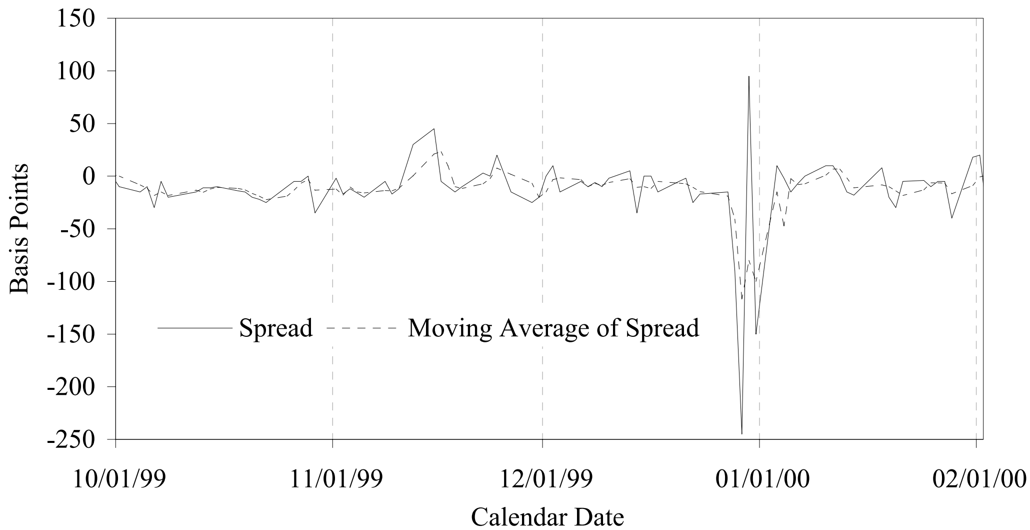

Figure 4: Repo Rates around Y2K Reported by the Fed

Reprint of Chart 21 in *Domestic Open Market Operations during 1999* by the Federal Reserve Bank of New York. The chart displays the average of morning levels of Treasury repo rates, mortgage-backed security repo rates, and Federal Funds rates around year-end.

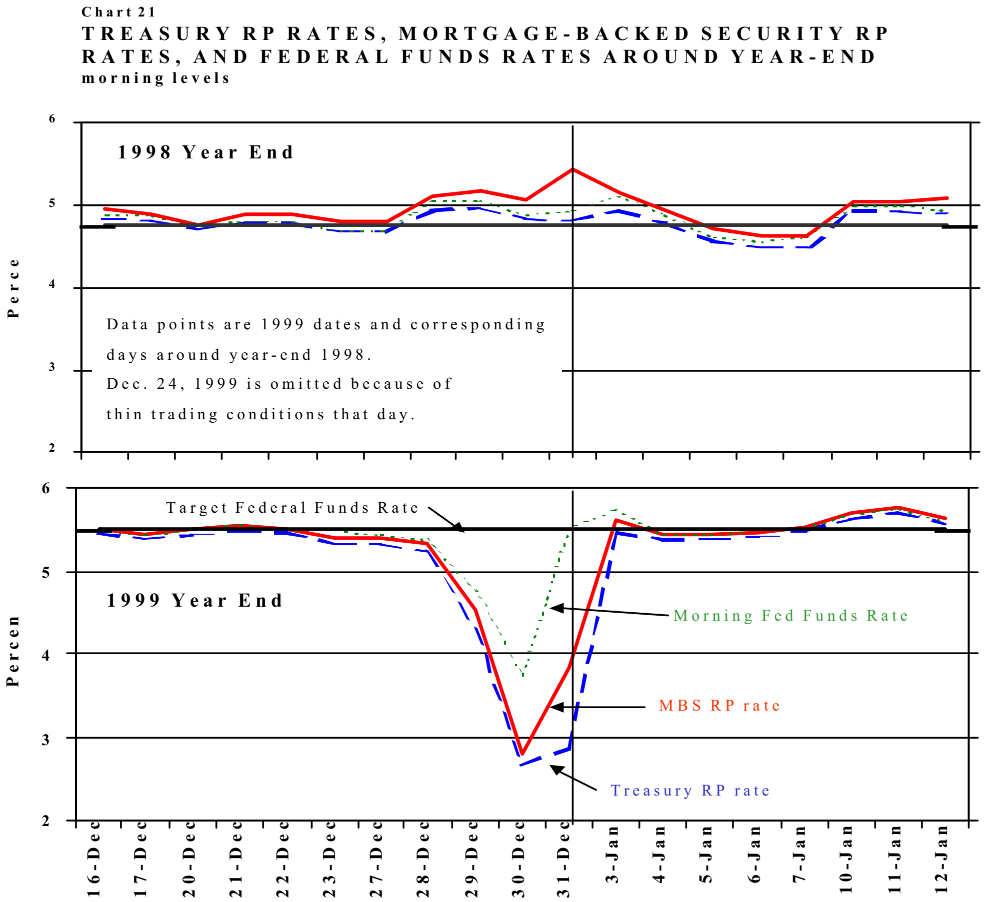

Figure 5: Implied Volatility of Y2K Options

Based on the stop-out rates of Y2K options, implied volatilities are calculated from Black's formula for interest rate caps. The implied volatility of each strip of Y2K options is plotted over the seven auction dates.

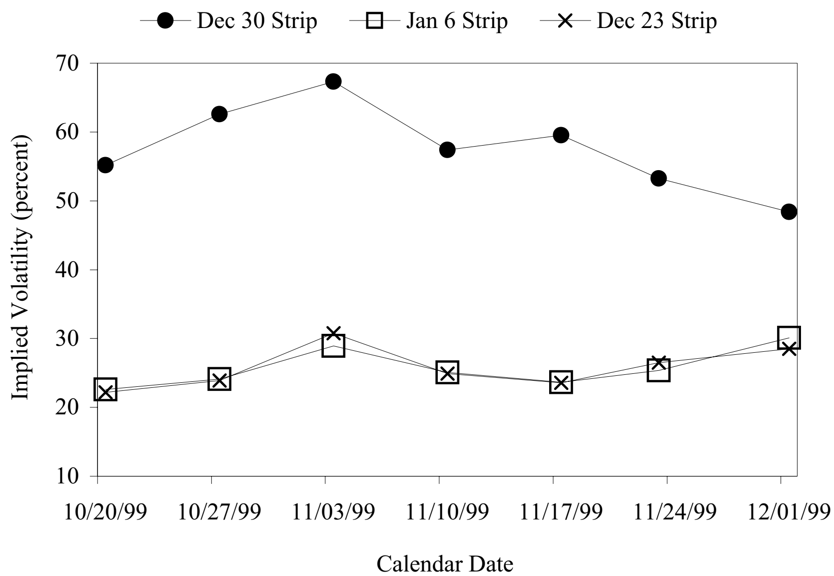

Figure 6: The Demand Curves in the Auctions of Y2K Options

Demand and supply in auctions of the December 30 strip of Y2K options. The accepted amount (supply) is indicated by the vertical line that meets the demand curve, and a horizontal line indicates the price (stop-out rate).

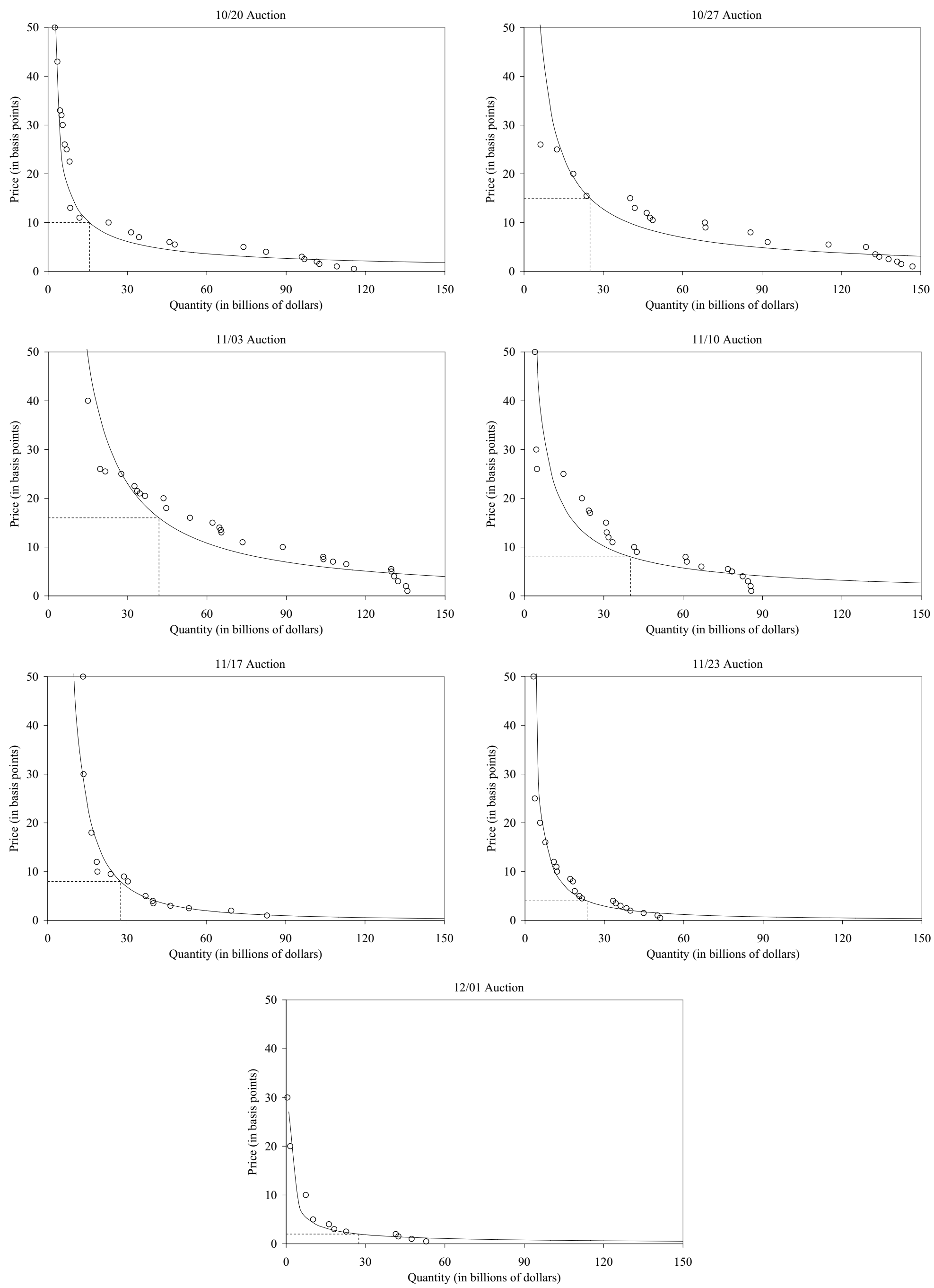

Figure 7: Aggressiveness of Demand for Y2K Options

A demand function is estimated by a regression of log quantity on log stop-out rate. The aggressiveness of a demand is the value of $e$ to the power of the intercept. The aggressiveness of demand for each strip of Y2K options is plotted over the seven auction dates.

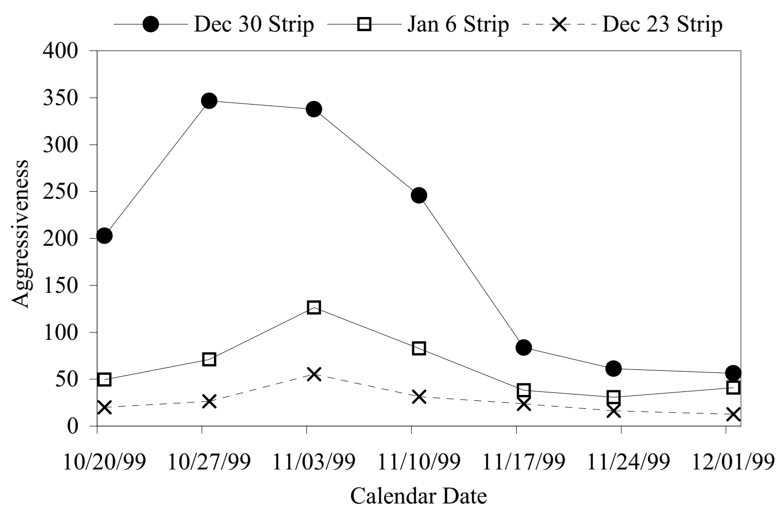

Figure 8: Behavior of the On/off-the-run Spread in 1999

The average spread of on/off-the-run spreads on five-year and 10-year Treasury notes from January 1, 1999 to January 31, 2000. The dotted vertical lines indicate the dates of the quarterly auctions of the five-year and 10-year Treasury notes. The solid vertical lines indicate the dates of the first and last auctions of Y2K auctions.