EFFICIENT MARKETS: THE SPACE SHUTTLE *CHALLENGER* STORY

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ABSTRACT

The theory of efficient markets states that capital markets instantly adjust to incorporate all relevant information. When new information arrives about a firm or an industry, efficient markets theory dictates that the price of the firm or industry in question move to incorporate this information. This theory provides a basis for studying the effects of news on firms. By performing what is called an event study, a researcher can assess how the market perceives some news on the company in question.

The study here focuses on the effect of the explosion on Tuesday, January 28, 1986, of the space shuttle *Challenger*. The null hypothesis that was disproved was that due to the explosion, firms involved in the shuttle program would expect to see a drop in returns on the day of the accident. This is what was seen, except for one company, Morton Thiokol, the manufacturer of the solid rocket booster. The cause of the accident was completely unknown until a few days later, but the market reacted on the day of the accident; Morton Thiokol's firm value dropped twelve percent. The reaction largely stemmed from knowledge that the joint design of the solid rocket boosters was faulty and nothing had been done about it.

The market expected substantially lower returns in the future for Morton Thiokol. Morton Thiokol dropped out of the bidding for NASA's next generation solid rocket boosters, some believe because of political pressure. The contract had to receive Congress's approval, but after the revelations about the faulty design of the solid rocket boosters joint, many felt it unlikely that Morton Thiokol would ever win the contract. Morton Thiokol also performed *pro bono* the design work on the new solid rocket boosters.

On the day of the accident and because of the faulty design of the solid rocket booster's joints, the market indicated that Morton Thiokol would face some future loss. The explosion caused information of the faulty joint to become widely held, and the market reacted to past information it held about substantial penalties paid by at-fault companies.

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DEDICATION

This thesis is dedicated to the seven astronauts who lost their lives in the explosion of the *Challenger* on Tuesday, January 28, 1986. They were Francis R. (Dick) Scobee, Commander; Michael John Smith, Pilot; Ellison S. Onizuka, Mission Specialist One; Judith Arlene Resnik, Mission Specialist Two; Ronald Erwin McNair, Mission Specialist Three; S. Christa McAuliffe, Payload Specialist One; and Gregory Bruce Jarvis, Payload Specialist Two.

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CHAPTER 1

INTRODUCTION

This thesis describes the Space Shuttle *Challenger* accident on Tuesday, January 28, 1986. The following discussion uses a financial markets analysis to show that the market implicated Morton Thiokol in spite of a number of false signals on the day of the accident. The markets were efficient in determining who was at fault and in ignoring the false signals.

Challenger exploded 73 seconds after lift-off, killing all seven crew members. On the day of the accident, an observer on the ground would likely have guessed that the accident had been caused by the external tank or the space shuttle main engines, not the solid rocket boosters. However, several days later, the solid rocket boosters were implicated as the cause of the accident.

The stock market was not so easily fooled by appearances. On the day of the accident, the manufacturer of the solid rocket boosters, Morton Thiokol, experienced a statistically significant twelve percent decline in returns. The other space shuttle contractors studied here (Rockwell International, Lockheed, Grumman, and Martin Marietta) experienced much smaller drops in returns, around four percent. This indicates that the market had information about the failure of the Morton Thiokol solid rocket booster.

Chapter 2 discusses relevant financial literature in order to construct a framework for conducting event studies. Event studies allow us to study the returns of the firms in question to assess the impact of the shuttle disaster. The first topic discussed in this chapter is efficient markets literature along with theories arguing that stock prices move randomly, or according to a random walk. The theory of random walks was expanded by Samuelson and Mandelbrot to illustrate that we would expect prices to move randomly in efficient markets. Fama built upon this foundation, devising three tests of market efficiency. Fama pointed out that the interesting result is not whether markets are efficient, but instead what degree of efficiency these markets exhibit. Part of the reason for this is the joint-hypothesis problem which requires that when testing for efficient markets, the researcher must use a model of asset pricing to devise a world where there is no excess demand. Tests of efficiency are confounded by this additional requirement of an asset pricing model; efficiency cannot be proven. The degree of market efficiency becomes the relevant area of emphasis.

Following the discussion of efficient markets is a section on the capital asset pricing model (CAPM), the asset pricing model used in this paper. CAPM is based on the trade-off between return and risk in the capital markets. It is assumed that an investor can obtain what is called the risk-free rate as a return on his investment. The linear relationship between the risk-free rate and the set of minimum variance assets is called the security market line and reflects the cost of risk. This linear relationship is used to devise the market model, which shows that the riskiness of a security or portfolio in question is a linear function of the market portfolio.

A statistical means of testing for abnormal returns can be built from this foundation. This means of testing is called and event study. Abnormal returns are the residuals from an ordinary least squares regression of the security's return on the market portfolio. An event study is study of these residuals to determine what effect an piece of news had on a firm.

The next chapter, Chapter 3, discusses the space shuttle program. The various budgetary tradeoffs are discussed as well as the reliability of the two forms of putting the orbiter into space. One method was to use liquid hydrogen and a fuel. The other was to use solid rocket boosters. NASA chose to use a combination of the two. Using both methods, instead of just liquid hydrogen, reduced the development costs of the shuttle.

The development of the liquid propulsion system was overshadowed by test failures and delays. The solid rocket propulsion system, on the other hand, went relatively smoothly. This also compared favorably with the high reliability of the solid rocket technology. Although these would be the largest solid rockets ever manufactured, many in NASA believed that they represented proven, safe technology.

The chapter continues to discuss in detail the accident itself and how this detail was not available on the day of the accident because most information had been recovered from telemetry that had fed straight from the shuttle into NASA's computers. There were visual signs of a problem as well, but the shuttle had executed a roll maneuver and moved the faulty right solid rocket booster away from news cameras. It was only when NASA analyzed footage from other cameras that they found the obvious evidence of a problem with the right solid rocket booster.

An observer on the ground would not have suspected the right solid rocket booster was the culprit as the explosion signaled the large external tank as the cause. Another possible cause was the main engines, a conclusion drawn largely from the fact that the shuttle exploded three seconds after the main engines increased power to 104 percent of the rated maximum.

The chapter continues by describing the possible causes of the accident investigated by the Rogers Commission. After careful analysis by the commission, the right solid rocket booster (SRB) was found to be involved. The Commission eventually concluded that the rubber O-rings that provide sealing in the SRB failed, allowing hot gasses to burn through the solid rocket booster and ignite the external tank. The Commission also found that although the problem with the O-rings was known for some time, nothing was done.

The final section details the history of O-ring problems and how widespread the knowledge was. The reports of problems date back to 1977, but the problem started to become acute in 1985. NASA had been using a technique to assess whether the

O-rings were seated. The technique often resulted in hot gasses scorching the O-rings after the solid rocket booster was fired. Morton Thiokol and NASA set up task forces to study the problem, but no progress was made.

Chapter 4 analyzes the empirical results of the event studies performed for the accident. If markets are efficient, it is expected that the market should reflect the real cause of the accident in the price of the firms working on shuttle projects. Although it might have looked as though the cause of the accident were the main engines or the external tank, the market would reflect the true cause of the accident if such information is available. Had the information about the faulty joints not been known, or had the joint not been faulty, it is expected that there would not have been a firm-specific reaction. But the case studied here shows that from information available, Morton Thiokol was the most likely culprit in the accident.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews efficient market, asset pricing, and event study literature in order to provide an overview of the theory. The first area addressed will be relevant efficient markets literature. Early efficient market literature dealt primarily with what are called random walks, or the random behavior of security prices, until work by Fama showed that random walks are a certain form of efficient markets. Prior to Fama's work, there was some work that studied the underlying distribution of security prices. That is, it answered the question of whether security prices follow a normal distribution. This led to discoveries of what we will call here "depth of efficiency," namely that the interesting question with regard to efficiency is not whether exists. Rather, the interesting question is to what degree or depth are markets efficient.

The capital asset pricing model (CAPM) is then covered along with its relationship to efficient markets through the joint-hypothesis problem. The joint-hypothesis problem appears in studies of efficient markets because these studies require that two hypotheses be tested. First, efficiency is tested in the study (generally what is wanted), and, second, an asset pricing model is required to define efficiency. Thus, tests of efficiency are not performed without this model of capital assets and therefore cannot test purely for the effects of efficient markets.

Next, event study literature is discussed. The current literature points out the problems of event studies, which are statistical techniques for determining whether a firm or portfolio realized an abnormal return for the date in question (termed an "event"). Event studies are based on Fama's early work in different forms of market efficiency, particularly in what he called semi-strong form efficiency. Later, in fact, Fama changed the naming of semi-strong form efficiency to "event studies."

Efficient Markets

At the turn of the century Louis Bachelier (Bachelier 1900) wrote his doctoral dissertation in mathematics on the movement of stock prices. His findings were that stocks moved in a random manner, a random walk.

This finding meant that there were no opportunities that could be exploited in order to reap profits; if stocks moved at random, there was no way of devising what is termed a *trading rule* to make abnormal returns, or, here, profits. The random movement of stock prices, on the surface, had a number of implications. The finding of randomness was the main implication, meaning that stock prices exhibited no "intelligence." The finding of randomness precluded the formulation hypotheses about stock price movements. There was evidence that stock prices did not move randomly. A missing link existed somewhere. Stock prices did move randomly, but they also responded to news. Empirical studies showed what appeared to be nonrandom stock price movements, unexplained by the theory. In effect, there were a series of empirical results that were in search of a theory. The random walk hypothesis provided part of the answer, but it was only with the work of Samuelson (Samuelson 1965) and Mandelbrot (Mandelbrot 1966) that this theory was provided; Samuelson and Mandelbrot found the link between the random walk hypothesis and efficient markets. An efficient market is one which adjusts instantaneously to new information, denying a trader the opportunity of making abnormal profits. If there were opportunities to be exploited (that is, a trading rule exists) efficiency requires that these opportunities be instantly exploited until the marginal benefit of exploiting it (the abnormal returns) was bid away until it equaled the marginal cost. The theory that was tested was that no abnormal returns existed in capital markets.

Samuelson and Mandelbrot found that we would expect prices to move randomly under an efficient market regime, but that is only because the market quickly (almost instantaneously) incorporates information into the price of securities. They refined the random walk theory to show it is a special case of efficient markets. The securities market, in adjusting so rapidly to new information, appears only to be a random walk. A true random walk model, as will be shown later, would be indifferent to news or new information arriving about the underlying value of the firms. The securities market is thus a clearinghouse for information. This observation leads to some interesting possibilities for statistical analysis of stock prices (actually returns) to determine the impact of new information. This statistical analysis is called an "event study" and will be discussed later.

Fama (Fama 1970) expanded on Samuelson's and Mandelbrot's research, defining different tests of efficiency. Fama was not concerned whether the market was efficient. Rather, he concerned himself with to what degree or depth the market was efficient. He first clarified the theory of efficient markets. In doing so he modeled efficiency formally as,

$$x_{j,t+1} = p_{j,t+1} - E(p_{j,t+1} \mid \Phi_t). \tag{1}$$

In this equation $p_{j,t+1}$ is the price of security j at time $t+1$. E is the expectations operator, and Φ_t is the information held by the markets. This equation represents what is termed a "fair game" with respect to the information set Φ_t when

$$E(\tilde{x}_{j,t+1} \mid \Phi_t) = 0. \tag{2}$$

Definitionally, $x_{j,t+1}$ refers to an abnormal price. When $x_{j,t+1} = 0$ we find a fair game. That is, the expected future price is equal to the future price; there is no systematic bias in expected returns. If there were a difference between the left hand side and the right hand side, we might expect to find the possibility for abnormal returns.

Fama continues the same discussion using returns instead of prices. He defines,

$$z_{j,t+1} = r_{j,t+1} - E(\tilde{r}_{j,t+1} \mid \Phi_t), \tag{3}$$

and a "fair game" (with respect to the information set Φ_t) as

$$E(\tilde{z}_{j,t+1} \mid \Phi_t) = 0. \tag{4}$$

In these equations $r_{j,t+1}$ is defined as a "return" or a percentage change over two time periods t and $t+1$ of security j's price. Or $r_{j,t+1} = (p_{j,t+1} - p_{j,t})/p_{j,t}$. The distinction between prices and returns becomes more important later due to problems using prices with event studies instead of returns.

Submartingales and Random Walks

Fama then discusses two special cases of efficiency, submartingales and random walks. He defines a submartingale formally as

$$E(\tilde{p}_{j,t+1} \mid \Phi_t) \geq p_{j,t}. \tag{5}$$

which is equivalent to

$$E(\tilde{r}_{j,t+1} \mid \Phi_t) \geq 0. \tag{6}$$

This says that the expected value of next period's price (return) is greater than or equal to the current price (return). In other words, the price is expected to rise. Tomorrow's price (return) is expected to rise.

Fama points out the empirical implications of a submartingale. Namely, if tomorrow's price is expected to rise, then a study of stock prices must take this into consideration. A test of abnormal returns must compare the portfolio's return to a strategy of buying and holding securities (which, following a submartingale, are expected to rise). Without this consideration, a study would be biased upward.

Finally, Fama discusses formally the random walk model. The random walk model was what Bachelier used to model security prices at the turn of the century. Fama defines random walks as a special case of efficient markets. His model of random walks consists of two hypotheses. First, successive price changes are independent and second they are identically distributed (or they are i.i.d.). Fama defines these conditions formally as

$$f(r_{j,t+1} \mid \Phi_t) = f(r_{j,t+1}). \tag{7}$$

This defines the equality between tomorrow's returns conditional on information set Φ_t (with f as a probability density function) and tomorrow's returns without the information set. More simply, the probability density functions are the same with and without the information set. This is a strong requirement; it requires that the distributions both have the same mean, variance, skewness, and kurtosis regardless of the information set. A random walk thus has the requirement that not only that the difference between expected future returns (or prices) and future returns must equal zero, but also that the distribution of returns is the same whether or not a set of information Φ_t is used. This additional requirement of equivalent distributions makes a random walk a special case of the efficient market.

Fama addresses the issue of sufficient conditions for market efficiency, conditions where a security's price fully reflects all available information. There are three. First, there are no transaction costs. Second, all available information is costlessly available to all market participants. Third, all participants agree on the implications of the information on a security's future prices. That is, there is no disagreement about how an announcement (dividend change, positive NPV project, accident) will affect a company's health.

Fama continues by describing tests of efficient markets. He divides the tests into three increasing levels. Each level represents a progressively "deeper" incorporation of information into the market. These tests are often later referred to not as *tests* of market efficiency, but as different degrees of market efficiency. For instance, some authors refer to weak-form efficiency rather than "weak-form *tests* of efficiency." Fama actually referred to the tests, not varying degrees of efficiency.

The first test, called a weak-form test of efficiency, tests whether the securities market is efficient with respect to historical prices. A market that is efficient in terms of past security prices (no trading rule can be devised based on past stock price information and technical analysis is ineffective) could be called *weak-form efficient*. Traders have known that historical information affects securities in a certain manner and have bid away all of the profits associated with this knowledge.

The second test, which we will be concerned with here, is called a semi-strong form test of efficiency. Semi-strong form tests of efficiency show that once information becomes public, the market will react, removing any opportunity for profit from this information. A market that exhibits this characteristic is called "strong-form efficient." Strong form efficiency is "deeper" than weak-form in the sense that any publicly available information is incorporated into the current price. This encompasses any publicly available information, but also includes historical returns (a weak-form efficiency requirement) to determine future prices. A trader cannot make abnormal returns by using information such as earnings and investment reports. Efficiency in the semi-strong form requires that as soon as this information becomes public the abnormal returns have been bid away. Semi-strong form tests form the basis of event studies. Since strong-form efficiency requires that the market adjust to take into account information that has just become public, a news item will instantly affect a firms price. This effect can be discerned using statistical techniques, confirming or rejecting a hypothesis a researcher might have about the certain news on companies or an industry.

The third form of market efficiency is called strong-form efficiency. Strong-form efficiency means that any and all information is quickly incorporated into the market price of a security. That is, company directors and executives have inside information on their firm which they use trying to obtain abnormal returns. Strong-form efficiency is not of interest here because the markets are not, in general, strong-form efficient. This notion is reinforced by the existence of laws that outlaw insider trading.

These three forms of efficiency form the basis for empirical studies of market efficiency. Fama (Fama 1991) reviews the current literature in efficient markets. He changes the tests of efficiency from weak form to “tests of return predictability,” from semi-strong form to “event studies,” and from strong form to “tests for private information.” In this paper Fama points to one of the problems with assessing market efficiency. Namely, tests of efficiency must be undertaken with some model of asset pricing. This is most often the capital asset pricing model, or CAPM, which evaluates riskiness of assets as the covariance between the (risky) asset in question and a market portfolio (all assets). This is related to one of the characteristics of efficient markets that Fama pointed out in his earlier work (Fama 1970): “all agree on the implications of current information for the current price and distributions of future prices of each security.” This assumption is that all traders operate under the same model of efficiency in the capital markets.

This is what is termed the joint hypothesis problem. Fama states the problem this way, “as a result, when we find anomalous evidence on the behavior of returns, the way it should be split between market inefficiency or a bad model of market equilibrium is ambiguous.” (Fama 1991) But this does not mean that tests of efficiency are not useful; on the contrary, the vast literature spawned by this research and the changes on the investment community cannot be understated. The end result, however, is that they symmetry between tests of efficiency and an asset pricing model will make it impossible to know precisely how efficiency works.

Capital Asset Pricing

The joint-hypothesis problem requires that we address the issue of equilibrium models of markets as they are necessary for any tests of capital market efficiency. An equilibrium model of capital markets provides a framework for understanding why there is no excess demand in the securities markets. One of the first to devise such a framework was William Sharpe. His paper "Capital Asset Prices: A Theory of Market Equilibrium Under Conditions of Risk" (Sharpe 1964) lays out what would later become known as the capital asset pricing model (CAPM). CAPM (or the security market line) will not be derived here, but some of the salient points will be covered.

CAPM provides a model of asset pricing using a linear function of the risk-free rate. The risk-free rate is the rate on return that prevails on riskless assets. CAPM uses this risk-free rate to determine the return and variance of an efficient portfolio. A given portfolio is seen as a tradeoff between risk and return. A curve traced out showing this tradeoff is called the minimum variance opportunity set. By drawing a line from the risk free rate to the upper portion of the minimum variance opportunity set, one can determine the optimal portfolio. This linear function, called the security market line, captures the price of risk as its slope; the slope is called beta.

Beta is defined as the covariance with the market divided by the variance of the market, or (Copeland and Weston 1988, p. 198),

$$\beta_i = \frac{\sigma_{im}}{\sigma_m^2} = \frac{cov(R_i, R_m)}{var(R_m)}. \tag{8}$$

The beta of the market portfolio is defined as,

$$\beta_m = \frac{cov(R_m, R_m)}{var(R_m)} = \frac{var(R_m)}{var(R_m)} = 1. \tag{9}$$

Thus, β_i gives an indication of the relationship between asset i's risk versus the market portfolio's risk. CAPM dictates that these two measures should move together, unless the underlying riskiness of the asset changes. It is from this model that we can formulate event studies. Event studies become a matter of regressing the return of asset i on the market portfolio, R_m.

Event Studies

The second form of efficiency (called semi-strong form) has spawned a vast literature in what are termed event studies. Event studies are a statistical technique of measuring the abnormal performance on a securities return.[1] An event study allows researchers to test for market efficiency firstly, but also enables the study of firm related issues. For instance, an event study would allow a researcher to test hypotheses of how the stock market views dividends or how the market views different capital structures.

The event study is based on a statistical model of security prices. Current event studies generally use a simple linear function to model abnormal returns. That is,

$$R_{it} = \alpha_i + \beta_i R_{mt} + \varepsilon_{it}, \tag{11}$$

$$\varepsilon_{it} \sim N(0, \sigma^2), \tag{12}$$

where R_{it} is the return of security i at time t, R_{mt} is the market return at time t, ε_{it} is the error term, and α_i and β_i are estimated parameters. The error term, ε_{it} is assumed to be distributed normally with mean zero and variance σ^2. This is a simple linear regression of a security's returns on the market returns. The residuals are

[1]Returns are defined as

$$R_{j,t+1} = \frac{P_{j,t+1} - P_{j,t}}{P_{j,t}}, \tag{10}$$

where $R_{j,t}$ is defined as the (one period) return for time t, $P_{j,t}$ is security j's price at time period t, and $P_{j,t+1}$ is security j's price at time $t+1$.

measures of abnormal performance. According to CAPM, the security's return movements should be a function of the market's returns. When there are large residuals (verified by t-tests) the researcher fails to reject the hypothesis that that the event had no effect on the value of the firm.

When an event study is performed where an actual date is at issue, a different model is often used,

$$R_{it} = \alpha_i + \beta_i R_{mt} + \gamma_i D_i + \varepsilon_{it}. \tag{13}$$

D_i is a dummy variable is set to one for the date (or dates) of the event and zero otherwise. This has two purposes. The first is to allow the statistical software to calculate a t-test of the coefficient's significance. The other is an *a priori* assumption that the event is significant and thus an outlier. If it were not "dummied out" it would bias the estimation of the coefficient on β.

When the date of the event is not so clear-cut, or the information reached the market over time, it is often useful not to use the event dummy variable and simply analyze the abnormal returns (or residuals). Fama, Jensen, and Roll (Fama, Fisher, Jensen and Roll 1969) devise a technique of studying the error terms (the ε_{it}'s). One measure they use is called the cumulative average residual, defined as

$$U_m = \sum_{k=1}^{m} \frac{\sum_{j=1}^{N_k} \hat{u}_{jk}}{N_k}. \tag{14}$$

This is simply the sum of the portfolio average residuals summed from the beginning of the period until the current time period. It is a running sum of the average portfolio residual. This is valuable (assuming that beta remains constant) for showing graphically how a stock's abnormal return moved versus the market. Under normal efficient conditions, the cumulative average residual should move around zero, not unlike white noise.

Nonsynchronicity of Daily Returns

With the arrival of the Center for Research in Security Prices (CRSP) tapes has come the ability to easily study daily data. Unfortunately, using daily data presents the researcher with some problems, which a number of papers address. Two papers are discussed here that investigate the nonsynchronous nature of daily data. The nonsynchronous nature of stock returns stems from the uneven spacing of daily prices (which are used to compute returns) and because often smaller stocks do not trade every trading day. These are called unobservable returns. Scholes and Williams, state, "errors in variables result when measured returns are used as proxies for true unobservable returns" (Scholes and Williams 1977, p. 311). They say that, "with daily data this problem [of nonsynchronous daily data] appears particularly severe" (Scholes and Williams 1977, p. 309). Since securities are traded at discrete, stochastic intervals of time, Scholes and Williams argue there are errors in variables, finding that OLS estimates of α and β are in error. They provide a method for obtaining consistent estimators.

Dimson (Dimson 1979) devises a simpler technique for obtaining a true estimate of beta, which he calls the "aggregated coefficients (AC) method." Dimson represents this as,

$$\hat{R}_t = \hat{\alpha} + \sum_{k=-n}^{n} \hat{\beta}_k \hat{M}_{t+k} + w_t. \tag{15}$$

The regression equation thus contains a series of terms for the market return. That is, it contains leading, lagged, and matched values for the market return. Dimson claims this market equation returns the true systematic risk. Thus, "...the true systematic risk ...can be obtained from security price data which is subject to infrequent trading..." (Dimson 1979, p. 204) as,

$$\hat{\beta} = \sum_{k=-n}^{n} \hat{\beta}_k. \tag{16}$$

Brown and Warner (Brown and Warner 1985) conduct a simulation study to study the various event study methodologies. The data studied are from the CRSP tapes and consist of firms and dates chosen at random. In some studies they perturb the event date by adding or subtracting some amount from the return for that day. This allows them to study the various aspects of event studies including nonsynchronous trading, event window, event clustering, small samples, and power of the tests. The finding of interest here is nonsynchronous trading problems. They find that using techniques other than OLS "…convey no clear-cut benefit in detecting abnormal performance" (Brown and Warner 1985, p. 26).

Beta Shift

Another problem that appears is a shift in beta after the event. A shift in beta indicates the firm (or portfolio) in question realized a change in riskiness. This can be remedied (in fact, it is often specifically tested for in studies of the effect of regulation on industries) by using this market model,

$$R_t = \alpha + \beta R_m + \delta D_t + \gamma D_t R_m + \varepsilon. \tag{17}$$

The dummy variable D_t takes on one or zero depending on how the systematic risk test is structured. For some studies, D_t is set to one during the event period and zero otherwise to test whether systematic risk changed during the event period.

Other studies (such as regulation studies) set D_t to one after the event (and zero otherwise) to determine whether the event shifted the beta thereafter.[2]

Non-Stationarity of Beta

Another problem is non-stationarity of beta. Beta is assumed to be stable over the event period, but it actually changes over time. Beta changes should represent white noise; they should be nonsystematic. If these changes are systematic such as beta increasing over time, the event study will be biased. One way to test for this is compute moving average beta over time (beta is computed using a window that shifts forward one day at a time). A beta is computed for one period of time. Subsequent betas are computed by adding one trading day to the regression and deleting the last. For instance, if the estimate of beta extend from $t-n$ to $t+n$ trading days, the next estimate of beta would extend from $t-n+1$ to $t+n+1$ trading days. The first order differences of these betas is then computed and checked for correspondence with white noise (using the runs test or correlation between successive differences). A first order difference is, for example, $\tilde{\beta}_{t+1} - \tilde{\beta}_t$, where $\tilde{\beta}_t$ represents the current beta and $\tilde{\beta}_{t+1}$ represents the beta calculated from shifting the window forward one day.

Summary

This chapter tied together some of the disparate literature and theory on security prices, the capital asset pricing model, and capital market efficiency. Stock prices have been studied for many years until a model of their movement was discovered—called a random walk. This model was not entirely satisfactory and turned out to be a special case of efficient markets. After Fama devised various

[2]In regulation studies a shift in beta would indicate a new state of the world and if this new state of the world affects the company in a significant way (indicated by a change in the riskiness of the shares). For example, regulation that grants monopoly-like privileges to the company would be hypothesized to lower beta (lower risk) after the regulatory event.

degrees of market efficiency and performed what appears to be the first event study, the use of statistical methods to calculate compliance of semi-strong form efficiency to real-world data as been a growth industry. The problem of the joint hypothesis remains, but it is not a barrier to discovering important findings in studies of efficient markets.

Event studies themselves have been the subject of much study, and the arrival of the CRSP tapes has allowed researchers to study abnormal performance in depth using daily returns. Daily returns present some problems, the most important of which is nonsynchronous trading. However, actual empirical simulations by Brown and Warner (Brown and Warner 1985) showed that the nonsynchronous trading problem is not as grave as was believed by others such as Dimson (Dimson 1979) or Scholes and Williams (Scholes and Williams 1977).

CHAPTER 3

HISTORY

This chapter discusses the space shuttle program in order to provide an overview of the information the security markets might have incorporated into prices of the shuttle firms. The chapter begins with an overview of the shuttle program and how the current design came about. It is followed by a section on mission 51-L, the *Challenger* mission that was lost. Following this is a very detailed discussion of the accident itself to illustrate what was eventually determined to have happened. The purpose of this section is to show that the true events could not have been discerned on the day of the accident. In fact, the accident appeared to be caused by many things other than what really caused it. The sources of incorrect information about the cause of the accident are covered. Finally, the chapter closes with a discussion of what investigators determined to be the actual cause of the accident and how widespread knowledge of this possible failure path was known.

Space Shuttle

The space shuttle program was initiated in the 1960s to provide relatively inexpensive access to space. The giant Apollo program was winding up, and the war in Viet Nam required an increasing portion of the budget. NASA needed to find a cheaper means of transportation to space when they devised the Space Transport System or STS. The lower costs came about from complete reusability of the components, contrasted with the Apollo program that required giant disposable rockets. Complete reusability would make space travel more economical, and, it was hoped, would allow the program to pay for itself.[3] A problem remained, however; the

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[3]NASA envisioned selling cargo space on the STS for satellites, military and commercial.

program needed Congressional approval. If the system were entirely reusable, it would entail development costs (1970) of $10 to $12 billion (spread over seven or eight years) (Lewis 1988, p. 57). Congress and the Office of Management and Budget refused to go along with this plan, forcing NASA to redesign the system.

In order to receive Congress's approval, NASA shifted the costs from development to operation. The craft would be cheaper to develop, but would cost a lot more to operate. In doing so, NASA scrapped the idea of a manned first stage that would carry the orbiter (riding piggy back) to orbit and then return to earth. The manned first stage was replaced by a combination of solid rocket boosters and a liquid tank that would contain fuel for the orbiter's main engines (located at the aft area of the orbiter and fed by a series of pipes from the external tank). They also scrapped the idea of jet engines in the orbiter,[4] complete reusability, and an orbiter with a large wingspan.

These changes put the final development costs at $6.2 billion in 1972 dollars (Presidential Commission 1986, vol. 1, p. 4). The final system, the one in use today, consists of a delta-winged orbiter mounted on a large, rust-colored tank. Mounted to the tank are two solid rocket boosters, the largest ever made. The external tank that the orbiter is attached to contains three smaller tanks. The first, located at the top of the tank, contains liquid oxygen, some 143,000 gallons at -297 degrees Fahrenheit. The other tank, located in the aft, or tail, section of the external tank contains liquid hydrogen at -423 degrees Fahrenheit (Presidential Commission 1986, vol. 1, p. 8). The third, called the intertank, sits between the liquid oxygen and hydrogen tanks and houses instrumentation needed to assure operation of the external tank. These three tanks comprise the external tank, which is manufactured by Martin Marietta and is 154 feet long and $27\frac{1}{2}$ feet in diameter (Presidential Commission 1986, vol. 1, p. 8).

[4]Air-burning jet engines would allow the orbiter more flexibility in returning to earth or aborting a mission but would add a lot of weight and design effort.

The main shuttle engines feed from this external tank through a maze of pipes, pumps, and valves. The engines fire for about $8\frac{1}{2}$ minutes after liftoff and can generate 375,000 pounds of thrust (at sea level) at 100 percent throttle, burning a mixture of liquid hydrogen and liquid oxygen supplied from the external tank (Presidential Commission 1986, vol. 1, p. 7). The main engine's range of operations extends from 65 percent to 104 percent of throttle (Presidential Commission 1986, vol. 1, p. 8). The engines themselves are manufactured by Rocketdyne, a subsidiary of Rockwell International, the manufacturer of the orbiter.

Attached to the external tank are two of the largest solid rocket boosters ever manufactured. They provide about 80 percent of the total thrust and burn for roughly two minutes until exhausted. The boosters themselves are made up of four segments that are shipped to NASA by rail. The segmented design allows for easier shipment to and from the Morton Thiokol's (the manufacturer's) plant in Utah to NASA. The SRBs, as the Solid Rocket Boosters are called, are 116 feet long when the four segments are joined and held together with 177 steel pins. The joint (called a field joint) itself is made up of a tang and clevis; a clevis is a U-shaped part into which a tang fits. The joint is depicted in Figure 1.

The gap between the tang and clevis is sealed with a pair of rubber rings called O-rings. The segmented design represents the weakness in the solid rocket boosters. By joining the boosters together in four segments, four escape paths for the hot gasses are provided. The O-rings are supposed to provide a sealing action to prevent these hot gasses from escaping through a field joint, but the O-rings were never meant to survive the heat of the gasses themselves. Zinc chromate putty is packed between the solid rocket core and the O-rings. The putty is flame-proof, and, in theory, should become plastic and melt around the O-rings, protecting them from the heat.

This current design represents a compromise over the original design. Higher operating costs (not complete reusability like the original design) were traded off for

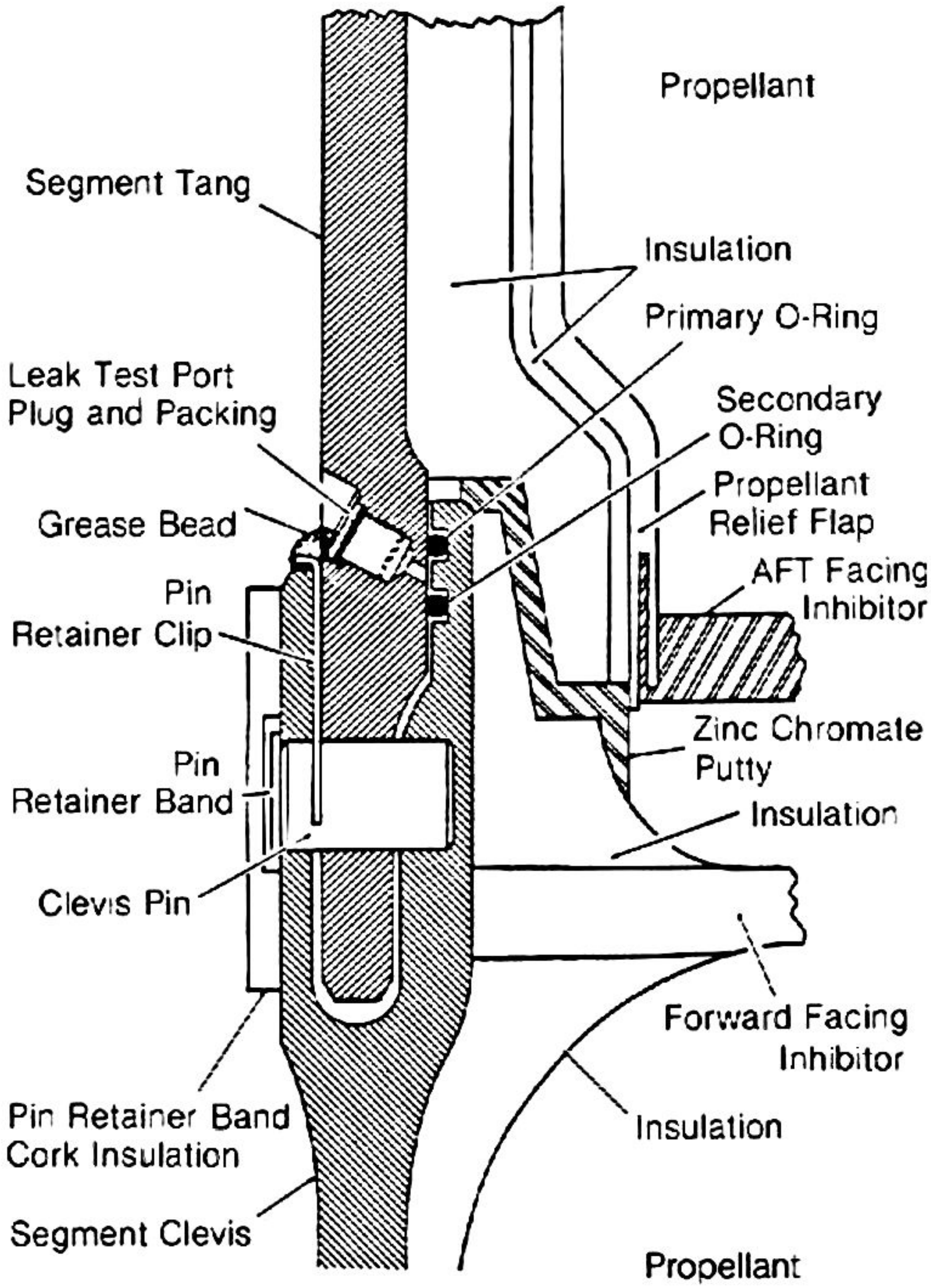

Figure 14
Solid Rocket Motor cross section shows positions of tang, clevis and O-rings. Putty lines the joint on the side toward the propellant.

Figure 1: The solid rocket booster field joint (Presidential Commission 1986, vol. 1, p. 57).

much lower development costs (half of the original amount). The compromise represented a compromise in crew safety as well. Although the SRBs provided more thrust than an equally sized liquid propellant system, they exposed the crew to a two minute window when escape was “nonsurvivable” (Lewis 1988, p. 59). Yet solid rocket technology was considered one of the most reliable around. In fact, “before the Challenger accident, it was believed by some shuttle observers. . . that the SRBs were as safe and reliable as rockets could be” (Lewis 1988, pp. 63–64). Also, “the perception that the SRBs were virtually foolproof was widely shared in NASA during shuttle development and was strongly communicated to the news media correspondents” (Lewis 1988, p. 64).

Mission 51-L

Flight 51-L was the *Challenger* mission that was lost. NASA’s numbering system designated this mission 51-L with the first digit (“5”) representing the fiscal year that the launch was originally supposed to occur. The second digit indicated where the launch was to occur (here “1” represents Kennedy Center). The third, a letter, specifies which launch in that fiscal year (with “A” as the first mission). Mission 51-L was unique because Christa McAuliffe, the first “Teacher In Space,” was aboard. She and her six other crewmates[5] faced four postponements and one scrub of the mission. The flight was originally scheduled for July of 1985 (Presidential Commission 1986, vol. 1, p. 10), but changes in payloads pushed the date back to November, 1985. More delays occurred, and the mission was moved to January of 1986. As the mission was pushed back again and again, there was increasing pressure to launch to keep up with NASA’s ambitious launch schedule. NASA also faced a constraint in that a payload

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[5]They were Commander Francis R. (Dick) Scobee, Pilot Michael John Smith, Mission Specialist One Ellison S. Onizuka, Mission Specialist Two Judith Arlene Resnik, Mission Specialist Three Ronald Erwin McNair, and Payload Specialist Two Gregory Bruce Jarvis. Christa McAuliffe’s title was Payload Specialist One.

needed to be launched by March to investigate Halley's Comet; a *Challenger* launch delay could prevent this comet probe from being launched in March.

The launch was finally scheduled for Tuesday, January 28, 1986. The temperature at the time of launch was 36 degrees Fahrenheit, causing some concern among the shuttle's contractors. Executives of Rockwell International, the builder of the orbiter, expressed concern about the ice on the launch pad.[6] The concern centered around the possibility that ice might break off under the enormous acoustic shocks when the engines are ignited. Falling ice could dislodge the heat resistant tiles that line the underside of the shuttle. The tiles protect the orbiter from the heat of re-entry.

NASA had sent an "ice team" to investigate the problem. The ice team measured the temperature of the right solid rocket booster and found it to be about 19 degrees Fahrenheit, well below the manufacturer's (Morton Thiokol's) contracted low temperature of 40 degrees Fahrenheit. The contract between NASA and Thiokol stipulated that the SRBs operate above 40 degrees Fahrenheit. The temperature finding was not reported up the chain of command.

Morton Thiokol's engineers[7] were concerned as well about the low temperature. The engineers had never fired test rockets at such a low temperature and were concerned about something they observed in January, 1985. The January, 1985 launch was unique because it had been the coldest to date. Although they had no statistical data to suggest there was a correlation, the engineers felt there was a correspondence between temperature and the O-rings not sealing. By not sealing, the O-rings had allowed hot gasses to escape through the joint, burning (eroding) several hundredths of an inch from the secondary O-ring. Damage occurred in both solid rocket boosters in the January, 1985 launch.

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[6]The launch structure was covered with ice because, fearing frozen pipes, NASA officials decided to allow water to trickle from the water pipes.

[7]Morton Thiokol manufactures the solid rocket boosters.

The engineers were overridden, however, and Thiokol gave approval for the launch. The engineers were put in the position of having to prove that the O-rings would fail, rather than prove that they would work. There was also no launch constraint for temperature; no one really knew how cold it could be.

The Accident

The Space Shuttle *Challenger*, Mission 51-L of Tuesday, January 28, 1986, had been postponed four times and scrubbed once. When the craft was finally launched at 11:38 am EST, the mission progressed normally until T+73 seconds[8] when the *Challenger* exploded and killed all seven crew members. It was not immediately obvious what had happened, and some of the people on the ground thought the smoke indicated the planned-for separation of the orbiter from the external tank.

In spite of the uncertainty about the cause of the problem, there was visual indication of some problems immediately after ignition of the solid rocket boosters; no one noticed the problem until enhanced photographs of the shuttle were analyzed. The right SRB emitted several puffs of black smoke at 0.678 seconds into the launch (T+0.678). A total of nine puffs of smoke appeared between 0.836 and 2.500 seconds at a lower joint on the right SRB (Presidential Commission 1986, vol. 1, p. 19). The smoke's color suggested that the O-rings between joins had burned, causing what is called "blow by." It appears that no one at NASA noticed this blow by, and had anyone, it would have been impossible to stop the solid rockets, as they burn continuously until they are exhausted. At 2.733 seconds, the last positive evidence of smoke was visible from the right aft field joint;[9] the shuttle was moving upward and the aft smoke intermingled with plumes from the rocket.

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[8]This notation (T+73 seconds) refers to 73 seconds after launch.

[9]The smoke first appeared on camera E60, a 16mm motion picture camera with a 32mm lens. The camera was located 1270 feet from the shuttle and shot 100 frames per second (Presidential Commission 1986, vol. 3, p. N-9).

All this time the shuttle's main engines had been burning (they were ignited 6.6 seconds before launch in order to get up to full thrust by the time of launch). The shuttle system was bolted to the launch structure, which bends under the force of the main engines. The launch structure bends back in what is called a "twang" motion. At this time the pyrotechnic bolts are exploded, releasing the launch structure's stored energy. The Rogers Commission report explains, "the maximum structural loads on the aft field joints [where the black smoke appeared] of the Solid Rocket Boosters occur during the 'twang,' *exceeding even those of the maximum dynamic pressure period experienced later in flight* [emphasis added]" (Presidential Commission 1986, p. 19). This pressure is part of the reason the joint failed.

The command to increase thrust of the main engines to 104 percent of their rated maximum was given at 4.339 seconds into the mission. In Houston, Stephen Nesbitt, public affairs officer for the Johnson Space Center Mission Control announced the mission progress,

> ...roll program confirmed. *Challenger* now heading down range. Engines beginning to throttle down to 94 percent. Normal throttle for most of the flight is 104 percent. Will throttle down to 65 percent shortly. Three engines running normally...Velocity 2,257 miles per hour. Altitude 4.3 nautical miles. Engines throttling up. Three engines now at 104 percent.

The roll program meant the shuttle rolled over on its back, moving the leaking right SRB away from any news cameras. No one (outside of NASA) could then visually determine what had happened, since the footage showed the completely normal left solid rocket booster. On Saturday, February 1, 1986 (the accident occurred on Tuesday), the *New York Times* reported that "the television pictures of the *Challenger* explosion seen by the public show the right booster on the far side of the camera, behind the shuttle, which had rolled on its back. NASA is examining photographs taken from other angles, and it was reported that one view suggested a jet of flame shooting from the side of the right booster rocket."

Telemetry[10] began recording an anomaly in the right SRB at 5.674 seconds; the pressure was 11.8 psi above nominal. Next at T+7.724 the shuttle began a programmed roll, rolling the craft on its back. The engines were then throttled back to 94 percent of rated power. Everything appeared normal as the shuttle entered, between 37 and 64 seconds into the mission, an area of high altitude wind shear, placing wildly varying forces on the craft. The computers automatically adjusted, executing pitch and yaw maneuvers to adjust the crafts attitude.

At 51.860 seconds into the mission the main engines again throttled up to 104 percent. Mission Control, Houston, said, “Go at throttle up.” Commander Scobee replied, “Roger, go at throttle up,” acknowledging the command as the computers executed it. The first evidence of a flame appeared at 58.788 seconds. It was localized to the right hand solid rocket booster, in computer-enhanced film of the launch. Camera E207 showed the flame grow larger, becoming a well-defined plume one frame later at 59.262 seconds. A pressure differential at T+60 seconds between the right hand and left hand solid rocket boosters was reported by telemetry (the right booster’s pressure was lower).

The plume began to be deflected at 60.238 seconds by aerodynamic forces toward the liquid oxygen and hydrogen filled external tank. The shuttle’s computers began to compensate for the thrust differential between the two solid rocket boosters. Telemetry reported the onboard computers automatically directed the left solid rocket booster’s thrust vector control (nozzle) to correct for the increased yaw introduced by the malfunctioning right hand booster. For about nine seconds the control computers continued to correct for the increasing yaw and pitch rate errors introduced by the damaged right hand booster with little success.

[10]Telemetry consists of readings taken from various sensors and instruments aboard the shuttle and radioed back to NASA. Most of the data is simply stored on computer tape for later analysis with little actually presented in real time to the controllers at Marshall and Kennedy.

Aerodynamic forces were beginning to tear the craft apart, and the control systems continued in vain to correct for them. Then, at 64.660 seconds the external tank began leaking liquid hydrogen as indicated by telemetry. At 72.204 seconds the right hand and left hand SRBs experienced massively divergent yaw rates, then pitch rates. This was caused when the lower strut that attached the right hand SRB to the external tank was torn away allowing the right hand SRB to rotate freely. The yaw and pitch introduced was outside the range of possible compensation by the on-board control computers.

The tearing off of the strut released about 2.8 million pounds of thrust as massive amounts of hydrogen poured through the tear in the external tank. The right SRB swung around and impacted the liquid oxygen tank causing total failure of the external tank at 73.137 seconds. The liquid hydrogen and oxygen spewing from the failed tank ignited a few milliseconds later into a huge fireball, enveloping the *Challenger* and causing massive structural failure of the orbiter. Film footage indicated the orbiter broke into several sections, one of which was the crew compartment.

Autopsy reports indicated that at least some of the crew survived the explosion, as they activated their emergency oxygen tanks, and the *g* forces were well within human survivability. The crew compartment reached a height of 65,000 feet (12 miles) before it began its descent, striking the ocean 165 seconds later at a speed of 204 miles per hour (Lewis 1988, p. 177). The 200 *g* force experienced on ocean impact was outside human survivability limits.[11]

Stephen Nesbitt of Johnson continued his commentary, "Flight controllers are looking very carefully at the situation. Obviously a major malfunction. We have no

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[11]Dr. Joseph Kerwin of Life Sciences at the Johnson Space Center found evidence that the crew survived the explosion, but died either from ocean impact or the sudden loss of air after the compartment was thrown free of the explosion.

down link. We have a report from the flight dynamics officer that the vehicle has exploded." There was thus no real understanding of what had happened or why. On the surface it appeared as though the craft exploded because the throttle to the main engines was increased to 104 percent. The explosion occurred approximately three seconds after Commander Scobee relayed "go at throttle up." to mission control.

Cause of the Accident

President Reagan appointed the Rogers Commission (also called the Presidential Commission) to investigate the accident. The Commission was chaired by former Secretary of State William Rogers. The Rogers Commission investigated each possible cause of the accident, dividing the possible causes into the following areas:

1. external tank,
2. space shuttle main engines,
3. orbiter and related equipment,
4. payload/Orbiter interfaces,
5. payload, inertial upper stage, and support equipment,
6. solid rocket booster.

Here we will only discuss possible failure of the external tank, orbiter motors, and solid rocket boosters.

External Tank

The large, rust-colored external tank contains an oxygen tank, a hydrogen tank and a tank between the two. The external tank is manufactured by Martin Marietta (main contractor). Visibly, this external tank exploded, suggesting to observers that this was the cause of the explosion. In fact, the right SRB, after tearing free of its aft connection to the external tank began rotating. This allowed it to rotate around and strike the liquid hydrogen tank, releasing great quantities of hydrogen which subsequently ignited. It would have been almost impossible to discern these events at the time of the accident as they were only obtained from telemetry analysis and enhanced photographs. Recall that the shuttle had seconds earlier performed a roll maneuver that placed the right SRB away from the cameras of the news media.

The Rogers Commission investigated several possible failures with the external tank, rejecting all of them. The first cause investigated was that there was a premature detonation of the range safety destruct devices.[12] The destruct devices were recovered from the ocean and found intact and therefore could not have prematurely exploded.

The next cause investigated was a structural failure of the tank. Some small imperfection in the tank could have grown in size due to mission stresses and resulted in total collapse. Upon analysis of the construction history test data and x-rays, this possibility was rejected.

Damage to the hydrogen tank at liftoff was considered and rejected after detailed analysis of the photographic evidence showed no vapor or frost to indicate a leak. This possible cause was thus rejected.

Next the commission turned to an analysis of structural loads on the external tank and whether the rated loads had been exceeded. The commission found that there had been no excessive loads on the external tank up to the explosion.

Overheating of the external tank was another possible cause that was analyzed. After analyzing the data, overheating of the external tank was ruled out as a possible cause of the accident.

The commission thus "…found nothing relating to the External Tank that caused or contributed to the cause of the accident" (Presidential Commission 1986, vol. 1, p. 42). Speculation in the press did center on the external tank, largely because it contained highly explosive hydrogen. The morning after the accident, the *New York*

[12]These explosive devices are used to remotely destruct the external tank if it is headed toward a populated area.

Times reported that the external tank had been the cause of the accident (Browne 1986, p. A1), "…suspicions quickly focused on the craft's huge external fuel tank, a potential bomb that carried more than 385,000 gallons of liquid hydrogen and more than 140,000 gallons of liquid oxygen at liftoff."

Space Shuttle Main Engines

The space shuttle's three main orbiter engines were built by Rocketdyne, a division of Rockwell International. The engines had been the subject of much controversy during their development as there were a number of test failures (Lewis 1988). This contrasted with the mostly trouble-free development of the SRBs.

Additionally, the casual observer would have guessed the main engines failed as the shuttle exploded approximately three seconds after Commander Scobee said, "Roger, go at throttle up." According to a GAO report, avoiding this throttle up would make the launch safer, "…eliminating or reducing about 175 potential failure modes, according to NASA" (General Accounting Office 1989). The day after the accident, the *New York Times* reported, "certainly, the external fuel tank was being subjected to great mechanical stresses at the instant it blew up; the explosion occurred a few seconds after the shuttle's main engines were boosted to full power" (Browne 1986, p. A4).

However, the commission, after a thorough investigation of the main engines, found that the main engines had not failed. The only failure they found was caused when the computers shut down the main engines because the oxygen to hydrogen ratio increased, which caused the main engines to overheat. This was because the hydrogen they normally burn was escaping through a hole in the external tank caused by the right SRB tearing its strut off the external tank. The fuel burned by the main engines was liquid hydrogen, with liquid oxygen provided to enable the burning of hydrogen to take place in the upper atmosphere where there is very little oxygen.

Solid Rocket Boosters

Both SRBs had been manually exploded by the range safety officer after the left SRB appeared headed toward New Smyrna Beach, Florida. Operating the range safety devices required that both SRBs be destroyed, and since the charges detonated at 110 seconds into the launch (the craft exploded 73 seconds into the launch), they could not have caused the accident. After an extensive analysis, the commission found that "the left Solid Rocket Booster, and all components of the right Solid Rocket Booster, except the right Solid Rocket Motor,[13] did not contribute to or cause the accident" (Presidential Commission 1986, vol 1, p. 53). The *New York Times* of January 29, 1986 (the day after the accident) questioned: "Might one of the joints between sections of a booster rocket have failed, somehow forcing a jet of white hot gas through the thin skin of the external fuel tank?" (Browne 1986)

The Commission began to concentrate on the solid rocket motor. After eliminating other causes, the commission studied the joints between the four segments of the SRB, and found that the aft field joint had failed allowing hot gasses to breech the SRB and ignite the liquid hydrogen as it spewed from the damaged external tank. The Commission ruled that the field joint had suffered from a faulty design and that the O-rings in the joint had failed to seal. The Commission did not merely find that the O-rings failed, but that the problem was known by engineers at both NASA and Morton Thiokol (the designer of the field joint) and had not been addressed.

History of O-Ring Problems

The O-ring problem dated back to the early 1980s, but it was only in 1985 that the problem became acute, resulting from the method Thiokol and NASA chose to test

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[13]The Solid Rocket Motor is simply the solid rocket booster without a nozzle and nose cone.

whether the O-rings were sealed. This test involved forcing air into the joint from a test port to seal the secondary O-ring. NASA originally tried 50 psi of pressure, but found that inadequate to seal the O-rings. They continued to increase the pressure of the air forcing into the joint until they were using 200 psi. There was a major problem with using 200 psi of pressure; the zinc chromate putty that protected the O-rings from hot gasses often developed holes that allowed jets of hot gasses to reach the O-rings. This resulted in O-ring erosion. Normally, the putty becomes plastic and flows around the O-rings, but holes blown in the putty focus hot gasses on the O-rings, resulting in erosion.

Each of the four joints in the SRB contained two O-rings. The primary O-ring was designed to provide the sealing necessary for the joint. The other O-ring, the secondary O-ring, was redundant and allowed the joint to be considered fail safe. Nevertheless, on November 24, 1980 in what is called a “Critical Items List,” the O-rings were classified “Critical 1R” whose failure would result in “loss of mission, vehicle, and crew due to metal erosion, burnthrough, and probable case burst resulting in fire and deflagration” (Presidential Commission 1986, vol. 1, p. 239).

The problem with the O-rings surfaced in January 1985 when flight 51-C’s field joints experienced blow-by and scorching (erosion) of the secondary O-ring. In April of 1985, flight 51-B experienced primary O-ring erosion in the right and left boosters. The mounting evidence of the O-ring problem and its correlation with lower launch temperatures caused the engineers at Morton Thiokol to oppose the launch of 51-L (the Challenger mission that was lost). The main reason was the unseasonable cold; it was predicted to drop to 18 degrees the night of January 27, 1986 (the shuttle was launched January 28). The engineers believed that there was a correlation between temperature and O-ring erosion, but they had no statistical data or burn tests at that temperature to prove it. There was no launch constraint[14] for low temperature. The only constraint from Morton Thiokol's point of view was that the SRBs not be launched under 40 degrees F. [15] The ambient temperature at launch was 36 degrees F.

Because of the cold temperatures, NASA began running water through the pipes of the launch structure to prevent the pipes from freezing. The running water soon formed ice. In order to assess the effect of this ice on the launch structure, NASA sent out an "ice team." They found that the right SRBs aft section measured about 19 degrees F, much colder than it should have been at launch. This finding was not reported up the command hierarchy. It is not known why they did not report this finding up the chain of command; speculation is that the joint was so cold that the reading was disregarded as an instrument malfunction. Later, Richard Feynman, Nobel Prize winning physicist from Caltech and a Presidential Commission member, found that the instrument was properly calibrated and the low reading was probably the result of winds that had blown across the external tank (which was filled with liquid hydrogen and oxygen hundreds of degrees below zero) during the night and onto the right SRB.

The launch was approved, however, over the heads of the engineers. A Morton Thiokol manager signed a paper that allowed the launch to proceed. The CEO of Morton Thiokol, Charles S. Locke, stated after the accident (in a March 16, 1986 *Business Week* interview), "If we'd been consulted here [at Morton Thiokol headquarters in Chicago], we'd never have given clearance, because the temperature was not within the contracted specs" (Dobrzynski 1988, p. 82).

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[14]A launch constraint would prevent launch should the condition described in the constraint exist at the time of the launch. For instance, rain was a launch constraint because it would damage the heat resistant tiles on the underside of the shuttle.

[15]Morton Thiokol specified that the lowest operating temperature for the SRBs was 40 degrees Fahrenheit.

The concerns about temperature were never forwarded to managers higher up at NASA or Morton Thiokol. In the end, "the Commission concluded that the Thiokol Management reversed its position and recommended the launch of 51-L, at the urging of Marshall [Space Center] and contrary to the views of its engineers in order to accommodate a major customer" (Presidential Commission 1986, vol. 1, p. 104). One reason, perhaps, for this overruling of the engineers is that "[on] January [21], 1986 NASA announced another plan to develop a second source for shuttle [solid] motor production" (General Accounting Office 1986, General Accounting Office 1989). In other words, a few days before the launch, NASA announced that it would be seeking another source for the SRBs, quite an incentive to go along with NASA's desire to launch.

Cook Memos

Richard C. Cook, a budget analyst with NASA, was assigned the task of identifying "threats" to the budget. A threat was anything that could impact the budget in a major way. One threat he found was the O-rings. The memo, which he directed to his superior, Michael B. Mann, was dated July 23, 1985 (six months before the accident) and begins, "earlier this week you asked me to investigate reported problems with the charring of seals between SRB motor segments during flight operations. Discussions with program engineers show this to be a potentially major problem affecting both flight safety and program costs" (Presidential Commission 1986, vol. 4, p. 391).

On Monday, February 3, 1986, about one week after the accident, and the day President Reagan issued Executive Order 12546, founding the Presidential Commission on the Space Shuttle Challenger Accident, Cook wrote another memo at the request of his superior, Michael B. Mann. In this memo, Cook said,

> there is a growing consensus that the cause of the Challenger explosion was a burnthrough in a Solid Rocket Booster at or near a field joint. It is

> also the consensus of engineers in the Propulsion Division, Office of Space Flight, that if such a burnthrough occurred, it was probably preventable and that for over a year the Solid Rocket Boosters have been flying in an unsafe condition. This has been due to the problem of O-ring erosion and loss of redundancy caused by unseating of the secondary O-ring in flight (Presidential Commission 1986, vol. 4, p. 393).

Other Documents

The earliest known mention of the O-ring problem occurred in 1977 in a briefing chart by Marshall engineer Leon Ray. He stated that failing to change the joint and leaving it as is was “unacceptable—tang can move outboard [away from the clevis] and cause excessive joint clearance resulting in seal leakage” (Presidential Commission 1986, vol. 1, p. 233). In a memo dated January 9, 1978, written by Leon Ray, and signed by chief of the Solid Rocket Motor branch at Marshall, John Q. Miller, Miller urges that the joint be redesigned to “prevent hot gas leaks and resulting catastrophic failure” (Presidential Commission 1986, vol. 1, p. 234–235). Once again, in a memo written by Leon Ray and signed by John Q. Miller dated January 19, 1979, the joint design is found inadequate. Ray states, “we find the Thiokol position regarding design adequacy of the clevis joint to be completely unacceptable. . . ” (Presidential Commission 1986, vol. 1, p. 236).

Roger Boisjoly, an engineer with Morton Thiokol, became concerned about erosion of O-rings after the 1985 flights (when higher pressures were used to test the sealing of the O-rings, causing holes to form in the heat-resistant zinc chromate putty protecting the O-rings). In a memo to Robert Lund (Vice President of Engineering, Morton Thiokol) dated July 31, 1985 (six months before the accident), he stated, “this letter is written to insure that management is fully aware of the seriousness of the current O-Ring erosion problem in the SRM joints. . . ” He stated that if the secondary O-ring failed, and “. . . it is a jump ball as to the success or failure of the joint. . . ,” “the result would be a catastrophe of the highest order—loss of human life" (Presidential Commission 1986, vol. 1, p. 249).

A "seal task force" was set up in order to address the problem, but they made little progress. In a memo dated October, 3, 1985, Robert Ebeling, manager of Morton Thiokol's Solid Rocket Motor ignition system, begins, "HELP! The seal task force is constantly being delayed by every possible means" (Presidential Commission 1986, vol. 1, p. 252). He concludes with, "This is a red flag" (Presidential Commission 1986, vol. 1, p. 252).

Summary

This chapter discussed the history of the space shuttle program and how the present design came about. The discussion then moved on to show that a wide group of people had knowledge of a possible failure of the space shuttle. This information about the true cause of the shuttle explosion could not have been readily discerned after the Challenger explosion because the explosion was caused by ignition of liquid hydrogen from the external tank, casting suspicion on the tank itself. Additionally, the explosion occurred three seconds after Commander Scobee confirmed, "go at throttle up." A casual observer would guess the orbiter's engines or the external liquid hydrogen/liquid oxygen tank had failed, not the solid rocket boosters, which represented mature technology. Lewis says,

> An astonishing aspect of this situation [the O-ring problem] was that so far as the public was concerned, it was one of the best-kept secrets of the space age. The documents describing it were not classified and did not need to be. They were buried in the files at NASA headquarters in Washington and the Marshall Space Flight center in Huntsville, Alabama.
>
> Along with the general public, the astronauts who were flying the shuttle were unaware of the escalating danger of joint seal failure. So were the congressional committees charged with overseeing the shuttle program.
>
> NASA never told them that the shuttle had a problem.

CHAPTER 4

EMPIRICAL RESULTS

This chapter describes the results of a financial markets analysis of the *Challenger* accident. The first section describes the five companies studied. They are Morton Thiokol, the manufacturer of the solid rocket boosters that failed; Rockwell International and its subsidiary Rocketdyne, the manufacturer of the main orbiter and the shuttle's main engines, respectively; Martin Marietta, the manufacturer of the external tank; Lockheed, the firm that prepared the shuttle between missions; and Grumman, the firm that operated the ground control computers.

The next section discusses what we would hypothesize to happen after the explosion of the *Challenger*. That is, the null hypothesis that we wish to disprove is that due to the accident we would expect the shuttle operations to shut down, generating no revenue for the shuttle contractors.

The next section discusses what we actually found. The shuttle firms did experience losses, but Morton Thiokol experienced an approximately twelve percent decline value, and nearly four percent of the company's shares traded that day. Morton Thiokol experienced substantial negative returns.

Company Data

Five shuttle contractors are analyzed for the market's reaction to the shuttle accident. The firms are Morton Thiokol, Rockwell International, Lockheed, Grumman, and Martin Marietta. Lockheed controls the largest portion of the shuttle contract, some seventy five percent (Harris and Beazley 1986). The next largest holders of shuttle business are Grumman and Morton Thiokol. Table 1 contains financial data for the companies under study.

Table 1: Financial data for firms studied.

	Morton Thiokol	Rockwell International	Martin Marietta	Lockheed	Grumman
Shares Outstanding (millions, 1986)	47.08	287.78	56.31	65.61	32.60
Sales (millions $, 1985)	1,832.30	11,338.00	4,410.10	9,535.00	3,048.50
Earnings Per Share (1985)	2.44	1.96	3.05	6.10	2.65
Profit margin (1985)	6.5	5.3	4.0	4.2	2.7
Long-term debt (millions $, 1985)	152.7	647.5	220.4	35.0	263.4
Market value (Jan. 27, 1986, millions $)	1,736.075	10,144.245	1,949.734	3,067.270	884.275

From the table it can be seen that Morton is the smallest in terms of sales, but when viewed from a market-value perspective, they are twice Grumman's size and almost the same size as Martin Marietta. Lockheed has the least long term debt, followed by Morton Thiokol.

Rockwell International

Rockwell International built the space shuttle *Challenger.* Its subsidiary, Rocketdyne, built the shuttle's main engines. Rockwell provided spare parts and consulting on the shuttle, as they had built all that NASA was using at the time.

Morton Thiokol

Morton Thiokol was a well diversified company at the time of the accident. According to Value Line, thirty four percent of sales are specialty chemicals, forty seven percent are aerospace (this includes solid rocket motors, flares, and munitions), nineteen percent salt (Morton salt) (Grant 1986). Value Line predicted in April, 1986, that Morton Thiokol would suffer five to ten cent decline per quarter in earnings (Grant 1986). Value Line also states: "As to any liability for the [shuttle] accident, indemnifications and insurance appear to provide full protection" (Grant 1986). Further, Value Line, states, "the reduced [launch] schedule makes competition from a second booster rocket source unlikely, as does the required high cost and long development time" (Grant 1986). Thus, according to analysts at Value Line, Morton Thiokol would be expected to face lower returns only because of a loss of sales due to the accident.

Lockheed

Lockheed held the contract to prepare the space shuttle for launch. Lockheed controlled some seventy five percent of the shuttle contract (Harris and Beazley 1986). They would thus be expected to be impacted by the shutdown of shuttle operations after the accident. Additionally, according to Value Line, Lockheed would also face a loss of revenue in satellite construction due to the space shuttle standstill (Siegel 1986).

Grumman

Grumman operated the ground control computers at the time of the accident. They were after Lockheed in terms of revenue from the shuttle program. As with Lockheed, we would expect the firm to experience negative returns the day of the accident.

Martin Marietta

Martin Marietta manufactured the external tank. The external tank was implicated by the *New York Times* the day after the accident (Browne 1986). The external tank was a continuing source of revenue for Martin Marietta.

Results

The null hypothesis that we used is that due to the accident, all of the firms under study should experience negative returns due to a loss of revenue from the space shuttle program standstill. The market would, according to the efficient markets theory, incorporate this new information into the prices of the firms in question. Analyzing the returns for the five firms under study shows that they all (except Grumman) received negative returns on the day of the accident. This is shown in Table 2. The day of the accident is marked.

Table 2: Returns for market and five firms studied.

Date	Market (EWRETD)	Morton Thiokol	Rockwell International	Martin Marietta	Lockheed	Grumman
860124	0.008	0.010	0.000	0.038	0.019	0.009
860127	0.002	0.010	0.000	0.011	0.003	-0.048
•860128	0.003	-0.119	-0.025	-0.032	-0.021	0.005
860129	-0.006	-0.015	0.018	-0.011	0.011	0.009
860130	0.003	0.008	-0.011	0.000	0.000	-0.014
860131	0.007	-0.031	0.022	0.004	-0.003	0.014
860203	0.005	0.032	0.028	0.023	0.005	0.023
860204	-0.005	0.023	0.017	0.022	0.022	0.000

Morton Thiokol was a different case. On the day of the accident, Morton Thiokol experienced a negative twelve percent return. This allows us to reject the null hypothesis that Morton Thiokol would experience a loss because of the shuttle program shutdown. Rather, it indicates that the market guessed that Morton Thiokol would experience more future losses than the other firms.

Shares traded data for Morton Thiokol is also skewed. The volume of shares that traded hands increased nearly ten times over the previous day, as shown in Table 3. The day of the accident is marked.

Most firms experienced increases in volume on the day of the accident (except Grumman). Morton Thiokol's volume increased so nearly four percent of its total shares outstanding traded (although some shares traded more than once). Martin

Table 3: Shares traded (volume) for firms studied.

Date	Morton Thiokol	Rockwell International	Martin Marietta	Lockheed	Grumman
860124	85,100	136,900	182,600	181,700	26,200
860127	190,300	73,000	117,500	226,600	98,700
•860128	1,739,900	563,200	446,200	667,500	34,500
860129	1,680,500	252,500	840,300	364,900	31,300
860130	730,100	154,000	212,800	329,600	146,300
860131	895,400	179,900	163,000	603,400	90,400
860203	1,516,900	204,600	287,700	479,600	43,200
860204	972,200	400,500	605,200	739,100	31,900

Marietta experienced a 1.5 percent turnover in shares outstanding, double the volume of the previous day. Recall that it appeared on the day of the accident that the external tank, manufactured by Martin Marietta, had caused the accident. Table 4 shows the percentage turnover of each firms stocks. The table was created using 1986 data on shares outstanding. The day of the accident is marked.

Table 4: Percent shares traded (volume/shars outstanding × 100) for firms studied.

Date	Morton Thiokol	Rockwell International	Martin Marietta	Lockheed	Grumman
860124	0.18	0.05	0.32	0.28	0.08
860127	0.40	0.03	0.21	0.35	0.30
•860128	3.70	0.20	0.79	1.02	0.11
860129	3.57	0.09	1.49	0.56	0.10
860130	1.55	0.05	0.38	0.50	0.45
860131	1.90	0.06	0.29	0.92	0.28
860203	3.22	0.07	0.51	0.73	0.13
860204	2.07	0.14	1.07	1.13	0.10

Figure 2 shows graphically the increase in volume for Morton Thiokol.

Another indication of the market's belief that Morton Thiokol would experience larger than normal losses (than the other shuttle firms) is the loss in value of the firm on the day of the accident. Morton Thiokol lost about $206 million in market value on the day of the accident, shown graphically in Figure 3.

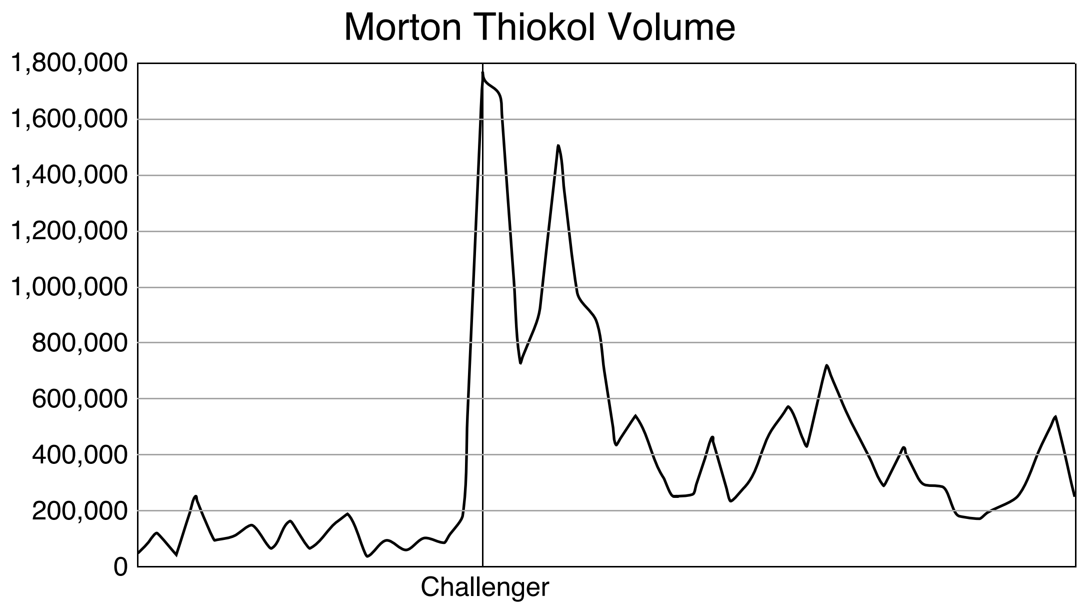

Figure 2: Morton Thiokol volume for 50 days from January 2, 1986 to March 13, 1986.

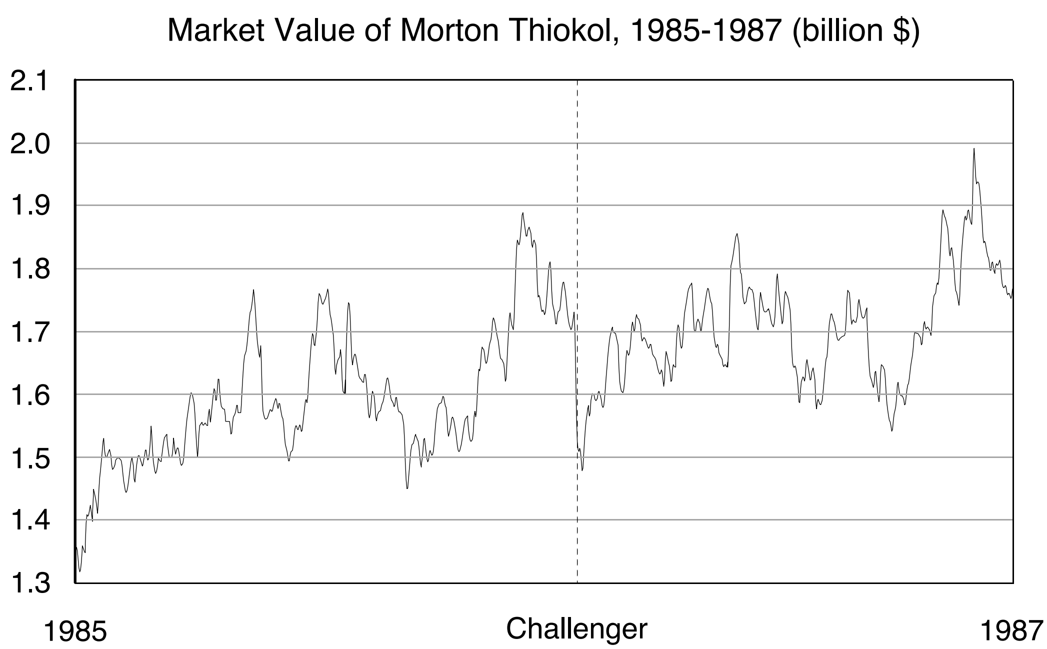

Figure 3: Market value of Morton Thiokol for 1985, 1986.

Figure 4 shows Morton Thiokol's cumulative abnormal returns for fifty days around the event. They are as expected. That is, they tended around zero before the accident and moved under zero after the accident.

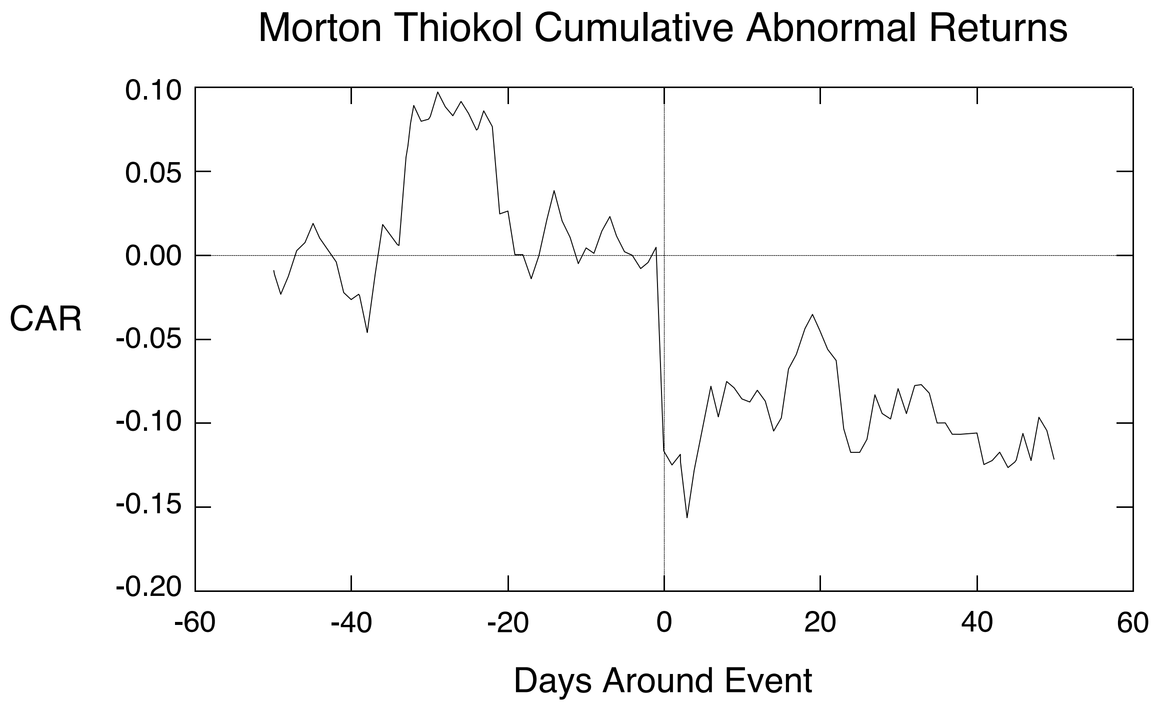

Figure 4: Morton Thiokol cumulative abnormal returns for 50 days before and after the event.

Aftermath

As a result of the space shuttle accident, Morton Thiokol was required to redesign the solid rocket boosters. *Business Week* of March 14, 1986 reported that, "Thiokol has agreed to perform $409 million worth of redesign work for NASA at no profit" (Dobrzynski 1988, p. 91). Another result of the accident is the Advanced Solid Rocket Booster (ASRB) project and Morton Thiokol failing to bid for the project. The ASRB project was a complete redesign of the solid rocket boosters ostensibly to provide more thrust (for bigger payloads and to take some of the work off the shuttle main engines). Morton Thiokol failed to bid for this project due to what some feared was political pressure. The contract for ASRBs called for the winner of the contract to design, develop, and test the motor with a delivery of six sets and an option for forty four more (General Accounting Office 1989, p. 13).

Summary

This chapter has shown that, as a result of the shuttle accident, firms involved in shuttle work should experience a decline in stock returns on the day of the accident. This was shown to be true, except for Morton Thiokol which experienced substantial negative returns. The suggested cause of this negative return was the aftermath of the accident Morton Thiokol, the at-fault company. The return would be expected to be especially large because the problem that resulted in the accident—the failure of the shuttle's O-rings—was known by engineers in NASA and Morton Thiokol. In fact, Morton Thiokol did face losses in addition to the loss of sales during the time the shuttle program was shutdown. That is, they dropped out of bidding for the next generation of solid rocket boosters, although they (in 1984) manufactured some fifty percent of all the boosters manufactured in the United States (General Accounting Office 1986, p. 18). They also performed redesign work on the solid rocket boosters at no profit.

CHAPTER 5

CONCLUSION

Chapter 2 reviewed the relevant efficient market, capital asset pricing, and event study literature in order to provide a foundation for the study that followed. The joint-hypothesis problem was reviewed as were problems in performing event studies. The joint-hypothesis problem is caused by the requirement of an asset-pricing model to accompany any tests of market efficiency. This confounds results of studies of efficiency in markets because the result could be due to an inappropriate asset pricing model. This is one of the reasons that Fama refers to various tests for degrees of market efficiency rather than tests only for the existence of efficiency in security markets.

Chapter 3 reviews the space shuttle program and the decision making that went into the design of today's space shuttle. The space shuttle program was conceived in the late 1960s as a means of transporting satellites and people cheaply into space. The development costs of the ideal (ideal in the sense of low operating costs) system were too high, and Congress and the Office of Management and Budget balked. This caused NASA to redesign the system to use, among other things, solid rocket technology. Although solid rockets had never before been used in manned space flight, they had a proven record in missiles and satellite launches. This introduced a concern into the program because the crew would be unable to escape the shuttle during the two minute period when the solid rocket boosters burn.

The chapter then turned to the accident and analyzed the accident from the viewpoint of telemetry and enhanced visual images. This showed that the right solid rocket booster caused the accident, but this was not obvious on the day of the accident. In fact, on the day of the accident it appeared that the external tank and the main orbiter engines were the cause of the accident. This was later ruled out by the Rogers Commission, but the information about suspected causes leaked out earlier after some of the enhanced images were released by NASA.

The Commission eventually found that the joint on the solid rocket boosters was faulty, and that this problem was known for some time. The remainder of the chapter details the length of time this knowledge was known and by whom. The problem surfaced in about 1977 during the pre-launch days of the shuttle. It was in 1985 that the problem became more evident because of a method NASA used to assure that the O-rings between joints of the solid rocket boosters were sealed. The test they used blew holes in the putty that guarded the O-rings against the hot gasses of combustion as the central core of the SRB burned. The blow holes allowed hot gasses to reach the O-rings and burn (or erode) them.

Chapter 4 discussed the statistical results of this study, finding that the market has quite a depth of information available about causes. The results showed what was expected; all firms experienced negative returns. The finding that lends credence to the hypothesis of efficient markets is that the return on Morton Thiokol was negative twelve percent on the day of the accident when no one really knew what caused the accident, but many suspected the O-rings because it had been a problem for some time. The market thus performed to expectations by instantly incorporating information about the cause of the *Challenger* accident into the firm at fault.

APPENDIX A

PERFORMING EVENT STUDIES

This appendix provides two programs written by the author for performing the event studies used in this thesis. The first program performs event studies with Stata and the second, written for SAS, analyzes dates around a given date to find statistically significant event dates.

Listing A.1: Event studies with Stata

```
*! version 1.0 06/18/92
program define es
  version 3.0
  local options "BS(int 0) Caldt(real 0) Start(int 0) End(int
     0) BE(int 0) AE(int 0)"
  parse "`*'"

  capture drop event ashift bshift
  local i=_N
  local found=0
  local jl=0
  local ju=_N+1
  local ascnd=caldt[_N] > caldt[1]
  while (`ju'-`jl' > 1) {
    local jm=int((`ju'+`jl')/2)
    if((`caldt'>=caldt[`jm']) == `ascnd') {
      local jl=`jm'
    }
    else {
      local ju=`jm'
    }
  }
  local edate = `jl'
  di "Event date " caldt[`edate']
  local bevent=`edate'-`be'
  local aevent=`edate'+`ae'
  local edelta=`be'+`ae'+1
```

```
di "Event study on " "$S_FN"
di "Event window from " caldt[`bevent'] " To " caldt[`aevent']
di "   (" `edelta' " trading days)"
if (`bs' == 1) {
  di "   (testing for beta shift)"
}
if `caldt' == caldt[`edate'] {
  local lower=`edate'-`start'
  local upper=`edate'+`end'
  if(`bs'==1) {
    quietly {
    generate bshift=cond(_n>`edate' & _n<=`upper',ewretd,0)
       in `lower'/`upper'
    generate ashift=cond(_n>`edate' & _n<=`upper',1,0) in
       `lower'/`upper'
    }
  }
  generate event=cond(_n>=`bevent' & _n<=`aevent',1,0)
  di "Event study regression from " caldt[`lower'] " to "
     caldt[`upper']
  if(`bs' == 1) {
    regress ret event ewretd ashift bshift in `lower'/`upper'
  }
  else {
    regress ret event ewretd in `lower'/`upper'
  }
  drop event
  if (`bs' == 1) {
    drop bshift ashift
  }
}
else {
  di "Could not find " `caldt' " in the data"
}

end
```

Listing A.2: Event studies with SAS

```
options nonotes;
```

```
DATA ELIST;
  INFILE X;
  INPUT edate EPERM ELABEL $ 14-78;
  IF EDATE > 620000;

DATA _NULL_;
   SET ELIST END=LAST;
   CALL SYMPUT('MPERM'||LEFT(_N_), TRIM(EPERM));
   CALL SYMPUT('MLABEL'||LEFT(_N_), TRIM(ELABEL));
   CALL SYMPUT('MDATE'||LEFT(_N_), TRIM(EDATE));
   call symput('ldate'||left(_n_),
      put(input(put(edate,z6.),yymmdd6.),weekdate.));
   IF LAST=1 THEN CALL SYMPUT('NEVENTS',_N_);

%MACRO EXPPERMS(NUMBER, VAR);
%LOCAL I;
  &VAR in (
%DO I=1 %TO &NUMBER;
   &&MPERM&I
   %END;
   )
%MEND EXPPERMS;

%MACRO GETCNAME;
%LOCAL I;
%DO I=1 %TO &NEVENTS;
   IF PERM=&&MPERM&I THEN CALL SYMPUT('CNAME'||LEFT(&I),
      TRIM(NAME));
   %END;
%MEND GETCNAME;


Data tmpcname;
   set y.header;
   if %expperms(&nevents, perm);

proc sort data=tmpcname; by perm decending namedt;
proc sort data=tmpcname nodupkey; by perm;
DATA _NULL_;
   SET tmpcname;
```

```
    %GETCNAME;

DATA RET(KEEP=PERM RET T MISSING);

INFILE R MISSOVER;
RETAIN BEGRET ENDRET

INPUT @9 PERM IB4. @13 SEGMENT IB4. @ ;

  IF %EXPPERMS(&NEVENTS, PERM) THEN DO;
IF SEGMENT=1 THEN
  input @97 begret ib4. @101 endret ib4.;

IF SEGMENT = 11 THEN DO;
 FIRST=BEGRET+1;
 LAST=ENDRET-BEGRET+1;
 MISSING=1;
 DO IRET=FIRST TO LAST;
   IF IRET<=0 THEN IRET=1;
   AT=13+IRET*4;T=IRET+BEGRET-1;
   INPUT @AT RET RB4. @;
   IF RET <-9 THEN RET=.;
   IF RET=. THEN MISSING=MISSING+1;
   IF RET ^=. THEN MISSING=1;
   OUTPUT RET;
   END; END;
END;

DATA I; SET I.DATA; T=_N_; KEEP T CALDT EWRETD;

PROC SORT DATA=RET; BY T;
DATA RET; MERGE RET I; BY T; IF RET^=.; DROP T;
PROC SORT DATA=RET; BY PERM CALDT;


%MACRO REGRESS;
%DO I=1 %TO &NEVENTS;
  DATA _NULL_;
    SET RET;
    IF CALDT=&&MDATE&I AND PERM=&&MPERM&I THEN
```

```
        CALL SYMPUT('CDATE'||LEFT(&I),_N_);

    %DO J=75 %TO 125 %BY 25;
      %DO K=1 %TO 10;
         %LET UPPER=%EVAL(&K/2);
         %LET LOWER=%EVAL((&K-1)/2);

        DATA REGS;
    SET RET;
    IF PERM=&&MPERM&I;
    IF %EVAL(&&CDATE&I-&J)<=_N_<=%EVAL(&&CDATE&I+&J-1);
    IF(&&CDATE&I-&LOWER)<=_N_<=(&&CDATE&I+&UPPER) THEN
       EVENT = 1; ELSE EVENT = 0;

   PROC REG NOPRINT OUTEST=TMPEST COVOUT;
    MODEL RET=EVENT EWRETD;

   DATA _NULL_;
    SET TMPEST;
    IF _TYPE_='PARMS' THEN
      CALL SYMPUT('EVENTEST', EVENT);
    IF _TYPE_='COV' AND _NAME_='EVENT' THEN
      CALL SYMPUT('STE', SQRT(EVENT));

  DATA TMPRESLT;
     WINDOW=&K;
     TRADE=2*&J;
     ESTIM=&EVENTEST;
    T=&EVENTEST/&STE;
     P=(1-PROBT(ABS(T),(&J*2)-3))*2;

     IF P <= 0.01 THEN SIG="***";
     ELSE IF P <= 0.05 THEN SIG="**";
     ELSE IF P <= 0.1 THEN SIG="*";

  PROC APPEND BASE=RESULTS DATA=TMPRESLT; RUN;

  %END;
    %END;
```

```
PROC PRINT DATA=RESULTS;
   TITLE1 "EVENT STUDY FOR &&CNAME&I Perm: &&MPERM&I";
   TITLE2  "EVENT: &&MLABEL&I";
   TITLE3 "EVENT DATE: &&ldate&I";
   FOOTNOTE1 "* P<=.10   ** P<=.05   *** P<=.01";

   PROC DATASETS LIBRARY=WORK;
       DELETE RESULTS;
 %END;
 %MEND REGRESS;

%REGRESS;
```

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