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Publication Date

2004-03-01

CSEM
Center for the Study of Energy Markets

CSEM WP 128

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March 2004

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Technology Adoption and Regulatory Regimes: Gas Turbine Electricity Generators from 1980 to 2001

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March 2004

Abstract

We examine the adoption of gas turbine electricity generators by electric utilities and independent power producers from 1980 to 2001 in search of evidence of economic regulation inducing particular *type* of technology adoption and development. We focus on three major attributes of gas turbines - capacity, heat rate, and age - and two major economic regulatory regimes - vertically integrated utilities operating price-regulated monopoly franchises and independent power producers competing in restructured, wholesale electricity markets. We argue and demonstrate using sales data that the decade long move toward greater "deregulation" of the electricity industry in the U.S. has led to a stronger incentive for firms to adopt large capacity, heavy frame turbines well suited for combined cycle, baseload applications. This suggests that recent and current developments of "CCGT" technology are examples of economic regulation-induced innovation.

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1 Introduction

Economists have long hypothesized that the innovation process not only initiates but also responds to changes in the economic environment faced by firms. Most famously, Sir John Hicks hypothesized that relative factor prices can "induce" particular factor-augmenting technical change. In this study, we consider a different aspect of the economic environment that might induce innovation: economic regulation. By altering the manner in which firms compete against each other for the right to serve as well as the compensation for such service, changes in economic regulation can lead to firms seeking different types of production technology. This in turn can provide a "demand-pull" for certain types of innovation. We search for empirical evidence of such regulation-induced innovation by examining the adoption and development of different types of gas turbine electricity generators in recent decades, under different regulatory regimes.

There is a growing literature on the impact that regulation can and does have on both the innovation and diffusion of technology. Much of the empirical portion of this literature has focused on regulations that explicitly affect the technology adoption decision of firms; the regulation of focus often dictates improvement in some dimension of the production technology – notably environmental emissions.[1] For example, in the empirical literature on the relationship between environmental regulation and technology adoption, much of the studied environmental regulation tend to be of the "command-and-control" variety, ordering firms to reduce/limit harmful emissions by a set amount.[2] Thus, firms wishing to continue producing at current levels are compelled to adopt new technology that emit less. The empirical exercise at the heart of these studies is the measurement of the degree to which emission-abatement technology is adopted/innovated. The results from recent aggregate studies are suggestive – Lanjouw & Mody (1996) find a positive relationship between more stringent environmental restrictions and greater pollution control patents and Jaffe & Palmer (1997) find a similar relationship between environmental restrictions and R&D expenditures. More recently, Kerr & Newell (2003) find empirical evidence consistent with the conjecture that more market-oriented regulatory instruments (tradeable permits) may lead to more cost effective adoption of pollution control technology. These studies help form the foundation for the empirical evidence on regulation-induced innovation.[3]

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[1] See Jaffe, et al (2003) for an excellent overview of this literature

[2] There is also an analogous empirical literature on consumer goods and national standards. Notable examples include Greening, et al (1997), Goldberg (1998), and Newell, et al (1999). This study focuses on production technology adoption. We expect the technology adoption decision of firms and consumers to differ as consumers are ultimately their own "judge" while firms, in the end, serve consumers.

[3] "Regulation-induced" corresponds to what Kerr & Newell (2003) calls "policy-induced" innovation

While the regulations investigated in the above mentioned studies are largely "technology forcing" – dictating the nature of the change in technology adoption/innovation – economic regulation is, in contrast, a more blunt instrument. The regulation may help determine the level of competitive entry and the firm pricing/capacity decision, but does not necessarily indicate the type of technology that must be adopted.[4] The impact of such economic regulation on technical change is more indirect, channelling through various market and regulatory forces. Consequently, the manners in which a firm can respond to such regulation, technology-wise, are more diverse. The resulting type, as well as rate, of technical change will depend on the possibly unintended interaction of regulatory incentives and market forces.[5] Moreover, the impact of economic regulation on technical change touches up on another major theme in the economics literature: the impact of market structure on innovation. Given that economic regulation is often implemented to develop particular market structures – for example, the familiar utility structure of a price-regulated, vertically integrated monopoly – the manner in which economic regulation affects technical change will depend in part on the manner in which a particular market structure affects technical change. Thus, we would expect the evidence from studies on environmental regulation, while suggestive, would not be indicative of economic regulation.

Among the existing studies on technology adoption, there has been some empirical studies that have considered economic regulation, most notably Hannan & McDowell (1984) and Greenstein, McMaster, & Spiller (1995). However, these existing studies, like the studies on environmental regulation, have focused on the timing/rate of adoption of a major class of technology, with Hannan & McDowell studying automated teller machines in banking and Greenstein, et al, fiber optics in telecommunications. Consequently, we seek to complement these existing studies by examining the empirical relationship between economic regulation and the *type* of technology adopted. We believe that studying the adoption of gas turbine technology by utility and non-utility electricity generation firms over the past two decades provides us with an opportunity for such an investigation. The industry and time period are opportune as both the technology and relevant economic regulation underwent significant changes for this chosen industry and study period. Moreover, although we focus just on gas (combustion) turbine electricity generators, within this class of technology, firms face a wide array of choices, each offering a different bundle of product characteristics. As a result,

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[4] There are some exceptions where the economic regulation is bundled with environmental regulation. Prominently, the Public Utility Regulatory Policy Act (PURPA) of 1978 introduced limited competition into electricity generation but limited the type of generation technology that could be used by the new entrants.

[5] While much of the literature on environmental regulation-induced innovation has focused on rate of innovation, a notable exception is Newell, Jaffe, & Stavins (1999) study of consumer durables and energy efficiency standards. Following in their footsteps, we will also embrace a product-characteristic approach.

we can infer from this choice among different turbine models how economic regulation affects the relative value of various product characteristics of gas turbine generators.

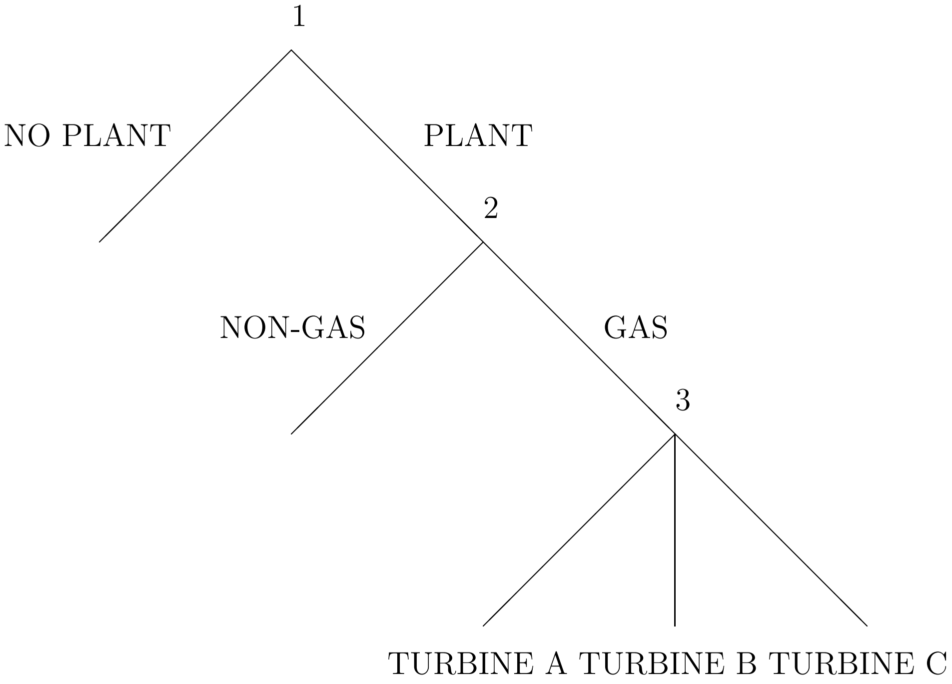
Furthermore, the focus on the electricity generation industry has the additional benefit of being a well-studied industry of significant policy interest. This allows us to draw from a rich, existing literature. The technology investment decision of *electric utilities* has been studied extensively, ranging from Peck (1974) on early turbogenerator sets to Rose & Joskow (1990) on supercritical coal-fired steam generators. Additionally, the issue of technical change under “rate of return” regulation in the electricity industry has attracted substantial study as well. Beginning with Nelson (1984) and as recently as Frank (2003), economists have estimated the *aggregate* production function of electric utilities, finding a negative impact of “rate of return” regulation on the rate of technical change. Our study can be considered an attempt to bridge these two existing literatures on the electricity generation industry. We explore the impact of the economic regulatory regime on technical change at the micro-level, using the individual firm technology adoption decision as our unit of study.

We conduct our study by relating observed differences in technology adoptions by regulated utility and non-regulated independent power producer to hypothesized differences in adoption incentives faced by the two types of firms. In section 2, we analyze the technology adoption decision of each type of firm, operating in its regulatory environment, and propose several hypotheses. In section 3, we examine the distribution of turbine sales by product characteristics. In section 4, we examine turbine sales by specific models. In section 5, we examine turbine sales by intended application. Through these various examinations of turbine sales and specification data, we conclude that recent, state-level restructuring of the electricity industry toward greater market-orientation has had a substantial impact on gas turbine technology adoption. The distribution of turbine sales shifts toward greater capacity, lower heat rate turbines during the late 1990s, a period during which most turbines were purchased by independent power producers. Moreover, this shift in sales distribution can be attributed to the increased popularity of modern heavy frame turbines well suited for the provision of baseload power in a combined cycle set-up. We argue that recent state-level regulatory restructuring is responsible for this increased popularity. Consequently, we raise recent developments in combined cycle gas turbine (CCGT) technology as examples of regulation-induced innovation in the electricity generation industry. Further implications of our study are discussed in the conclusion.

2 Technology Adoption Decision

The technology adoption decision of an electricity generation firm can be characterized as a sequence of three major decisions. The firm must first decide whether it wants to build a new power plant, either to increase capacity or replace retiring capacity. Second, assuming that the firm decides to build a new power plant, the firm must decide among several classes of basic fuel type / prime mover categories for the new power plant: coal boiler, gas turbine, nuclear, and – to a much lesser extent – hydroelectric and other renewables. Lastly, assuming that the firm decides to build a gas turbine based power plant, it must select the particular turbine model.

Figure 1



Influences of the regulatory regimes that affect the first two decisions can be considered as factors that largely have a “uniform” effect on gas turbine adoption: they make the firm more/less likely to adopt a gas turbine technology but does not substantially bias adoption toward any particular turbine model. Similarly, influences that affect the third decision would be “discriminatory” as it affects the relative value that generation firms place on one model over another.

Prominent examples of U.S. regulation that have affected the first two decisions include the Power Plant and Industrial Fuel Use Act (PIFUA) of 1978 and the Clean Air Act Amendments (CAAA) of 1990. The former regulation (PIFUA), motivated by foreign policy concerns surrounding the "Oil Crisis," severely limited the use of natural gas fuelled generators by electric utilities – effectively preventing the wide-spread adoption of gas turbines until the revocation of the regulation in 1987.[6] Thus, the regulation uniformly lowered adoption of gas turbines. The latter regulation (CAAA), which extended the Clean Air Act to cover power plant emissions, created a premium for "clean-burning" technologies. With natural gas turbines less polluting than generators driven by coal boilers, the Clean Air Amendments helped lower the cost of natural gas turbines vis-a-vis coal based technologies. Given the relatively limited variance in emissions among different gas turbine technologies, the impact of this regulation can also be considered uniform, providing a stronger incentive to adopt gas turbines on the whole. We leave the explicit study of such "uniform" effects of regulation on gas turbine adoption for later. The focus of this study is on the final decision, chosen from among the different turbine models.

Specifically, we examine how recent changes in economic regulatory regimes appear to have influenced turbine adoption along three major turbine characteristics: capacity, heat rate, and "age." These are the three main characteristics considered by the firm from an economic viewpoint.[7] Capacity refers to the maximum output of electricity that can be generated by the turbine. A smaller capacity allows for a more modular construction but per-unit capital cost is generally lower for larger capacity plants. Heat rate is a measure of the thermal efficiency of the turbine; it measures the fuel energy necessary to generate a standard amount of electricity.[8] Clearly, all else being equal, a firm strictly prefers a turbine with a lower heat rate; but a lower heat rate often comes at a cost with respect to other characteristics: for example, the turbine models (aeroderivatives) currently rated the most thermally efficient are also some of the smaller and newer turbines. Lastly, we consider "age" as a reflection of both the proven reliability of the model and the availability of complementarities, such as a large parts market. While newer models often exhibit better characteristics "on paper," they are also associated with greater performance risk and less support. Following the intuition of a hedonic model, we attribute the adoption of a particular model by an electricity generation firm as an indication of its preference over the product-characteristic space. Moreover, we argue that these preferences change depending on the incentives provided by the economic regulatory regime.

In particular, we focus on two main categories of economic regulatory regimes: the electric utility operating a geographic monopoly franchise under price regulation and the non-utility in-

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[6] There was also a similar directive by the European Community that restricted the use of natural gas in public power stations,effective from 1975 until 1987

[7] See Stephens (1997), with "age" approximating availability/reliability

[8] Usually, heat rate is measured as the amount of British thermal unit of fuel necessary to generate a single kilowatt-hour of electricity, i.e. Btu/kWh.

dependent power producer operating in a non-price regulated wholesale electricity market. For the U.S. experience, this corresponds to an examination of technology adoption across time and across states. Across time, electric utilities have slowly relinquished their hold on generation services beginning in 1978 with the passage of the Public Utility Regulatory Policies Act (PURPA). This shift from utilities to independent power producers accelerates in 1996 with the issuance of Federal Energy Regulatory Commission (FERC) Orders 888 and 889 and subsequent enactment of state comprehensive regulatory restructuring legislation. Consequently we might attribute some of the aggregate changes in technology adoption during the late 1990s to this shift in generation responsibility from regulated utilities to unregulated non-utilities. Across states, the amount of regulatory restructuring differs. Thus, we might expect technology adoption in a state that has enacted much more market-oriented restructuring, such as California, to represent technology adoption in the "new" regulatory regime than a state, such as Florida, that is much more entrenched in the traditional utility-based regulatory regime.

The economics literature does provide some wisdom as to why we would expect gas turbine adoptions to differ along the chosen characteristics across the two regulatory regimes. With respect to capacity, there is a sizable literature on capital cost and utility regulation, centered largely around the "Averch-Johnson" (A-J) effect, with the literature extended to analyze induced innovation by Smith (1974, 1975) and Okuguchi (1975). While the "naive" A-J model has been refuted, most notably in Joskow (1974), the basic intuition of the model may still be relevant: capital expenditure can be an instrument by which regulated utilities convince regulators to authorize higher electricity charges. Consequently, we might expect a regulated utility to be less sensitive to capital costs than a non-regulated independent power producer. Moreover, as Joskow (1997, p.125) argues:

> Once regulators approve the construction costs of a generating plant or the terms of an energy supply contract, these costs (amortized in the case of capital investments) continue to be included in regulated prices over the life of the investment or contract, independent of whether the market values of these commitments rise or fall over time as energy prices, technology, and supply and demand conditions change.

Thus, regulated utilities are afforded some protection from the consequences of bad capital expenditures – further insulating them from capital cost concerns. These arguments would seem to suggest that, *ceteris paribus*, regulated utilities would be more likely to adopt a modular construction involving smaller (higher per-unit capital cost) turbines than non-regulated, independent power producers. This leads us to our first proposition:

> **Proposition 1:** Electric utilities operating under price regulation are *more* likely to adopt *smaller* turbines than independent power producers serving non-price regulated wholesale electricity markets, *ceteris paribus*

A similar line of argument can be established for the case that regulated utilities are less sensitive to fuel costs, and hence less concerned about heat rates. With the wide-spread adoption of automatic fuel adjustment mechanisms (FAM) by 1980, regulated utilities were able to pass on higher fuel costs to consumers automatically.[9] While regulated firms (even non-regulated monopolies) have an incentive to lower operational cost, it would seem that this incentive would be weaker, compared to an independent power producer working in a regime where electricity prices are market-determined. All firms, whether regulated utility or non-regulated independent power producer, prefer a turbine with lower heat rate. However, the two types of electricity generation firms can differ in their willingness to pay/sacrifice for heat rate. For an independent power producer, a turbine with a lower heat rate not only translates into lower fuel costs but also provides some buffer against risks associated with both fuel cost volatility and competition. Regulated utilities are much less exposed to these two risks - as FAM provides insurance against fuel volatility and state regulators grant the utility a geographic monopoly franchise - and would presumably be less willing to pay for protection against such risks.

> **Proposition 2:** Electric utilities operating under price regulation are *less* likely to adopt *lower heat rate* turbines than independent power producers serving non-price regulated wholesale electricity markets, *ceteris paribus*

The economics literature is, perhaps, most informative with respect to the "age" component of the gas turbine adoption decision. The benefit of adopting a newer technology is subsumed in its better characteristics: lower heat rate, more affordable capacity. However, the benefit comes at an opportunity cost of forgoing the reliability and support associated with an older but "proven" popular model. The electricity generation industry places an emphasis on reliability. Advertisements for gas turbines proclaim the number of commercial operational hours associated with a model. The primary industry association for North American electric utilities, the North American Electric Reliability Council (NERC), publishes reliability statistics by power plant categories, including various sized gas turbine plants. While newer models may look better in terms of "specs," firms may be hesitant to adopt the new technology until the model is commercially proven. Furthermore,

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[9] See Gollop & Karlson (1978) and Clarke (1980)

by waiting until the model "matures," the generation firm may have access to improved parts and labor (human capital) markets associated with the new turbine model.

These factors, suggesting potential delays in new turbine adoption, could be considered examples of adoption costs that play a central role in game-theoretic models of technology adoption.[10] While the exact predictions of these models differ, a basic intuition shared by these models is that the early adoption of the new technology by one firm adversely affects the value of later adoption by other firms. Therefore, even though adoption costs fall over time, firms competing against other firms have an incentive to adopt the new technology earlier than a monopolist who does not have to worry about a "preemptive" adoption.[11] Given that regulated utilities operate in a *de jure* monopoly and independent power producers in a more competitive wholesale market, this would suggest that independent power producers would be more likely to adopt new gas turbines earlier than regulated utilities, *ceteris paribus.*

> **Proposition 3a:** Independent power producers are *more* likely to adopt *newer* gas turbines due to preemptive adoption incentives

However, this might be misleading as it only focuses on one aspect of the economic regulation (market structure). Other aspects may suggest differently.

One alternative aspect to consider is the impact of the economic regulatory regime on firm size. Following the pioneering work of Joseph Schumpeter (1942), many economists have both hypothesized and empirically investigated the proposition that larger firms are more likely to innovate and adopt new technology.[12] Most relevant for the electricity generation industry, Rose & Joskow (1990) find that, among U.S. electric utilities, larger firms were more likely to adopt the then-new supercritical coal-fired generation technology. Therefore, to the extent that one regulatory regime fosters larger firms, we might expect more rapid diffusion of new gas turbines in that regime. Unfortunately, it is not clear which, if any, of the two considered economic regulatory regimes supports larger firms. For similar markets, we would reasonably expect the electric utility to be larger, as the size of a monopolist is limited only by demand while demand is "shared" in a competitive market.[13]

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[10] See Reinganum (1981a,1981b) and Fudenberg & Tirole (1985)

[11] Although the marginal benefit of deferring investment – the reduction in adoption cost – is the same for both types of firms, the marginal cost differs as the firm in the non-monopoly market faces not only the foregone profits associated with early adoption but also the prospective cost of early adoption by a competing firm.

[12] See Cohen & Levin (1989)

[13] Technically, output is generally lower for a monopoly than a more competitive market; thus, it is possible for a monopolist to be smaller if the larger competitive output compensates for the smaller market share.

However, it is not clear that markets would be similar under the two regulatory regimes.[14] An examination of the sizes of current electric utilities and independent power producers does not resolve the issue either as much of the largest and smallest firms tend to be electric utilities.

Perhaps more importantly, the game-theoretic models mentioned above abstract away from a key aspect of the adoption of new gas turbine technology: each adoption of the new model lowers the cost of subsequent adoptions.[15] As firms purchase and operate the new gas turbine, the turbine logs more commercial operation hours that help resolve uncertainties associated with the new turbine. Moreover, this benefit from adoption can largely be considered a public good as it is difficult to hide such information from competitors.[16] Consequently, independent power producers competing in wholesale electricity markets may suffer from the "tragedy of the commons" and undervalue the adoption of a new turbine: independent power producers can appropriate the value of lower adoption cost from *their* subsequent adoptions but *not* from their *competitors'* subsequent adoptions. This is in contrast to electric utilities who - by virtue of the fact that they operate in legally separated markets - may be able to coordinate with each other such that the industry, as a whole, more fully appropriates the full benefits from early adoption.[17]

> **Proposition 3b:** Electric utilities are *more* likely to adopt *newer* gas turbines as they can better appropriate the benefit from early adoption

A prominent example of such coordination is the Electric Power Research Institute (EPRI). EPRI is funded by a consortium of U.S. electric utilities. Among their work include some of the earliest development and operation of gas turbines (especially combustion turbines in combined cycle units) that helped reduce adoption cost for member utilities. Consistent with the public goods argument raised above, Cohen & Sanyal (2003) find that funding for EPRI falls with the spread of regulatory restructuring throughout the United States.[18] With growing market-oriented regulatory restructuring of the industry, electric utilities are less able to appropriate the benefit of early adoption and, hence, less willing to coordinate on such early adoption.

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[14] For example, in California, independent power producers operating in the recently developed wholesale electricity market (California PX) compete for the entire state. But electric utilities, prior to restructuring, served only parts of the state, with Pacific Gas & Electric (PG&E) and Southern California Edison (SCE) roughly splitting the state.

[15] In the game-theoretic models cited earlier, the evolution of adoption costs is assumed to be exogenously given.

[16] This argument is akin to the argument in Arrow (1962) that cost of innovation depends not on individual but industry experience. Also, Hirsh (1989) documents the open flow of information among U.S. electric utilities

[17] This corresponds to a situation like "collective innovation," as proposed by Allen (1983). Also, a similar argument was made by the defense during the 1982 AT&T antitrust case, Noll & Owen (1994)

[18] It should also be noted that the authors find a decrease in overall R&D expenditure as well. This larger trend would be consistent with an extended version of the public goods argument raised in this study.

The conventional wisdom in the current economics literature make clear suggestions as to the difference in incentives facing regulated utilities and non-regulated independent power producers along capacity and heat rate. However, the literature is less clear with respect to age. While market competition provides incentives for preemptive adoption, competition also undermines the ability of early adopters to appropriate the full societal benefit of early adoption. In the next section, we empirically investigate these propositions by examining the distribution of turbine sales during the 1980s and 1990s. Using the idea that market-oriented restructuring is much more wide spread later in the period, we associate changes in these aggregate sales to changes in the economic regulatory regime.

3 Distribution of Turbine Sales

A commonly made statement about gas turbines during the studied period is that market-oriented regulatory restructuring, in conjunction with falling natural gas prices, has spurred the development of gas turbines, especially combustion gas turbines used for combined cycle applications.[19] Figure 2 illustrates the stylized fact that motivate much of this statement: in the U.S., non-utilities eclipse utilities in terms of aggregate investment in combined cycle units. Although not shown here, the share of overall capacity that is combined cycle or, more generally, natural gas-fuelled, is also much larger for non-utilities, with the difference growing over the 1990s. Some industry observers have concluded from this data that non-utilities have a stronger incentive to adopt the "newer" gas turbine models than their utility counterparts.

This conclusion can be misleading. As raised in Schmookler (1966) and empirically demonstrated for the case of electric utilities in Rose & Joskow (1990), it is important to control for the *opportunity* to adopt when making any conclusion about the incentive to adopt new technology. In many industries, including the electricity generation industry, technology is embodied in a capital good. Consequently, the decision to adopt a new technology can be confounded with the decision to invest in a capital good. Electric utilities may not be observed adopting the new technology not because they face different technology adoption incentives but rather because they face different capital investment incentives from independent power producers. In terms of Figure 1, this corresponds to the need to control for the decision at the first (whether to build new capacity) and second (whether to choose natural gas over other fuel sources) nodes, in order to analyze the decision at the final (which turbine model) node.

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[19] Combined cycle refers to electricity generation units where the waste heat from the primary generator is used to drive a secondary steam turbine – thus increasing the overall thermal efficiency of the combined unit.

Ideally, we would propose and estimate an empirical model that incorporated all three components of the gas turbine adoption decision, in unison. We plan such an analysis for a subsequent study. For the purpose of this study, we address the need to control for adoption opportunity by examining data on realized gas turbine transactions only – observations where the firm is observed buying some type of gas turbine electricity generator. The key variation is the variation in the turbine model actually bought by the firm and not the more discrete 0-1 variation of whether the firm bought a gas turbine generator. Naturally, this raises some concerns about sample selection: by selecting on just firms that bought gas turbines, we might be biasing the sample by systematically selecting along some other, unintended factor influencing technology adoption. For example, if natural gas is a more available fuel in some regions than others, we would expect the sample to consist mainly of purchases by firms from those regions.[20] To the extent that there are important, uncontrolled regional differences that affect gas turbine adoption, the analysis would confuse the effect of our variables of interest with the unaccounted regional effect. While this is a valid concern, we believe it is less so for the main empirical purpose of this initial study: the establishment of stylized facts that characterize gas turbine adoption during the 1980s and 1990s. In comparing these stylized facts with our earlier propositions, we seek to motivate further inquiries, rather than conduct a formal verification of these propositions.

The turbine sales data we use is obtained from the industry standard, "Gas Turbine World" (GTW), published by Pequot Publishing. The publication issues an annual "Handbook" that contains, among other things, information on gas turbine transactions and the design specifications of gas turbine models. The Data Appendix provides a more complete discussion of the data. However, it is important to note a drawback of the data: transaction data are listed for the previous 12-40 months, depending on the volume. Unfortunately, this implies that some of the transactions listed for one volume may be re-listed in subsequent volume(s). Due to difficulties eliminating these duplications, we report the data from each volume as is. Therefore, given that the coverage period varies by volume, the "year" attributed to a data series in the following figures refers to the publication (volume) year and not the transaction year. For these initial figures, we limit confusion from duplicate entries by examining data from volumes published five years apart.

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[20] Alternatively, some regions may be experiencing more rapid electricity growth - and, thus, greater need for additional generation capacity.

3.1 Trade-offs across Turbine Characteristics

A key aspect of gas turbine technology is the lack of a strict quality ordering across the turbine models: with most models having some advantage over other models. Formally, this translates into a statement that product differentiation in gas turbines is better characterized by horizontal than vertical differentiation. The adoption of a turbine with an improvement in one product characteristic usually necessitates a sacrifice in some other characteristic – creating differences in turbine preference ordering across firms depending on their priorities in product-characteristic space. We describe these trade-offs in product characteristics through a series of scatter plots.

Figures 3a-3e plots the heat rate against capacity for turbine models represented in the worldwide sales data during the indicated volume year.[21] Capacity is measured in megawatts (MWs) and heat rate in British thermal units per kilowatt-hour (Btu/kWh). A linear regression line is also fitted through the scatter plot for heuristic purposes. The figure shows that gas turbines exhibit weak economies of scale, with heat rate roughly decreasing with capacity. However, it is clear that such economies of scale are exhausted by the 1990s. During the latter part of the study period, two technology paths appear to develop. In one, capacity expands beyond 300 MWs but heat rate plateaus at 9000 Btu/kWh. In the other, heat rate drops to 8000 Btu/kWh but capacity is limited to 50 MWs.

The emergence of these two technology paths may be attributed to inter-firm differences in the importance of capital costs vis-a-vis fuel costs. Table 1 depicts the results from a series of simple price regressions ran on turbine price (nominal $ per kilowatt) against capacity (kilowatts) and heat rate (Btu/kWh). We run the regression for the case where all the coefficients are allowed to differ yearly as well as the pooled case where the coefficients before capacity and heat rate are constrained to be the same ($\beta_{1t} = \beta_1,\ \beta_{2t} = \beta_2\ \ \forall\ t$). Here, the reported year does roughly correspond to the transaction year.

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[21] We include only models actually sold during the period in order to eliminate obsolete models that appear in the catalog but are not really being marketed any longer.

Table 1: Gas Turbine Unit Price Regression

Per Unit Price $_{it} = \beta_{1t} + \beta_{2t}$ Capacity $_{it} + \beta_{3t}$ Heat Rate $_{it} + \epsilon_{it}$

	Gas Turbine World Handbook Volume (t)								
Variable	1988	1992-93	1995	1996	1997	1998	1999-00	2000-01	Pooled
Constant	271.32	134.48	133.41	93.32	443.12	55.72	42.72	81.22	varies
(β_{1t})	136.76	109.41	55.96	56.35	131.00	52.65	58.61	46.67	
Capacity	0.0081	0.0246	0.0267	0.0316	-0.0077	0.0338	0.0348	0.0300	0.0299
(β_{2t})	0.0124	0.0096	0.0047	0.0048	0.0129	0.0045	0.0049	0.0041	0.0020
Heat Rate	-0.0015	-0.0012	-0.0011	-0.0012	-0.0009	-0.0009	-0.0009	-0.0008	-0.0010
(β_{3t})	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
R^2	0.6443								0.6288

Price is in \$/kWh, heat rate in Btu/kWh, and capacity in kW

Standard error is given below parameter estimate; N = 597 for full sample

We prefer not to stress the price regression too strongly as: [1] the prices are the prices quoted to the publishers of GTW [2] actual transaction prices for a given model vary substantially across firms and regions and [3] the regression does not control for important time variant factors, such as demand. However, we believe two important conclusions can be drawn from the regressions.[22] First, as alluded earlier, per unit capital costs are lower for larger capacity turbines. The significant and substantial negative coefficient before capacity corroborates this standard industry claim. This would suggest that the two different technology paths embody different trade-offs between capital cost (capacity) and fuel costs (heat rate). The firm interested primarily in lowering capital cost would prefer the "top" technology path while the firm interested primarily in lowering fuel cost would prefer the "bottom" path. This fork in the technology development may very well be an outcome of this divergence in preferences among electricity generation firms.

Second, the "prices" for heat rate and capacity seem stable, especially during the latter half of the 1990s. The coefficients before heat rate and capacity neither substantially nor significantly vary across years. The standard F-test and χ^2 tests of the null hypothesis that the yearly heat rate and capacity coefficient values are equivalent to their constrained values (from the pooled regression) cannot be rejected at any conventional significance levels.[23] This suggests that the relative price attached to firms achieving certain points on the product-characteristic space has been fairly constant during the 1990s. A 1 megawatt (1000 kilowatts) increase in the capacity of

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[22] We interpret the price regressions not as true hedonic regressions but rather as estimates of the best linear predictor (BLP) of turbine price given capacity and heat rate. Given that the purpose of the regression is to illustrate the within-sample relationship between price and (capacity, heat rate), we feel that the BLP interpretation is appropriate. See Goldberger (1991).

[23] This can be verified simply by examining the R^2 associated with each regression.

the turbine is generally associated with a \$1 decrease in the per kW unit price of the turbine while a 100 Btu/kWh improvement (decrease) in heat rate is associated with a \$3 decrease in the per kW unit price of the turbine. Given this apparent stability in the "prices" for capacity and heat rate, we feel confident that (at least for the 1990s), informative comparisons of technology adoption across time can be done without explicitly accounting for turbine prices.[24]

The major turbine characteristic that is omitted in the hedonic price regression is age. This omission helps explain the surprising positive coefficient before heat rate in the hedonic regressions.[25] Heat rate is correlated with age, as newer turbines are associated with lower heat rates. A standard industry practice is to offer initial price discounts for new ("unproven") turbine models in order to encourage early adoption that can "demonstrate" the turbine to the industry. Therefore, the positive heat rate coefficient may be reflecting this initial price discount. The omission of age from the regression is a consequence of the lack of a readily available measure of age, relevant for our purposes. The Gas Turbine World Handbook does provide the commercial introduction year for most of the reported turbine models. However, constructing age based on this information is problematic given the precise definition of models used by GTW. For example, GTW reports the General Electric gas turbine package PG7241(FA) as having a commercial introduction year of 1994 despite the fact that the model is largely based on the MS7001 design that has been around since 1970 and, more specifically, the PG7200 series of major uprates introduced in 1988.[26] The 1994 date refers to the last moderate uprate of the model. For our purposes, the more relevant year would be 1988, as 1988 (or possibly 1970) is a truer indication of the proven reliability and familiarity of the turbine. We are currently in the process of constructing a better measure of age.

But for this study, we present Figures 4a-4e which plots heat rate against age (defined as AGE = Volume Year − GTW Commercial Start Year − 1) for the same set of turbine models as in Figures 3a-3e.[27] The Figures show that, as expected, heat rate is generally lower for newer turbines. Perhaps more interesting, the figures also show the introduction of a substantial number of new turbines during the early 1990s, consistent with a turbine manufacturer supply response to the sudden increase in demand associated with the repeal of the Power Plant & Industrial Fuel Use

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[24] The overall price for turbines have steadily increased during the period, but the increase has been comparable (if not a bit less) to the overall increase for manufacturing – based on comparing the producer price indices for SIC 3511 (Turbines and Turbine Generator Sets) and total manufacturing industries, U.S. Bureau of Labor Statistics

[25] The two conclusions drawn from the price regressions are robust to the inclusion of the "age" variable adopted later for the age vs. heat rate scatter plots

[26] MS7001 historical information is courtesy of GE Power Systems document GER-3571H

[27] The observations with "negative" age correspond to models that have been sold as prototypes, prior to their official commercial introduction.

Act in 1987 and the significant fall in natural gas prices in 1985. Furthermore, the new turbines seem to correspond to models from both the "top" and "bottom" technology path in the heat rate vs. capacity plots. However, as will be demonstrated later, the turbines from the "top" path are mostly moderate uprates of long-existing turbine designs while the turbines from the "bottom" path represent more substantial recent developments.

3.2 Distribution of Turbine Sales by Capacity

We now examine how the distribution of sales across these turbine models change over time. Figure 6a graphs the distribution of world-wide turbine sales by capacity for the following five chosen GTW Handbook volumes: 1980, 1985, 1990, 1995, 2000. The densities are smoothed for aesthetic reasons, using the Epanechnikov kernel and bandwidth chosen according to Silverman (1986). We focus on world-wide sales as we expect turbine innovation and development to respond to total sales, rather than U.S. sales. However, the distribution for just U.S. sales are qualitatively similar – mainly because the U.S. constitutes the largest national market for gas turbine electricity generators.[28] For the volumes 1980, 1985, and 1995, we find that turbine sales are concentrated on models with capacity less than 50 MWs. This is not a surprising result for volumes 1980 and 1985 as they correspond to sales from 1979 and 1983-1984, respectively – years characterized by the high relative cost of natural gas and the enactment of the Power Plant & Industrial Fuel Use Act in the U.S. These two factors clearly hamper the feasibility of large natural gas based generation capacity, limiting any gas turbine purchase to a few small units. Similarly, the 1995 result might be attributable to a bump in natural gas prices during 1993.[29]

In contrast, volumes 1990 and 2000 show a more dispersed sales distribution, with significant mass for models with capacity larger than 100 MWs. The 1990 volume reports sales from January 1988 to June 1989, corresponding to the period right after the repeal of the Power Plant & Industrial Fuel Use Act and the natural gas price crash. Consequently, it is reasonable to think that the 1990 turbine sales reflect a "pent-up" demand for natural gas capacity, held in check during earlier years by a combination of U.S. regulation and high natural gas prices. The return of turbine sales to much smaller turbine models by the mid-1990s (volume 1995) also corroborate such a rationale. The 2000 volume corresponds to sales from January 1999 to June 2000. By the end of 1998, 12 states – including California, New York, and Pennsylvania – had enacted comprehensive electricity

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[28] The histograms capturing these U.S.sales distribution available on request

[29] See "Historical Natural Gas Annual - 1930 to 2000" published by the Energy Information Administration, available at http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/nat_data_publications.html

restructuring legislation or regulatory orders, with an additional 11 states following suit in 1999. Internationally, the United Kingdom, Australia, and Argentina have adopted similar electricity restructuring and liberalization policies. Therefore, the volume 2000 sales data reflect a period during which a substantial amount of the electricity supply responsibility has been shifted from price-regulated electric utilities to non-price-regulated independent power producers. The increase in sales of larger capacity turbines is consistent with Proposition 1 – with independent power producers purchasing the larger capacity turbines in order to reduce capital costs.

A possible alternative explanation is technical change: the choice set available to firms changed significantly between the time periods covered in volumes 1995 and 2000. But this alternative is unlikely given the distribution of sales from volumes 1997 and 1998. As shown in Figure 6b, there is no "bump" in gas turbine purchases in the 150-200 MW category in volumes 1997 (January 1995 - December 1996) and 1998 (January 1996 - December 1997), as there is for volumes 2000 (January 1999 - June 2000) and 2001 (January 2000 - June 2001) – despite the fact that the same 150-200 MW turbines were available throughout the entire period. The few notable differences in the choice set from 1995 to 2000 are associated with the introduction of much higher capacity and much lower heat rate models (corresponding to leaders in the two heat rate vs. capacity technology paths). A *caveat* to this finding is age: a turbine model available in 1997 may have the same capacity and heat rate in 2000 but still be a "different" model due to its younger age. We believe, for this instance, that the five year difference in age from volumes 1997 to 2000 is not substantial; while the two models that make up most of the 150-200 MW capacity sales have commercial introduction years of 1989 and 1994, respectively, each is based on a basic design that has been around since at least the early 1980s.[30]

Seemingly, the only difference in the time periods associated with volumes 1997-1998 with 2000-2001 that might explain the difference in distribution is the arrival of more substantial regulatory restructuring. Although a more disaggregated examination that confirms that independent power producers are, indeed, the major purchasers of the 150-200 MW capacity turbine is needed, Figure 6a is our first stylized fact suggesting that economic regulation alters the incentives driving technology adoption.

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[30] The two models are the General Electric MS7001FA and the Siemens W501F

3.3 Distribution of Turbine Sales by Heat Rate

Figure 7a graphs the distribution of world-wide turbine sales by heat rate for the 5 chosen GTW Handbook volumes. The Figure shows the distribution shifting left over time, with most sold turbines achieving heat rates below 11,000 Btu/kWh by 2000. Although this stylized fact is consistent with Proposition 2, there are other, possible factors that can explain this result as well. One such factor is technical change; but technical change is unlikely to be a major explanation for much of the same reasons as in the earlier capacity analysis. A more compelling factor is the price of natural gas. Natural gas prices spiked sharply during 1999.[31] To the extent that firms believed this higher price to be persistent, the natural gas price spike could have induced firms to value heat rates more, apart from any impact of regulatory restructuring.

In order to investigate the degree to which the price spike might explain the shift in distribution, we seek to compare the sales distribution for two periods between which there was a similarly significant change in natural gas price but no major regulatory restructuring. A similar increase in natural gas prices occurred between 1980 and 1983, with prices remaining at the high level until 1985. The data shows no really discernible difference in the sales distribution during this period, as reflected in the volumes 1980 and 1985 distributions in Figure 7a. But very few gas turbines were being bought during this period, in part due to the Power Plant and Industrial Fuel Use Act. A slightly moderate increase in natural gas prices occurred between 1995 and 1997. Figure 7b depicts the sales distribution for volumes 1997 and 1998, which span the years 1995-1997. Unfortunately, volumes 1997 and 1998 both contain all the transactions that occurred during 1996. Moreover, natural gas prices had fallen by 1998. Consequently, the sales distribution for 1997 and 1998 can look similar even if the natural gas price had a real effect. This implies that while we find no strong evidence of a natural gas price effect, we cannot rule it out. Therefore, we can only claim that Figure 7a provides weak support for Proposition 2 – until the impact of the natural gas price spike can be properly accounted.

In addition to the shifting of the distribution, another prominent aspect of Figure 7a is the concentration of sales in three tight heat rate categories for volume 2000. The three peaks characterizing the sales distribution for volume 2000 center around 8500, 9500, and 10,500 Btu/kWh. Given that a lower heat rate is a normal good, desired by firms in both regulatory regimes, the presence of these peaks suggest three "sweet-spots" in product-characteristic space, with the firms purchasing turbines in the 9500 and 10,500 Btu/kWh range doing so in order to gain along some

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[31] U.S. electric utilities were paying around \$3 per 1000 $(ft)^3$ at the beginning of the year but nearly \$4 per 1000 $(ft)^3$ by the end of the year

other turbine characteristic. As will be discussed in more detail later, the 9500 Btu/kWh turbines are, among the three, the ones with the most capacity and the 10,500 Btu/kWh turbines are, among the three, the ones introduced the earliest ("oldest").

3.4 Distribution of Turbine Sales by "Age"

Figure 8a graphs the distribution of world-wide turbine sales by "age" for the 5 chosen GTW Handbook volumes. "Age" is defined as before: AGE = Volume Year − GTW Commercial Start Year − 1. The interpretation of the sales distribution by age is, perhaps, the most difficult of the three sales distributions by product characteristic as the essence of the characteristic necessitates change in sales distribution over time. Even if the set of available gas turbines was the same and firms faced the same incentives, we would expect to see the distribution change – the distribution would shift right, but not necessarily uniformly as the marginal benefit of age may not be constant. Consequently, the "natural" progress of the age sales distribution needs to be distinguished from changes that are regulation-induced. Further complicating the identification of the regulated-induced age effect is the arrival of new models and retirement of old models that can alter the sales distribution without any change in technology adoption incentives.

This difficulty in identification is reflected in Figure 8a: it is difficult to discern any substantial trend or result from the figure. This may also be a reflection of the chosen method of measuring age, as alluded earlier. One result that does appear in Figure 8a is the relative lack of sales for new/prototype turbines (Age $\leq$ 2) for volume 2000. But this may be largely explained by the relative lack of new model introductions during the period. Without the introduction of new models, a firm cannot choose to buy a "young" technology. This is further corroborated by the larger market share for new/prototype turbines for volumes 1980 and 1995 – time periods characterized by the introduction of several major new models. Figure 8a also suggests that the most popular models in volume 2000 were either not available or were not as popular in earlier years. Much of the volume 2000 sales are for models aged 3-10 years old – models that were commercially unavailable for volumes 1980 and 1985 and less popular for volumes 1990 and, to a lesser extent, 1995.

To investigate these results further, we graph the distributions for volumes 1997, 1998, and 2001 in Figure 8b. Interestingly, Figure 8b, well as Figure 8a, shows that turbine models become commercially obsolete after 15-20 years. Given that there were few new model introductions between the 1997-1998 volumes and 2000-2001 volumes (and none major enough to initiate substantial obsolescence), this suggests that age has an eventually diminishing marginal value that might even become negative. The negative marginal value might be due to the decision of the manufacturer to curtail support for much older (and presumably less profitable) models. But more relevant for the main research goal of this study, Figure 8b indicates that the much of the popular models in volumes 2000-2001 are of similar vintage as those popular in volumes 1997-1998: the main peak for 1997-1998 is to the right of the main peak for 2000-2001 by 2-3 years. This signifies that the sales distribution for volumes 2000-2001 does not provide an endorsement for either Proposition 3a or 3b, as the major changes in economic regulation in the U.S. occurred between 1996 and 1999. This is not surprising as the economics literature itself is inconclusive about the net effect of regulatory restructuring on age preferences. We would find convincing evidence in the sales distribution only if one of the two propositions was much more relevant than the other.

4 Turbine Models: Aeroderivatives and Heavy Frames

The examination of the sales distribution by different product characteristic yields some suggestive evidence supporting Propositions 1 and 2. The examination also shows how much of the turbine sales for volume 2000 are concentrated in three areas of the capacity - heat rate - “age” product characteristic space. In this section, we examine the identity of the firms that inhabit each of these three areas. Conveniently, but not surprisingly, the three favored areas of the product characteristic space conform largely to three different turbine models produced by the industry leader, General Electric: the LM6000, MS7001EA, MS7001FA. Therefore, we focus our attention on sales transaction for these three models. While there are important models offered by competing manufacturers, we avoid possible manufacturer-specific quality differences by considering just the General Electric (GE) models. For example, the major excluded model is the W501F manufactured by Siemens-Westinghouse. The W501F is based on the same design principle as the MS7001FA but, in standard specification, report slightly better heat rate and capacity. The 2000-2001 GTW also reports W501F as being slightly cheaper: $199 per kW versus $239 per kW. Yet, the GE MS7001FA is by far much more popular, especially in the U.S. There is some evidence that this could be because of reliability considerations.[32]

The MS7001EA and MS7001FA belong to the major technology category known as “heavy frame” while LM6000 belong to the much newer “aeroderivative” category. Although all gas turbines are essentially derived from aeronautics technology, the aeroderivatives are literally the aircraft engines used to power military air transport, adapted for electricity generation. This is in contrast to the heavy frames which are designed and built with ground power in mind. This ex-

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[32] See GER-4194

plains one of the major differences in the two technologies: capacity. The heavy frame generators can achieve capacity over 300 MWs but the aeroderivatives are limited to 50 MWs. Although there are important design constraints, the capacity limitation of the aeroderivatives is largely driven by the need to keep production cost down by making the aircraft engine and the aeroderivative engine interchangeable. Although limited in capacity, the aeroderivatives excel in two other dimensions: they are both smaller and lighter and achieve significantly lower heat rate (in single cycle) than their heavy frame counterparts. Therefore, aeroderivatives are modular, easier to install and replace, and more thermally efficient. However, they are also more expensive (capital cost) and less proven/reliable given their relative newness.[33]

In terms of the patterns observed in the sales distribution, the aeroderivative LM6000 corresponds to the sales in the 8500 Btu/kWh, 0-50 MW, age 0-5 years category. So the LM6000 corresponds to the "bottom" technology path in the capacity vs. heat rate plots. The MS7001EA and the MS7001FA correspond to different spots on the "top" technology path. The MS7001EA correspond to the sales in the 10,500 Btu/kWh, 50-100 MW, 15-20 years category and MS7001FA to the sales in the 9,500 Btu/kWh, 150-200 MW, 5-10 years category. Therefore, among these three popular GE models, the LM6000 is the most thermally efficient, the MS7001FA the largest capacity, and MS7001EA the oldest. Very simplistically, this implies that firms that place priority on heat rate would prefer the LM6000, on capacity MS7001FA, and on "age" MS7001EA. We investigate who such firms may be by examining the distribution of sales for these three models by firm type for volumes 1995, 1997, 2000, and 2001.

4.1 Market Shares

Table 2 depicts U.S. turbine sales for each of the three models.

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[33] Cohn & Scheibel (1997)

Table 2: U.S. Turbine Sales for Select General Electric Models

	Specifications[1]			Turbines Sold[2]			
Model	Start Year	Capacity	Heat Rate	1995	1997	2000	2001
MS6001B	1978	40 MW	10,650 Btu/kWh	8	2	7	22
MS7001EA	1984	85 MW	10,430 Btu/kWh	20	8	99	66
MS7001FA	1994	172 MW	9,360 Btu/kWh	4	8	249	153
LM6000 (various)	1992/1997	44 MW	8,538 Btu/kWh	28	9	109	130
Total (incl. non-GE)				196	102	721	559

[1] Specifications are "representative" and are provided for rough comparison purposes only

[2] Years listed are GTW volume years

The table shows that gas turbine electricity generator sales were much higher after the enactment of substantial state-level regulatory restructuring (volumes 2000, 2001) than before (volumes 1995, 1997). This basic phenomenon in the data might be explained by the presence of uniform effects raised earlier, as well as a consequence of the resolution of some regulatory uncertainty associated with the timing of restructuring.[34]

A second, prominent phenomenon in the table is the substantial increase in popularity of the MS7001FA model in the later, more restructured period. Excluding some very small (1-2 MW) mobile generators, LM6000 and MS7001EA were, by far, the two most popular turbine generators sold in the U.S. during the 1995 volume year.[35] Sales were much more dispersed over the models during the earlier years. However, by the late 1990s, the MS7001FA overtakes these two models and becomes the dominant model, sales-wise – accounting for 1 in every 3 gas turbine generator sold in the U.S. in the 2000 volume (and 1 in 4 for the 2001 volume). Sales overall becomes much more concentrated on a few, heavy frame models, with the MS7001EA, MS7001FA, and the Siemens-Westinghouse W501F accounting for over half the turbine sales in the 2000 volume. This translates the basic results found in the sales distribution in terms of actual turbine models. The increase in popularity of the MS7001FA explains both the shift in sales distribution toward 150-200 MW turbines and the shift toward better heat rate from 1997-1998 to 2000-2001, as firms de-emphasized the older, smaller heavy frame models (10,500 Btu/kWh) for the newer, larger, and more thermally efficient MS7001FA (9,500 Btu/kWh).

Despite the popularity of the MS7001FA, some of the older heavy frame models, notably the MS6001B and the MS7001EA, continue to be commercially viable; this is in spite of MS7001FA's

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[34] See Ishii & Yan (2003) for a study on the impact of regulatory uncertainty on generation investment post-1996

[35] For our purposes, we lump together the various LM6000 packages: LM6000, LM6000PC, LM6000 Sprint, LM6000 PC Sprint. All of these packages exhibit similar capacity and heat rate. But they differ in commercial introduction year: the original was introduced in 1992 while the later packages around 1997.

superior "on paper" specifications. Part of the commercial viability of these older heavy frame models may be due to particular capacity size needs of turbine consumers; but another important factor appears to be reliability. The MS7001FA that incorporates the new F-class turbine technology has been marred with reliability problems that have kept both the average capacity and availability factors below initial expectation.[36] Similar issues also troubled the MS7001EA during its initial years. This stresses the importance of proven reliability as a turbine characteristic for electricity generation firms. The capacity and heat rate advantages given up by adopting an older heavy frame model is compensated by greater proven reliability.

4.2 Sales by Firm Type

Tables 3a-3c classify sales for each of the three highlighted General Electric models by "type" of purchasing firm: electric cooperatives (COOP), industrial consumers (IND), independent power producers (IPP), municipal utilities (MUNI), and private utilities (UTIL).[37]

Table 3a: U.S. Turbine Sales for LM6000

	Turbines Sold[1]			
Firm Type	1995	1997	2000	2001
COOP			3	12
IND	5			
IPP	12		84	83
MUNI	5	4	1	2
UTIL	4	5	21	33
TOTAL	28	9	109	130

[1] Years listed are GTW volume years

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[36] See Cohn & Scheibel (1997) and Swanekamp (2003)

[37] For some years, the sum across the five types will be less than the total. This is because [1] there were some purchasers, such as the Tennessee Valley Authority, that did not fall into the five types and [2] for some transactions there were insufficient information reported in GTW for a proper classification

Table 3b: U.S. Turbine Sales for MS7001EA

	Turbines Sold[1]			
Firm Type	1995	1997	2000	2001
COOP				5
IND	2			
IPP	4	2	78	34
MUNI		1	1	
UTIL	14	5	20	16
TOTAL	20	8	99	66

[1] Years listed are GTW volume years

Table 3c: U.S. Turbine Sales for MS7001FA

	Turbines Sold[1]			
Firm Type	1995	1997	2000	2001
COOP			2	4
IND	1		3	4
IPP	2		161	117
MUNI		1	2	
UTIL	1	7	81	27
TOTAL	4	8	249	153

[1] Years listed are GTW volume years

These sales tables confirm that the explosion in turbine sales between the less and more restructured periods can be attributed to the increased purchasing activity of independent power producers. Although not explicitly shown here, the sales of turbines during the earlier periods (1980-early 1990s) were dominated by utility purchasing. In contrast, during the latter periods, independent power producers account for the majority of turbine purchases, as exemplified in the tables above. Consequently, it is fair to attribute the shift in sales distribution reported earlier to the difference in purchasing decisions by utilities during the earlier years and independent power producers in the more recent years.[38] An apparent *caveat* to the above statement is that recent utility turbine purchases seem to mimic those of independent power producers, albeit at an overall lower level. This would suggest that any change in turbine adoption incentives brought about from regulatory restructuring have had a similar impact on both utilities and independent power producers.

However, this is misleading as the utilities purchasing the MS7001FA are markedly different from the "traditional" utilities imagined in the development of the earlier propositions. Of the 81 MS7001FA turbines bought by utilities, 18 were purchased by utilities operating in states that had already enacted restructuring legislation and an additional 46 by utilities owned by holding companies with sizable independent power producing subsidiaries. The 18 utilities operating in states with restructuring legislation correspond to Dominion-Peoples, Public Service Electric & Gas, and Virginia Power, which operate in Illinois, New Jersey, and Virginia, respectively.[39] Although these utilities face some differences in turbine adoption incentives - given that they can "hedge" some of their investments with their own wholesale electricity demand - their incentives are much more aligned with independent power producers as they serve the same, non-price regulated wholesale market. The 46 turbines bought by utilities with sizable independent power producing subsidiaries

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[38] Of course, the choice set faced by each firm differs depending on year

[39] Illinois enacted HB362 in December 1997, Virginia enacted HB1172 in April 1998 and SB1269 in March 1999, and New Jersey enacted A10/S5 in February 1999

correspond to Carolina Power & Light, Southern Company, and Florida Power & Light. While the regulated utility company is technically operated separately from the independent power producing subsidiary, there are important transfers that can and do take place between the two units of the same parent company – such as the sharing of information/skills gained from operating a particular turbine model. Interestingly, in the same 2000 volume, we find the independent power producing subsidiary of Southern, Florida Power & Light, Dominion, and Public Service Electric & Gas purchasing 57 turbines.[40] Positive externalities between the regulated utility and associated non-regulated independent power producer would suggest that these utilities, too, have incentives more aligned with those of independent power producers.

The exclusion of these "co-aligned" utilities reveals a utility turbine purchasing pattern across the three GE models for volume 2000 that is fairly similar to volume 1997. This suggests that the increased interest in MS7001FA may be attributed to the incentives faced by independent power producers, operating primarily in restructured states. Therefore, explaining the recent popularity of the MS7001FA among independent power producers may help further illuminate the impact of restructuring on the turbine adoption decision.

5 Turbine Applications: Simple versus Combined Cycle

The policy question central to this study is why these firms prioritized turbine characteristics in their revealed manner. We maintain that the incentives created by economic regulation is key. In the earlier propositions, we focus primarily on the impact of regulation on the incidence of cost/risk and the amount of competition introduced by the economic regulatory regime. However, economic regulation may also create a more fundamental shift: markets under each regulatory regime may favor different turbine applications. Currently, there are two major applications of gas turbine electricity generators: provision of baseload power using a combined cycle set-up and provision of more load-following, peak/cycling power using a simple cycle set-up.[41] Although each of the three highlighted General Electric models can be used for both applications, the MS7001FA is better suited for baseload, combined cycle and the LM6000 for load-following, simple cycle. This is demonstrated in Table 4 which breaks down U.S. turbine sales for each model by intended application, as reported to GTW.

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[40] This includes 4 turbines by FP&L and 4 by PSEG which were joint with non-utility-affiliated independent power producer, Panda Energy

[41] Baseload and load-following power, here, refer to power generated continuously over a long interval and power generated in bursts of short intervals, respectively

Table 4: U.S. Turbine Sales for Select GE Models by Application

		Turbines Sold[1]			
Model	Application[2]	1995	1997	2000	2001
LM6000	Simple Cycle	6	5	97	103
	Combined Cycle	7	2	12	7
MS7001EA	Simple Cycle	14	6	96	63
	Combined Cycle	6	2	3	3
MS7001FA	Simple Cycle	0	7	68	51
	Combined Cycle	4	1	181	100

[1] Years listed are GTW volume years

[2] Excludes some other stated applications, e.g. cogeneration

From an engineering standpoint, this difference in application preference between the MS7001FA and LM6000 is driven by the fact that simple-cycle operation is optimized at higher pressure but combined cycle at modest pressure with more emphasis on higher firing temperature.[42] The MS7001FA is characterized by a 15.5 pressure ratio while the LM6000 by a much higher 28.0, according to the *Gas Turbine World Handbook* 2000 volume. Consequently, the LM6000 exhibits higher thermal efficiency in simple cycle but the MS7001FA in combined cycle.[43]

The association of combined cycle application for baseload power and simple cycle for load-following, peak/cycling power is driven by the different economics underlying the two types of power provision. In baseload power, the unit is expected to operate at a yearly capacity factor of 50 to 90%, compared to 0 to 50% for peak/cycling power.[44] Accordingly, fuel costs and, hence, heat rates are of primary importance for baseload operation. However, peak/cycling power requires the turbine to ramp up and down electricity output much more frequently. The frequent "cycling" leads to greater maintenance needs, more rapid performance degradation, and shorter life for turbines providing load-following power.[45] As such, capital and maintenance costs are emphasized more for load-following power. Table 5 provides a cost break-down for advanced simple cycle and heavy frame (F-class) combined cycle, as well as for two modern coal-based generating technologies.[46]

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[42] See GER-4206

[43] Roughly, the LM6000 combined cycles achieve a thermal efficiency of 45-50% and the MS7001FA 50-55%. In simple cycle, the thermal efficiency of LM6000 approaches 40% and MS7001FA 35%

[44] Capacity factor is the ratio of total generation and total possible generation. e.g. a 90% yearly capacity factor for a 100 MW plant would indicate $0.9 \times 24\text{hrs/day} \times 365\text{days/yr} \times 100\text{MW} = 788,400$ MWh/yr of operation

[45] See Lefton, Besuner, & Grimsrud (2002) for details on cycling damage

[46] The table uses data from the EIA and not GTW. While common variables between the two sources are roughly similar, the EIA data reports larger heat rates and capital costs compared to GTW (6000 Btu/kWh, $350/kW for GE S207 combined cycle). We use EIA gas turbine data to ensure comparability with coal-fired data

Table 5: Cost Characteristics of New Fossil Generating Technologies[1]

	Overnight Capital[2]		O&M Costs		Heat Rate[3]		Carbon
Technology	Early	Later	Variable[4]	Fixed[5]	Early	Later	Emissions[6]
Pulverized Coal	1,079	1,079	0.325	22.5	9,585	9,087	519
IGCC Coal	1,833	1,206	0.187	24.2	8,470	7,308	417
Simple Cycle (Advanced)	325	325	0.500	5.7	9,700	8,000	249
Combined Cycle (F-Frame)	440	440	0.200	15.0	8,030	7,000	250

[1] Data from EIA October 1998 Report, "Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity," Table 16

[2] Units in 1996 \$/kW [3] in Btu/kWh [4] in 1996 cents/kWh [5] in 1996 \$/kW [6] in Pounds/MWh

The table shows the heat rate (fuel cost) being lower for the heavy frame combined cycle unit but capital and operation & maintenance (O&M) costs (at low to moderate level of generation) lower for the simple cycle aeroderivative unit.[47] The greater cost for the combined cycle unit despite the lower turbine cost for the MS7001FA stems from the additional cost of heat recovery steam generator(s) (HSRG) necessary for combined cycle application. Therefore, the adoption of simple cycle for load-following allows firms to keep capital and O&M costs low and the adoption of combined cycle, fuel costs. Moreover, this trade-off between fuel cost and capital cost suggests an additional factor, apart from reliability concerns, that can explain the continued popularity of older heavy frame models: the adoption of the older MS7001EA (and MS6001B) allows firms to further reduce their capital cost in exchange for even higher heat rates.[48]

By considering turbine model and application, we can recast the earlier analysis on turbine sales in a different light. The shift toward larger capacity turbines exhibited in both the 1990 and 2000 volumes can be attributed to an increased desire during those two periods to invest in combined cycle, baseload capacity. The U.S. sales for the larger capacity turbines consist primarily of the MS70001 turbines (MS7001EA for 1990 and MS7001FA for 2000) intended for combined cycle application.[49] Table 5 illustrates why combined cycle gas turbines (CCGT) might be the preferred technology for new baseload capacity. Although fuel costs are lower for coal plants given current relative fuel prices (ranging from 1.5 to 4 times coal for equivalent Btu content during the 1990s), CCGT plants exhibit substantially lower capital, O&M, and environmental (carbon

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[47] Although the EIA document does not explicitly state it, the stated specifications suggest that the advanced simple cycle units refer to the aeroderivatives

[48] The 2000 volume of the GTW Handbook reports the turbine cost of MS7001EA as \$246/kW and the various LM6000 packages at around \$340/kW

[49] Even among those with stated application of simple cycle, there is evidence that the firms, especially independent power producers, intend eventually to convert to combined cycle. A popular modular investment strategy is: install the gas turbines first then the requisite HSRG later - running the turbines in simple cycle during the interim

emission) costs. Overall cost is lower for CCGT when the relative price of natural gas is less than 5 times that of coal.[50] This raises the question: why was there significant interest in natural gas fired baseload capacity in volumes 1990 and 2000-01 but not between 1980-1990 and 1990-2000? The lack of interest between volumes 1980 and 1990 may be explained by the U.S. and EU directives that restricted natural gas as a primary fuel for electricity generation. However, there was no similar constraint binding utilities between 1990 and 2000.

An explanation consistent with the ideas underlying Propositions 1 & 2 would be the difference in incentives for economic replacement of existing generation capacity under the two regulatory regimes. While the enactment of the Public Utility Regulatory Policy Act (PURPA) of 1978 and associated subsequent federal and state-level regulatory orders allowed independent power producers to compete for the right to serve *new* wholesale electricity demand in some states, it was not until the arrival of state-level comprehensive restructuring legislation, such as California's AB1890, that enabled independent power producers to compete for the right to serve *existing* demand currently met by utility power plants. Consequently, the replacement of existing baseload capacity was left at the discretion of the incumbent utility until recent years. To the extent to which the regulated "high" retail electricity prices were justified by the presence of costly baseload plants in the rate base, utilities would have little incentive to replace promptly old, expensive baseload capacity with new, cheaper CCGT capacity. Furthermore, as argued in Proposition 3a, without the threat of competitive preemption, utilities can choose to wait until adoption costs had suitably fallen, including the opportunity cost of replacing "profitable" older capacity.

This is in contrast to a restructured market with competitive entry by independent power producers. In such a market, a firm will invest in CCGT baseload capacity as soon as it becomes economical. Given that some of the older coal baseload plants have heat rates surpassing 13,000 Btu/kWh and gas high capacity factor plants heat rates above 11,000 Btu/kWh, some modern CCGT can be economical even with respect to variable costs.[51] But more importantly, independent power producers have an incentive to sink capital preemptively into new CCGT capacity, in anticipation of the physical retirement of existing baseload capacity over the near future. As long as the difference in variable cost is less than the amortized capital cost for the "future" CCGT model, independent power producers can earn a first mover advantage by investing in CCGT now.[52] With

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[50] See Linden (1997)

[51] At over 13,000 Btu/kWh and a relative price of gas roughly twice that of coal, a modern CCGT unit can exhibit comparable, if not lower, variable costs after factoring in the lower O&M costs. The coal heat rate information is from *Power Magazine*, July-August 2002 issue; gas heat rate information is from Mitnick (2002)

[52] For the precise arguments on sunk costs and first mover advantages, see Sutton (1991).

over half the U.S. investor-owned utility capacity listed as being older than 25 years (*Inventory of Power Plants*, 1997, Energy Information Administration), independent power producers have an incentive to build substantial amount of baseload capacity now. Therefore, the lack of large gas turbine investments by electric utilities from volumes 1990 to 2000 may be attributed to the lack of incentive to replace existing capacity. Similarly, the surge in large gas turbine investments by independent power producers for volumes 2000-01 may be attributed to independent power producers rushing to be "first in line" to replace much of the soon-to-be-retired utility baseload capacity.[53]

The data on turbine sales coupled with the above arguments would seem to suggest that recent regulatory restructuring of the electricity industry has changed gas turbine technology adoption by making it more attractive for gas turbines to be used for baseload power. While the literature on the recent "deregulation" of the electricity industry has highlighted the role of gas turbines in spurring greater restructuring (by reducing minimum operational scale), our study would seem to suggest a complementary feedback effect: restructuring further emphasizes the use of gas turbines. Instead of gas turbines being used just for load-following applications, gas turbines are also used for baseload power. The *caveat* to this argument is the uncertainty surrounding a presumed counterfactual: utilities, under continued traditional regulation, would either have chosen not to adopt or have adopted much later gas turbines for baseload power. To test this presumption, we examine the volume 1990 sales. As show earlier, sizable amount of large turbines were purchased during volume 1990, suggesting that utilities might also choose to invest in CCGT for baseload application.

Table 6: U.S. Turbine Sales for *Gas Turbine World Handbook* Volume 1990

	Specification		Application		
Model	Capacity	Heat Rate	Turbine Sales	Combined Cycle	Peak Load[1]
MS6001B	38.3 MW	11,460 Btu/kWh	11	3	8
MS700EA	83.5 MW	11,050 Btu/kWh	34	12	22
W501D5	104.4 MW	10,040 Btu/kWh	5	4	1
Total			70	23	47

[1] "Simple Cycle" was not a classification for intended application in Volume 1990

Table 6 depicts the break down of U.S. turbine sales for volume 1990. We find that there were some gas turbines being purchased for combined cycle application, primarily the heavy frame MS7001EA (the pre-cursor to MS7001FA) and W501D5. This would appear to imply that utilities,

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[53] This "rush" to be first to replace retiring baseload capacity is a prominent aspect of the investment strategy for several leading independent power producers. For example, see Schultz (1997) which details Duke Energy's strategy

in due course, may have adopted gas turbines for baseload power. But this is misleading as most of the MS7001EA and W501D5 purchases for combined cycle use were purchased by *independent power producers*. 7 of the 12 MS7001EA turbines for combined cycle purposes were purchased by independent power producers, most notably 4 by Ocean State Power who used the turbines to build a merchant power plant in Rhode Island. Furthermore, 4 of the 5 W501D5 turbines for combined cycle use were purchased by independent power producer Intercontinental Energy Corporation for their Bellingham (MA) and Sareville (NJ) facilities. A close examination of the 1990 volume sales shows that much of the larger turbine sales, and especially those intended for combined cycle use, were made by non-utilities, either independent power producers or industrial consumers. This suggests, if anything, that electric utilities would not have adopted CCGT for baseload power applications as enthusiastically as independent power producers.

The above analysis suggests that the main effect of restructuring on turbine technology adoption is the stronger incentive on adopting turbines well-suited for combined cycle, baseload applications. However, this stronger incentive depends on market forces. The over 40% drop in MS7001FA turbine sales for combined cycle applications from volumes 2000 to 2001 would suggest the importance of the interaction between regulatory and market forces in a restructured wholesale electricity market.[54] A key difference in market forces between the 2000 and 2001 volumes is the sudden rise in natural gas prices during year 2000: the average price of natural gas delivered to U.S. utilities jumped from \$2.62 to \$4.38 per thousand cubic feet from 1999 to 2000.[55] Given that "clean coal" plants become competitive with CCGT at natural gas prices around \$5 per thousand cubic feet (assuming the stable coal price of \$1 per million Btu), the 2000 price spike seriously threatened the viability of CCGT baseload capacity. At natural gas prices above \$6 per thousand cubic feet, we would expect turbine technology adoptions to be more similar between utilities operating a traditional price-regulated monopoly franchise and independent power producers serving a restructured wholesale electricity market: both firms would adopt gas turbines primarily suited for the provision of load-following power.

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[54] This "actual" drop may even be larger as the two volumes potentially share some transactions from January-June 2000

[55] Summary tables from Energy Information Administration based on FERC Form 423; further note that 1 cubic feet of natural gas $\approx$ 1,026 Btu of natural gas

6 Conclusion

By examining gas turbine sales over the past two decades, we find evidence that indicates that regulated utilities and unregulated independent power producers prefer different types of gas turbines. During the early years, we find gas turbine sales primarily focused on small capacity units with low heat rates, presumably for the provision of load-following power. Much of this observed decision from the 1980s can be explained by fuel use restrictions adopted by both the U.S. and the European Community, as well as the high natural gas prices that prompted such restrictions. However, in the 1990s, with the fuel use restrictions revoked and natural gas prices falling to affordable levels, U.S. electric utilities are found largely purchasing the same type of turbines while independent power producers, as early as 1988-89, are observed purchasing larger capacity turbines better suited for combined cycle applications.

This difference in technology adoption is amplified from 1998 onward, coinciding with the implementation of comprehensive regulatory restructuring by many states. Heavy frame turbines, especially the GE MS7001FA, become the dominant model for independent power producers. Among the electric utilities observed purchasing MS7001FA turbines, we find that most are either utilities operating in restructured markets or utilities with ties to independent power production through their parent company. We argue that such utilities face incentives that are more co-aligned with incentives faced by independent power producers. Using the same basic arguments underlying Propositions 1, 2, and 3a, we conclude that the observed increased popularity of heavy frame models such as the GE MS7001FA and the Siemens-Westinghouse W501F is a result of recent market-oriented regulatory restructuring creating a stronger incentive for firms to adopt combined cycle gas turbines (CCGT) as replacement for existing, soon-to-be-retired, baseload capacity. This suggests that recent state-level restructuring creates a “demand-pull” for innovation that furthers the applicability of gas turbines for combined cycle, baseload applications.

This should come as no surprise to industry observers. This study provides formal evidence supporting the claim made by many industry participants and experts:

> Indeed, it is evident that PURPA’s requirement that utilities contract with certain independent power suppliers, combined with competitive generation procurement programs in the late 1980s, helped to stimulate the technological innovation in combined cycle generating technology (CCGT) using natural gas as a fuel. (Joskow, 1997, p.125)

Even more directly, the manufacturers themselves reveal that much of their development in CCGT was a response to perceived changes in market demand for turbines. For example, GE developed its

F-class technology (embodied in the MS7001FA) with an eye toward developing a turbine that would have a larger capacity and a higher firing temperature in order to lower power plant specific cost and increase combined cycle efficiency – desirable properties for a gas plant intended for high capacity factor use.[56] The recent introduction of the GE "7H-class" and Siemens-Westinghouse W501G turbines – incorporating closed-loop steam cooling – can be seen as a continuation of this goal, as both turbines top 400 MWs and achieve combined cycle thermal efficiency of 60%. Consequently, it seems reasonable to argue that this study establishes recent and current developments in heavy frame combined cycle technology as evidence of innovation induced by market-oriented regulatory restructuring of the electricity generation industry.

In the absence of regulatory restructuring, the data suggests that heavy frame CCGT technology would have developed much slower. Utility demand for gas turbines seems primarily focused on turbines best suited for load-following applications. This would indicate that manufacturers would focus more on explicitly aeroderivative turbines – turbines that provide superior load-following capabilities and high thermal efficiencies at simple cycle.[57] In such a world, we might expect firms building plants much like Kinder-Morgan's "Orion" plant: 6 LM6000s and 1 MS7001EA in a limited combined cycle set-up. While aeroderivative combined cycle units provide much less thermal efficiency than a traditional heavy frame CCGT (45-50% compared to 55-60%), the modular design, centered around multiple LM6000 turbines, allows for cost-effective rapid load response – making them ideal for peak and intermediate load use.[58] Furthermore, given the incentives faced by utilities with respect to capital cost, we might expect heavy frame gas turbines to be developed mainly within the context of the "integrated gasification combined cycle" (IGCC) application.[59] As shown in Table 5, IGCC plants have a much higher capital cost (due to the additional cost of a "gasifier") but lower fuel cost than traditional CCGT plants, as IGCC plants can use coal and other inexpensive carbon-based fuels for feedstock. Instead of parallel development, the heavy frame turbines might have developed complementary with gasifiers: the demand for large scale turbines depending on the availability of affordable, reliable gasifiers.

Lastly, we note that the demand for CCGT for baseload capacity is predicated on the affordability of natural gas. As sales for the 2001 volume suggest, a sustained price spike in natural

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[56] See GER 3950c

[57] Improvements in heavy frame turbines stem largely from the adaptation of aeroderivative technology. Therefore, we conjecture that manufacturers would focus less research on such adaptation and more on methods that either increase the performance or lowers the cost of explicitly aeroderivative turbines

[58] See http://www.kindermorgan.com

[59] IGCC is a combined cycle unit where, instead of natural gas, synthgas obtained from the "gasification" of carbon-based solid feedstock is combusted

gas can shift (relative) sales away from gas turbines suited for baseload capacity and toward those suited for load-following capacity. Moreover, once a suitable amount of new CCGT capacity is built, the demand for CCGT will subside as the presence of sunk costs deters firms from investing in new CCGT plants that are only "marginally" more efficient.[60] These market forces suggest that the demand-pull for gas turbines from independent power producers operating in restructured wholesale markets over the next ten years will be different from the previous ten years. Incremental innovation will most likely focus on developing turbines with superior load-following capability and resiliency. We can also imagine emphasis on more radical innovation, such as turbine/fuel cell hybrid systems, as new gas turbine baseload capacity will only be adopted for substantial efficiency gains. Additionally, to the extent to which distributed generation becomes popular, we might see a return toward much smaller-scale turbines ("micro-turbines").[61] These speculations reiterate the importance of the interaction between market and regulatory forces when analyzing induced innovation from economic regulation.

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[60] Development of plants with thermal efficiencies reaching and surpassing 70% will require a new class of generators, due to the limits of the Brayton and Rankine cycles that characterize CCGT power generation.

[61] Progress is being made in all three dimensions. See the Department of Energy, Advanced Turbine Systems Program Brochure, November 2000, http://www.netl.doe.gov

Bibliography

Allen, R. (1983) “Collective Invention,” *Journal of Economic Behavior and Organization*. Vol. 4. pp.1-24

Arrow, K. (1962) “The Economic Implications of Learning by Doing,” *Review of Economic Studies*. Vol. 29. pp.155-173

Clarke, R. (1980) “The Effects of Fuel Adjustment Clauses on Systematic Risk and Market Values of Electric Utilities,” *Journal of Finance*. Vol. 35. pp.347-358

Cohen, L. and P. Sanyal (2003) “Investment in R&D in Restructured Industries: Evidence from the US Electricity Industry,” October mimeo. University of California, Irvine.

Cohen W. and R. Levin (1989) “Empirical Studies of Innovation and Market Structure,” *Handbook of Industrial Organization*. Vol. 2. Chapter 18. Amsterdam: Elsevier Science B.V.

Cohn, A. and J. Scheibel (1997) “Current Gas Turbine Developments and Future Projects,” Presentation for the Advanced Turbine Systems Annual Program Review Meeting. October 28-29, 1997. Department of Energy. Available online at http://www.netl.doe.gov/

Frank, M. (2003) “An Empirical Analysis of Electricity Regulation on Technical Change in Texas,” *Review of Industrial Organization*. Vol. 22. pp.313-331

Fudenberg, D. and J. Tirole (1985) “Preemption and Rent Equalization in the Adoption of New Technology,” *Review of Economic Studies*. Vol. 52. pp.383-401

General Electric Reference (GER) Document 3571H, “Performance and Reliability Improvements for Heavy-Duty Gas Turbines,” October 2000. Available online at
http://www.gepower.com/prod_serv/products/tech_docs/en/all_gers.htm

General Electric Reference (GER) Document 3950C, “The F Technology Experience Story,” October 2000. Available online at
http://www.gepower.com/prod_serv/products/tech_docs/en/all_gers.htm

General Electric Reference (GER) Document 4194, “The 7FB: The Next Evolution of the F Gas Turbine,” April 2001. Available online at
http://www.gepower.com/prod_serv/products/tech_docs/en/all_gers.htm

General Electric Reference (GER) Document 4206, "Combined Cycle Development: Evolution and Future," April 2001. Available online at
http://www.gepower.com/prod_serv/products/tech_docs/en/all_gers.htm

Goldberg, P. (1998) "The Effects of the Corporate Average Fuel Efficiency Standards in the U.S.," *Journal of Industrial Economics.* Vol. 46. pp.1-33

Goldberger, A. (1991) *A Course in Econometrics.* Cambridge, MA: Harvard University Press

Gollop, F. and S. Karlson (1978) "The Impact of the Fuel Adjustment Mechanism on Economic Efficiency," *Review of Economics and Statistics.* Vol. 60. pp.574-584

Greening, L., A. Sanstad, and J. McMahon (1997) "Effects of Appliance Standards on Product Price and Attributes: An Hedonic Pricing Model," *Journal of Regulatory Economics.* Vol. 11. pp.181-194

Greenstein, S., S. McMaster, and P. Spiller (1995) "The Effect of Incentive Regulation on Infrastructure Modernization: Local Exchange Companies' Deployment of Digital Technology." *Journal of Economics and Management Strategy.* Vol. 4. pp. 187-236

Hannan, T. and J. McDowell (1984) "The Determinants of Technology Adoption: The Case of the Banking Firm," *Rand Journal of Economics.* Vol. 15. pp.328-335

Hirsh, R. (1989) *Technology and Transformation in the American Electric Utility Industry.* New York: Cambridge University Press.

Ishii, J. and J. Yan (2003) "Investment under Regulatory Uncertainty: U.S. Electricity Generation Investment Since 1996," May mimeo. University of California, Irvine

Jaffe, A., R. Newell, and R. Stavins (2003) "Technological Change and the Environment," *Handbook of Environmental Economics.* Chapter 11. Amsterdam: Elsevier Science B.V.

Jaffe, A. and K. Palmer (1997) "Environmental Regulation and Innovation: A Panel Data Study," *Review of Economics and Statistics.* Vol. 79. pp.610-619

Joskow, P. (1974) "Inflation and Environmental Concern: Structural Change in the Process of Public Utility Price Regulation," *Journal of La and Economics.* Vol. 17. pp.291-328

Joskow, P. (1997) "Restructuring, Competition and Regulatory Reform in the U.S. Electricity Sector," *Journal of Economic Perspectives.* Vol. 11. pp.119-138

Kerr, S. and R. Newell (2003) "Policy-induced Technology Adoption: Evidence from the U.S. Lead Phasedown," *Journal of Industrial Economics.* Vol. 6. pp.317-344

Lanjouw, J. and A. Mody (1996) "Innovation and the International Diffusion of Environmentally Responsive Technology," *Research Policy.* Vol. 25. pp.549-571

Lefton, S., P. Besuner, and G. Grimsrud (2002) "The Real Cost of Cycling Powerplants: What You Don't Know Will Hurt You," *POWER Magazine.* December Issue. Available online at http://www.platts.com

Linden, H. (1997) "Operational, Technological and Economic Drivers for Convergence of the Electric Power and Gas Industries," *Electricity Journal.* May Issue.

Mitnick, S. (2002) "Overbuilding? Fuhgeddaboutit!" *Public Utilities Fortnightly.* Vol. 140. pp.10-12

Nelson, R. (1984) "Regulation, Capital Vintage, and Technical Change in the Electric Utility Industry," *Review of Economics and Statistics.* Vol. 66. pp.59-69

Newell, R., A. Jaffe, and R. Stavins (1999) "The Induced Innovation Hypothesis and Energy-Saving Technological Change," *Quarterly Journal of Economics.* Vol. 114. pp.941-975

Noll, R. and B. Owen (1994). "The Anticompetitive Uses of Regulation: United States v. AT&T (1982)," in *The Antitrust Revolution: The Role of Economics.* eds. J. Kwoka & L. White. New York: HarperCollinsCollegePublishers

Okuguchi, K. (1975) "The Implications of Regulation for Induced Technical Change: Comment," *Bell Journal of Economics.* Vol. 6. pp.703-705

Peck, S. (1974) "Alternative Investment Models for Firms in the Electric Utilities Industry," *Bell Journal of Economics and Management Science.* Vol. 5. pp.420-458

Reinganum, J. (1983a) "Uncertain Innovation and the Persistence of Monopoly," *American Economic Review.* Vol. 73. pp.741-748

Reinganum, J. (1983b) "Technology Adoption under Imperfect Information," *Bell Journal of Economics.* Vol. 15. pp.57-69

Rose, N. and P. Joskow (1990) "The Diffusion of New Technologies: Evidence from the Electric Utility Industry," *RAND Journal of Economics.* Vol. 21 pp.354-373

Schmookler, J. (1966) *Invention and Economic Growth.* Cambridge, MA: Harvard University Press

Schulze, D. (1997) “Convergence of the Gas and Electric Industry: The Role of the Advanced Turbine Systems,” Presentation for the Advanced Turbine Systems Annual Program Review Meeting. October 28-29, 1997. Department of Energy. Available online at http://www.netl.doe.gov/

Schumpeter, J. (1942) *Capitalism, Socialism, and Democracy.* New York: Harper

Silverman, B. 1986) *Density Estimation.* London: Chapman and Hall

Smith, V. (1974) “The Implications of Regulation for Induced Technical Change,” *Bell Journal of Economics and Management Science.* Vol. 5. pp.623-636

Smith, V. (1975) “The Implications of Regulation for Induced Technical Change: Reply,” *Bell Journal of Economics.* Vol. 6. pp.623-636

Stephen, D. (1997) “Combustion Turbines / Combined Cycles,” Presentation for the Advanced Turbine Systems Annual Program Review Meeting. October 28-29, 1997. Department of Energy. Available online at http://www.netl.doe.gov/

Sutton, J. (1991) *Sunk Costs and Market Structure: Price Competition, Advertising, and the Evolution of Concentration.* Cambridge, MA: MIT Press

Swanekamp, R. (2002) “Raising the Relibability of Advanced Gas Turbines,” *POWER Magazine.* March-April Issue. Available online at http://www.platts.com

List of Figures and Tables

Figures (Appended at End of Document, except Figure 1)

Tables (In Main Body of Document)

Data Appendix

The main source of data for this study is the annual *Gas Turbine World Handbook* (GTW Handbook) published by Pequot Publishing (Fairfield, CT). This is the standard reference for gas turbine specifications for the electricity generation industry. Although the content of the *Handbook* differs from volume to volume, most recent volumes contain the following information:

1. Quoted Prices for Popular Models (1987 onward only)
2. News on New Models, Uprates, Retirements
3. Performance Specifications for Most Models
4. World-wide Orders and Installations

We merge information from items 3 and 4 to build the main data set for this study. Unfortunately, for some models, specification data was not available in the same *Handbook* volume. In such cases, we tried to obtain the specification data from either a previous or later volume, using the "just previous" volume whenever possible. For some cases, mainly some older General Electric models, the specification data was obtained directly from the manufacturer, correcting for possible uprates. For specific variables:

- **Capacity**: Whenever possible, the ISO-rated nameplate capacity was used
- **Heat Rate**: Whenever possible, the ISO-rated LHV content heat rate was used
- **Age**: The commercial introduction year listed in the *Handbook* was used
- **Price**: The quoted nominal price listed in the *Handbook* was used
- **Sales**: The number of sales listed in the *Handbook* was used

As noted earlier, the sales data in each of the volumes cover an overlapping period of varying length. Although in the earlier volumes, dates were provided for each transaction, later volumes do not provide such information. The table below provides the coverage period for each volume

Sales Coverage for Select *Gas Turbine World Handbook*	
Volume	Coverage
1980	January 1979 - December 1979
1985	January 1983 - December 1985
1990	January 1988 - June 1989
1995	January 1993 - June 1994
1997	January 1995 - December 1996
1998	January 1996 - December 1997
2000	January 1999 - June 2000
2001	January 2000 - June 2001

The sales data include turbines used for primary purposes other than electricity generation, such as mechanical drive. Therefore, we select only transactions where the stated intended application was electricity generation: baseload, cogeneration, combined cycle, IGCC, peakload, power generation, simple cycle. Note: GTW changed its classification of intended application over time. A comparison of these sales data with power plant investment data collected by the author for a different project suggests that the sales data is fairly comprehensive and can be considered a reflection of the population of major sales (at least for the U.S. in recent years).

For the vast majority of transactions, the GTW Handbook lists the name of the firm and, for most cases, the location of the facility for which the turbine(s) is intended. We use these two pieces of information to classify the "firm type" of the turbine purchaser. Various industry resources were used. Of particular assistance was the annual publication on independent power companies published by the editors of industry trade press, *Global Power Report* (McGraw-Hill Publishing, New York). The title varies year from year; the 1999 edition is titled *205 Independent Power Companies: Profiles of Industry Players and Projects.* Information on utilities, plant development costs, and fuel costs were obtained from various publications from the Energy Information Administration (EIA), especially the October 1998 Report, "Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity" and the monthly "Cost and Quality of Fuels for Electric Utility Plants," both of which are available online at http://www.eia.doe.gov

While the current volume of *Gas Turbine Handbook* is fairly widely available, finding an archive of back issues proved to be difficult. To our knowledge, there is no public library in the United States that has a complete set of back issues from 1980 to 2001. Consequently, the data was obtained piece-wise from three different libraries:

1. Electric Power Research Institute (EPRI) Library; Palo Alto, California

2. California Energy Commission (CEC) Library; Sacramento, California
3. Department of Energy (DoE) Lbrary; Washinton D.C.

All volumes from 1980 to 2001 (volumes 5 - 22) were found except for the volume issued in 1991 (appropriately, volume 13). The library staff at each of these institutions was very helpful. We would especially like to thank Karen Hamilton, Hannah King, and Judith Mills at the CEC, DoE, and EPRI libraries, respectively. Information from each of these volumes was digitized by means of scanning and use of optical character recognition software. The digitized data was reasonably hand-checked for scanning/character recognition error. In some instances, the *GTW Handbook* volume appears to print some suspicious information (e.g. possible typographical errors). Except for the cases where the error could be verified with confidence, such errors were not corrected.

Figure 2: U.S. Combustion Turbine Capacity

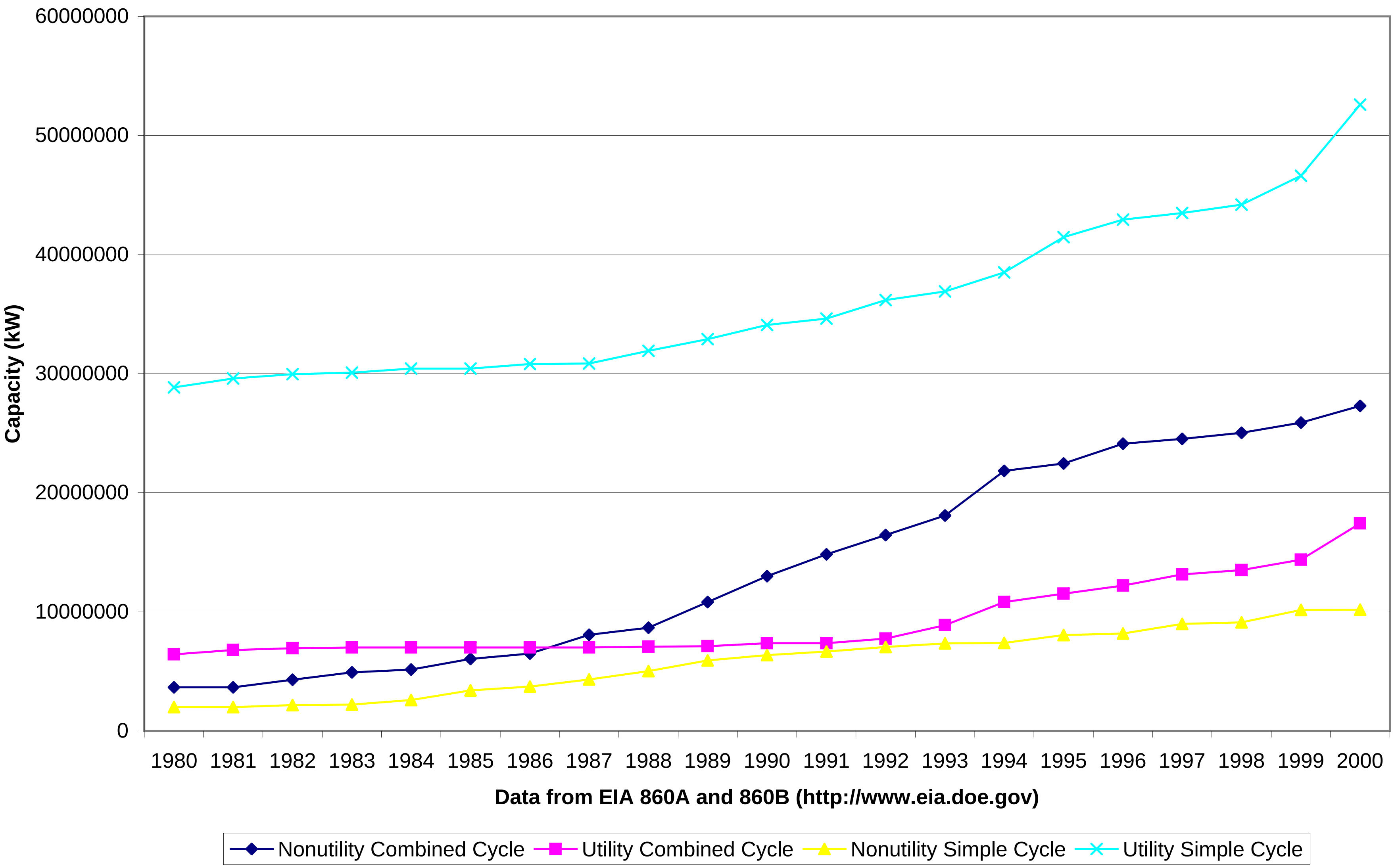


Figure 3a: 1980 Capacity & Heat Rate

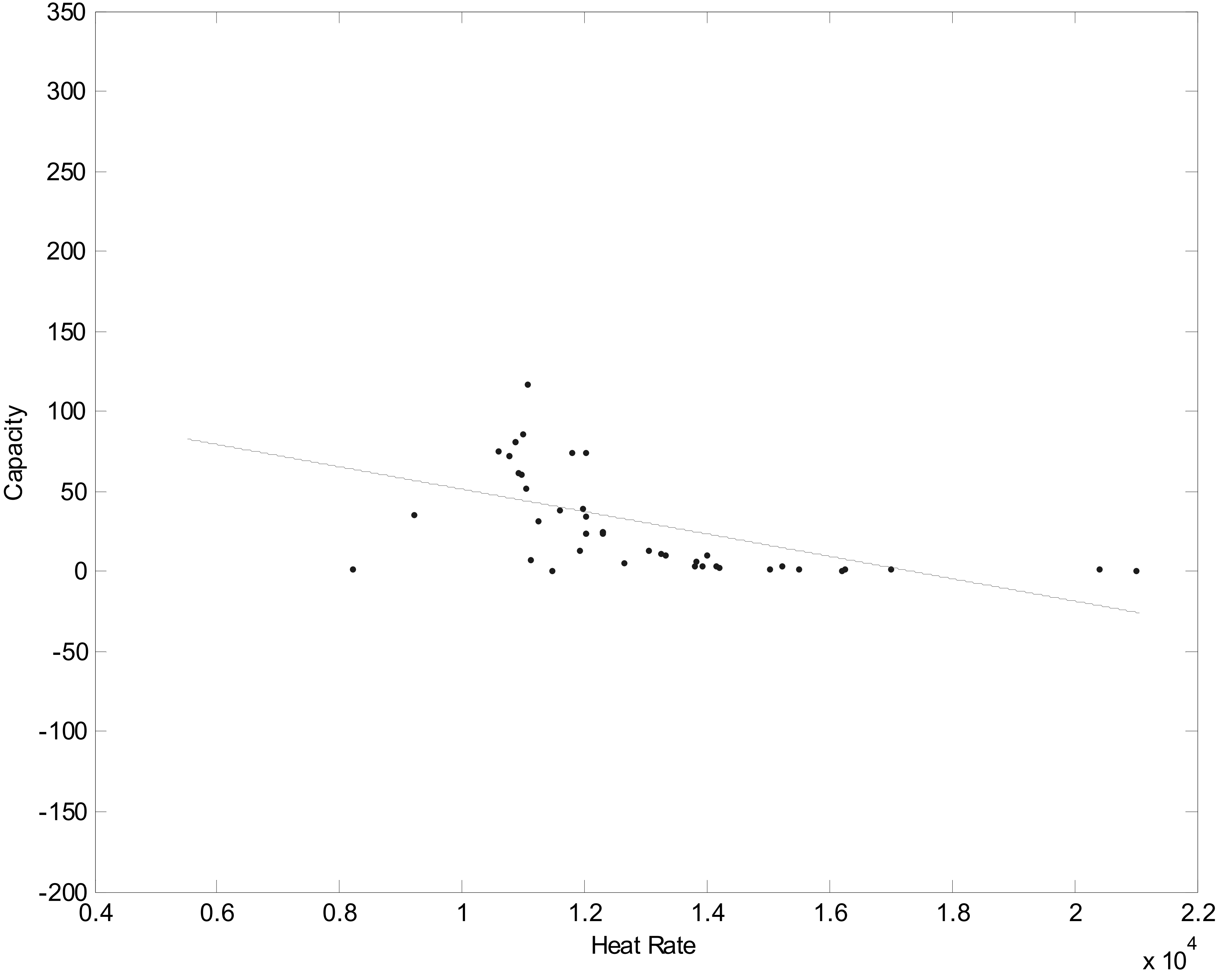


Figure 3b: 1985-86 Capacity & Heat Rate

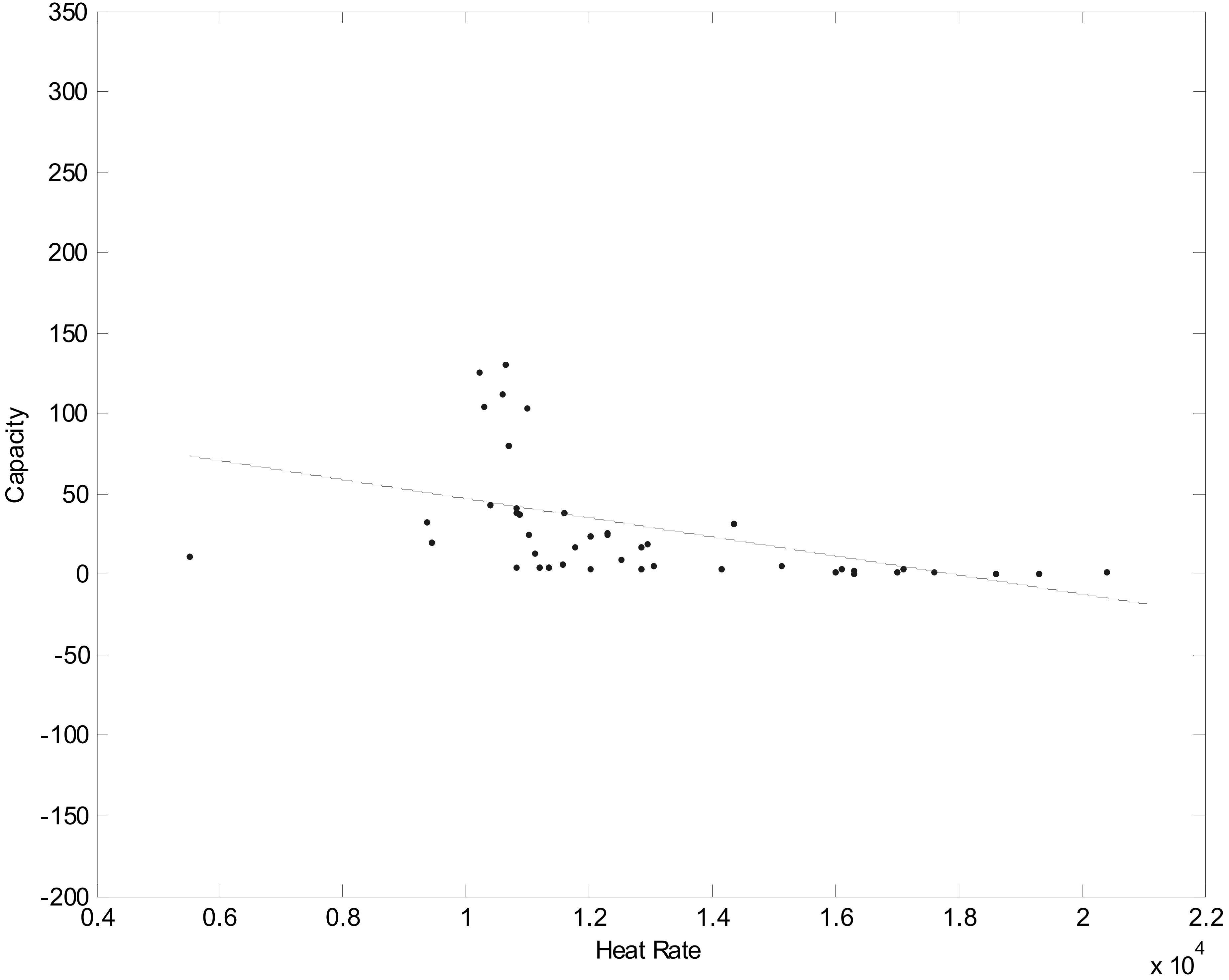


Figure 3c: 1990 Capacity & Heat Rate

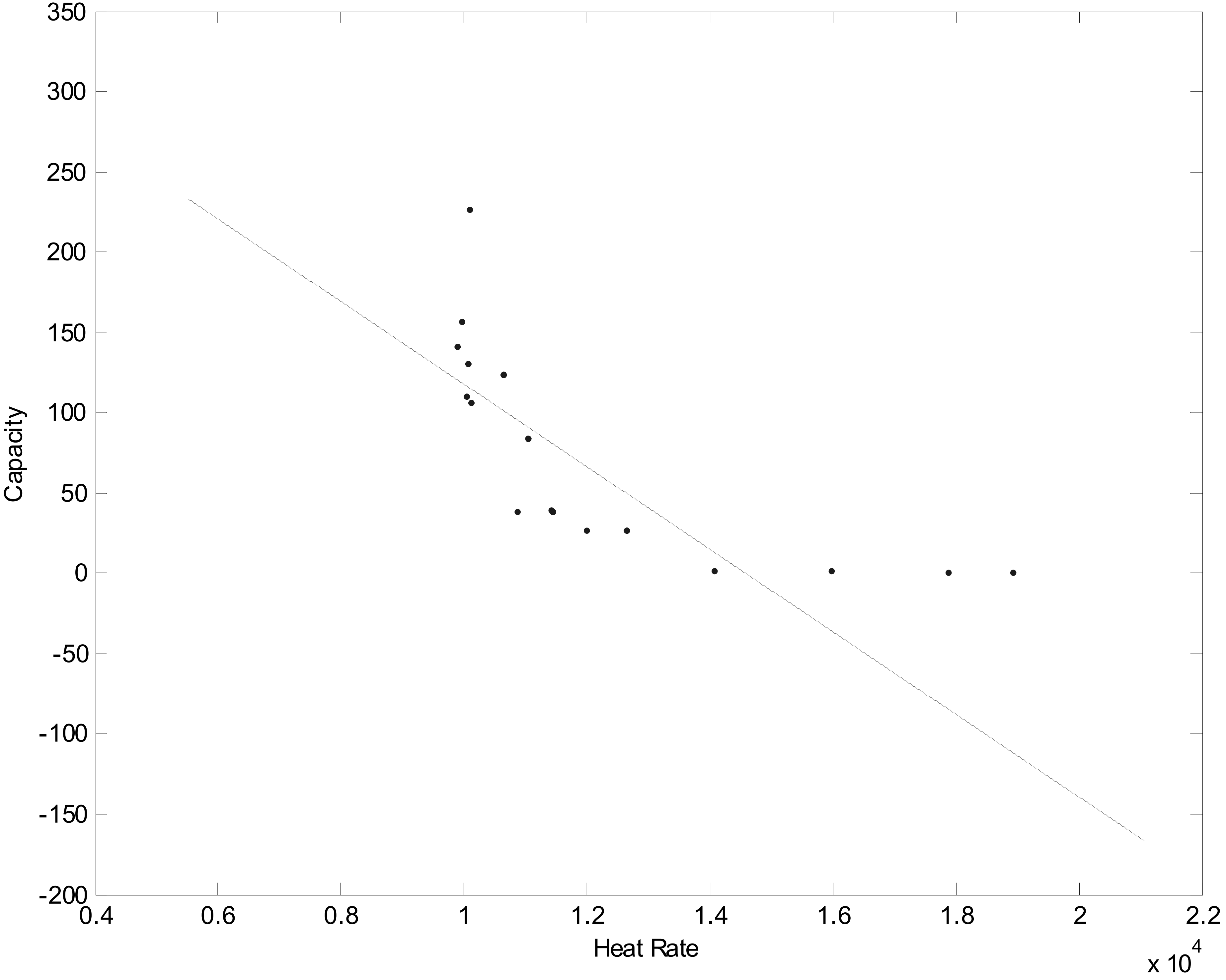


Figure 3d: 1995 Capacity & Heat Rate

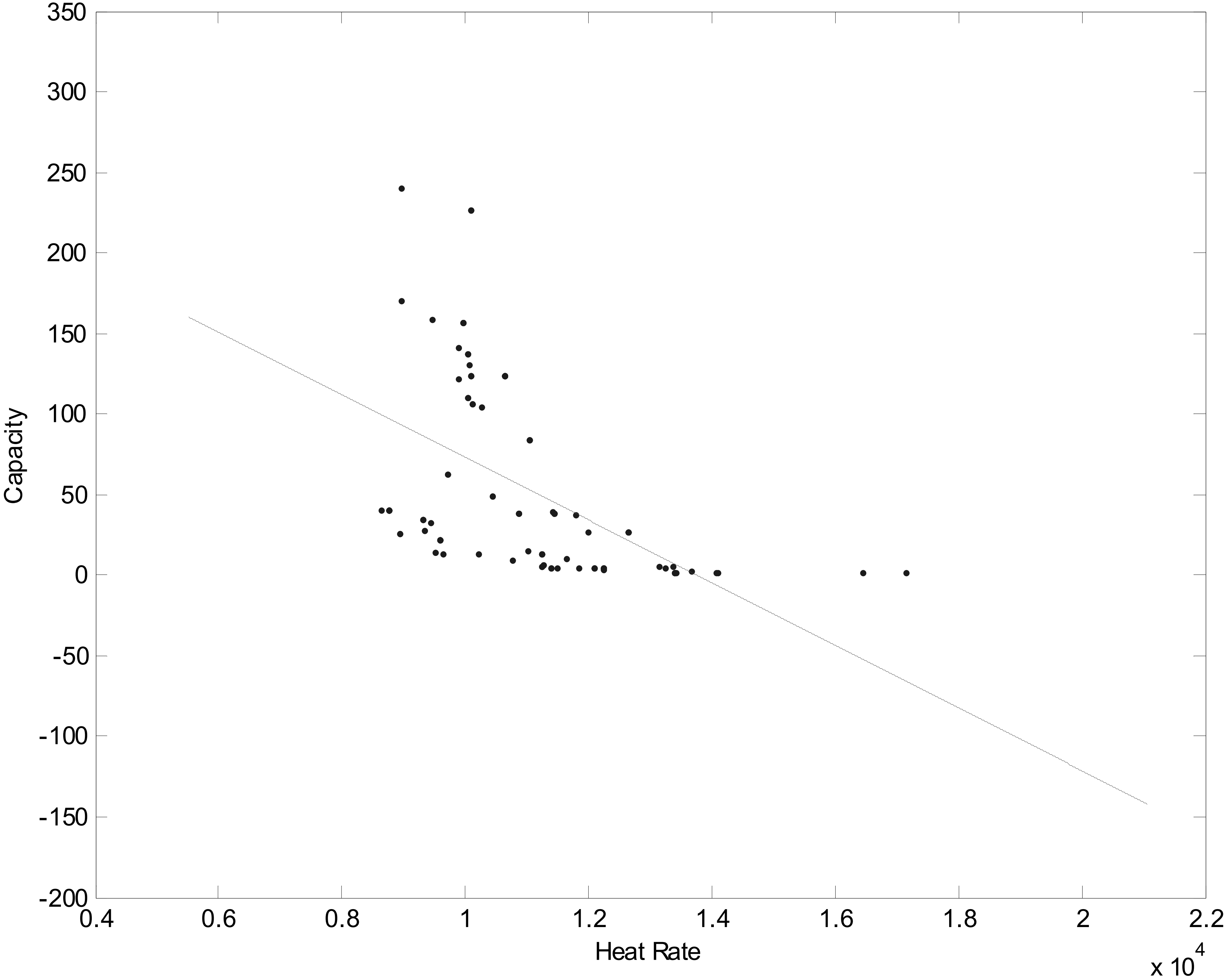
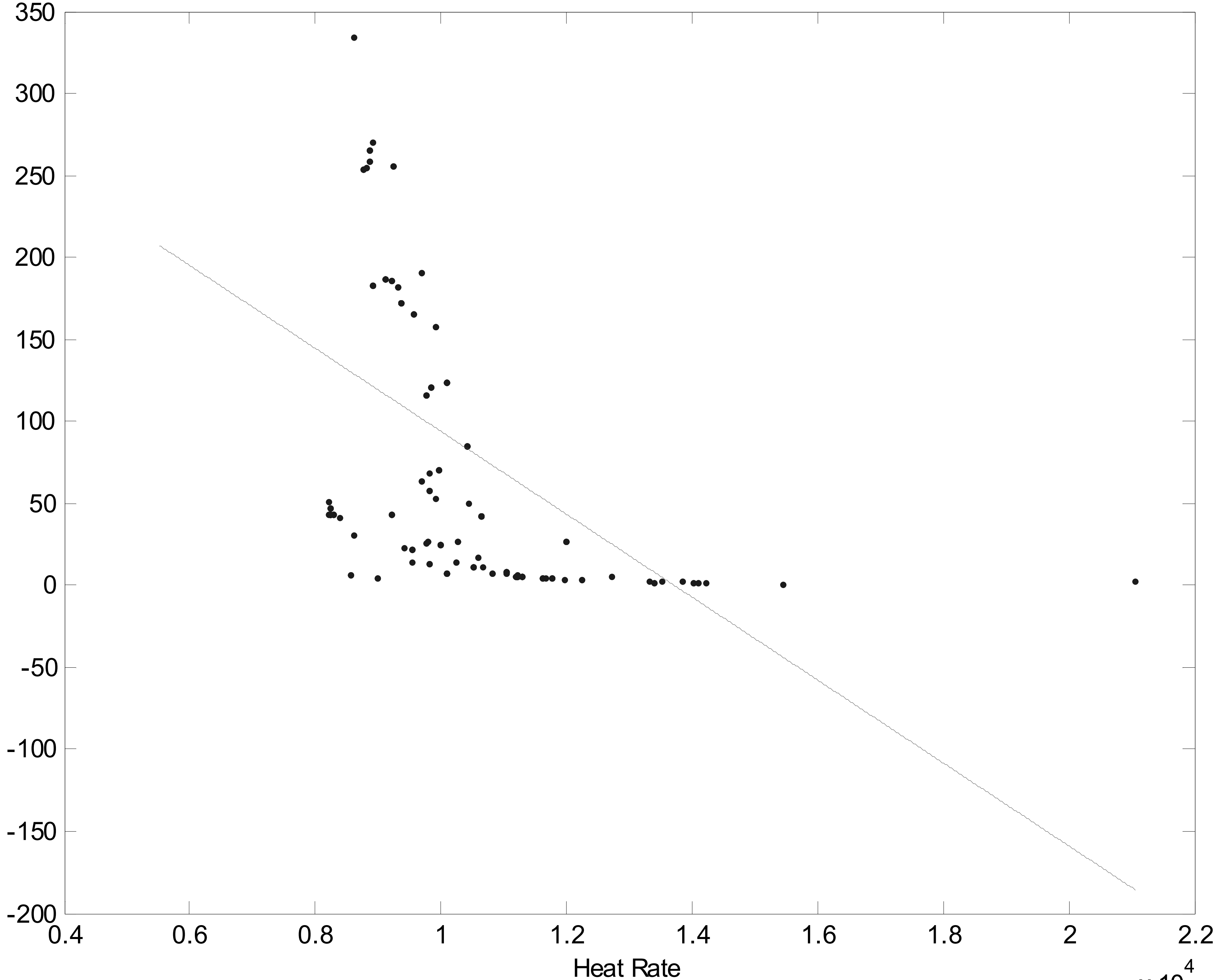


Figure 3e: 2000 Capacity & Heat Rate



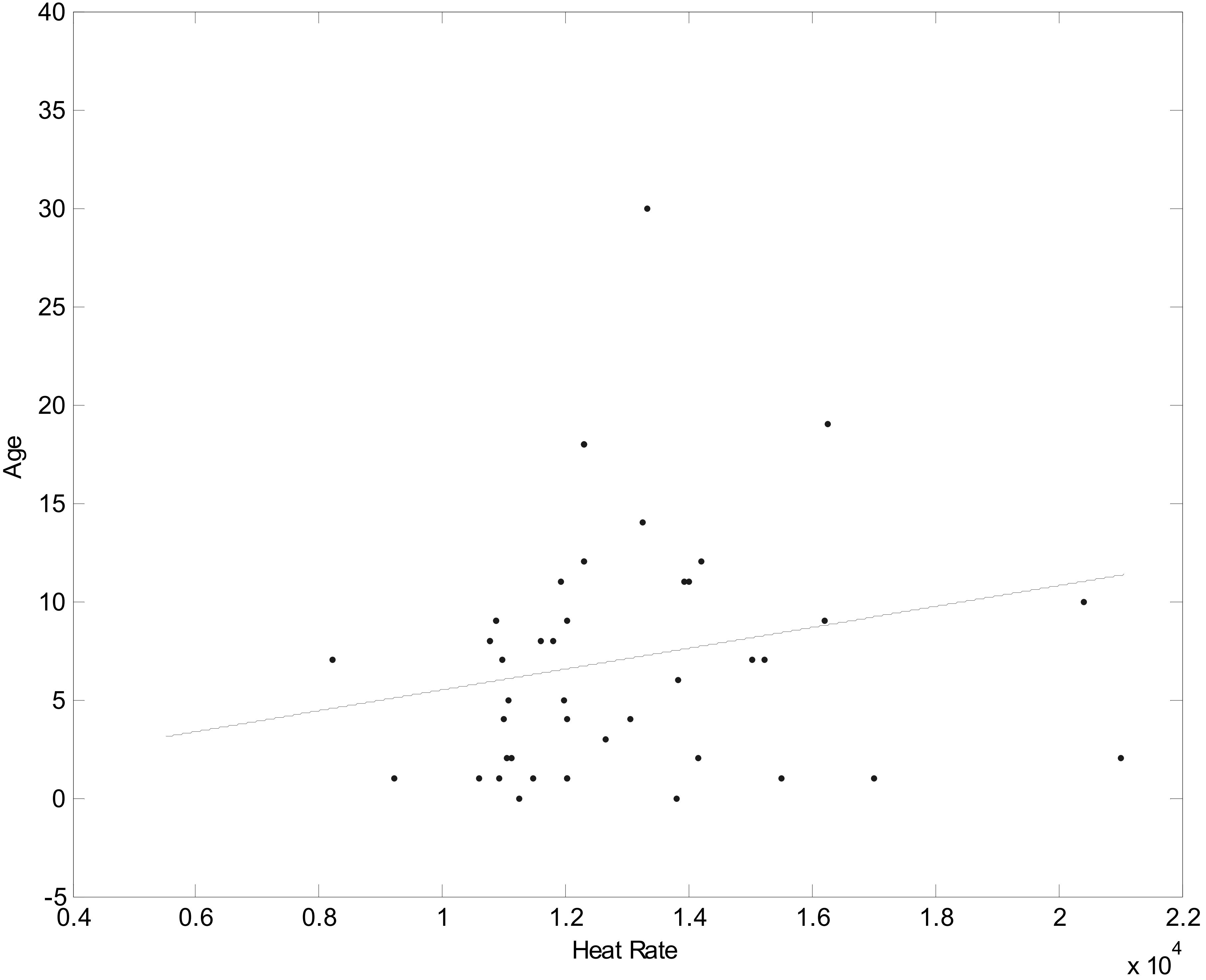


Figure 4a: 1980 Age & Heat Rate

Figure 4b: 1985-86 Age & Heat Rate

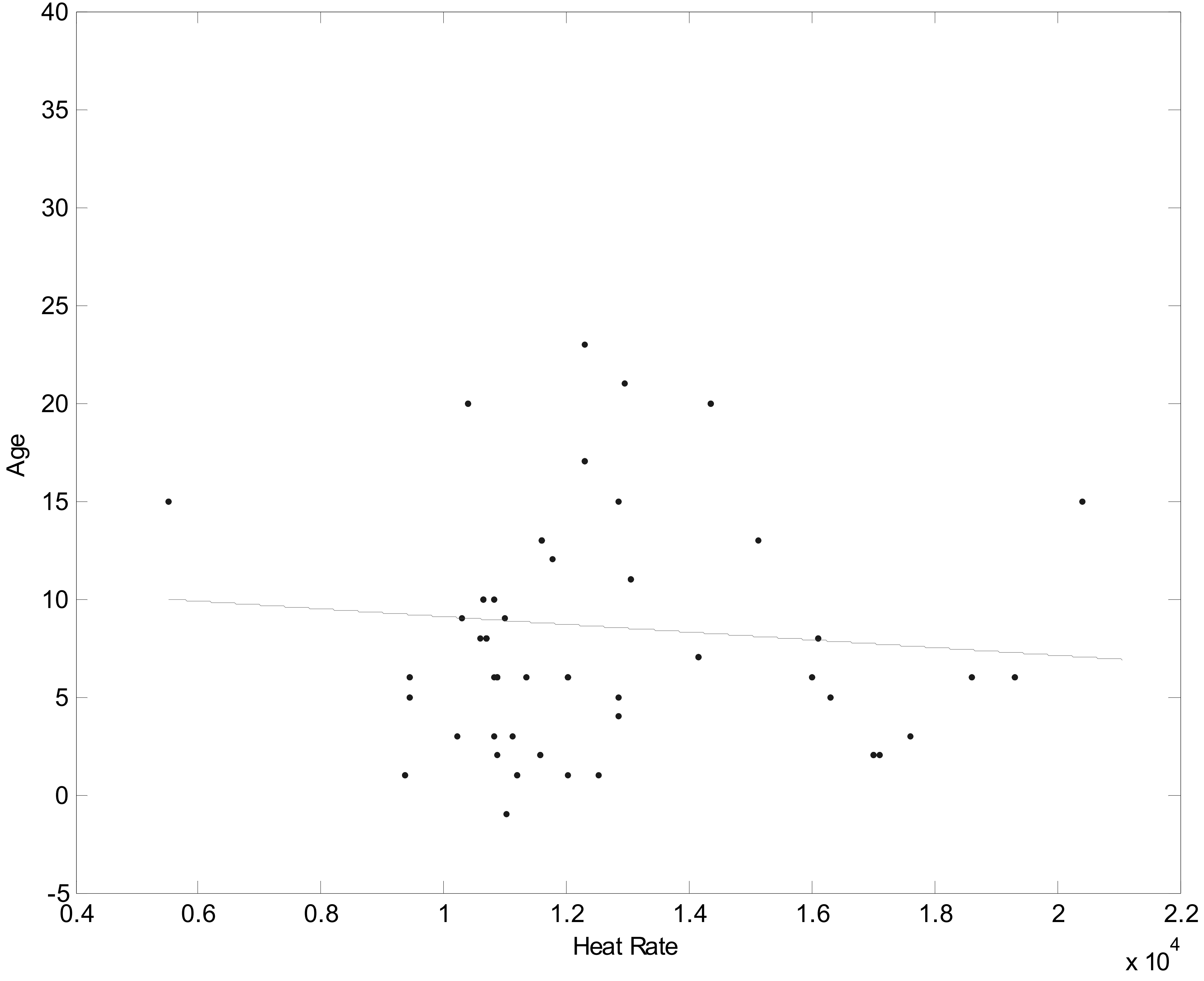


Figure 4c: 1990 Age & Heat Rate

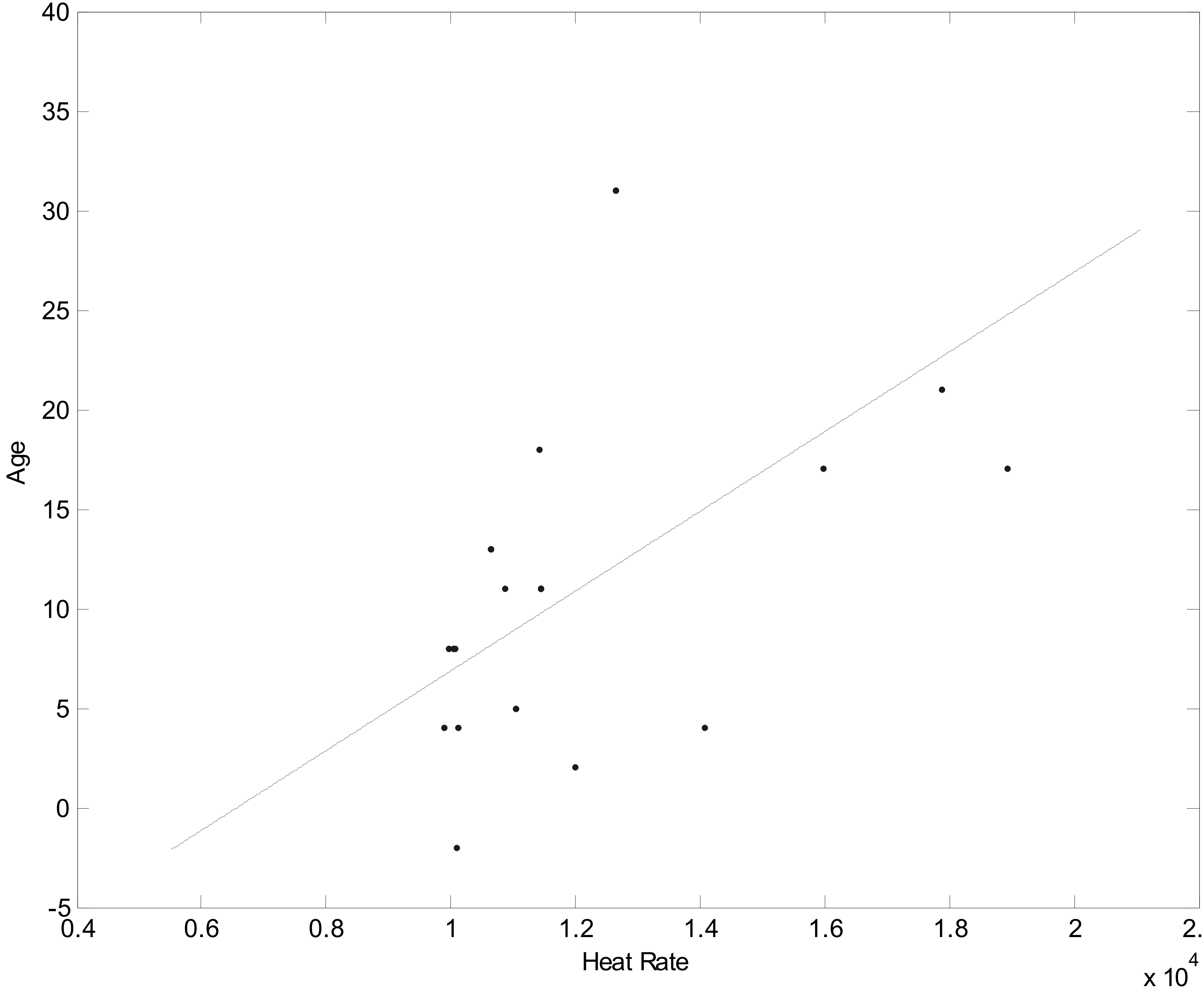
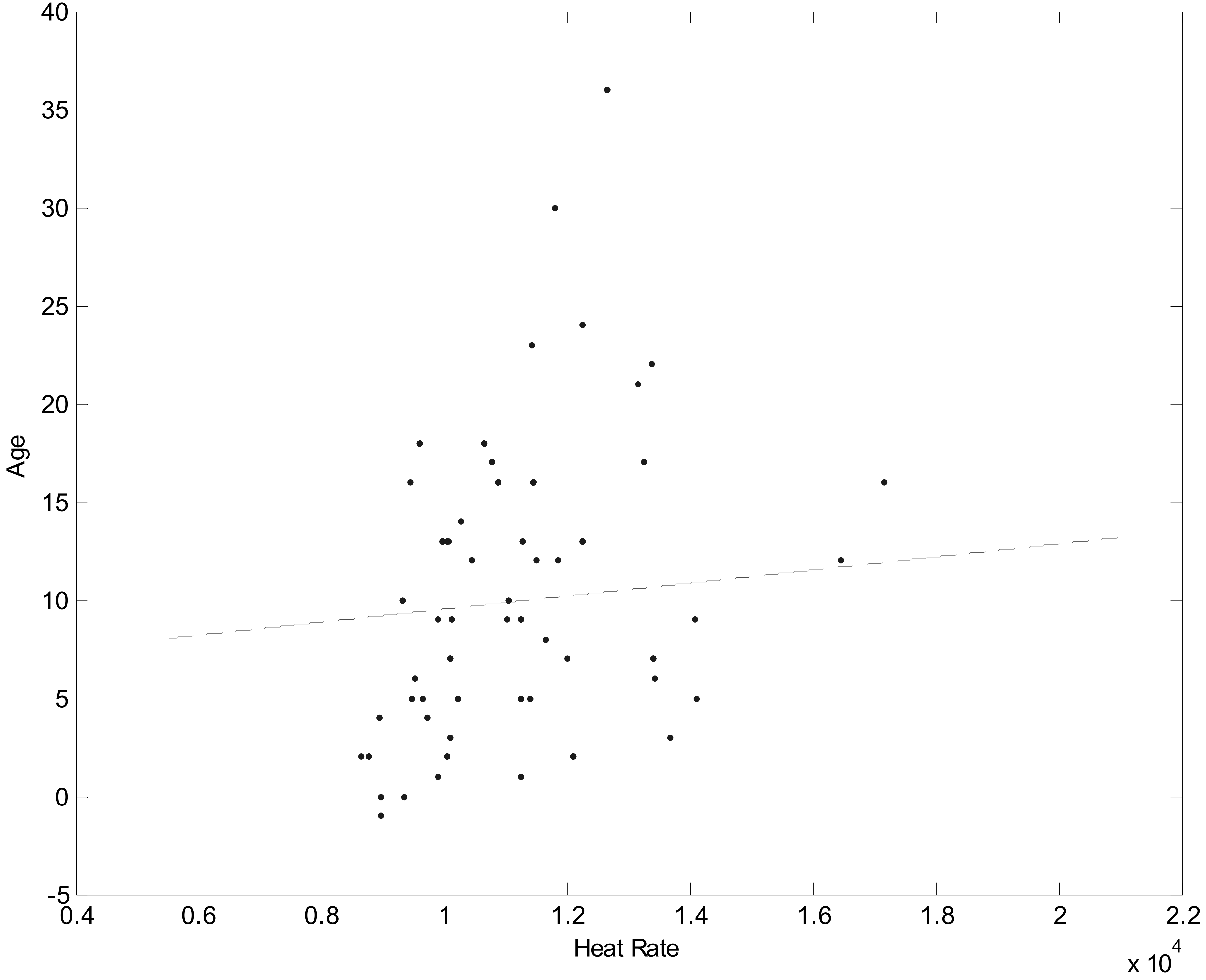


Figure 4d: 1995 Age & Heat Rate



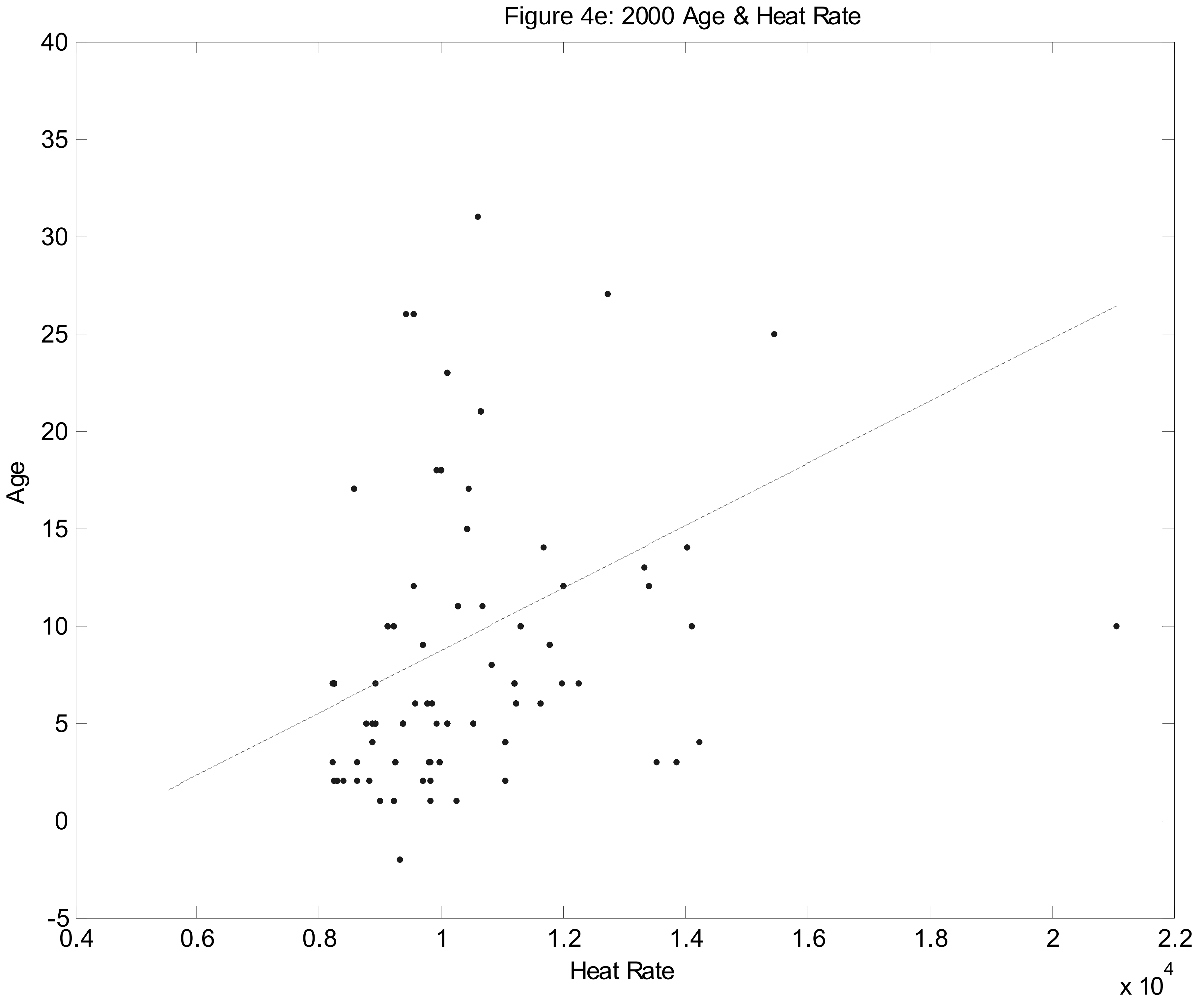


Figure 4e: 2000 Age & Heat Rate
Age
40
35
30
25
20
15
10
5
0
-5
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
Heat Rate
$x\ 10^4$

Figure 6a

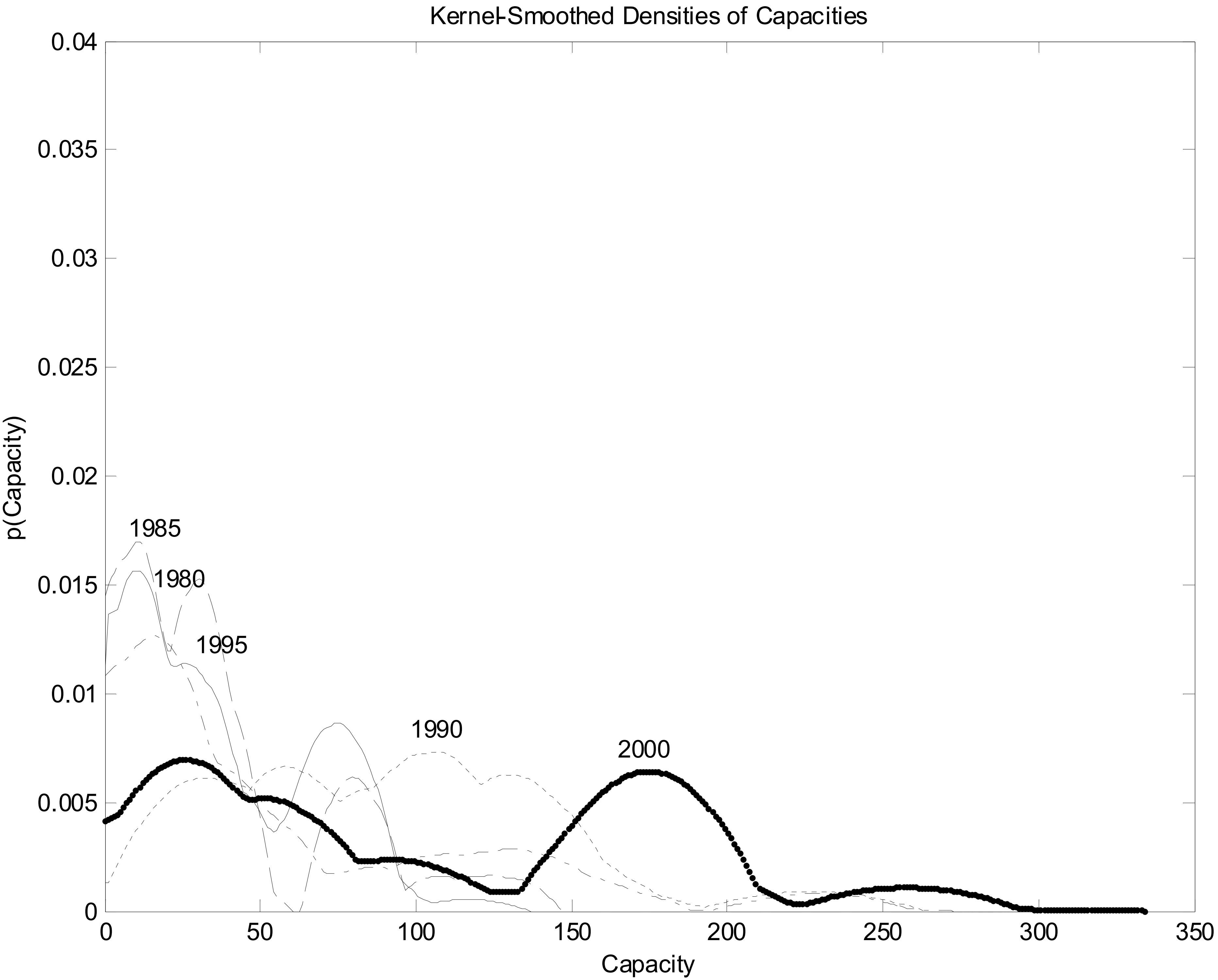

Kernel-Smoothed Densities of Capacities
p(Capacity)
Capacity
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
50
100
150
200
250
300
350
1985
1980
1995
1990
2000

Figure 6b

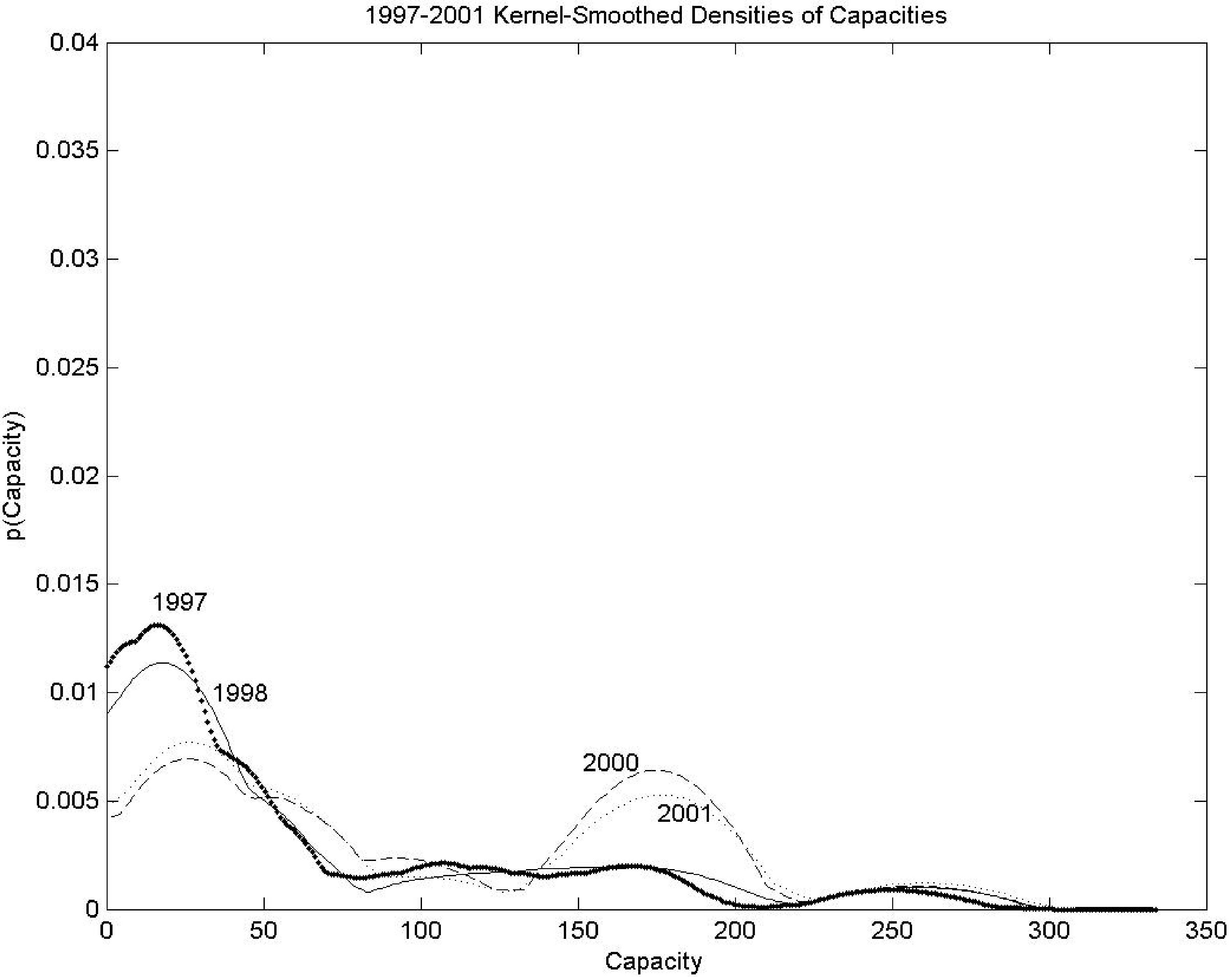

1997-2001 Kernel-Smoothed Densities of Capacities
p(Capacity)
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
50
100
150
200
250
300
350
Capacity
1997
1998
2000
2001

Figure 7a

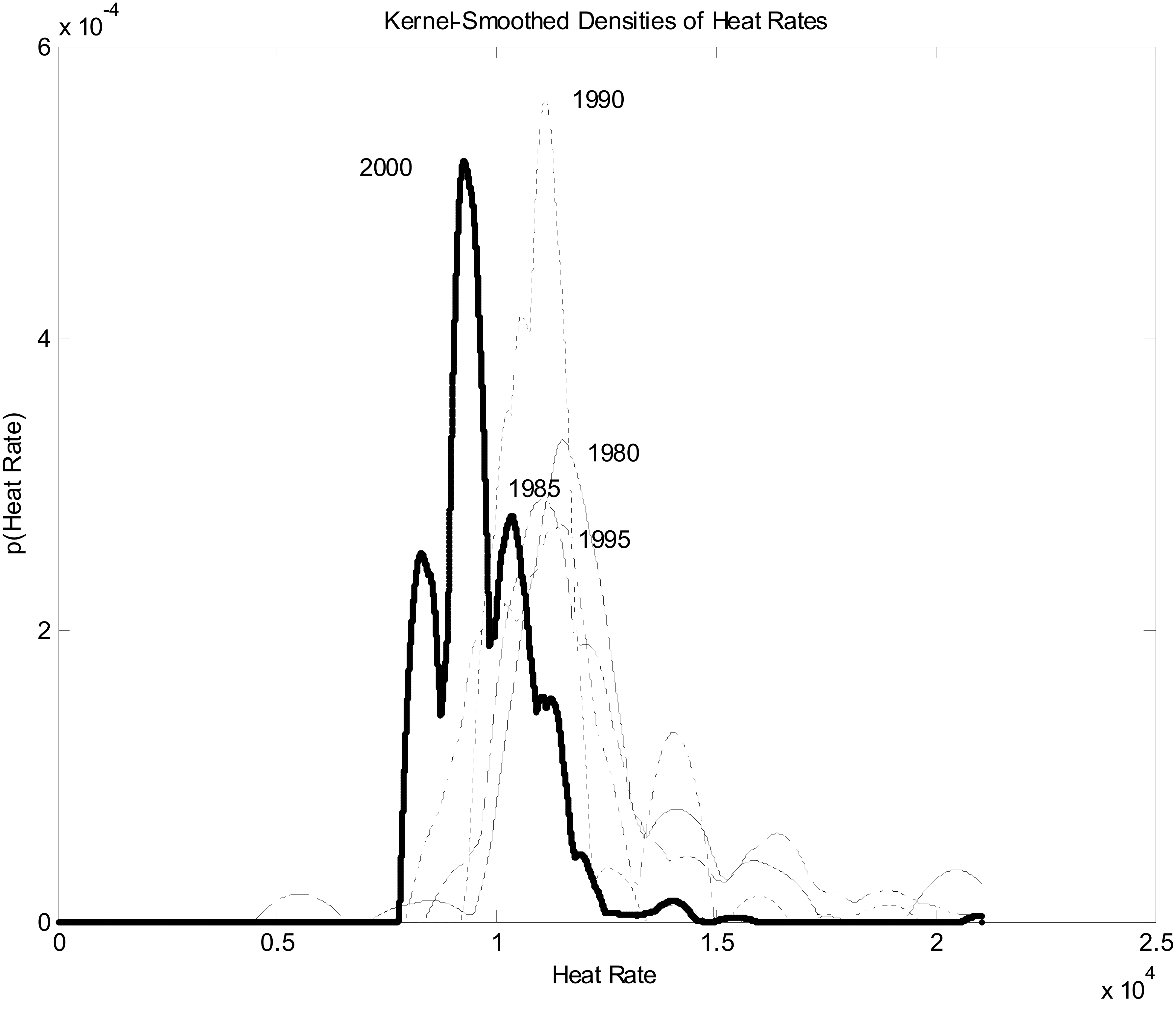

Kernel-Smoothed Densities of Heat Rates
x 10^-4
6
4
2
0
p(Heat Rate)
1990
2000
1980
1985
1995
0
0.5
1
1.5
2
2.5
Heat Rate
x 10^4

Figure 7b

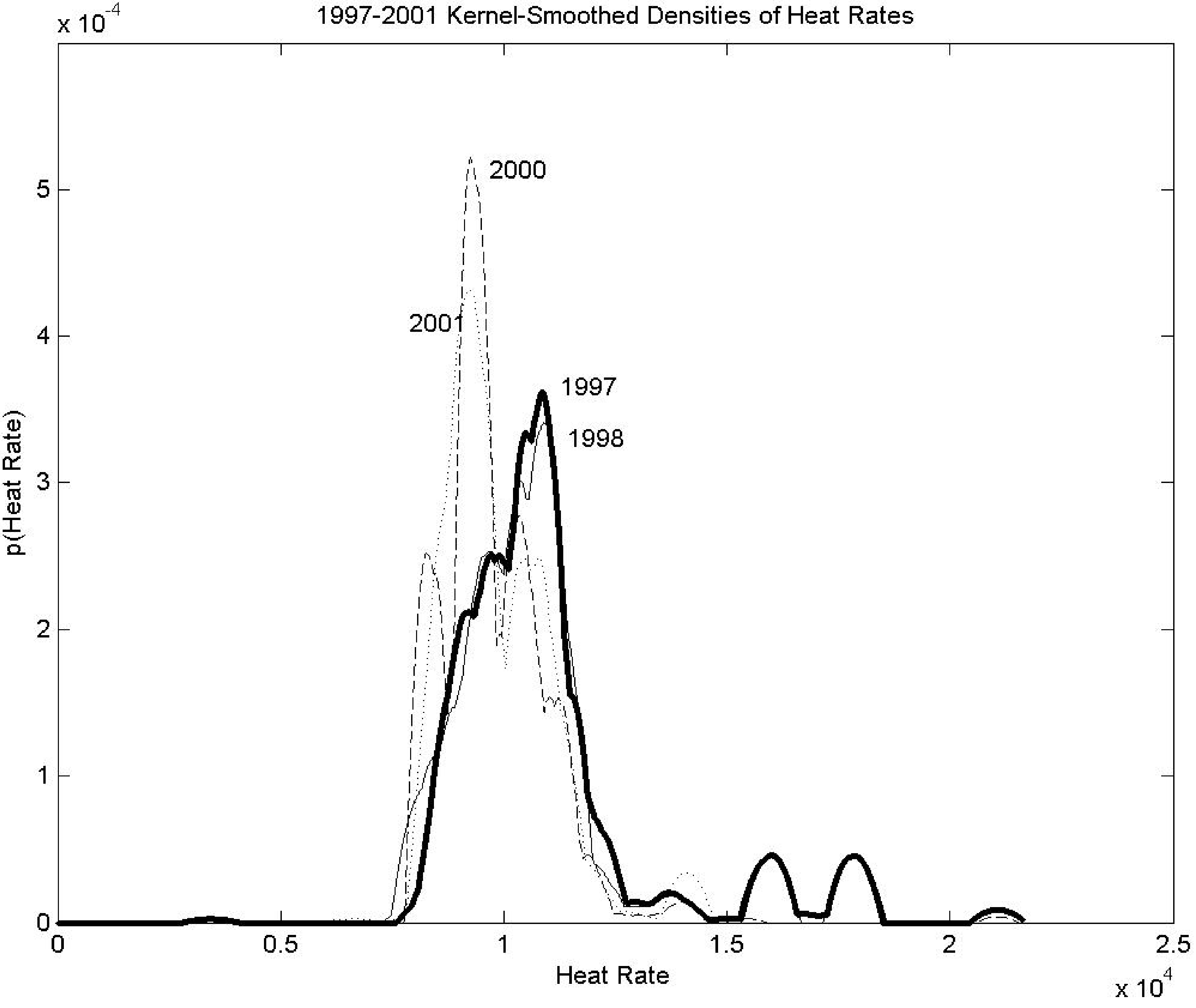
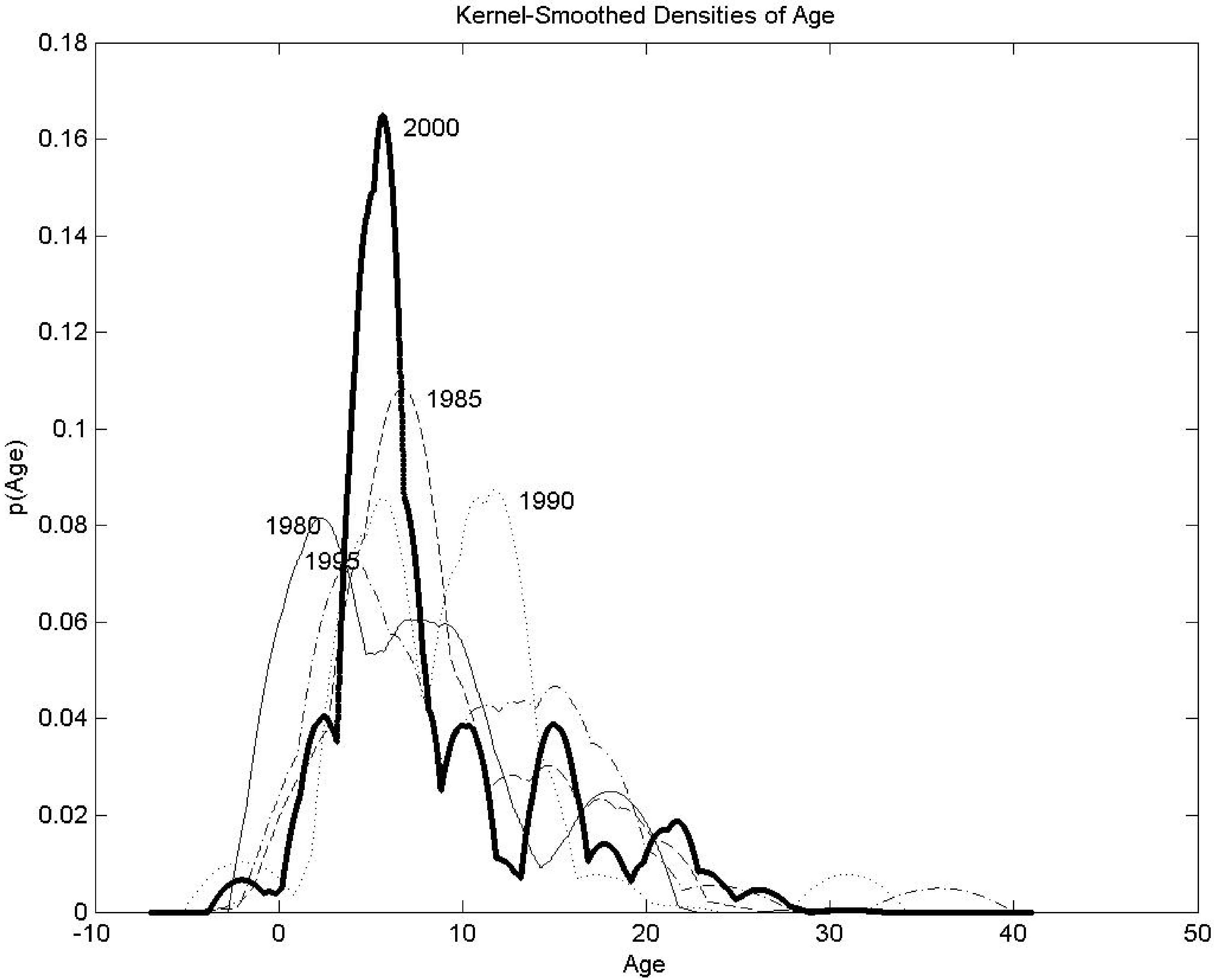
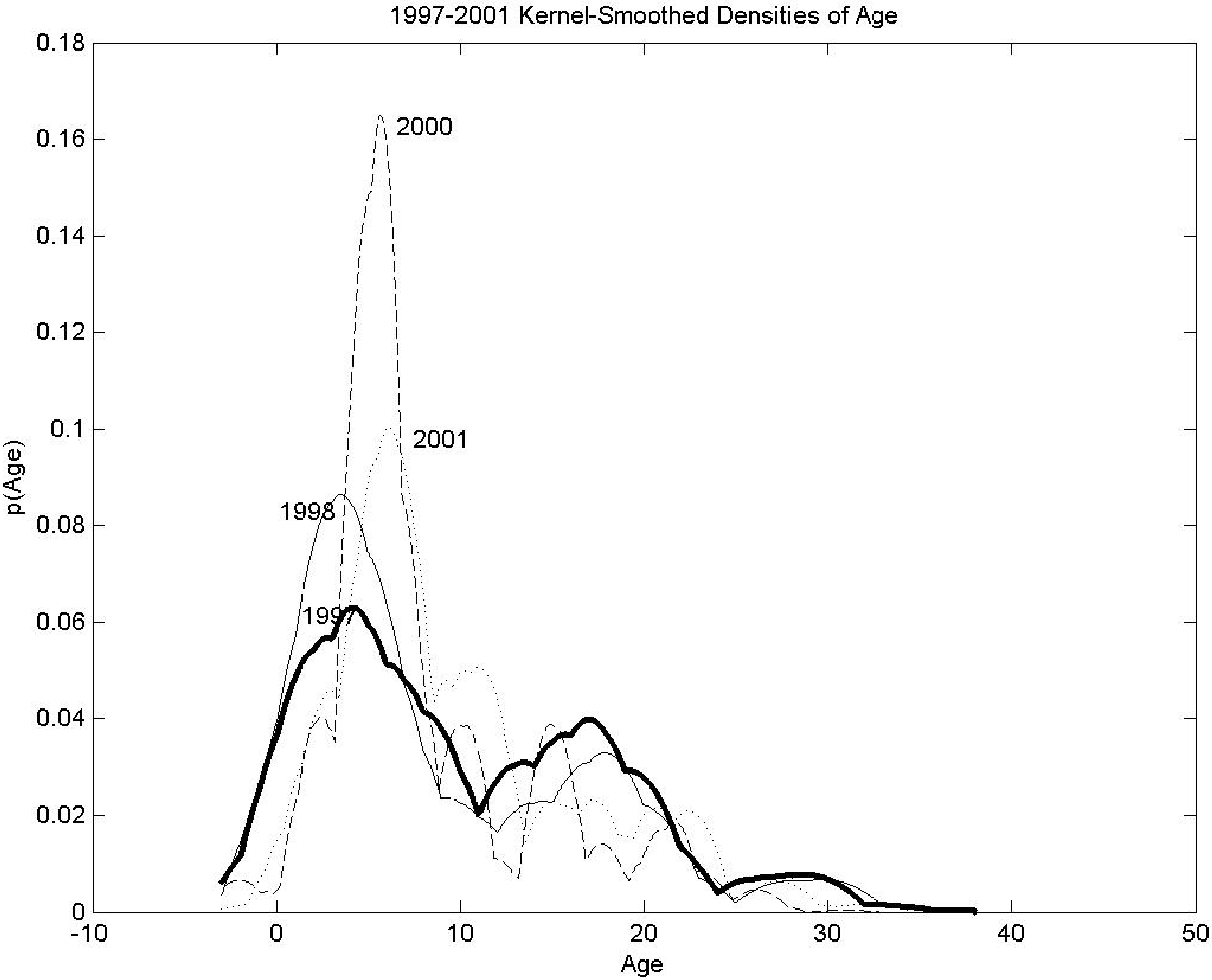

1997-2001 Kernel-Smoothed Densities of Heat Rates
x 10^-4
p(Heat Rate)
0
1
2
3
4
5
2000
2001
1997
1998
0
0.5
1
1.5
2
2.5
Heat Rate
x 10^4

Figure 8a



Kernel-Smoothed Densities of Age
p(Age)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-10
0
10
20
30
40
50
Age
2000
1985
1990
1980
1995

Figure 8b


1997-2001 Kernel-Smoothed Densities of Age
p(Age)
Age
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-10
0
10
20
30
40
50
2000
2001
1998
1997